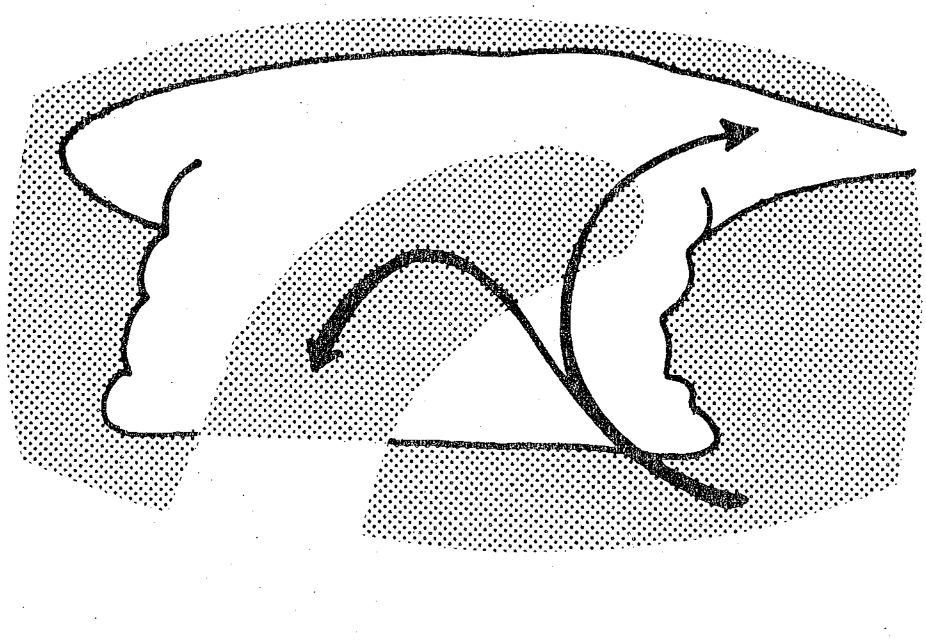
NATIONAL HAIL RESEARCH EXPERIMENT
PROJECT PLAN 1975-1980



NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

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National Center for Atmospheric Research
Boulder, Colorado

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SUMMARY

In 1971, the National Science Board authorized the National Science Foundation to support a National Hail Research Experiment (NHRE) throughout the first two of five planned hail seasons. NHRE is managed by the National Center for Atmospheric Research (NCAR), with participation by university research groups, governmental agencies, and private industry.

The purpose of this document is to provide the Foundation with sufficient information to seek authorization to support NHRE to its completion, and to make certain recommendations as to changes and concepts of the plan of attack, particularly changes in scientific strategy, time tables, and budgets.

As is described in Section I, NHRE was conceived and organized in response to the opportunities apparently offered by hail suppression activities abroad, principally in the Soviet Union, where plausible claims of success at protecting crops and property from hailstorms were being made. However, the verification processes, as well as the physical explanations of how the suppression was achieved and how the methods could be optimized, were deemed inadequate. Therefore, the American experiment was designed not only to determine statistically if damaging hail was being suppressed by cloud seeding techniques, but also to produce sufficient physical evidence to support the statistical conclusions, to recommend how the suppression methods could be optimized, and how they could be adapted to the suppression of storms in other climatic regimes. A further part of the effort is to assess the societal impacts and economic benefits and disbenefits of projected operational hail suppression, so that the end products of the Experiment will be not only to answer the question, "Can we suppress hail?" but also "Should we?".

After two seasons in the field (a third is near completion), plus considerable periods of analysis and reevaluation, NCAR and NSF management have concluded that while the original plan was as soundly conceived as was then possible, our experience to date, plus rapid advances in certain theoretical aspects of the study of convective clouds, have led us to recommend changes in the remainder of the program. These changes, including those in scheduling and budget, are limited to activities we now consider to be essential to the successful accomplishment of the objectives of NHRE, newly stated in Section II.

In Section III of this plan, the essential background of the hail problem, the nature of the most important questions facing NHRE, and the design of the suppression experiment are discussed; Section IV presents preliminary results of the suppression experiment and NHRE achievements; Section V treats special problems and solutions; Section VI describes general plans and budget; Section VII presents detailed plans and budgets; and Section VIII discusses organization and personnel. In this summary, we present the highlights of the overall plan.

A. Research Objectives

The overall goal of NHRE is to determine the potential for suppressing hail by cloud seeding and the extent to which hail suppression can be accomplished effectively on an operational basis. This overall goal translates into the following specific objectives:

(1) to conduct a statistical experiment aimed at proving or disproving the efficacy of hail suppression by the introduction of artificial seeding material such as silver iodide into storm systems;

(2) to conduct a broad-based but highly focused and integrated research program aimed at understanding the mechanisms of both natural hail development and the effects of seeding on hail growth;

(3) to conduct economic, social, and legal studies aimed at assessing costs of a hypothetical hail suppression system, benefits and disbenefits, and social and legal factors relevant to the implementation of an operational system.

B. Research Plan

1. Suppression Experiment

a. The present design aims to test the hypothesis that the introduction of artificial ice nuclei will create an overabundance of ice crystals, increasing the competition for moisture, and preventing the growth of any to damaging sizes.

b. The suppression operation comprises the following essential features: (1) declaration of a 'hail day' when the reflectivity first reaches a prescribed threshold (45 dBZ) at a height exceeding the −5°C level in any storm projected to hit the target area in 20 minutes; (2) such 'hail days' are seed or no-seed days on a random draw; (3) on seed days, aircraft are vectored to likely inflow and updraft regions under radar control, but final choice of seeding site is made by the pilot upon isolating the major updraft; (4) silver iodide flares and rockets are fired alternately as long as the updraft and the radar reflectivity maintain minimum specified strengths.

c. The target or "protected area" (PA) of 625 sq. mi. is instrumented with 240 hail/rain separators to record time resolved total hail and rainfall rates and 240 hailpads to record time-integrated hail size distributions. An additional 120 rain gages are dispersed in a border region of about 1600 sq. miles surrounding the PA.

d. Evaluation of effects has previously comprised the statistical comparison of total hail and rain masses and hail/rain ratios in the PA for seed and no-seed days. It is proposed to evaluate other measures including hail size and concentration, radar reflectivity, dual wavelength radar hail signals, and the time-space variations thereof.

e. Synoptic and mesoscale studies aim to identify critical distinctions between hail and non-hail days and seed and no-seed hail days, the latter to assure that the seed days are from a homogeneous sample of hail days and to permit subsequent stratification of seeding potential. Hailstorm predictability is also under study for ultimate operational use.

f. Rain and hailfall samples are taken for studies of silver content to determine whether or not the seeding material was actually taken up and to deduce its time-space trajectory. Silver analyses are also made for health hazard and downwind effects studies.

g. Research in direct support of the suppression experiment includes: (1) microphysics investigations of the nature and activity of the silver iodide (AgI) and the concentrations of AgI and ice crystal products in seeded clouds; (2) macrophysics studies of air motion related to the trajectories and dispersion of the AgI and to the optimum seeding sites; (3) radar studies aimed at detecting direct physical effects of seeding; and (4) numerical modeling to simulate the effects of seeding, to optimize seeding methodology, and to evaluate other seeding material and methods.

h. Operations research aimed at optimizing the entire suppression program and ultimately at the design of an operational system is a continuing effort.

Detailed design of an operational system will be undertaken later in the program if hail suppression is indicated to be feasible.

i. The suppression experiment is planned to extend for seven hail seasons, in order to gather the minimum of 105 samples required to reach statistically significant conclusions on a hailfall reduction of about 30% (see Section IV A for supporting rationale).

j. Planned changes, compared with previous NHRE plans: (1) extend the suppression experiment from five to seven hail seasons; (2) deploy hail-size spectrum sensors in PA in summer 1975 to permit measurement of the fundamental parameters hypothesized to be affected by seeding; (3) major enhancements in analysis and support staff for the suppression program to permit intensive continuing analysis.

k. The physical, statistical, and operational design of the experiment will undergo an additional critical review by UCAR/NCAR management in the fall of 1974. Progress and performance will continue to be critically evaluated at regular intervals by UCAR/NCAR management and the NHRE advisory panel.

2. <u>Economic, Social, Legal Studies</u>

a. Crop damage functions are related to hailfall parameters and changes in hailfall within the PA are compared to damage on adjacent cooperating farms. Rainfall changes in the PA are related to crop yields. Results are converted to market value to deduce economic benefits of both hail reduction and rain enhancement.

b. A hypothetical operational hail suppression program is being evaluated in terms of cost/benefit ratios; costs are based in part upon estimates provided by commercial weather modifiers. Preliminary results indicate that a 10% hail reduction would be cost effective. Also the benefits of 20% reduction in hail would be negated by a 5% associated reduction in rainfall at the critical part of the growing season.

c. Effects of silver iodide on insects, animals, and on the entire food chain are being studied under subcontract. Downwind effects of silver iodide and rainfall changes are under investigation.

d. Social response studies to the NHRE experiment and to a future operational program are in progress. Changes in existing laws and regulations necessary to permit a limited-risk operational program will be investigated.

3. <u>Supporting Research</u>

a. Microphysics: (1) study the nature, activation spectra, and mode of activation of both natural ice nuclei and silver iodide; (2) determine concentrations of AgI and ice crystal products in seeded storms; (3) investigate locations of hail embryos through coordinated penetrations and radar, and deduce subsequent hail growth histories from rate of development of first echoes and reflectivity gradients in radar overhang of mature storms.

b. Macrophysics: (1) determine essential features of airflow in and around hailstorms through coordinated aircraft circumnavigation and penetration and Doppler radar measurements; (2) determine hailstone trajectories through (1) above and with the aid of the dual wavelength radar hail signals; (3) study the trajectories and dispersion of seeding material; (4) evaluate storm water budgets and precipitation efficiency with special attention to the effect of seeding on efficiency; (5) validate the dual wavelength radar for hail detection; (6) investigate the relations between the evolving 3-dimensional fields of radar reflectivity, Doppler velocity, radar hail signals and the direct manifestations of hail; (7) integrate all of the above with the aim of synthesizing a model of a hailstorm.

c. Numerical Modeling: Develop sequentially one and two-dimensional time dependent numerical storm models with improved microphysics and realistic dynamics aimed at providing an integrated validated model which (1) identifies the environmental factors controlling hailstorm genesis and evolution, (2) reproduces the hailstone life-cycle, (3) simulates the microphysical and dynamic changes induced by seeding, and (4) permits the optimization of seeding techniques to maximize the joint benefits of hail suppression and rain enhancement.

4. <u>Emphasis in FY-75 and FY-76</u>

a. Suppression Experiment: Top priority will be given to the critical review of the experimental design. Electro-optical hail size sensors will be procured and deployed by summer 1975. Suppression analysis staff will be greatly enhanced by reassignments and new hires. Data base management system will be reorganized with stress on accuracy, accessibility, and comprehensiveness. Intensive analysis will be undertaken with the aims of (1) examining of the bulk of past data, (2) identifying those parameters which are most sensitive to seeding effects, and (3) establishing optimum statistical tests and methodology. Data reduction and analysis will be a continuing effort beyond 1976.

b. Economic, Social, Legal: Emphasis will be on economic benefits and health hazard effects. Cost-benefit studies of a hypothetical operational suppression program will be continued and intensified in later stages of the program.

c. Supporting Research: 1975-76 period will concentrate heavily on those factors critical to the suppression experiment, including: (1) laboratory AgI studies, (2) in-cloud measurements of AgI and ice crystal products, (3) the location and growth rates of hail embryos, (4) airflow and radar studies relevant to hail trajectories, the pin-pointing of preferred seeding sites and times, and the trajectories and diffusion of seeding material, (5) dual wavelength radar hail detection, and (6) numerical modeling of seeding effects. Other supporting research will be accomplished in 1975-76 only to the extent that it is necessary to these objectives and is a natural consequence thereof; otherwise such studies will be delayed until 1977.

C. Organization and Management

NHRE was completely reorganized in the spring of 1974. The organizational charts are presented in Figures 17-20. Figure 17 shows the new staff organization with all internal NHRE assignments; Fig. 18 shows the field management organization for 1974 indicating primary managerial responsibilities of key internal staff, subcontractors, and other agency participants for various components of the field activities. Figure 19 illustrates 1974 field operations organization and the key staff responsible for the various functions during a typical operation. Figure 20 is an overall organizational chart indicating the prime functions of all participants including subcontractors, NCAR support activities and cooperating government agencies.

The key NHRE staff are:

Dr. David Atlas - Director

Mr. Richard W. Sanborn - Deputy Director

Dr. Keith A. Browning - Chief Scientist (1 October 1974 through 30 September 1975, possibly longer)

Dr. Clifton C. Lovell - Manager, Suppression Experiment

Dr. J. Doyne Sartor - Senior Consultant, Suppression Experiment

Dr. Charles A. Knight - Manager, Microphysics Program

Dr. Jan Rosinski - Lead Scientist, nucleation studies

Dr. Thomas G. Kyle - Lead Scientist, precipitation microphysics

Dr. G. Brant Foote - Manager, Macrophysics Program, and Acting Manager Numerical Modeling Program

Mr. James C. Fankhauser - Lead Scientist, air motions studies.

Dr. Peter J. Eccles - Lead Scientist, radar studies

Dr. Tsutomu Takahashi - Lead Scientist, numerical modeling

All of the above devote 100% of their efforts to the NHRE program.

D. Utilization Plan

NHRE has organized and holds regular meetings of a Citizens' Council comprised of local farmers and other interested individuals to maintain communications regarding on-going activities and general awareness of progress, thereby encouraging overall understanding, support, and acceptance of future operational activities. Weekly news releases are made during the field season to maintain general public awareness and acceptance. Continuing societal reponse studies by Professor Haas of the University of Colorado aimed at assessing public reactions to both research and a future operational suppression program and suggest necessary public and political steps required for the implementation of operational programs. Joint studies with the U. S. Department of Agriculture attempt to assess the viability of operational hail suppression programs in the Great Plains using on-going projects as examples. Exchange of data with the Crop Hail Insurance Actuarial Association should lead to improved estimates of local crop losses and the relation of physical hail parameters to crop damage. Economic studies based on these data may lead to an ultimate operational strategy of combined hail insurance and suppression to minimize economic losses and risk. Preliminary legal studies already done will be followed by an in-depth investigation of the legal and political factors associated with an operational hail suppression program which involves a multiplicity of private and public groups and organizations and crosses county and state boundaries. All these activities promise to set the stage for the utilization of operational hail suppression by the public and private sectors if and when suppression is demonstrated to be feasible.

E. Related Projects

The USSR is spending over $100 million per year on 11 projects in hail suppression research. South Africa is spending $500,000 in government funds and about $2 million in private funds. Kenya is spending over $500,000 in private funds. The State of South Dakota has in operation a hail suppression program funded jointly by governmental and private sources. The Canadian government has sponsored a full scale hail program which is now being operated by private sources. There are also hail programs in Yugoslavia, France, Italy, Switzerland, and Argentina. A modest program is also underway in the Peoples Republic of China.

The NSF/RANN Weather Modification Program funds small grants to University groups to do research related to NHRE, but not contained in the core of NHRE.

NHRE maintains regular contacts with the programs in Canada, Argentina, and South Africa and monitors developments in the other areas irregularly through visits, international meetings, the literature, and correspondence.

F. Work Plan

1. The <u>basic work plan</u> is outlined in the following charts. It reflects the emphasis presented under Section B of this summary (Research Plan) and the priorities discussed in Section VI (General Plans and Budget). As indicated in the latter section, all efforts related to the suppression experiment and the economic, social, and legal studies will be undertaken; in these areas, priorities indicate only the probable sequence in which the work will be accomplished. In the areas of supporting research, those investigations which are critical to the suppression experiment will generally receive the earliest attention. Other supporting studies will be done simultaneously only to the extent that the effort is a natural consequence thereof and can be accomplished in parallel; otherwise, they will be undertaken subsequently. Because the supporting research deals with problems of a very basic nature, no assurance can be given as to completion dates, or indeed, as to whether or not definitive results will be forthcoming. For these reasons, the execution of the lower priority studies is dependent upon the completion of those of greater importance.

2. <u>Reductions</u>: The budgetary target figures specified by NSF for FY 75 and 76 preclude certain important activities in order to put sufficient resources into the correction of previous deficiencies noted by NHRE and NCAR management and by the NHRE Review Panel and to enhance the effort in more urgent areas. Some of the key reductions in FY 75 and 76 are: (a) the Wyoming Queen Air; (b) the CHILL radar (operated by the University of Chicago and Illinois State Water Survey); (c) the Desert Research Institute (University of Nevada) studies of rain and hail silver content; (d) two upper air radiosonde stations instead of five; (e) no major improvements in the CP-2 radar, the Data Acquisition and Display System, or the surface mesonetwork.

Figure 1

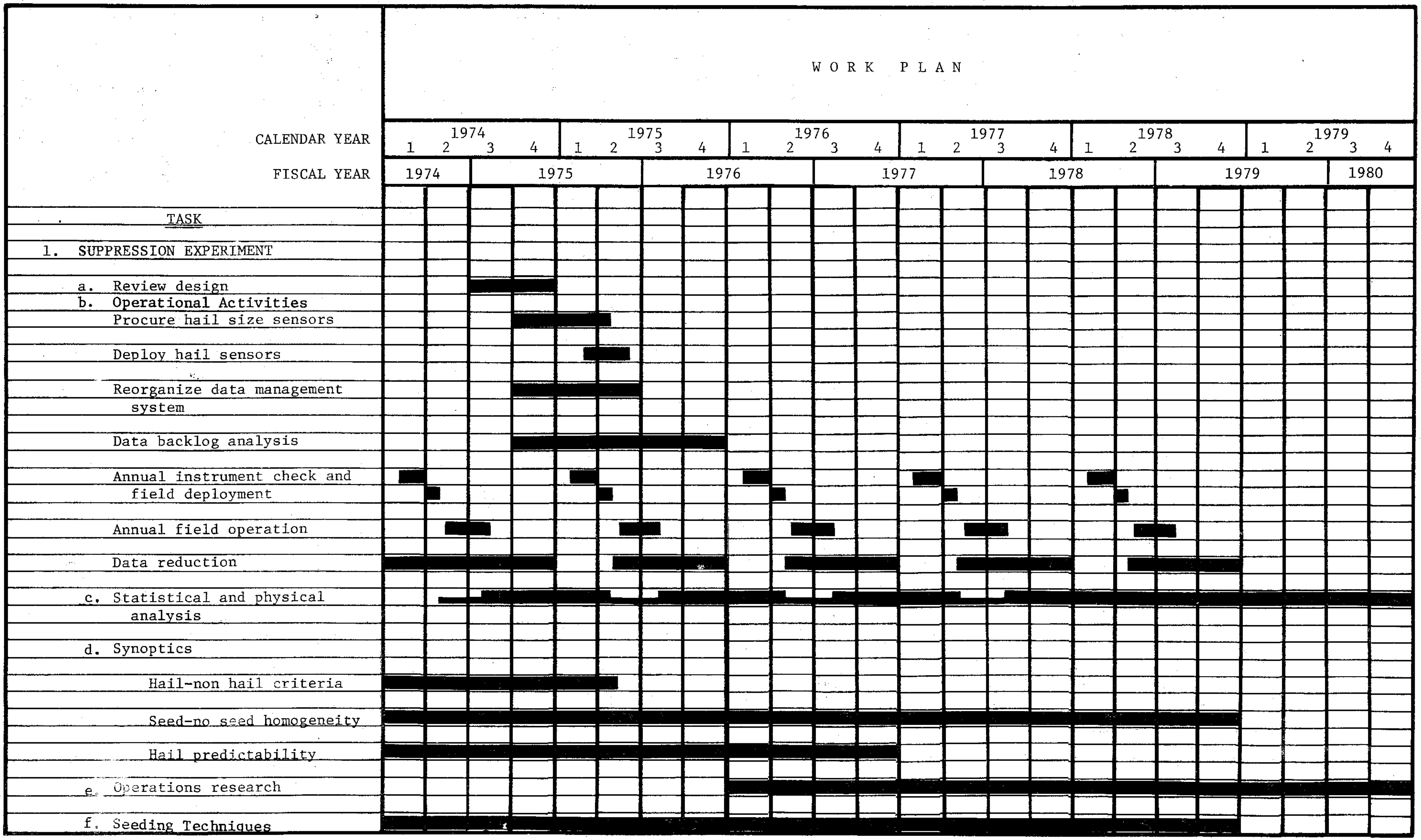

WORK PLAN
CALENDAR YEAR
1974 1 2 3 4
1975 1 2 3 4
1976 1 2 3 4
1977 1 2 3 4
1978 1 2 3 4
1979 1 2 3 4
FISCAL YEAR
1974
1975
1976
1977
1978
1979
1980
TASK
1. SUPPRESSION EXPERIMENT
a. Review design
b. Operational Activities
Procure hail size sensors
Deploy hail sensors
Reorganize data management system
Data backlog analysis
Annual instrument check and field deployment
Annual field operation
Data reduction
c. Statistical and physical analysis
d. Synoptics
Hail-non hail criteria
Seed-no seed homogeneity
Hail predictability
e. Operations research
f. Seeding Techniques

Figure 2

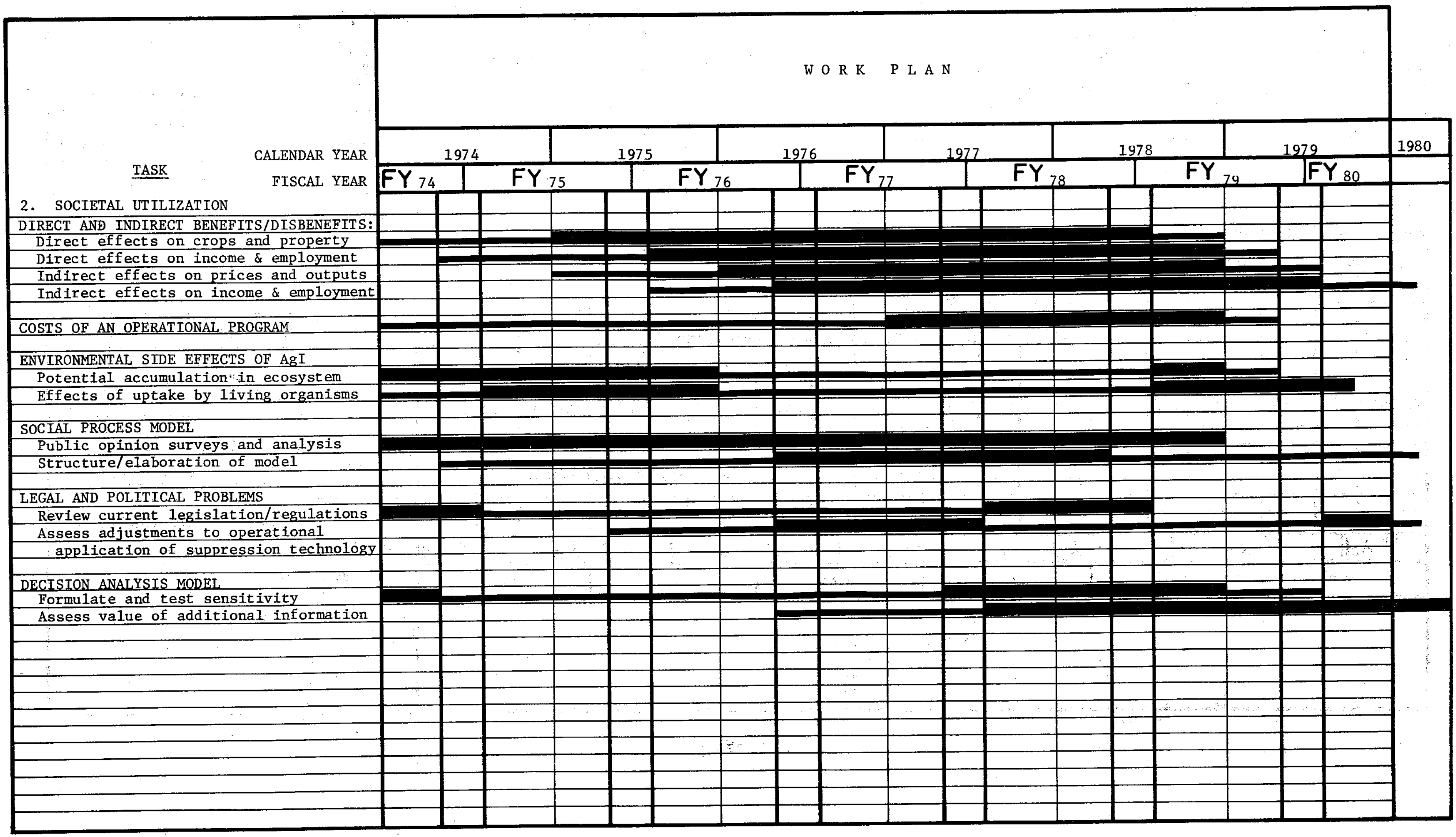

WORK PLAN
TASK
CALENDAR YEAR
FISCAL YEAR
1974
1975
1976
1977
1978
1979
1980
FY 74
FY 75
FY 76
FY 77
FY 78
FY 79
FY 80
2. SOCIETAL UTILIZATION
DIRECT AND INDIRECT BENEFITS/DISBENEFITS:
Direct effects on crops and property
Direct effects on income & employment
Indirect effects on prices and outputs
Indirect effects on income & employment
COSTS OF AN OPERATIONAL PROGRAM
ENVIRONMENTAL SIDE EFFECTS OF AgI
Potential accumulation in ecosystem
Effects of uptake by living organisms
SOCIAL PROCESS MODEL
Public opinion surveys and analysis
Structure/elaboration of model
LEGAL AND POLITICAL PROBLEMS
Review current legislation/regulations
Assess adjustments to operational
application of suppression technology
DECISION ANALYSIS MODEL
Formulate and test sensitivity
Assess value of additional information

Figure 3

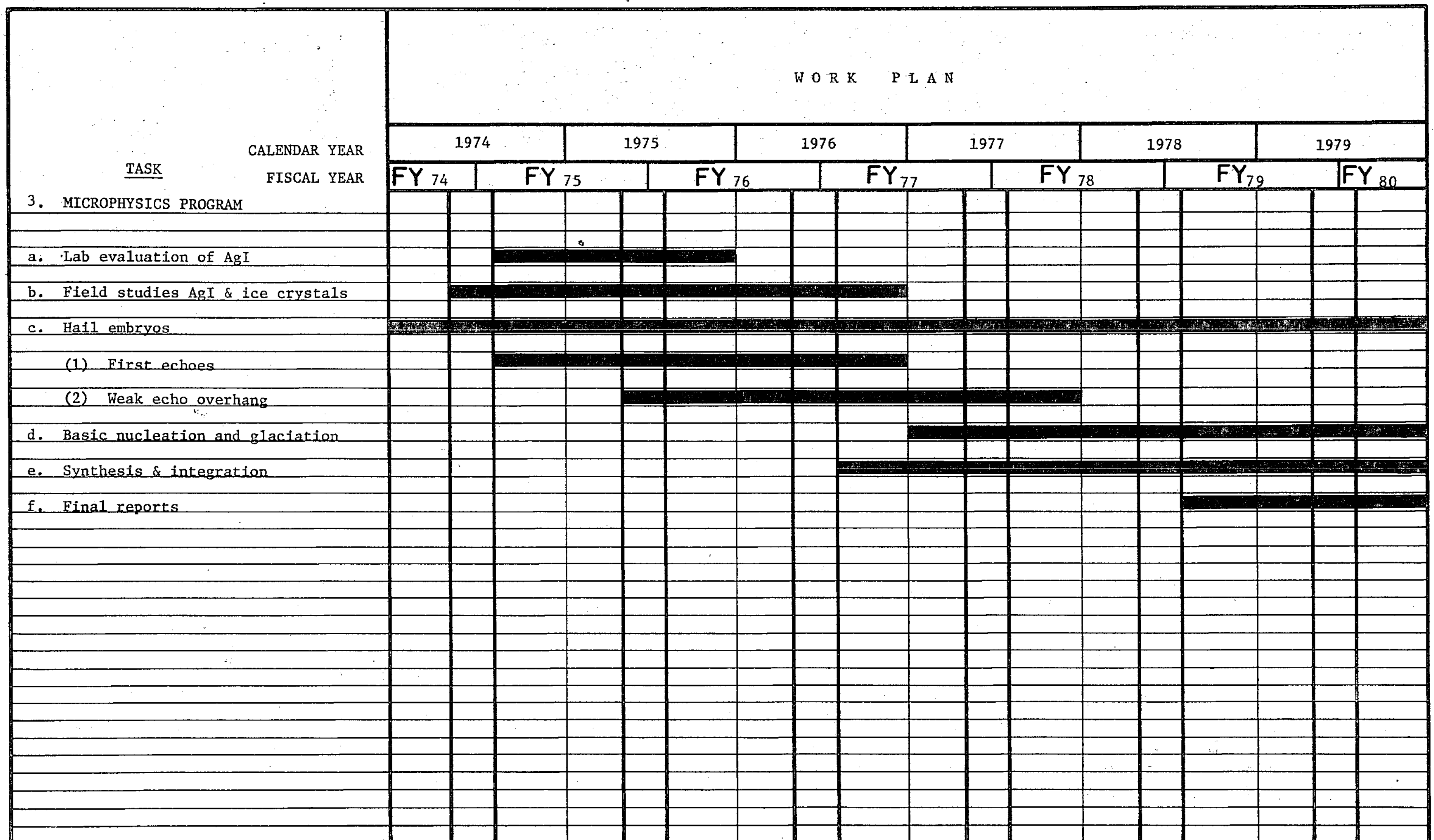

WORK PLAN
TASK
CALENDAR YEAR
FISCAL YEAR
1974
1975
1976
1977
1978
1979
FY 74
FY 75
FY 76
FY 77
FY 78
FY 79
FY 80
3. MICROPHYSICS PROGRAM
a. Lab evaluation of AgI
b. Field studies AgI & ice crystals
c. Hail embryos
(1) First echoes
(2) Weak echo overhang
d. Basic nucleation and glaciation
e. Synthesis & integration
f. Final reports

Figure 4

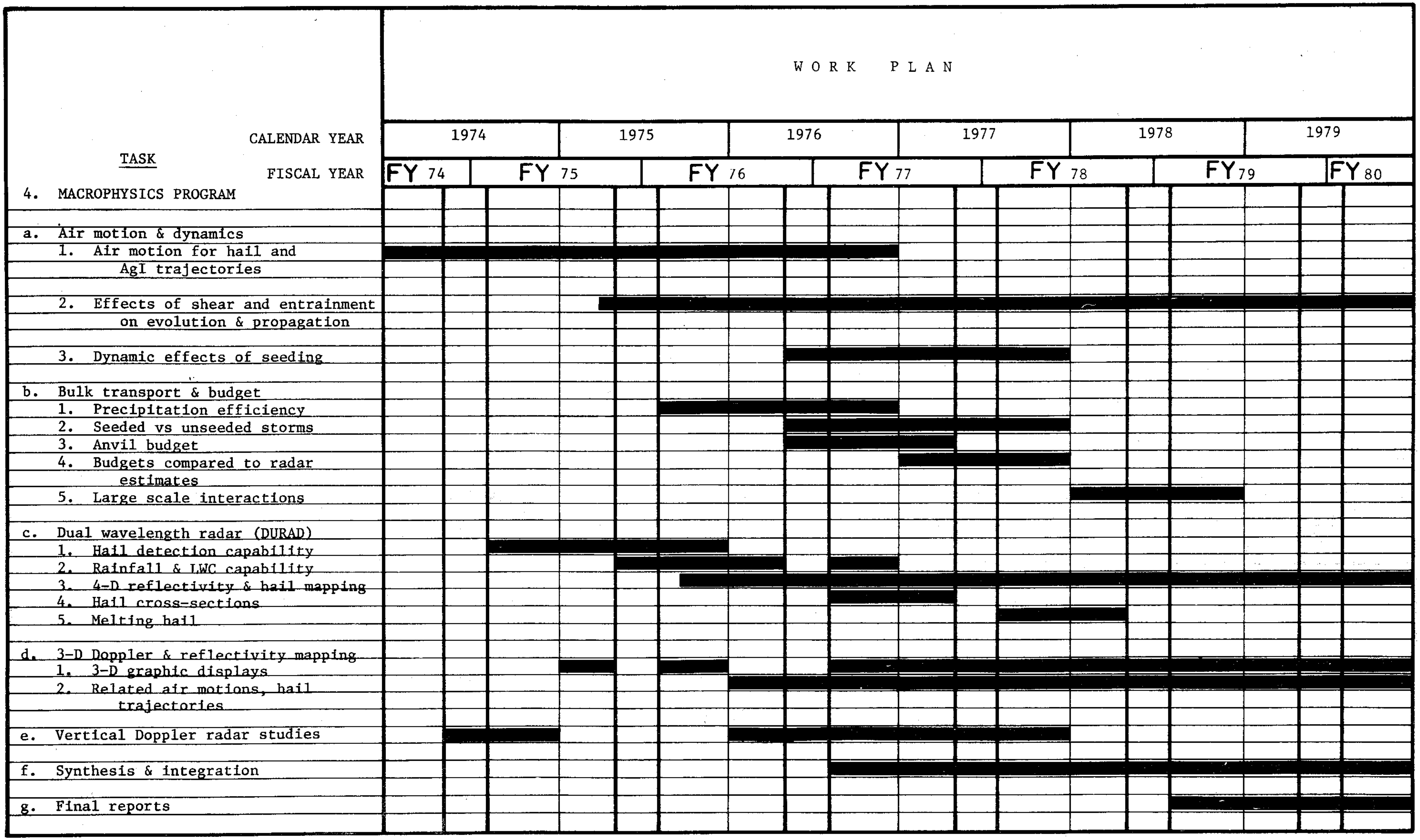
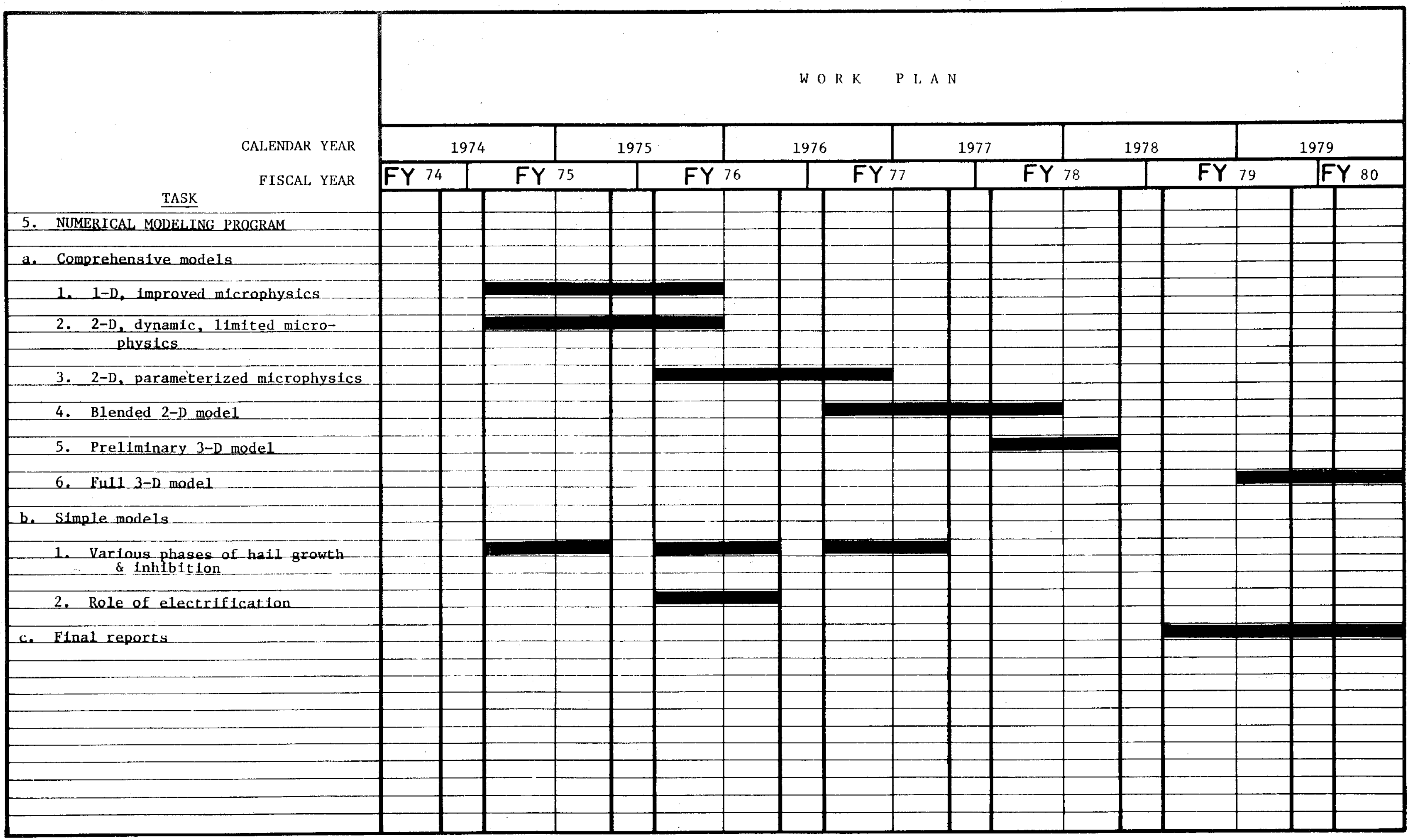

WORK PLAN
TASK
CALENDAR YEAR
FISCAL YEAR
1974
1975
1976
1977
1978
1979
FY 74
FY 75
FY 76
FY 77
FY 78
FY 79
FY 80
4. MACROPHYSICS PROGRAM
a. Air motion & dynamics
1. Air motion for hail and AgI trajectories
2. Effects of shear and entrainment on evolution & propagation
3. Dynamic effects of seeding
b. Bulk transport & budget
1. Precipitation efficiency
2. Seeded vs unseeded storms
3. Anvil budget
4. Budgets compared to radar estimates
5. Large scale interactions
c. Dual wavelength radar (DURAD)
1. Hail detection capability
2. Rainfall & LWC capability
3. 4-D reflectivity & hail mapping
4. Hail cross-sections
5. Melting hail
d. 3-D Doppler & reflectivity mapping
1. 3-D graphic displays
2. Related air motions, hail trajectories
e. Vertical Doppler radar studies
f. Synthesis & integration
g. Final reports

Figure 5


WORK PLAN
CALENDAR YEAR
FISCAL YEAR
TASK
1974
1975
1976
1977
1978
1979
FY 74
FY 75
FY 76
FY 77
FY 78
FY 79
FY 80
5. NUMERICAL MODELING PROGRAM
a. Comprehensive models
1. 1-D, improved microphysics
2. 2-D, dynamic, limited micro-physics
3. 2-D, parameterized microphysics
4. Blended 2-D model
5. Preliminary 3-D model
6. Full 3-D model
b. Simple models
1. Various phases of hail growth & inhibition
2. Role of electrification
c. Final reports

3. Enhancements: (a) increased scientific and support staff for the suppression experiment (see Section VI); (b) statistical consultant for suppression experiment; (c) a network of electro-optical hail-size sensors; (d) refinements in the data management system; (e) additional radar meteorologist and programmer in radar studies to solve data reduction backlog and accelerate analysis; (f) establishment of a numerical modeling group; (g) modest contracts to University of Arizona for modeling and Clemson University for suppression effects analyses; (h) reorientation of other university contracts to emphasize top priority analyses; (i) improvement of critical instruments on sailplane and T-28 penetrating aircraft; (j) sailplane penetrations of weak echo region and sampling of AgI and ice crystal products by both sailplane and T-28 in seeded storms; (k) improved signal averager for dual wavelength radar; (l) low cost 3-D color display for Data Acquisition and Display System and new program routines to permit additional display options.

G. Achievements

A comprehensive list of NHRE achievements to date in the scientific and technological areas is presented in Section IV., B. These accomplishments demonstrate that NHRE is well equipped to carry forth the suppression experiment to a successful conclusion, that much has already been learned about some of the key processes of natural storms and their susceptibility to modification, and that there is good promise that definitive results will be forthcoming.

H. Budget

The overall program budget for FY 75 through FY 80 follows. Detailed budgets for each of the sub-programs are shown within the main body of the plan (Section VII). The FY 76 total is 5% above the FY 75 level to account for inflation. The increase in FY 77 is required to bring the program back to optimum strength in certain critical areas (the Wyoming Queen Air, the CHILL radar, enhanced analytical studies by university participants).

It is to be noted that additional support for NHRE is provided as part of the NCAR program funded by the NSF National and International Programs Directorate. The estimated cost of this support in FY 1974 was: Research programs, $500,000; support by Atmospheric Technology Division, $600,000; administrative and general support, $600,000. Similar levels of support are planned for through FY 78, expect for FY 75 when the NCAR aircraft will not be used extensively.

I. Introduction

The yearly loss to agriculture caused by hailfall on a world-wide basis is estimated at approximately one billion dollars. In the United States alone the Department of Agriculture estimates the loss in excess of $500 million per year. Damage to property is more difficult to assess, but is estimated to be some 10-20% of the latter figure.

Though the economic incentive to suppress damaging hail has long existed, the immediate stimulus causing the recent interest and activity in hail research in a number of countries was undoubtedly the claim of spectacular success by workers in the Soviet Union in the late fifties and early sixties. However, while visiting U. S. scientists found these claims impressive, the verification procedures used were and remain unsatisfactory, and there developed the conviction in this country that the time was ripe for a controlled experiment to investigate the feasibility of hail suppression.

In May 1965, the Interdepartmental Committee for Atmospheric Science (ICAS) recommended to the Federal Council for Science and Technology that the National Science Foundation, in consultation with other interested government agencies, should develop a plan for hail suppression research. It was recognized that such a project was big enough to require a collaborative effort, a coordinated experiment and under the direction of one institute, with expert participation by universities, government agencies, private research groups, and industry.

In response, NSF formed the Hail Suppression Research Steering Committee under the chairmanship of Professor V. E. Suomi, which prepared the "Outline of a Hail Suppression Test (forerunner of a National Hail Suppression Program)" (1968). This report was submitted by NSF to ICAS, which approved it and, in

December 1968, NSF requested the National Center for Atmospheric Research to prepare a detailed plan for a national research experiment on the suppression of hail.

A Select Planning Group, drawn from the country at large and supplemented by NCAR staff, prepared the "Plan for the Northeast Colorado Hail Experiment" (NECHE), which was submitted to ICAS and endorsed by that body in April 1969. ICAS thereupon requested NSF to designate management responsibility for the project and, in September 1969, NCAR was so authorized by NSF. The original NECHE plan had called for an intensive investigation into hailstorms to be conducted over a five-year period. The NSF set calendar year 1972 as the first year for full-scale field operations.

During the period 1968-70, studies of hailstorms in northeast Colorado were sponsored by NSF and carried out under the Joint Hail Research Project (JHRP). These studies, collaborative between NCAR, NOAA, and Colorado State University, provided much useful background knowledge and experience for the planning of the envisaged national experiment.

In the authorization from NSF, the project was proposed to start full-scale operations in the summer of 1972, with the period prior to that being devoted to planning and preparation. During the summer of 1971, field trials of such equipment as was already available were carried out, not so much for the purpose of acquiring definitive research material, as to gain experience in operational procedures and techniques. These trials were undertaken and are discussed in the 1971 Summary Report (NHRE, 1972a).

Summaries of the research highlights and reviews of field activities for the first two years of full-scale operation have also been presented (NHRE, 1972b; NHRE, 1973). The 1973 Summary Report includes a list of over one hundred references to research completed by NHRE investigators and their colleagues. In the current document, we present NHRE plans for the 1975-1980 period as they have evolved in the light of ideas and experience gained over the last few years. An intensive reevaluation of the program strategies has been recently conducted to assure that the program focus continues to be on the most important scientific problems and to identify the most promising lines of attack. The emphasis on hail suppression naturally leads us to select the most important problems related to processes most amenable to alteration to achieve hail suppression.

Section II of this document presents the revised NHRE objectives recently approved by both NCAR and NSF/RANN. Section III summarizes the present state of knowledge concerning the hail problem, outlines the important questions which need to be addressed, and presents the design of the suppression experiment. Preliminary results of the suppression experiment and NHRE achievements are treated in Section IV. Section V discusses special problems and solutions concerning organization and management, project integration, university relations, and key scientific issues. Section VI presents general plans and budgets while detailed plans and budgets are given in Section VII. Section VIII deals with organization and personnel.

It will be evident from the body of this plan, that it represents a comprehensive rethinking of the entire problem and the best judgments of both the NHRE staff and its advisors from the universities and elsewhere on approaches necessary to attain NHRE's goals. The plan also responds to the recommendations of the report of the NHRE Review Panel (dated July 16, 1974) within the constraints of budget, facilities, and staff. Needless to say, detailed plans for each year will and should be evaluated and revised as our experience guides us. Nevertheless, the outlines of a sound program are clear.

References:

NHRE, 1972a: National Hail Research Experiment, Summer 1971 Summary Report, NHRE Tech. Report 72/1, NCAR, Boulder, 63 pp.

NHRE, 1972b: National Hail Research Experiment, Summer 1972 Summary Report, NHRE Tech. Report 72/2, NCAR, Boulder, 92 pp.

NHRE, 1973: National Hail Research Experiment, Summer 1973 Summary Report, NHRE Report 73/2, NCAR, Boulder, 93 pp.

II. NHRE Objectives

The original authorizing letter from NSF stated that the goal of NHRE was to perform a coordinated study of hailstorm microphysics and dynamics, with the objective of eventually understanding the mechanisms well enough to develop effective hail suppression techniques. The program was therefore viewed as being comprised of essentially two parts (1) the search for storm mechanisms, and (2) the seeding experiment.

In the light of the evolution of the interpretation of these goals and in response to the desires of NSF/RANN (which assumed NSF responsibility for this program after the initial objectives were established) we have agreed to the following revisions:

<u>The overall goal of NHRE is to determine the potential for suppressing hail damage by cloud seeding and the extent to which hail suppression can be accomplished effectively on an operational basis.</u> The following research objectives have been set out in pursuit of the overall goal.

1. To conduct a statistical experiment aimed at proving or disproving the efficacy of practicable suppression of hail by the introduction of artificial seeding material such as silver iodide into the storm systems.

2. To conduct a broad-based but highly focused and integrated research program aimed at understanding the mechanisms of both natural hail development and the effects of seeding on hail growth with the aims of (1) providing persuasive physical evidence in support of the statistical conclusions, whether positive or negative, (2) generalizing and extending the seeding methodology to other storm types and geographical regions, and (3) assessing the feasibility of hail suppression by other seeding methods.

3. To conduct economic, social, and legal studies with the aim of assessing costs of a hypothetical hail suppression system, benefits and disbenefits including potentially harmful side effects, and social and legal factors relevant to the ultimate implementation of an operational hail suppression program.

Interpretive Comments:

(1) While one of the goals of the supporting research is to permit the generalization and extension of any suppression results to other storm types, regions, and methodologies, it is understood that the result of the statistical seeding experiment will be strictly valid only for the Colorado plains and adjacent areas and for the seeding techniques employed by NHRE.

(2) Because an economically beneficial effect of hail reduction may be negated by a simultaneous reduction in net rainfall, and because the seeding may logically lead to increased rainfall, an associated objective of the statistical experiment is to assess the effects of seeding on rainfall in and downwind of the target area.

(3) Because of the large variability of natural hailfalls, the statistical experiment implies a large enough sample of both seeded and unseeded storms to detect a specified average reduction in hail. As noted in Section IV.A, the detection of a 60% reduction in hail crop damage will require a minimum of 75 'hail days' or 5 years with the average of 15 hail days per year in the NHRE protected area; reductions less than 60% would not be detectable with confidence with such a sample size. Similarly the detection of a 30% hail reduction in hail crop damage would require a minimum of 105 samples and about 7 years of operation with the present size target

area. Because a 30% hail reduction appears to be economically beneficial and because a 60% reduction is now thought to be overly optimistic, the present plan calls for a two year extension of the suppression experiment to obtain approximately 105 samples.

(4) While the economic, social, and legal factors pursuant to any ultimate operational hail suppression program will continue to be investigated throughout this program, the detailed design of a model operational hail suppression program must await demonstration of reasonable promise of positive suppression effects from the statistical experiment. If positive effects are indicated at the end of the 5th or 6th year of the experiment, NHRE will design such a model operational suppression program and assess its cost-effectiveness, its operational capabilities in terms of areal, seasonal, and diurnal coverage, potential side effects such as health hazards, and downwind reductions in rainfall, and social-legal risks.

III. Background

A. The Hail Problem

The National Hail Research Experiment, as in any systematic, scientific effort, attempts to build upon the body of knowledge and theory that already exists. It is appropriate, therefore, to give a very brief synopsis of this body of knowledge and theory; to update this knowledge based upon recent findings of NHRE; to show where old hypotheses need to be tested and where new ones need to be constructed and evaluated; and to set the context for the present and planned research efforts. The literature is truly voluminous. Completeness is not the purpose here; only a few references are given. More detailed background material is to be found in the specific sub-program plans of Section VII.

There is a large amount of fanciful and often mystical historical material on hail, with hail suppression techniques that strike us nowadays as amusing (see, e.g., Morgan, 1973). In fact, one might be surprised at how recent the scientifically important works on hail and hailstorms are, until one realizes that on the one hand, the occurrence and importance of supercooled water has only been recognized commonly for the last fifty years or so, even in the laboratory, and on the other, little could be learned about the air motion in storms before aircraft became available. Before World War II, much of the hail work consisted of observations of hailstones themselves and of hailswaths (Weickmann, 1953). Since World War II there have been great strides in understanding hailstone growth processes, primarily as a result of laboratory work, and substantial advances in understanding storm dynamics, primarily from analysis of information gained in extensive field measurement efforts. While there have been attempts to discover which aspects of storms are necessary for hail formation, many of the efforts to understand the physics of hailstone growth and the air circulation inside severe storms have in fact been separate.

The question of how fast hailstones grow has of course been one of pivotal importance, because this is what determines how long they must be supported in the storm to grow to the observed size. An early idea was that the latent heat of fusion would limit the possible growth rate. If a hailstone grows so fast that it heats up to 0C, then any extra accumulated water is not frozen on, but rather is shed. This growth rate was called the Schumann-Ludlam limit. List (1959) and Macklin (1961) showed that this limit was not real. Instead of shedding water the stone continues to grow as an ice-water mixture (spongy growth). This discovery was touted as the explanation of rapid hail growth, thought at the time to be necessary on the basis of radar observations. Subsequent observations of natural hailstones, however, have shown that, while spongy growth does exist in nature, it is by no means necessary to form large hail, and appears to be rare in small hail.

A large amount of work has been done simulating hailstone growth in laboratories, with the result that hailstone growth processes seem fairly well understood. However, understanding in principle does not imply very precise predictability. Particularly in the case of large hail, complexities introduced by tumbling and by shape and roughness effects give large uncertainties in growth rates and fall velocities.

Work in the Thunderstorm Project (Byers and Braham, 1949) followed by investigations of severe storm structure by Newton, Browning and Ludlam, and others (see Air Motion and Dynamics Program in Section VII) has given a general picture of air motion within these storms. While many features of the circulation proposed by these authors have been subsequently verified, nevertheless, many of the factors that are important in hail formation are still poorly known - particularly the updraft extent, vertical profile, tilt, and steadiness. The few recent direct measurements of airflow within severe storms, by Doppler radar, aircraft, and dropsondes, have tended to show considerable complexity on fairly small scales.

Of the attempts at complete synthesis of hailstone growth in severe storms, those by Browning and collaborators and by Sulakvelidze and collaborators stand out, both in the completeness of conception and in the depth of physical evidence used for support. Both rely heavily upon radar information.

Browning's model was constructed to explain the growth of large hailstones in very large, severe storms. Utilizing radar reflectivity histories of storms,along with data on time and location of hailfall at the ground and microphysical arguments about hail growth (for instance, that the large hail grows in an environment of relatively low liquid water content and small drops; the "weak echo region"), Browning constructed a model in which the hail grows to large sizes while recirculating in a tilted updraft.

Sulakvelidze, in studying hailstorms in the Caucasus region of the Soviet Union, used radar and several other direct lines of evidence to construct a conceptual model of the smaller but nevertheless damaging storms that occur there. In his model, the hailstones do not require recirculation, but grow very rapidly in "accumulation zones," where large amounts of supercooled water in the form of very large drops are stably supported above an updraft maximum.

It is interesting and important to note that these two hail theories are almost totally at variance with each other in the microphysical events that they envision to be important; the dynamic requirements are also distinctly different. It is also interesting to note that neither model has had anything approaching direct verification. The radar evidence so important in both is quite ambiguous: even when attenuation problems are not serious, the reflectivities can be from ice or water, from high concentrations of small particles or low concentrations of large particles.

A fair summary of the state of knowledge of hailstorms is that several reasonable conceptual models already exist. What has not existed until NHRE has been the means for direct verification. The added measurements that NHRE can bring to bear involve direct aircraft observations of the microphysical content and the dynamic variables within the storms; extensive Doppler radar coverage to give internal air motion patterns and estimates of hail size spectra; and the promising dual-wavelength radar system for actually locating hail within storms. In coordination with these new techniques are the old: conventional 10-cm radar sets of high quality and sensitivity, rawinsonde ascents, a dense ground network for time-resolved hailfall data, and hailstone collection and analysis. The manner in which these and other measuring techniques are proposed to be utilized in the NHRE is discussed in some detail in the following section.

References:

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Macklin, W. C., 1961: Accretion in mixed clouds. Quart. J. Roy. Meteor. Soc., 87, 413-424.

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B. Storm Mechanisms

The hailstone (a dense ice particle greater than 5 mm in diameter) grows in the mixed-phase region of a thunderstorm by accreting supercooled water droplets. If it grows large enough it can reach the ground before melting. The three main features of the storm that must appear in combination for this to happen are discussed below.

1. Hail embryo

There must be an ice particle to serve as the embryo for subsequent growth. This initial growth unit is called a hail embryo. The nature of hail embryos is clearly of concern. There are two competing ideas regarding their origin. One is that they are frozen raindrops. The other is that they are snow pellets (graupel), formed by the low-density riming of an ice crystal by cloud droplets. Examination of the internal structure of hailstones by thin-sectioning generally gives an unequivocal determination, and in the climatic region of the NHRE experimental area, the graupel process is dominant. Aircraft observations indicating that the ice crystal process is the active precipitation mechanism in northeast Colorado, rather than the coalescence process, provide corroborative evidence.

These studies, while identifying the graupel process, have not answered a number of highly relevant questions. Where in the cloud do the embryos form, and particularly at what temperature? In what concentrations do they form? These questions must be answered before the hail process will be understood. There are, no doubt, embryo concentrations above and below which hail at the ground will not be damaging. At the lower limit the concentrations of stones will be small. At the upper limit there will be enough stones to deplete the supply of supercooled water and eliminate the fuel for further growth. The question of how many embryos are needed for the latter effect to occur is central to the problem of hail suppression, as we now envision it.

The region in which the embryos form surely influences their subsequent growth. Whether they must form outside the strong updraft and be transported into it, as some theoretical studies have postulated (on the basis of particle growth rates and transport times), or whether the process of ice nucleation followed by riming is unexpectedly fast needs to be determined. Presumably, the most favorable place to seed for hail suppression is close to or in the same location where nature provides its embryos.

Affecting all these processes is the nucleation of the ice phase, a subject which has received wide attention but still abounds with controversy. While knowledge of the activation spectrum and character of natural aerosols is highly desirable, measurement accuracy sufficient to answer the important problems is not yet in sight. Ice multiplication processes, if indeed they occur, cause additional complications.

The approach to the hail embryo problem being pursued in the NHRE is one of direct in-cloud measurement of ice particles by instrumented aircraft in coordination with high-resolution radar observations, and the continued study of hailstones collected at the ground. Details of this research are elaborated in Section VII. Airplanes involved will include the South Dakota School of Mines and Technology T-28, the NCAR/NOAA sailplane, and possibly the University of Wyoming Queen Air. Major instrumentation will be the Cannon camera system, formvar replicators, and the Knollenberg probe.

In addition to the field research, detailed numerical models will be constructed to examine these questions. Considerable input from the field work will be necessary both for initialization and verification of the model.

2. Hailstone growth

The growth of hailstones requires that the storm have a mixed-phase region containing both ice and water particles. Theoretically, the growth rate is proportional to the liquid water content, but there are a number of complicating factors. The problem of wet versus dry growth, and the complexities induced by tumbling, shape, and roughness effects have been mentioned in the previous section. While the effects of electric fields are not yet fully understood, it appears that they are important only for the smaller particles (less than a millimeter or so).

The question of whether liquid water contents greater than the adiabatic value can occur has received much discussion. The Soviets have made super-adiabatic water contents part of their hail theory. The first direct measurements of the condensed water in hailstorms were made in the NHRE by the T-28 aircraft. While high values have been found, questions remain regarding whether the precipitation is all-water, or some mushy mixture of water-and-ice. In the face of other measurements showing the ice-crystal process to be dominant, it is difficult to understand how super-adiabatic concentrations of liquid water (necessarily requiring large drops for the required sedimentation) can be present. To resolve this point, future measurements capable of unequivocally differentiating water and ice are planned.

While the question of growth rates is of interest, it is less so than embryo formation because the uncertainty in growth rate is far less than that in embryo concentration. In addition, there appears to be less opportunity for modifying the growth rate except by depleting cloud water contents. On the other hand the introduction of more ice nuclei, and thus more embryos, works both to deplete cloud water and increase the competition effect. Nevertheless, hail growth rates need to be considered in a variety of contexts if only to interpret the observations and fully understand the hail mechanism.

3. Updraft structure

Since hailstones fall quite fast (from 10 to 30 m sec^{-1} or more), substantial updrafts must be present to support them in the mixed-phase region. It is clear that the magnitude of the updraft maximum limits the hailstone size attainable, and if the maximum is too low, hailstones cannot form. No doubt it is this feature of cumulonimbus clouds that distinguishes them from other types in producing hail.

While as previously mentioned, and discussed in more detail in Section V, we have a fair general understanding of the storm's internal circulation, more details are required. For example, aircraft penetrations, Doppler radar observations, and dropsonde data all indicate that the updraft structure is highly variable. Careful, well-documented case studies are required to examine how this variability is related to hail growth. There is, in fact, conjecture that the fine-scale structure may be an essential ingredient.

Figure 1 shows a schematic, two-dimensional representation of an idealized storm. (Discussion of many of the features shown will be delayed

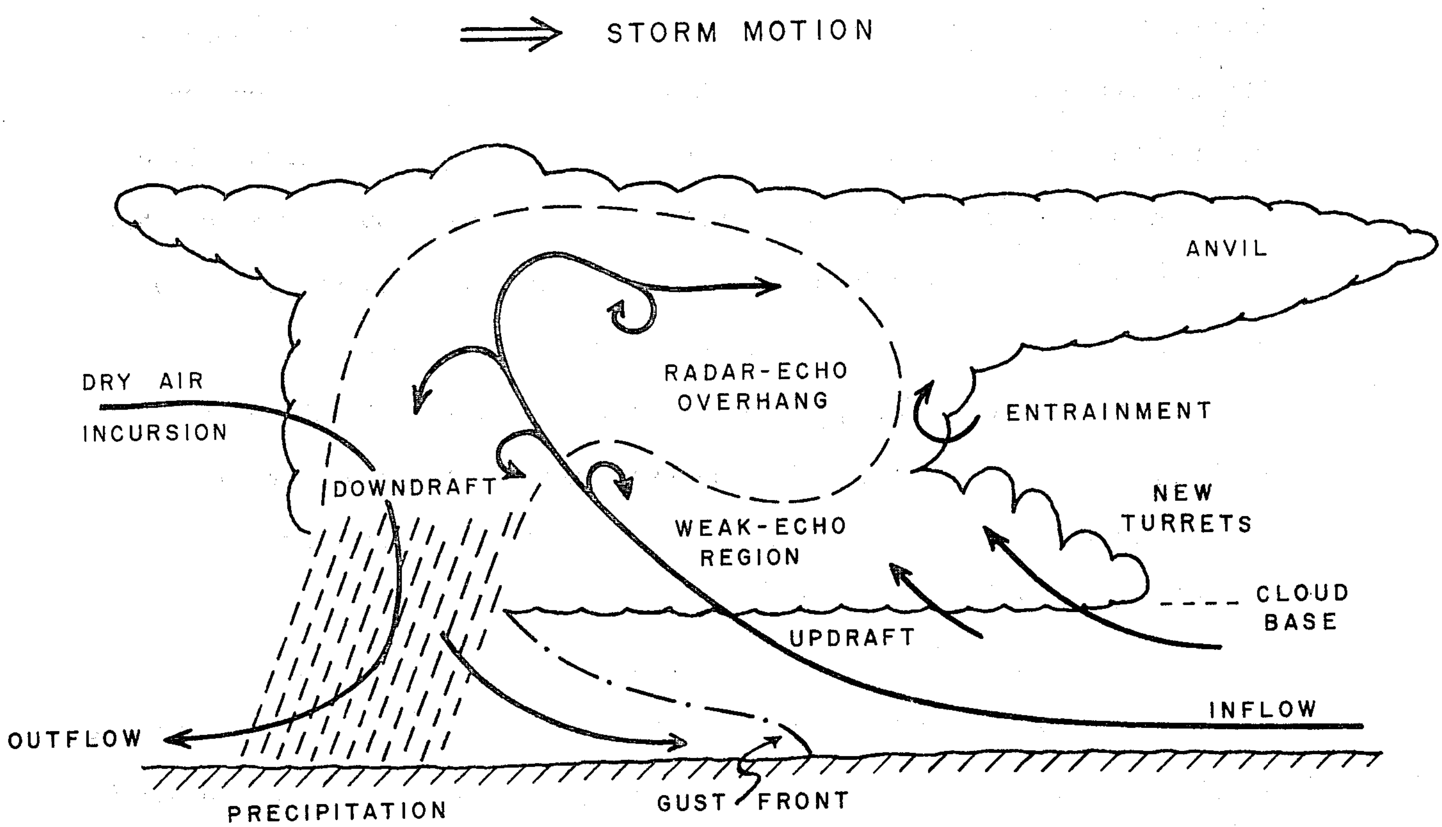

Figure 1. Schematic, two-dimensional representation of idealized storm structure showing cloud outline, mean streamlines, and echo contour (dashed).

until later sections.) Important features of this model are the sloping updraft originating in the moist layer near the ground, situated adjacent to the downdraft, which originates mainly as dry, mid-level air. Entrainment and turbulent mixing processes are indicated in the figure. Though little understood, they may have a dominating influence on the storm dynamics. The radar echo threshold is indicated by a dashed line. Hailstones are presumably growing within the radar contour. Whether they are formed in the weak-echo region of the strong updraft, or elsewhere, as in the new turrets, is a question that must be answered.

While an understanding of the airflow is essential to the hail problem it is necessary also for understanding how the storm, as a convective element, originates and maintains itself, typically in a strongly-sheared environment.

A better understanding of the storm's internal motion and dynamics is one of NHRE's main research objectives. A major attack on this problem is expected, with instrumented aircraft, conventional and Doppler radar (augmented by chaff releases), ground networks and upper-air networks being the primary data sources. With these systems all concentrating on the same storm, substantial refinement of our ideas should result. As with the hail-embryo problem, the field work will go hand-in-hand with numerical modeling endeavors. Indeed, much of the important interaction between the hail growth and the storm dynamics will require computer simulation for full understanding.

Figure 2 summarizes what is known about the airflow and thermodynamics of hailstorms; Fig. 3 outlines the gross features of the evolution of a hailstone and the key related questions. Figure 4 brings together the essential microphysical and dynamic processes which must be addressed and the main techniques which we propose to bring to bear to elucidate those processes. Otherwise, the diagrams are self-explanatory.

STORM DYNAMICS

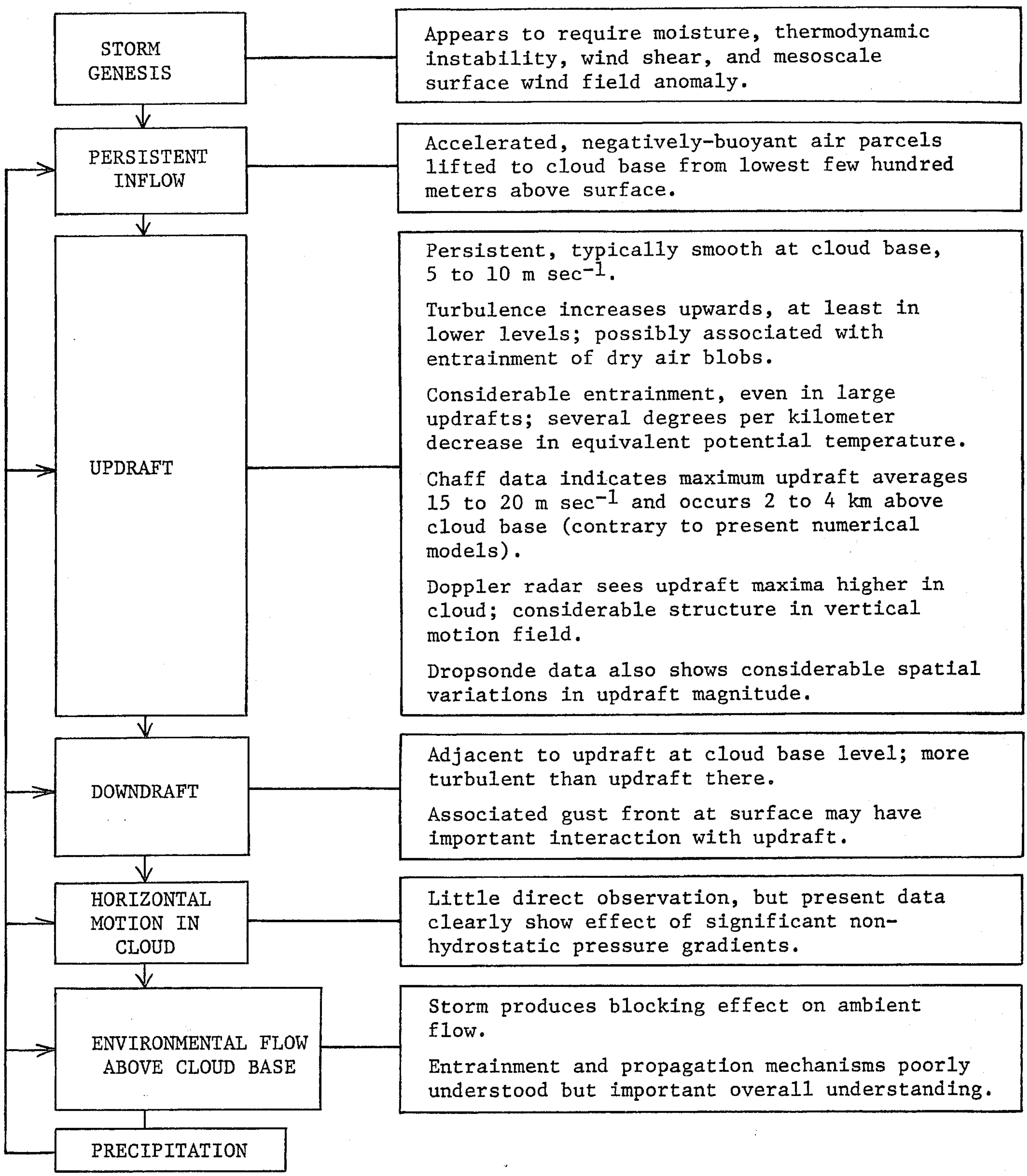

Figure 2. Summary of important features of storm dynamics and airflow. The interior flow is probably the most important but least understood feature.

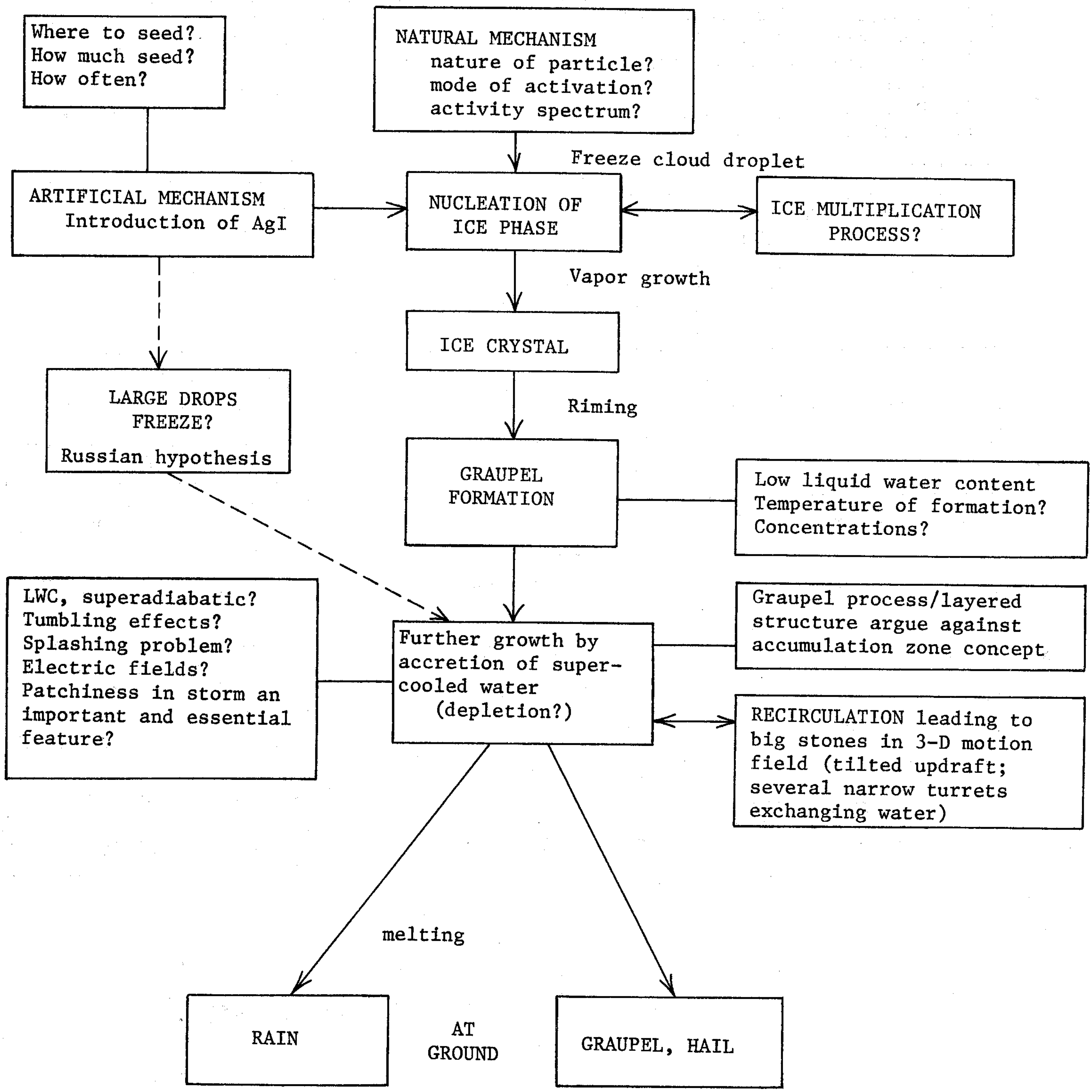

Figure 3. Evaluation of particle growth based on current knowledge, and important unanswered questions.

MOST IMPORTANT PROBLEMS

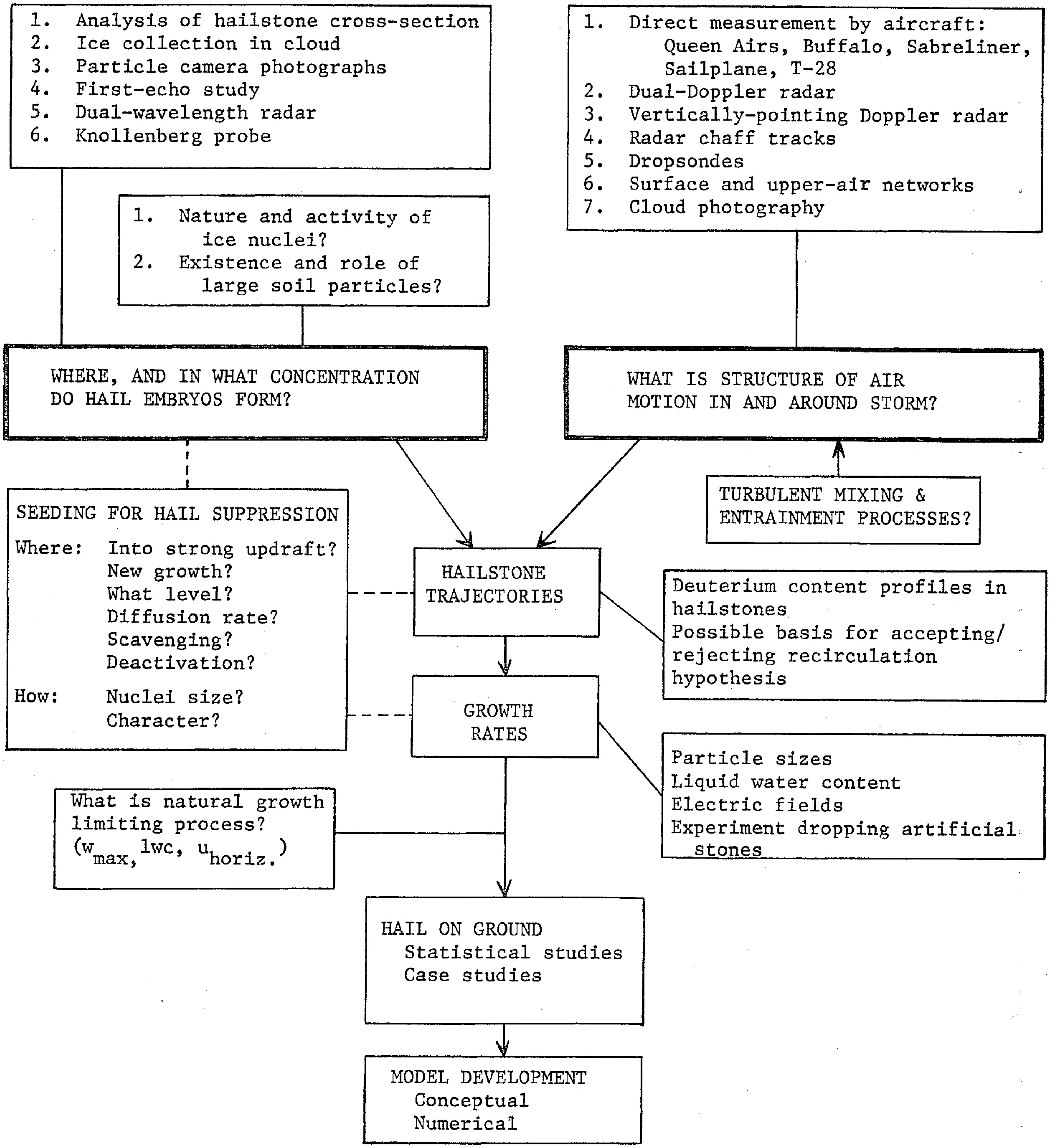

Figure 4. Summary of important questions that must be answered for adequate understanding of hail formation and hail suppression. The main experimental techniques being used in NHRE are indicated at the top of the figure. Numerical modeling will interact with almost all aspects of the field experiments.

C. Design of Suppression Experiment

Because of the long time required to test the effectiveness of any suppression scheme, given the great natural variability of hailstorms, it was proposed to conduct suppression tests from the outset of the project, using the technique considered best in the light of present knowledge. It was decided that once this technique was chosen it would be tested for a time sufficient to yield a statistically significant estimate of its efficacy, unless some compelling reason emerged for abandoning it earlier. The same time and economic limitations also made it impractical to attempt a design that would address more than one suppression hypothesis. The physical hypothesis underlying the proposal for hail suppression in the Plan for the Northeast Colorado Hail Experiment and elsewhere, was that large, damaging hailstones occur because of a natural deficiency of ice nuclei, and that the injection of suitable numbers of ice nuclei into the storm would promote the formation of a large number of smaller, less damaging hailstones, many of which could melt during their fall to the ground.

The statistical null hypothesis that there is no difference in damaging hail at the ground between treated and untreated samples is independent of the choice of a physical hypothesis. The statistical hypothesis depends only on the collection of untreated and treated samples for comparison, and is not affected by the manner of treatment as long as the treatment is consistent within the sample. If more than one treatment method were involved in the sample, and the differences in the methods were intended or expected to induce a different physical behavior, a more direct analysis of individual physical hypotheses of modification could be addressed. However, as already pointed out, the number of sample cases available within the time scale of the NHRE is not sufficient to deal with these kinds of questions.

While the physical hypothesis mentioned above was adopted by the NHRE, along with the use of AgI as the seeding agent, the question remained of where to inject the material. The Soviets, who were making the most substantive claims of success in hail suppression, used ground-based artillery and rockets fired into the high-reflectivity region of the storm, thought to characterize the hail growth zone. Other groups seeded in the updrafts at cloud base and let the storm itself carry in the material. A third method involved dropping flares into the growing turrets from aircraft flying above. The final decision was influenced by two considerations: first, that the agent be introduced at a sufficiently low level to ensure adequate diffusion throughout the hail-forming region of the cloud, and second, that it be injected at sufficiently low temperatures to avoid the deactivation claimed by some to occur at higher temperatures. It was believed that these conflicting requirements could be met by introducing the nucleant at about the -5C level.

1. <u>Delivery system</u>

It was decided that a seeding method was required that would allow for the placement of the nucleating agent in the updraft near the -5C isotherm, occurring in Colorado at an altitude of about 5 to 6 km MSL. A variety of systems for accomplishing this were considered. Among these were airborne rockets to be fired from outside of the cloud into its core, ground-launched rockets, artillery such as the Russians use, aircraft penetration through the clouds at the -5C level, and flares dropped in the clouds from above. Range and accuracy considerations eliminated the airborne horizontally-fired rockets.

Ground-launched rocket systems were eliminated from consideration due to the cost of maintaining a network of ground-based systems adequate to cover the area. Artillery was also eliminated due to problems associated with air traffic and the development of an artillery shell that would create no falling hazard. Cloud base seeding was finally chosen as a back-up system because of the extensive experience in cloud base seeding that exists and because of its ease of application. However, it was not accepted as a primary system because of the possibility of deactivation of ice nuclei. While cloud penetration at the -5C level can generally be accomplished by an aircraft such as the armor-plated T-28 owned by the South Dakota School of Mines and Technology, in order to conduct a suppression experiment with such aircraft, a fleet of at least five armor-plated aircraft would be required. The development cost of such a program would be prohibitive. In addition, a great number of problems exist in terms of radar control for penetrating a variety of cells simultaneously at the proper level and the proper location. Further, the system chosen needed to be able to treat all cells,and even with armor-plating there would be cells of sufficient intensity to prohibit penetration. Finally, the concept of dropping silver iodide flares in the clouds was eliminated because of (1) the height of storms in northeast Colorado requiring a high altitude aircraft, (2) the relatively common situation in northeast Colorado that the sky is obscured by cirrus during thunderstorm activity, and (3) the known inaccuracy of placement when dropping ballistic devices from aircraft at high altitudes over difficult-to-define targets.

Since the closest place to the desired delivery point is at cloud base, it was felt that some vertically-launched vehicle from cloud base was the appropriate and direct way to get the seeding material into the storm. As a result, the development program has been undertaken to provide a vertically-launched cloud-seeding rocket to be delivered into the updraft at about the -5C level from an aircraft flying at cloud base. Since finned rockets are aerodynamically unacceptable for this operation, a spin-stabilized rocket has been developed. The development was constrained by the FAA requirements for a toy rocket because of the need for operational flexibility and to avoid the need for a restricted airspace. These include the conditions that the rocket be non-metallic, weigh less than one pound and carry no more than 4 oz of propellant. The rocket finally developed is 21 cm long, 4.2 cm in diameter, weighs 426 gm, has an output of about 100 gm of silver iodide, and is boosted by 114 gm of propellant. The motor burn time is 620 msec, during which the rocket attains a velocity of 1.1 Mach, a spin rate of over 50,000 rpm and an altitude of 2.5 km above the launch point. At this altitude, the total dispersion about the mean position is expected to be less than 200 m. This system should allow for operationally consistent placement of the silver iodide material.

With the successful completion of the seeding rocket system, extensive consideration has been given to the question of whether or not to abandon the use of seeding by flares at cloud base. After deliberations with the NHRE Advisory Panel it was decided to use both flares and rockets in order to insure that the AgI is in fact being delivered to the desired target region, and to do this at least until the reliability of the rocket system was demonstrated beyond any question. With this conservative strategy the question of resolving which of the two systems is most effective will depend upon the availability of sufficient cases by the beginning of the last two years of operations. It may then be possible to switch entirely to the rocket system. While there is considerable concern about destroying the homogeneity of the experiment by the addition of the rocket system, the Advisory Panel argued persuasively that the primary goal must be to produce measurable effects, whatever the delivery system. The use of both methods is aimed at providing the greatest chance of producing such effects. The possibility of overseeding was considered small because the concentrations of AgI are unlikely to increase by more than a factor of two when both systems are used simultaneously.

2. Measure of effect

A major consideration in the statistical design for the NHRE was the choice of a primary measure against which to test the outcome of the experiment. The first problem was in defining damaging hail. The crux of this problem lies in the word "damaging". While an adequate definition exists for hail, damaging hail is quite a different matter. The degree of damage caused by hail depends on a variety of factors, including the local wind speed, the type of crop, the stage of development of the crop, kinds of property affected, and so forth. In fact, it would appear that practically any type of hail can be damaging, given proper conditions, while under a different set of circumstances it is possible for all hail to be non-damaging. It would, of course, seem reasonable to use the actual cost of hail damage as a measure of seeding effect. However, a large portion of the NHRE operational area is uncultivated grassland. Further, due in part to the high rates of hail insurance, a large portion of the agricultural crops in the region are not insured. Thus, insufficient records of hail damage are available. This is not to say that damage estimates are considered unimportant. Attempts are made each year to obtain estimates of hail crop loss and other damage costs on a selected basis as a possible secondary measure of seeding effectiveness.

However, it was decided to eliminate the concept of damage from the primary measure and look at the hailfall directly, with the intention of relating various measures of the hail to damage potential. Further, it was believed that while direct measures of hail are not, in turn, direct indicators of the economic advantages of suppression, they are better indicators of the physical effects produced by seeding.

A variety of direct measures of hail exist. Among them are the total mass of hail in a given area, average stone size, maximum stone size, number of stones, impact momentum, and areal extent. While mass, size and number distributions (integrated over time), and areal extent are all being measured, it was believed at the outset that the program should choose a primary measure of the hailfall on which the design of the experiment and the instrumentation could be centered. The final choice of total hail mass was dictated in part by the fact that this variable could be measured most reliably by a hail/rain separator which could be economically reproduced in large numbers. In fact, however, because crop damage is sensitive to the size distribution while total mass is an integral over that distribution, and since seeding may sometimes shift the average size without necessarily affecting the mass, it would have been preferable to measure the hail size-concentration spectrum. This measurement is now made possible by the recent invention of an economical electro-optical device, and it is planned to supplement the hail/rain separators by these devices in 1975 and remaining years of the program.

Another measure given serious consideration was the ratio of total hailfall to total rainfall by day. If the physical hypothesis is correct, one expects to reduce hail without altering the total precipitation. Thus, the rainfall should increase while the hailfall is decreasing, and one might think that the ratio would be more sensitive to the modification than either would be alone. However, since hail typically constitutes only one to three percent of the total precipitation, this ratio is highly sensitive to measurement errors. Further, both variables in the ratio are stochastic and while not independent, little is known about their interdependence. Preliminary analysis based on a limited amount of data has indicated that the variance in this ratio is at least as large with respect to the average as the variance of hail itself.

3. Statistical design

The problems associated with selecting an experimental design for weather modification experiments have been covered extensively in the literature. The extreme variability, randomness in occurrence of the basic phenomena being tested, lack of correlation between adjacent geographic areas, complicating influences of unmonitored meteorological variables and a host of other problems associated with control, make the classical approaches to experimental design generally inappropriate for weather modification experiments, and particularly for hail suppression.

Almost all the discussions in the literature deal with precipitation augmentation experiments and only a very few deal directly with the problem of hail suppression. In Thom (1957), the subject of hail suppression is dealt with thoroughly. It is pointed out that the correlation in the basic measure between the two areas is a measure of advantage in using the control-versus-target-area scheme. Since the correlation in hailfall in adjacent areas in northeast Colorado is insignificant, little or no advantage is gained from this approach. Two additional constraints influenced the decision to reject it. First, the Federal Aviation Administration provides an operating airspace for the NHRE in northeast Colorado. This airspace is bounded by major air traffic routes and is not sufficiently large to allow for two target areas separated in space to the degree necessary. Second, economic constraints make it clearly more advisable to attempt to maintain one well-instrumented target area rather than to spread the resources over two separated areas. While it would be desirable to enlarge the target area to obtain additional samples, this is not possible within the budgetary constraints.

Another possible experimental design was one in which every storm in the target area for the entire five years would be treated and results of the five years compared to historical data. The problems here are twofold. First, Schickedanz and Changnon (1970) have pointed out severe year-to-year variations in crop losses due to hail in northeast Colorado. While these data are affected by a variety of indirect influences, they are sufficient to make one wary of drawing an atypical five year sample. Second, and more important, is the fact that comprehensive hail data has not been maintained for northeast Colorado.

These considerations led the NHRE to choose a randomized target experimental design, sometimes referred to as a single area design, and sample seeded and unseeded events in roughly equal numbers. If sufficient historical data of the type currently being collected in the NHRE program were available, this data could have been used to enhance the information from the unseeded cases. In such a situation one could profitably sample seeded cases in a much higher proportion. However, adequate historical data simply does not exist, and thus a baseline of unseeded data must be established during the NHRE operations.

The attainment of an adequate number of samples during the NHRE lifetime is probably the most critical aspect of the program. Approximately 15 to 16 days of hail occur per year on the average within the NHRE target area (also referred to, after Soviet usage, as the Protected Area). However, of those 15 to 16 about one or two per year are extremely severe storms, another three or four per year are moderate, and the remaining 10 to 12 are light in terms of hail. The result is that a few storms dominate the statistics.

There are further characteristics of thunderstorms in northeast Colorado that add to the complexity of the problem. First, storms occur at random times, with peaks in the distribution occurring at approximately 1400 hours and again between 1630 and 1800. Between 3 and 5% of all hailstorms occur between 2200 and 1000. Second, there appears to be no easily-measured meteorological parameter other than the storm's radar reflectivity that is correlated with hail at the ground to a degree sufficient for use as a predictor.

Another point which influences the choice of an experimental unit, as well as the sampling problem, is the fact that in more than 70% of the cases, several storms will occur simultaneously in the vicinity of the target area. As these storms intensify, they often merge together into squall lines, eventually blanketing the entire area. This situation confounds the use of individual storms as statistical units. On the other hand, a small storm may only affect a small fraction of the protected area; in this case, any seeding effects may be masked in total precipitation amounts over the entire area. Accordingly, we must examine both precipitation over the entire area and that associated with individual storms.

One other major characteristic of the occurrence of hail in the target area has had to be carefully considered in the development of the sampling rationale and the choice of an experimental unit. This characteristic is that days with hail appear to be serially correlated. There is a sharp difference between the probability of hail, given the fact that it hailed or did not hail on the day previous. Further, it should be noted that the unconditional probability of hail is equal to the probability of hail given that hail occurred on each of the previous three days, and this represents a stronger interdependence between hail days than a strictly Markov process would imply. These data were based on information obtained in the Joint Hail Research Project between 1969 and 1970 and the NHRE in 1971.

The first major decision made by the NHRE concerning the overall sampling approach was the choice of an experimental unit. As has been pointed out, individual storms cannot always be used as experimental units because of the confusion in distinguishing individual cells. The discussion of serial correlation in the previous paragraph would imply that a reasonable choice of an experimental unit might be a sequence; that is, any block of days in which hail occurred on each day, the block being distinguished by a day without hail at either end. This possibility was seriously considered. However, if such collections of days were used as the experimental unit, the sample size would be grossly reduced. On the other hand, if such groupings were used exclusively for the purpose of determining what days would be seeded or not seeded, and then a smaller unit were used for analysis, the advantage to be gained from the similarity of days within a sequence would be wasted.

Based primarily on these arguments, along with certain operational considerations, the day was chosen as the experimental unit. Since hailstorms occur infrequently during the night and early morning hours, and since the equipment needs to be calibrated and occasionally repaired, a further decision was made that the day would begin at 1000 hours and end at dark.

Although all systems were intended to stand-by for operations on every day between 1000 and 2030 hours throughout the duration of the summer's operation, it was believed that criteria should be established by which a day would be selected for analysis. A major point should be made here. Unlike precipitation augmentation studies in which the intent is to add something at the ground that would not naturally be there, hail suppression intends to prevent something from occurring at the ground that might otherwise be there. While this distinction appears obvious, a subtle point exists. If, on a seeded day, there is no hail at the ground, one certainly does not want to reject that day from analysis. However, frequently convective clouds occur in the NHRE area producing virga or light precipitation at the ground and never develop beyond that stage. In addition, moderate to heavy rainstorms occur without producing hail at the ground. If hail suppression is effective, treated storms that might otherwise have hailed could appear to be only rainstorms. Conditional analyses based on the absence of hail is thus questionable.

Based primarily on these arguments, it was decided that a criterion should be established for determining a sample unit that would minimize the appearances of zeros in the hail data on unseeded days and that would be applied objectively and rigorously to all days. As has been pointed out, no available meteorological parameter other than radar reflectivity appears to be highly correlated with the occurrence of hail at the ground. However, if seeding affects the hail, it should also affect the reflectivity. Therefore, it was decided that radar reflectivity would be used as an indication of a storm's potential to produce hail at the ground prior to the commencement of seeding. Further, it was decided that the reflectivity value that would be used for assessing a storm's potential should be sufficiently high as to minimize the number of zeros, while at the same time should be sufficiently low to guarantee that no storm capable of producing hail at the ground would be missed.

The choice of a reflectivity value to use as this criterion was extremely difficult. To choose this value one would like to have a distribition of the maximum reflectivity in storms that did not produce hail, and a distribution of reflectivity in storms just prior to the actual onset of hail. A comparison of such distributions would allow the objective assessment of the proper number. However, data from the Joint Hail Research Project and the 1971 NHRE field program reflected only the maximum reflectivity of storms producing hail. Reflectivity at the time of onset of hail at the ground was not generally available. Further, since the study of severe thunderstorms tends to concentrate on those that are the most severe, reflectivity values were not generally kept on storms producing only rain. Therefore, a different analysis was necessary.

An attempt was made to assess the size of hailstones that could reasonably be present in a storm within the range of reflectivities known to be associated with hail at the ground. Using these size estimates and adjusting for melting during fall, the range of possible values to use for the criterion was substantially narrowed. The resulting range was approximately 45 to 50 dBZ (dB above reflectivity factor $Z = 1\ mm^6 m^{-3}$). The lower end of this range was selected as the criterion. Thus, any storm within 20 minutes of the area based on its own track and speed and having a reflectivity of at least 45 dBZ above the -5C isotherm was to be a sample case, and the day to be declared a Hail Day.

The final element required to complete the picture of the sampling process was the manner in which seed and no-seed decisions were to be made. As pointed out earlier, serial correlation between days producing hail exists in northeast Colorado. The effects of such a correlation on both the significance and the power of a statistical test as a function of the randomization scheme have been pointed out by Moran (1971) and Avara (1971). However, neither of these papers dealt with the specific situation faced by the NHRE in northeast Colorado.

In order to assess the effect of various randomizations on the outcome of the experiment, a Monte Carlo model was devised using the empirical data obtained by the JHRP and the NHRE between 1969 and 1971. This model was designed to reproduce sequences of days with serial correlations matching those observed. The approach chosen from the results of this analysis was one in which the treatment of the first day of a sequence was determined from a random number table, and the treatment was subsequently alternated from day to day throughout the duration of the sequence.

Because, in such a scheme, the decision of whether a day will be a seeded or unseeded day is known in advance a large portion of the time, it was necessary to make the declaration process as objective as possible. To this end, two individuals were chosen and carefully trained in the criteria. These two individuals, known as "Hail Day Declarers", are removed from the pressure of operations, cross check one another to ensure both objectivity and consistency and they alone decide when a storm has met the criteria necessary to make the day a sample case. When that decision is made by the Hail Day Declarers the decision is relayed to the Operations Room. If the day is to be a seeded one, seeding commences immediately, and all storms subsequently threatening the target area are likewise seeded. Complete radar records are kept on the declaration.

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IV. Preliminary Results and Achievements

A. Preliminary Results of Suppression Experiment

1. Introduction

The statistical design of NHRE is such that firm statistical conclusions about the results of seeding can be reached only after a sufficient sample is obtained; in midstream, any such conclusions must be tentative at best. It was determined in the beginning that this would take approximately five years. Nonetheless, it is worthwhile to examine the results to date in order to see what they suggest, to diagnose the problems which have arisen, to assist in assessing the validity of the experimental design and, if necessary, to alter it as appropriate, and to reevaluate the probability of reaching a definitive conclusion within the original five year time frame.

We emphasize the preliminary nature of the results. They have not been analyzed in full detail because serious questions have arisen concerning the validity of including certain days in the sample and because of a number of delays in processing the requisite radar data which is necessary to determine whether or not each sample actually met the criteria for inclusion. These problems will be highlighted later. Moreover, the conclusions reached may depend upon the measure being used--total hail mass over the protected area (the currently used measure), hail to rain ratio, hail rate (hail mass at the surface normalized for storm duration and areal extent), or hail size and concentration. It is entirely possible that one or more of these measures may show more sensitive effects than is presently indicated for total hail mass. The second, third and fourth alternative measures are being examined because of the need to insure that we are not overlooking a potentially more sensitive measure of the process than is now being used.

2. Discussion of the Data

Table 1 * presents the raw hail mass data by day from the 1972 and 1973 seasons. Date, mass of hail in the network, and the total number of instruments operating on that day are given. On any sample day some of the instruments are inoperable due to maintenance or vandalism, and thus the total sampling area varies from day to day. To account for this variation it is assumed that the operating stations give a representative sample and that the variation due to missing stations is randomly distributed. Therefore an adjusted mass normalized to a standard number of instrument stations and thus a constant sampling area is given. The latter number is obtain by dividing the mass for a day by the number of operating instruments to obtain the average mass per station and then multiplying by the total number of instruments. (There were 233 instruments inside the protected area in 1972 and 241 in 1973. All data are normalized to 241.) Finally, the hail to rain ratio of the adjusted masses is given. Table 3 gives the means and standard deviations for the seeded and unseeded samples by year and the composite for both years exclusive of certain days. The excluded days are discussed in the following paragraphs. Table 2 gives the same information for rainfall.

Before discussing the results, the following comments are necessary concerning the data included and excluded from Tables 1 and 2 , and the computations in Table 3 . In 1972, the program ran six days a week; twenty-two days were declared as sample days over the whole summer. However, an adjustment was made after mid-summer in the hail day declaration criteria to improve the decision process. The adjustment required that a storm's

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* Tables appear at the end of this section, pages 73 to 75 .

projected track would take it into the area rather than requiring it to be simply within ten miles of the area; this caused six days declared earlier in the summer to be suspect with respect to the adjusted criteria. Subsequent review of the radar data eliminated two of these previously declared hail days, while the data from the other four appear to be irretrievable. The data retrieval situation reflects problems in the recording system, now remedied, and the overall problem of data backlog. It should be noted that none of the six questionable days produced hail, and thus none of the data for these six days are included in the means and standard deviations for hail. One day had an unrecordable trace of hail; this is listed as a zero in Table 1 and is included in the calculations in Table 3 . In those cases with rain in the network, the data are included in the rain statistics. The data from 26 May 1972 are not included in the tabulated statistics since the data from storms on the 26th and 27th are not separable due to servicing problems on the 26th.

Four non-operational Sundays during the 1972 season had hail in the target area; this was to be anticipated from the pre-program statistics. There were no operations on Sundays in 1972, but a continuing concern over sample size led to adjustments in the staffing level prior to the 1973 season which allowed seven-day-a-week operations.

In 1973 only six days were declared. In fact, there were thirteen days with hail in the target area. All indications would lead to the conclusion that an error in the radar calibration was the cause of the loss of the seven days. An intensive calibration program was undertaken in 1974 to insure that such situations do not recur. The seven lost days in 1973 are associated with a bias that does not allow for their after-the-fact inclusion.

The 1972 and 1973 networks differed in three ways. First, due to operational requirements for the use of rockets the network was moved approximately ten miles due north of its 1972 location. There appears to be no reason to believe this should affect any aspect of the experiment other than perhaps the frequency of storms entering the area. The move was toward the region of higher hail incidence. Second, in 1973 careful contractual arrangements were made with land holders in the area to allow for a maximum degree of uniformity of instrument sites and year to year network consistency. This change in instrument distribution could have an effect on the data between the two years, and studies of instrument density and distribution effects on sampling are being conducted. Third, half of the rain/hail separators were automated in 1973. This allowed for a higher quality of data in general. While laboratory experiments showed no differences between data from the non-automated and automated systems, evaluations are continuing to insure that there are no differences in actual field performance.

The means presented in Table 3 show less hail on unseeded days than on the seeded days in 1972 and considerably more hail on unseeded days in 1973. The 1973 sample is sufficiently small as to be meaningless by itself. The two year combined means show approximately 30% smaller mean hailfall on seeded days, however, this difference is dominated by a single case.

By the Central Limit Theorem one should expect the means for seeded and unseeded days, and thus their difference, to become normally distributed as the sample becomes larger. Using the pooled estimate of variance from the 1972 and 1973 data and computing a 95% confidence interval with the two-tailed Student t factor of 2.09 times the standard deviation one sees that the difference could be anywhere from an increase of about 120% to a decrease of 100%. Clearly the 30% hail decrease in the data is not statistically significant. It should be noted that since the Central Limit Theorem is an asymptotic result, with this small sample size there is no assurance that the means are in fact normal. Further, the hail data are dominated by a very small number of cases.

The standard deviation for the unseeded hail cases presented in Table 3 is twice that computed from the hailpad data obtained in the Joint Hail Research Program (1969, 1970) and the NHRE pretrials (1971). Only hailpads were used in 1969 to 1971; both pads and separators were used in 1972 and 1973. While recent analyses of the relationship between the results of hailpads and the NHRE hail/rain separator show an impressive day-to-day correlation of .97 between the two arrays of instruments, the hailpads gave 0.6 of the masses measured by the separators on the average. This implies that the two systems are measuring the same phenomenon, but the hailpads most likely have a calibration error. Substantial tests of the separator have shown that it is impossible for rain to get into the hail side of the separator; thus it is assumed that errors in the mass measurements provided by the separator should be in the direction of smaller amounts than are actually present. Therefore it is reasonable now to assume that estimates of the mean and standard deviations of hail in the target used for the planning and design of the experiment were too small by a factor of 0.6.

The estimate of day-to-day standard deviation of the mass of hail estimated from 1969 through 1971 hailpad data was approximately 2700 cm^3.

When this is increased by a factor of 1.67, the result is reasonably close to the standard deviation for the unseeded data presented in Table 3 .

While the variance estimates between the pre-program and program data agree reasonably well, the means do not. If the pre-program mean is adjusted by the 1.67 scaling factor between pads and separators, the adjusted mean becomes approximately 4500 cm^3. If this adjustment is valid and the pre-program data is pooled with the unseeded hail data from Table 3, the resulting mean hail mass is approximately 4245 cm^3. The 95% confidence interval on the difference between the adjusted mean and the mean for the seeded cases ranges from a 100% decrease to a 55% increase. The difference in this confidence interval and the previous one is due to both the increased sample used for the estimate and the fact that when the historical data is included, the difference in the means of hail for seeded and unseeded days is increased from 30% to 50%.

In the case of non-negative data the magnitude of the standard deviation with respect to the mean value gives an indication of the skewness of the distribution. Since the distribution is bounded by zero, a small mean-to-variance ratio is characteristic of a long tailed distribution while a large ratio will be associated with a relatively shorter tail. Also, if the mean is shifted toward zero and the form of the distribution remains the same, there should be a relative effect on the variance. The standard deviations of hail for unseeded cases in Table 3 is larger than that for the seeded cases by a factor of about two. This suggests a possible decrease due to seeding of the larger hailfalls which contribute so strongly to the variance. But no firm conclusion can be drawn until the sample becomes larger and comparisons can be made between the form of the frequency distributions of hail masses on seeded and unseeded days.

Table 3 shows that the mean rainfall on seeded days is approximately 25% greater than that on unseeded days. The rainfall data are in general better behaved than the hail data, in that the size of the variation in the rainfall data with respect to the mean on unseeded days is less than one. The 95% confidence interval for the present data range from a possible 85% decrease to a possible 115% increase in rainfall. It is interesting that the standard deviation of the rainfall on seeded days is also larger than that on unseeded days; this suggests a possible enhancement of the larger rainfalls. However, no statistical significance can be attached to this result as yet. The fact that the rainfall standard deviation for unseeded cases is substantially less than the mean indicates that a firm conclusion with regard to the seeding effect on rainfall may be expected within five years.

An increase in rainfall on seeded days may be brought about in one of three ways: (1) by increasing the overall efficiency of the precipitation process, (2) by invigorating the storm and causing it to process more water, or (3) by converting hail to rain. The fact that the hail mass is generally less than 3% of the rain suggests the first. In either case, the evidence is suggestive of a real effect. The potential economic benefits of such an increase in rainfall are obvious, especially in Colorado where evaporation frequently robs rainfall from the surface.

Since the hail is numerically less and the rain numerically more on seeded days than on unseeded days, an immediate question is: How sensitive is the hail to rain ratio? When taken as the ratio of totals by day the results presented in Table 3 for seeded cases is still approximately 40% less than unseeded. Although this percentage is larger than the difference between hail masses, it is not statistically significant. The variance of the ratios are smaller with respect to their means than are the variances of the mass of hail with respect to their means. This apparent better behavior of the ratios is offset somewhat, however, by the fact that ratios are binomically distributed and therefore less sensitive to statistical testing than the mean mass.

Both the means of the ratios by day and the ratios obtained by dividing the grand rainfall mean for both years into the equivalent for hail give essentially the same result. This point is encouraging in that it further implies that the hail to rain ratio is a relatively consistent measure when considered by day. This is probably due in part to the smoothing that occurs when averages are taken over approximately 240 stations and in part to the fact that the ratio has a built-in normalization for areal extent of the storm system by day. The ratios taken by station are not nearly so well behaved and in fact are meaningless in the case of the few stations reporting hail and no rain. The daily hail to rain ratio appears to be a promising measure in terms of both its behavior and the fact that it directly reflects the hypothesis of converting hail to rain by the creation of smaller stones that melt on the way down.

In the case of mass of hail the variance on unseeded days is quite large, but possibilities exist for dealing with the problem. Among these are variance reducing techniques such as normalizations, transformations, and the use of predictor or control variables. Each of these have advantages and problems. A preliminary study is underway to assess normalizations based on the portion of the network exposed to the storms and the duration of exposure. This effort is intended to focus on the actual storm region and the portion of time that region was susceptable to modification. This approach attempts to eliminate those components of variance added by variations of extent and speed of the various storms. The important point here is that the normalizing factors themselves should be independent of the treatment. For example, if radar echo area is to be used as a measure of network coverage, then tests must first be made to assure that there is no statistical difference in the echo areas between seeded and unseeded days.

Variable transformation to account for the form of the distribution is a standard technique and may allow for the data to be tested using conventional tests without relying on a sufficient sample required to invoke the Central Limit Theorem. A prime example of this is the log normal distribution. Non-negative data and data from nature frequently assume this form. If the data are distributed log-normally, then the logarithms of the data admit the normal distribution. If the data do take this form, the transformed data may be tested using procedures that assume normality; in general, this permits the use of a smaller sample.

The other possibility is the identification of predictor or control variables. If such covariates exist and can be identified, then regression of them against the primary measure has the effect of reducing the effective variance in the data. For example, if the radar reflectivity is highly correlated with the hailfall as proposed, variations in the hail with respect to the radar reflectivity may be a better measure of suppression than the hail at the ground alone. In particular, because the equivalent radar reflectivity, Z, is nearly proportional to the product of MD_o^3 where M is the mass per unit volume of the scatterers, and D_o is their median volume diameter, the ratio Z/M should be a measure of D_o. Since the goal of seeding is to reduce hail size, and the total mass on the ground does not necessarily reflect such changes, we now believe that the ratio Z/M is an important parameter to measure. The key problem will be to convert the rate of hailfall at the ground to spatial hail mass concentrations.

3. Sample Size Requirements

With this background on the data to date, a review of the pre-program analysis of the expected sample sizes required to detect an effect and the impact of the more recent data on these analyses is in order.

The original NECHE plan was to conduct a five-year experiment of the hypothesis that seeding reduces the hailstone size sufficiently to prevent damaging hail at the ground. (As noted earlier, total hail mass was chosen as the test measure because it could be recorded more reliably and economically than size, and it was reasoned that changes in size would be manifested by changes in total mass; we now question this assumption.) Since the five-year period was established prior to the creation of the NHRE project office, the Illinois State Water Survey was commissioned to conduct a study to determine if five years was a reasonable period of time in which to expect an outcome from such an experiment. The results of this study, which was based on hail insurance data, are presented in Schikendanz and Changnon (1970). As a result of these investigations, it was concluded that it was reasonable to expect to see an 80% effect in two years and a 60% effect in four years when the data are adjusted to the average hail days per year in the target area. It should be noted that these numbers are statistical expectations; that is, they represent the "average" time which would result from many such experiments being conducted. (In fact Schikendanz and Changnon did note the extreme possibility of a year with no storms at all within the 600-square-mile protected area.)

A statistician was added to the NHRE staff in the summer of 1971; he conducted a similar study using field data obtained from the Joint Hail Research Project (JHRP) in 1969 and 1970, and the NHRE first year trials in 1971. The results of these two studies did not disagree significantly. Figure 5 shows the projected range of outcomes from the second study as a function of time for a 95% significance level if there is in fact (1) no effect, (2) 20% effect and (3) 40% effect. The dashed line in the figure is the value of the test statistic that must be exceeded for the result to be significant at the 95% confidence level. The range of the marks for each year and each level of effect represent the 0.20 to 0.80 probability range for that situation. This analysis did not consider year-to-year variability in sample size and relied exclusively on hailpad data as the data base. In other words, from these results one can conclude that if the program ran for three years and the effect of seeding was 60%, there would be a 50-50 chance of seeing that effect at the 95% confidence level.

The actual hail data from 1972 and 1973 reflect a substantially smaller difference between seeded and non-seeded cases than the original 60% assumed reasonable from the Soviet results and chosen as a baseline from the Schikendanz and Changnon work. The standard deviation in hail mass (2700 cc) estimated from the 1969 through 1971 hailpad data used in the original NHRE study differs from the 5400 cc standard deviation for unseeded cases obtained in 1972 and 1973. The difference, which is evidently due essentially to a scale factor between the hail masses measured by the hailpads and the hail-rain separators, does not however affect the statistics; i.e., the original variance adjusted for the scale factor is much the same as that for the 1972-73 data. Therefore, if we now consider a 30% decrease in hail as a reasonable prospect, we would require between

105 and 250 hailstorm samples in order to be reasonably sure of obtaining a statistically significant result.

It must be emphasized that the original conclusion that a 60% effect would be detectable in five years still stands. It was also evident at the start that a 30% effect would not be detectable in that number of years. In other words, the original choice of five years presumed that only the bigger effect could be established on reasonably firm statistical grounds, and that such a period would leave the detection of smaller effects in doubt. If we now wish to alter the rationale of the experiment to reliably test effects as small as 30% (which are still economically beneficial), then it is clear that more cases must be added. In that event, either the size of the protected area or the duration of the experiment, or both, must be increased.

We also reiterate the preliminary nature of the analysis. The picture may change significantly when we examine measures other than total hail mass as discussed earlier.

The annual variations in hail days reported by Schikendanz and Changnon for Logan County (the county most closely related to the target) ranged from approximately five to thirty-five days. Further, since 1957 they show a peak year every four to five years with the minimum occurring in the same pattern. Our experience in the protected area (about one-third the size of Logan County) extends that pattern with 1971 and 1972 being peak years. The relatively low level of thunderstorm activity in 1973 is not below the range of expectation based on their data. In fact the number of days per year for the period 1969 through 1973 vary reasonably about the expected fifteen days per year used in the original NHRE projections.*

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* Data from 1969 through 1974 show an average of 18 days per year and projections are now being based on that number.

While we cannot rely heavily on this periodicity, there is nevertheless some hope of increased activity in the forthcoming years.

One additional salient feature of the 1973 NHRE data is significant. In the period 1969 through 1971, day-to-day serial correlations were observed in the occurrence of hail. The 1972 data showed the same phenomenon. However, the thirteen actual hail cases in 1973 showed a marked absence of day-to-day correlation or persistence. It was noted by Thom (1957) that regions of high levels of activity exhibit a Markov process, in that the probability of hail in the immediate future is dependent on what is happening in the present, while low levels of activity are Poisson in nature in that there is no such dependence. The 1973 data exhibits the Poisson properties while 1969 through 1972 was Markov or stronger, with 1969 being the weakest year in this respect.

Day-to-day correlations are useful in that if pairs of seeded and unseeded events are highly correlated, the sample size required to detect an effect is reduced. In fact it would be ideal if all unseeded days were perfectly correlated. Then any difference that occurred on a seeded day would be immediately attributable to the seeding. Thus the lower activity periods are detrimental to the experiment in two ways. First, the overall sample size is reduced; second, the serial correlations are reduced or disappear entirely.

4. <u>Problem Areas</u>

A number of problems exist that inhibit the development of any firm conclusions about the experiment at this time. First of course is that the experimental design is not such as to yield such conclusions in midstream. Second, the problems with the radar data have prevented the

the reassessment of days to determine exactly which days should belong to the sample. Further, the servicing procedures for the network in 1972 were awkward and the network was not automated. This resulted in some data being confused and some lost. To date an automated hailpad has not been available, thus requiring that pads be serviced immediately after the storm, generally late at night. This system is still sufficiently cumbersome that it leaves a portion of the data from the pads questionable. The pads or a similar system continue to be important both for size measurements and as a check against separators which are not working properly. The new electro-optical size sensor presently undergoing testing is expected to eliminate this major data problem.

Certain analytical problems also handicap the ability to draw firm conclusions, either on the actual data or on the projections of the time required to complete the experiment. First among these is a proper estimate of the variance in the natural case. The problems contributing to this have been discussed and appear to be related mainly to antural secular variations and the dominance of the variance by a few severe storms. (The effect of the instrument network density upon the variance is not yet known, but is being studied.) Further, the large difference in the variance between seeded and unseeded storms makes the validity of classical tests of differences between means highly questionable. The large number of numerically small amounts of hail in both seeded and unseeded cases also reduces the utility of nonparametric tests. Tests on the variance and other techniques which concentrate on the behavior of the tail of the distribution, such as the distribution of extremes, are presently under consideration. However, it must be emphasized that the appropriate tests must await a determination of the form of the distribution, and this requires more samples.

At present the hailstorm sample is quite small, and the variance and the means are both dominated by essentially one case. The removal of that single unseeded case changes the numbers sufficiently to yield no appreciable difference of any kind between seeded and unseeded days. In fact, the hail mass for unseeded days becomes slightly less on the average. It may be that the appropriate experimental period depends entirely on the time required to sample a sufficient number of these extreme cases. Such cases occurred in the network once each year in 1972 and 1973, one of which was lost due to data problems; two such storms crossed the network in 1971. An additional storm of the extreme variety passed to the north and east of the target in 1972, just missing the instrumented network. It appears that every effort must be made to maximize the sampling of the severe storms if a firm conclusion is to be reached with respect to hail suppression. However, the data to date is insufficient to make a reasonable projection of the number of such cases that are required.

5. Conclusions

Because the design of the experiment is not such as to produce a fully adequate data base until the end of the experiment, we must be cautious in reaching conclusions. Nevertheless, there are a number of indications worthy of note and some new questions which must be addressed.

(1) The data to date indicate a possible decrease in total hail mass of 30% on seeded days. This is statistically insignificant; moreover, this result is dominated by just one case.

(2) The decreased standard deviation of hail on seeded days is also suggestive of a possible seeding effect on the larger hailfalls, but no statistical significance can be attached to this result until a larger

data set allows us to develop the form of the frequency distributions of hailfalls on seeded and unseeded days.

(3) The data indicate a possible increase of about 25% in rainfall on seeded days. While this too is not yet statistically significant, the chances are high that such an increase will be detectable with confidence within the five year period.

(4) The standard deviation of the rainfall data on seeded days is also larger than that on unseeded days, thus suggesting a possible enhancement of the larger rainfalls. The statistical significance of such an effect awaits enough samples to examine the differences in the form of the frequency distributions of rainfalls on seeded and unseeded days.

(5) While the statistical significance of the individual results in (1) and (4) above is questionable, they are consistent with one another and with a rational physical hypothesis of the effects which might be expected.

(6) To detect a suppression effect significantly smaller than 60% (the value used in the original design and based on estimates made in the Soviet Union), will require appreciably more than 75 cases originally contemplated. Precisely how many more are required cannot be estimated reliably until more storms have occurred and a more stable estimate of the variance of natural hailfalls has been obtained. However, using the present variance, a minimum of about 105 storm days is suggested to detect a 30% decrease in hail.

(7) We have serious doubts about using total hail mass over the protected area as a test statistic. The hail rate (i.e., mass normalized for storm area and duration) and reflectivity/mass ratio are now being

studied. The availability of an electro-optical hail size spectrum measuring device should also permit us to examine any alteration in the size distribution resulting from seeding.

(8) The large fluctuations in hailfall variance from year to year suggest that we have not yet reached a stable estimate. Measurements such as those being made by NHRE are the only ones which can reasonably be expected to provide the required data. The large variance itself and its year-to-year fluctuations raise doubts about the validity of claims of suppression effects in prior seeding experiments.

(9) Because the hail/rain statistics are so strongly influenced by the very few severe storms, every effort must be made to increase the number of such cases in the sample and to stratify the data according to storm intensity.

(10) Although the correlation of hail mass measured by individual hailpads to that measured by individual hail/rain separators is low, the total measured by an array of pads is well correlated to that measured by an array of separators (correlation coefficient of 0.97). The separators read systematically higher by a factor of 1.67.

(11) To increase the total number of cases and the number of severe storms also, we must either enlarge the protected area or extend the duration of the experiment or both. The conservative approach would be to do both, thus assuring a larger than minimally acceptable sample size. In view of the budgetary restrictions to an enlarged protected area, a two-year extension of the experiment is recommended to obtain about 105 samples sufficient to reach statistically valid conclusions on hail reduction effects of about 30% or larger.

(12) The dominance of the statistics by the few severe storms emphasizes the importance of searching for directly observable physical effects so that positive links in the relation of seeding to the hail formation and modification process can be delineated. This would allow for a tightening of the analytical procedures and may reduce the necessary sample.

Table 1

Hail in the Network (72, 73)

Seeded

Date	Hail (cc)	Operating Stations	Adjusted Hail (cc)	H/R Ratio
5/26/72 5/27/72	18335	?	-	-
6/ 2/72	0.0	211	0.0	-
6/10/72	0.0	NA	0.0	-
6/15/72	0.0	209	0.0	0.0
6/17/72	865	212	983	.0074
6/21/72	0.0	NA	0.0	-
6/23/72	1770	210	2031	.017
6/26/72	5	216	6	.0006
7/ 7/72	5715	213	6466	.0298
7/10/72	20	212	23	.0004
7/24/72	780	211	891	.0066
7/26/72	5430	194	6746	.0135
6/28/73	3630	217	4031	.0196
7/ 8/73	432	165	631	.0478

Unseeded

Date	Hail (cc)	Operating Stations	Adjusted Hail (cc)	H/R Ratio
6/ 3/72	435	204	514	.0028
6/ 9/72	65	202	78	.0004
6/16/72	0.0	205	0.0	-
6/22/72	0.0	213	0.0	-
6/27/72	540	212	614	.0223
7/ 6/72	755	209	871	.0042
7/11/72	0.0	214	0.0	-
7/22/72	30	214	34	.0005
7/25/72	0.0	218	0.0	0.0
7/27/72	1305	205	1534	.009
5/21/73	11194	143	18865	.1012
7/ 9/73	2752	203	3267	.0385
7/21/73	7360	216	8212	.0766
7/28/73	834	189	1063	.0132

Non-operational 1972 days with hail

Date	Hail (cc)	Operating Stations	Adjusted Hail (cc)	H/R Ratio
6/ 5/72	55	200	66	.0003
6/11/72	60	180	80	.0003
7/ 2/72	415	210	476	.0018
7/16/72	5600	207	6520	.0191

Table 2

Rain in the Network (72, 73)

Seeded

Date	Rain (cc)	Operating Stations	Adjusted Rain (cc)
5/26/72 5/27/72	389627	?	–
6/ 2/72	7285	211	8523
6/10/72	0.0	NA	0.0
6/15/72	48345	209	55747
6/17/72	116870	212	132857
6/21/72	0.0	NA	0.0
6/23/72	103920	210	119261
6/26/72	8000	216	8926
7/ 7/72	191785	213	216996
7/10/72	45365	212	51571
7/24/72	118823	211	135717
7/26/72	401405	194	498653
6/28/73	183439	215	205622
7/ 8/73	9037	165	13199

Unseeded Days

Date	Rain (cc)	Operating Stations	Adjusted Rain (cc)
6/ 3/72	155740	204	183987
6/ 9/72	172360	202	205637
6/16/72	11690	205	13743
6/22/72	98210	213	111120
6/27/72	24270	212	27590
7/ 6/72	178545	209	205882
7/11/72	10620	214	11960
7/22/72	59115	214	66573
7/25/72	9600	218	10613
7/27/72	145315	205	170834
5/21/73	113730	147	186455
7/ 9/73	71470	203	84840
7/21/73	95242	214	107259
7/28/73	63151	189	8212

Non-operational 1972 days with hail

Date	Rain (cc)	Operating Stations	Adjusted Rain (cc)
6/ 5/72	193585	200	233270
6/11/72	230965	180	309236
7/ 2/72	228821	210	262599
7/16/72	293535	207	341748

Table 3

Mean and Standard Deviations
for 1972 and 1973

Hail (cm^3)

	Seeded		Unseeded	
	Mean	σ	Mean	σ
1972	2143	2656	521	516
1973	2331	1700	7852	6865
Pooled	2181	2496	3187	5454

Rain (cm^3)

	Seeded		Unseeded	
	Mean	σ	Mean	σ
1972	136472	143113	100794	80063
1973	109411	96211	114772	42612
Pooled	131552	136196	104788	71675

Mean of Ratios -- H/R

	Seeded		Unseeded	
	Mean	σ	Mean	σ
1972	.0094	.0097	.0056	.0074
1973	.0337	.0141	.0574	.0339
Pooled	.0143	.0145	.0244	.0328

H/R -- Ratio of Means
(for days included in hail sample)

	Seeded		Unseeded	
	Mean	σ	Mean	σ
1972	.01406		.00418	
1973	.02131		.06841	
Pooled	.01516		.02635	

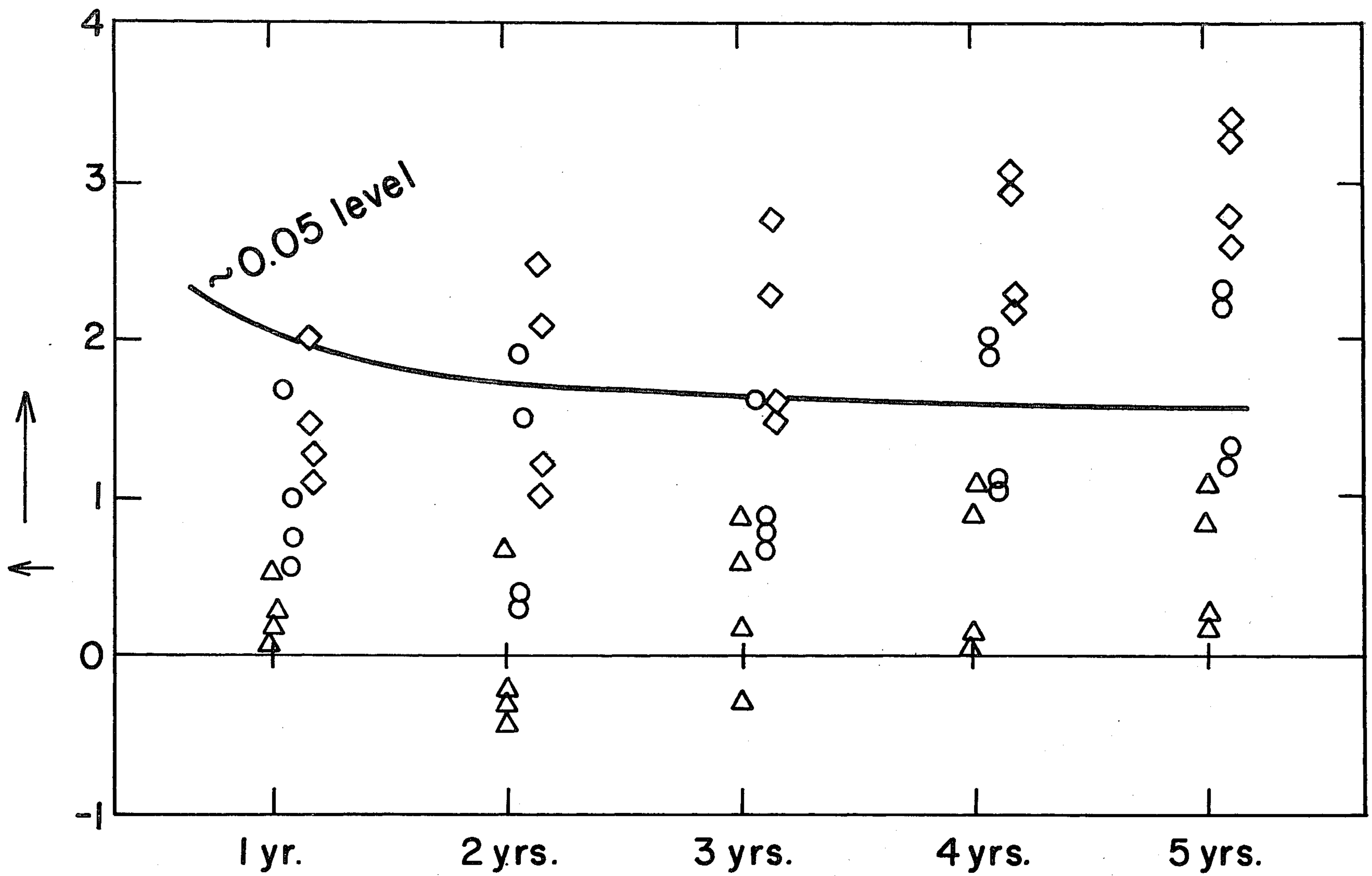

FIG. 5 PROBABILITY OF ACHIEVING .95 SIGNIFICANCE

△ ZERO EFFECT ○ 20% EFFECT ◇ 40% EFFECT

B. Achievements

To provide both an indication of what NHRE has already accomplished toward its goals and further background for the plans in the subsequent sections, we list here some of the more important achievements of NHRE in the scientific and technological areas. Most of the findings and developments listed below have been reported in NHRE progress reports and in more than 100 published papers. A few are more recent and will be described in future publications. Highlights follow.

1. Scientific Achievements and Findings

(1) Hail in northeast Colorado forms predominantly on graupel embryos, not on frozen raindrops. The environment of embryo formation is very probably one of small droplets (low radar reflectivity) and low liquid water content; not, as the Soviets have supposed in their suppression work, one of large drops and high liquid water content.

(2) While the condensed water measured in Colorado hailstorms can occasionally be several times in excess of the adiabatic value, this is generally not the case, and it does not appear that high water contents are important for hail formation.

(3) Deuterium content profiles in large and giant hailstones have shown simple growth trajectories, generally a simple up-and-down motion without important recirculation at large sizes. This contradicts some detailed models for forming large hail, and shows that the alternating clear and cloudy layers do not necessarily indicate significant up and down excursions.

(4) The dominant mechanism of precipitation formation in Colorado storms in their early and intermediate stages of development is growth through the ice process (Bergeron-Findeisen process).

(5) Typical concentrations of ice particles in clouds producing small showers are a few per liter. Concentrations of 100 per liter appear to be sufficient to deplete the supply of supercooled water in these smaller storms. This is the kind of concentration we must therefore aim at creating by artificial seeding.

(6) The concentration of drops larger than 100 μ diameter seem to be a few per cubic meter or less in the smaller storms.

(7) The droplet size distributions in the cumulus clouds in northeast Colorado are very continental in nature with typical concentrations of 500 to 1000 per cubic centimeter.

(8) Based on the microphysical similarities between these clouds in northeast Colorado and those over Israel which have been investigated and seeded by Gagin and his co-workers, there is probably potential for rainfall enhancement in the clouds in northeast Colorado.

(9) Observations obtained with the T-28 aircraft have shown that hail is not normally located in the high reflectivity zone of the storm. It can occur there, but it appears to be more frequently found on the flanks of the updraft.

(10) It has been shown that the variance of the water content in a given region of a cloud, as determined by an instrumented penetrating aircraft, is proportional to the radar reflectivity of that region. This result, while important as a consistency check between radar and <u>in situ</u> measurements, should also be useful in relating radar observations to the evolution of the drop size spectrum.

(11) It has been found that large aerosol (soil) particles act as accretion centers in clouds and shed hydrosol particles when injected into a drop; the shed particles can act as freezing nuclei.

(12) It has been shown in the laboratory studies that AgI particles produce ice through condensation-freezing when exposed to high water vapor flux around a freezing drop; however, the majority of natural aerosol particles act as condensation nuclei and produce droplets under these conditions.

(13) Laboratory studies have shown that the use of N-bromosuccinimide with AgI.KI generators eliminates the loss of AgI activity due to chemical complexing.

(14) A complex memory for ice nucleation is found for particles that have been subject to a condensation-evaporation cycle.

(15) The first radar detection of hail has been achieved in the intensively studied storm of 22 July 1972. Hail was detected aloft in the cloud; "snapshots" of hailshaft boundaries were produced on the NCAR computer; the resulting hailswaths compared favorably with those actually measured at the ground.

(16) The tracking of the movement of localized reflectivity maxima within the overhang of a large hailstorm has indicated the absence of recirculating trajectories.

(17) The dual-Doppler radar system of NOAA's Wave Propagation Laboratory was used to obtain for the first time full three-dimensional wind fields within severe storm cells. One case which occurred on 31 July 1973 was chosen for a detailed study. Because of the uniqueness of the data many new features of the storm airflow have been found. Among the most significant results are: (a) anticyclonic rotation of the updraft and cyclonic rotation of the downdraft; (b) a confluence line above the low-level region of high relfectivity with orientation along the mean environmental flow in the cloud layer; (3) a high reflectivity zone is

associated with downdrafts on the down-shear side of the updraft.

(18) It has been found that air entering the intense updraft of a severe storm originates within the lowest few hundred meters above the ground, and is usually negatively buoyant at cloud base.

(19) The updraft velocities at cloud base are generally in the range of 5 to 10 m sec^{-1}, with somewhat higher values observed on occasion.

(20) Air motion in the strong updraft is typically very smooth at cloud base, but breaks down into a turbulent flow of moderate intensity within a few kilometers above cloud base.

(21) Radar tracking of chaff packets have shown that storm updrafts usually have maxima at a rather low altitude, typically only 2 to 4 km above cloud base. These may not be the primary maxima however. The observations have also shown that the updraft is usually sloped.

(22) Aircraft penetrations of the weak-echo regions have shown that a surprisingly large amount of entrainment is taking place there, with vertical gradients in equivalent potential temperature of several degrees per kilometer.

(23) Instrumented sondes dropped into thunderstorms from above have generally revealed a very complex updraft structure, much like that shown by previous analyses of vertically-pointing pulsed Doppler radar observations. In one instance, however, a very broad updraft core was encountered. Updraft speeds are typically 15 to 25 m sec^{-1}.

(24) Aircraft observations in the subcloud region have provided the first documentation of the flow characteristics there, including the horizontal convergence and acceleration that take place, and have revealed an airflow structure of greater complexity than proposed by previous conceptual models.

(25) A relation has been found between precipitation efficiency and wind shear, with the strongly sheared storms being very inefficient rain producers; in these most of the condensed water is lost in the anvil. This suggests that seeding rates must be adjusted to the shear if the smaller crystals produced by seeding are not to be lost in the anvil and thus decrease surface rainfall.

(26) Airborne measurements utilizing an inertial navigation system have repeatedly shown that isolated clouds exert a blocking effect on the ambient mid-level flow.

(27) The design of the NHRE seeding experiment has certain characteristics that make it unique among weather modification experimental designs. The concentration of resources on the target without a control area is based on the absence of correlation between adjacent geographic regions, which minimizes the advantage of a control region. Further, the randomization employed is tailored to the statistics of the region, taking advantage of serial correlations when they exist.

(28) Most cloud seeding techniques rely on turbulent diffusion for proper dispersion of the seeding material. Diffusion estimates from turbulence data obtained with the T-28 penetrating aircraft, which detected moderate turbulent intensities at the mid-cloud levels, indicate that adequate dispersion may be an important problem which can limit the success of convective cloud seeding.

(29) Observations have shown that while considerable variability in silver concentration exists among ground sampling sites and among time periods, no significant increase in silver concentration appears to be occurring.

From the above findings it can be seen that we have already made significant strides toward: (a) a more complete understanding of the natural microphysical and dynamic structure and behavior of hailstorms, (b) providing a solid physical rationale for modifying the microphysical environment by seeding, and (c) optimizing seeding methodology.

2. Economic and Societal Factors

(1) A preliminary study of the economics involved in providing cloud-seeding services in the Great Plains implies a minimum size of approximately five million acres for an economically efficient program. A program of this size will incur direct costs in the range of 3¢ to 5¢ per acre of protected area or 12¢ to 20¢ per planted acre.

(2) Long-term average hail damage to crops in the northern Great Plains, estimated from insurance records and verified by a study of cropland transactions, falls in the range of $3 to $4 per planted acre based on 1972-73 grain prices. Therefore, in order for a suppression program to yield a ratio of direct benefits to direct costs in excess of unity, it must be capable of reducing prior hail damage by at least 6% to 8%.

(3) The effects of total precipitation received during the growing season could greatly enhance (or, if adverse, offset) its direct benefits. The additional crop yields associated with a 20% reduction in hail damage could be as much as doubled by a concomitant increase of 5% in early season precipitation.

(4) A comparison of actual crop losses to hail at harvest-time with those losses reported by ESIG's cooperative network of farmers during the

growing season indicates that they make an extremely accurate appraisal of the extent of crop damages from hail and that their estimates do not contain any systematic bias.

(5) Detailed estimates of property damage resulting from a severe hailstorm which struck Grover, Colorado, on June 11, 1973, indicated a mean amount of damage per residence in excess of \$800. Exterior damage to structures accounted for 66% of the total, while another 24% resulted from damage to vehicles.

(6) Monitoring of silver concentrations in soils, grasses, water, aquatic sediments, and aquatic plants in the NHRE experimental area has revealed no increases from before to after each seeding season. However, silver concentrations in both aquatic sediments and aquatic plants are measurably lower in mid-season than at the beginning and end of the season.

(7) Silver is taken up by corn, Kentucky bluegrass, and sugar beets when added to sand culture as silver iodide burn complex at 30 ppm dry weight. Highest uptake is by roots, followed by stems, leaves, and (in the case of corn) cobs, in that order. Total concentrations in cobs at maturity did not differ significantly between control and treated corn plants.

(8) The NHRE program enjoys widespread public support among the residents of northeastern Colorado with over two-thirds indicating that they would vote to have it continued and less than one in ten voicing opposition. Public acceptance increases as people gain more knowledge about the program. A majority of the people in the region, however, feel that an <u>operational</u> suppression program should be run at the local level rather than by the Federal government and over two-thirds indicate that they would be willing to make direct contributions towards the cost of such a program.

(9) The most successful operational hail suppression programs currently in existence in the Great Plains (where success is measured by continued public support and acceptance) are those exhibiting the following characteristics: (a) regular evaluation of project operations and effects; (b) extensive participation in policy decisions by public officials at the county level; and (c) the ability to raise a substantial fraction of required operating funds by exercise of taxing authority.

3. Technological Achievements

(1) Development of the NHRE hail-rain separator represents the first serious attempt to record timed hailfall amounts. The instrument records hail and rain amounts at one minute intervals, with 0.25 mm resolution for rain and 0.06 mm for hail. It is completely self-powered and remote and produces digital records on 35 mm film. An automatic film processor will soon be available to decode the data directly onto computer compatible tape.

(2) While the hailpads have a long history of development, NHRE has made significant improvements in their calibration and in rapid and economical methods of measuring size and concentration. The hailpads may well become a worldwide economical standard for use by farmers, insurance companies, and operational hail suppression agencies in assessing damage and in evaluating hail suppression efforts.

(3) An instrument has been developed to measure time-resolved hail size distributions using an optical scanning technique capable of resolution to 2.5 mm. The vertical fall speed of each particle can also be determined. The instrument is self-powered and uses the same digital recording system currently employed in the hail-rain separator.

(4) A vertically-launched spin-stabilized airborne rocket has been developed for use in NHRE. A high quality aircraft-safe launcher system for use with the rocket has been developed by NHRE personnel, and the system is fully operational.

(5) A practical method for efficiently detecting AgI on membrane filters has been developed. Measurements are in agreement with those from the CSU test facility. The method has been successfully field tested.

(6) A low pressure impactor system was developed for the T-28 penetrating aircraft to detect AgI versus time in a severe storm updraft system. It is also applicable to laboratory research. A time resolution, low weight membrane filter sampler was also developed for the sailplane to detect AgI in cumulus seeding experiments.

(7) Improvements were made in the NCAR continuous ice nucleus counter for quantitative detection of AgI in seeding experiments and long distance transport studies (up to 130 miles).

The latter three developments are crucial to planned experiments to measure the presence and concentration of AgI in seeded storms to determine whether or not it is reaching the intended target areas in required concentration.

(8) A continuous condensation nucleus counter capable of sampling over a wide range of concentrations was developed and flown to altitudes in excess of 40,000 ft.

(9) A photographic cloud and precipitation size sampler has been developed by Cannon and used on the NHRE sailplane. It represents a revolutionary achievement in terms of both the broad range of particle sizes which it detects (down to 8 microns diameter) and the large sampling volume (up to 1400 cm^3 per frame per 1/2 sec for particles of $\geq$ 5.3 mm diameter).

Most important is its ability to distinguish water from ice above 100 μm diameter and to depict particle shapes *in situ* particle distributions in each sample volume.

(10) The electrostatic cloud drop size probe was developed and improved by Abbott and Sartor from a prototype designed by Professor Keily at MIT. The result is an automated cloud drop distribution sensor presently operated in the size range between 4 microns and 120 microns radius.

(11) A sailplane was instrumented and developed into an integrated cloud physics observational system. The sailplane is an excellent real-time probe of atmospheric motions, particularly of the important vertical component. The sailplane instrumentation system includes the Cannon particle camera and the electrostatic disdrometer for drop and ice particle distribution information, and instruments to measure vertical velocity, temperature, humidity, pressure, and acceleration. By radar tracking, position and horizontal air motion information can be obtained.

(12) Design and development of two sophisticated dual-wavelength weather radars represents a major accomplishment of the NHRE program. Preliminary results reporting successful hail detection have already appeared in the literature and we have a high degree of confidence that these will be validated by further experiments. The most important NHRE application in the immediate future is the use of the dual-wavelength system for mapping hailswaths and evaluating hail suppression experiments. Atlas and Ulbrich have also done extensive theoretical analyses to show how a dual-wavelength radar system may be used to measure rainfall rate, liquid water content, and median volume diameter. The measurement of rainfall rates by this method should be much more accurate than that obtainable

from á priori assumptions of a simple regression equation between radar reflectivity and rainfall rate. Indeed, the most important application may eventually be in the remote measurement of surface rainfall.

(13) While NHRE has not yet exploited Doppler techniques to the fullest, the observations made by the NOAA Wave Propagation Laboratory's dual radar system during the 1973 NHRE field season already demonstrate exciting new features of the internal three-dimensional field of airflow. The observations of such detailed and comprehensive flow fields have never before been possible. We are therefore highly confident that the major attack on Doppler observations of storm motions and associated precipitation size distributions and trajectories to be mounted in the remaining years of NHRE will have a profound effect on the basic radar instrumentation, the data processing and display techniques, and fundamental understanding of storm motions and their interaction with precipitation.

(14) In response to immediate NHRE needs, the NCAR Field Observing Facility has developed the first digital 'false color' processor for the display of either contoured reflectivity or Doppler velocity data. The color display of radial Doppler velocity permits the real-time identification of major features of the storm airflow including divergence, vorticity, and the main inflow region. This display is expected to be most useful in locating the main inflow regions for deployment of the seeding aircraft. It will undoubtedly prove to be even more valuable for tornado detection.

(15) The NHRE Data Acquisition and Display System (DADS), utilizing a minicomputer, has demonstrated its great value in displaying contoured radar reflectivity data, the location of maximum reflectivities, in depicting

the overhang and weak-echo regions for the vectoring of seeding aircraft, and in displaying aircraft tracks for aircraft control. The DADS can also be used for quick playback in the post-analysis with the same capabilities that the real-time display system has.

(16) In order to analyze thunderstorm data collected by different aircraft, the aircraft systems must be compared in a meaningful manner and a measure of accuracy established for each aircraft instrumentation system. Toward this end NHRE has developed a reliable procedure for the checkout and correction where necessary of aircraft meteorological data. The successful implementation of this program has made possible intricate analyses of airborne data. The methodology has been adopted by other programs involving multiple aircraft (e.g., GATE).

While a number of improvements in instrumentation and methodology are still reguired, it is evident that these technological advances have solved a wide variety of problems which had previously prevented significant progress. Moreover, they provide unprecendented opportunities to obtain the crucial observational data necessary to understanding and to the conduct of effective seeding operations and evaluation.

V. Special Problems and Solutions

In this section we discuss some of the key problems which have come to light either in the course of normal activities over the last two years or as a result of the in-depth analysis which was a necessary precursor of this program plan. We also propose solutions. With the exception of organizational and management problems which are not adequately covered elsewhere, we present only the highlights with reference to the specific sections and page numbers where detailed discussion may be found.

A. Organization and Management

1. Organizational Structure

Partly as a result of the management style of the previous NHRE Director and partly because of the limitations in staff which required various people to function in multiple roles, the previous organizational structure of NHRE was essentially horizontal with all key staff reporting to the Director. This situation imposed extra-heavy communications burdens on the Director and immersed him in excessive detail; as a result, communication was sometimes inadequate.

The new organizational structure (Fig. 17, p. 276) is more classical in design with four discrete scientific groups and with all the support staff gathered under the Management and Engineering Group. With this pyramidal arrangement, the responsibilities of the group leaders are more clearly defined; related problem or support areas are more closely integrated; and all staff have a clearer picture of those to whom they must be responsive. Because certain individuals will still have to function in two roles, the organizational chart shows both their primary and secondary responsibilities.

2. Project Integration

The first two years of NHRE have led us to a more complete understanding of the relationships between various problem areas and group activities. The attainment of NHRE's goals now depends critically upon integration and synthesis (e.g., to generate an overall model of a hailstorm from the individual pieces of the puzzle).

A number of important steps have been taken or are in process to accomplish this integration. These are described below:

a. Chief Scientist: This position has been established (and will be filled for at least one year by Dr. K. A. Browning as of 1 October 1974) to provide a senior scientist who is free of administrative burdens and who will be responsible for maximum integration and synthesis. The Chief Scientist will act as overall scientific planner and coordinator for all components of NHRE including university participants. He will focus on the gaps in the program which are crucial to completing the full picture and will act as the scientific link between the individual groups to assure that all new findings are continually integrated into a progressively refined model(s) of a hailstorm. The Chief Scientist will also hold key responsibility for drawing together the individual contributions to a multi-faceted scientific problem or case study into a unified entity.

b. NHRE Steering Committee: This is an internal NCAR steering committee comprised of the Director, Chief Scientist, Group Leaders, selected key scientists, and one member from another NCAR program. It meets biweekly and as required to review overall plans and progress, identify problems, and offer solutions. Special attention is paid to inter-group activities and integration. The committee also acts as a resource allocation panel to identify priorities and shift support personnel and funds in response to the needs.

c. Integration of Cloud Physics and Nucleation Groups into Microphysics Group: The Cloud Physics and Nucleation Groups were previously components of the NCAR Atmospheric Physics Program. Now that they are full members of NHRE, their non-NHRE related activities have been phased out and they have been fully integrated into a single Microphysics Group under the leadership of Dr. C. A. Knight.

d. Numerical Modeling Group: This group will act naturally as a focal point for integration of all activities because the numerical models must include all aspects of the microphysics and macrophysics of hailstorms, and must also be capable of simulating seeding effects.

The ultimate goal is an observationally based and observationally validated numerical model of a hailstorm which is capable of (1) identifying all essential environmental variables which effect hail development, (2) reproducing hail formation and growth regions within the storm, (3) simulating the microphysical and dynamical effects of seeding and the resultant precipitation output, and (4) optimizing the seeding variables to maximize the joint benefits of hail suppression and rain enhancement. The successful achievement of this goal would thus represent the penultimate form of program integration.

e. Societal Utilization Program: This program continues to be conducted by the Environmental and Societal Impacts Group (ESIG) under the general direction of the NCAR Advanced Study Program (ASP). Discussions are under way concerning the advisability of placing the NHRE-related components of the group in NHRE in order to assure both a closer working relationship and responsiveness to NHRE's needs.

f. University and Other Agency Integration: Special attention must be paid to this area because of the obvious problems associated with separation from NCAR. Four steps are being taken as follows: (1) Quarterly symposia will be held with all key participants from NCAR and universities present to report on progress, identify problems, agree on coordinated plans, and generally to communicate and exchange ideas. One of these meetings will be a 2 or 3 day annual retreat. These symposia are expected to lead naturally to more NCAR-University joint research papers. (2) A monthly NHRE newsletter will be initiated with each group submitting a short progress report. (3) An internal NHRE manuscript review system has been established to provide reviews of papers prepared by all participants. This will permit us to watch for opportunities to integrate efforts before final publication and will assure that the NHRE management is fully apprised of significant developments as they occur. (4) Visits to all participating groups will be made at least annually by the NHRE Director or Chief Scientist.

B. University and Other Agency Relations

It is NCAR's policy to involve university scientists in joint projects to the fullest possible extent. NHRE represents a unique opportunity for such involvement. Indeed a large number of university scientists have participated since the very start. The broad array of facilities available within NHRE and through the various participating agencies and universities provides very attractive opportunities for all scientists to make a significant impact on our understanding of the mechanisms of severe storms in general and hailstorms in particular.

However, because NHRE has quite specific objectives and a well defined time schedule, and because NHRE's success will depend upon close cooperation and integration, it is necessary to exert tighter control upon all participants than would otherwise be the case. The exercise of this control must take a variety of forms including the initial selection of university participants, the regular review and reorientation of their efforts, and as necessary, the termination of such participation when they are no longer contributing directly to NHRE goals. This process is particularly delicate because university scientists are generally unaccustomed to working under such guidelines. The situation becomes particularly sensitive when an NHRE university subcontract has to be terminated or reduced for whatever reason.

There are no simple solutions to these problems. The general approach must be to encourage a high spirit of cooperation and recognition of mutual interdependence in working toward an exciting goal. It is our hope that the quarterly NHRE symposia, the monthly newsletter, and more regular visits to universities will work toward generating this spirit. But we would be naive to hope that such mechanisms will alleviate the antagonism which is bound to result when and if an NHRE subcontract must be reduced or terminated. While NHRE management cannot avoid the final responsibility for such decisions, we must exert great care to make sure that actions of this kind are not taken lightly or unilaterally. To reduce the possibility of internal bias in making such decisions, NHRE has used its Advisory Panel for the review of external proposals. We now propose to involve the Advisory Panel more deeply in assessing the quality of effort of university participants and in seeking their guidance with respect to questions of continuation, reduction, or termination.

Another highly sensitive issue relates to joint authorship. The kind of overall synthesis toward which we are aiming and the interdependence of all participants naturally implies multiple authorship of papers. For obvsious reasons, however, multiple authorship is a threat to many scientists. While it is believed that increased communications and interactions with university participants will encourage more joint authorship, we propose to ease the problem by at least two approaches. The first is to allow each of a set of contributors to author his (their) own contribution to an integrated study and to add a final but separate paper to the set which focuses upon the synthesis of the individual contributions. The integrating paper could be authored either jointly by all, by the lead scientists, or by the NHRE Chief Scientist or Director, as the case may be. In addition, in the case of joint authorship by co-equal contributors, the sequence of authors will be selected randomly.

University participation in NHRE, both past and future, is indicated in the attached table. Of course, future participation depends both upon funding and the crystallization of mutually acceptable plans.

C. Science-Related Problems

1. Numerical Modeling

The lack of a numerical modeling effort within NHRE has been the source of considerable criticism. This program plan proposes the establishment of a numerical modeling group (see p. 243).

2. Delays in Analyzing Results of Seeding Experiment

We are acutely aware of the need to maintain a continuing in-depth analysis of the results of the seeding experiment; this effort is lagging seriously. Such analysis must also be done in order to determine the validity of our original experimental design. While there are good reasons for the delays (e.g., NHRE's only statistician has had to concentrate heavily upon the rocket development problems and field operations), this

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		70	71	72	73	74	75	76	77	78	79	80
ISWS	NHRE Design	17,808										
DRI	DADS Design	46,361										
Wyoming	Microphysics Study		197,492	254,263	272,150	106,000	100,000	75,000	225,000	225,000	100,000	50,000
CSU	Cloud Interior		183,059	164,566	66,575	41,000	20,000	30,000	35,000	35,000	40,000	40,000
SDSMT	T-28		108,108	134,136	176,975	130,000	175,000	175,000	225,000	225,000	100,000	50,000
Chicago	CHILL Radar		71,645	140,857	117,820	40,000	40,000	50,000	120,000	120,000	75,000	50,000
Ill.	CHILL Radar		43,929	49,977	72,000				120,000	120,000	75,000	
CSU	Downwind			25,000	67,500	43,000						
Ill.	Microhail Study				10,000	12,000						
DRI	Ice Crystal Study			56,653	45,960							
DRI	Dynamics Study			41,880	53,320							
Denver	Nucleation Study			20,000								
DRI	Radar Tracking			23,262	33,400	28,000	24,000	25,000	27,000	28,000		
Okla.	A/C Intercomparison		33,208	34,898	12,000							
CSU	AgI Study			48,941	50,000	30,000	28,000	30,000	32,000	32,000	34,000	
SMU	Legal Implicat.			10,000				15,000	13,000	12,000		
Ore. St.	Boundary Layer				6,777	7,000	7,000					
Clemson	Radar Analysis						20,000	25,000	35,000	40,000	40,000	40,000
SDSMT	Modeling							40,000	40,000	45,000	45,000	45,000
Arizona	Modeling						22,000	22,000	25,000	30,000	30,000	30,000
DRI	Precip Samples				10,000	61,000			45,000	45,000	30,000	
Wyoming	Societal Utiliz.							12,000	13,000	15,000		
New Total (1974 Plan)		64,169	637,441	955,492	994,477	498,000	278,500	499,000	955,000	972,000	569,000	305,000
Old Total (1973 Plan)		64,169	637,441	955,492	994,477	1,049,300	1,087,900	1,100,500	345,000			

must be rectified. Accordingly, we plan to strengthen the suppression program greatly by reassignments and hiring. This will include five scientists, a programmer, and a part-time expert statistical consultant. Dr. Lovell will also be relieved of operational field responsibilities.

3. Inadequacy of Hail Day Sample Size:

This problem is addressed in Section IV A. The alternatives are: (1) to enlarge the protected area or (2) to extend the experiment in time. The first is precluded by budgetary constraints; we therefore propose a two-year extension. The expected total sample of 105 cases should be sufficient to reach statistically valid conclusions on hail reduction effects of about 30% or more.

4. The Proper Measure of Seeding Effects:

This problem is treated in Section IV A and on pp. 55 . The original choice of total hail and rain mass was a compromise between what needed to be measured and what could be measured reliably and economically. The recent invention of an economical electro-optical instrument should soon permit us to record the hail size spectra, the fundamental storm output which seeding aims to affect.

5. Use of Both Flares and Rockets in Seeding:

With the successful completion of the seeding rocket system, extensive consideration has been given to the question of whether or not to abandon the use of seeding by flares at cloud base. After deliberations with the NHRE Advisory Panel it was decided to use both flares and rockets in order to insure that the AgI is in fact being delivered to the desired target region, and to do this at least until the reliability of the rocket system was demonstrated beyond any question. With this conservative strategy the question of resolving which of the two systems is most effective will depend upon the availability of sufficient cases by the beginning of the last two years of operations. It may then be possible to switch entirely to the rocket system. While there is considerable concern about destroying the homogeneity of the experiment by the addition of the rocket system, the Advisory Panel argued persuasively that the primary goal must be to produce measurable effects, whatever the delivery system. The use of both methods is aimed at providing the greatest chance of producing such effects. The possibility of overseeding was considered small because the concentrations of AgI are unlikely to increase by more than a factor of two when both systems are used simultaneously.

6. Backlog in Radar Data Analysis:

As of June 1974, the bulk of the 1972 and 1973 radar data had not been reduced because of a variety of problems related to noisy data, complexities of the computer program routines, the need to 'massage' some data by hand, and inadequate programming support. Most of these problems have now been solved with the aid of the NCAR Computing Facility, and it is expected that all radar data will be reduced and available to all participants by about 30 October 1974. Additional scientific and programmer support for the radar program should also ease future problems in this area.

7. Error in 1973 Radar Calibration:

The 8 db error in the 1973 calibration of the CP-2 10 cm radar which led to an underestimate of the storm reflectivity and caused us to miss hail day declarations, is extremely serious. The radar operations routine now includes an intensive radar calibration program which will preclude the possibility of errors in excess of ± 3 db (i.e., state of the art). In addition, all prior data is being 'calibrated' against actual surface rainfall to provide knowledge of the day-to-day system calibration.

8. General Equipment Malfunctions:

In a program of this complexity which involves such a wide array of instruments, some equipment failures and malfunctioning are unavoidable. Our goal is to keep these to a minimum acceptable level. The problem is related to adequate funding and staffing and partly to the use of aging equipment (e.g., the DRI M-33 radar) and other shortcuts dictated by budgetary restrictions (e.g., no emergency power generator for the CP-2 radar at Grover). One of the purposes of the reduced field program proposed for 1975 (Section VI) is to permit the improvement and updating of all instrumentation so that we can minimize such malfunctions in the future and return to an all out final attack in the 1976-78 field seasons. In addition to the new and enhanced instrumentation indicated in the plans for FY 75 and 76 (Section VI) we plan to provide a replacement for the obsolescent DRI M-33 radar and emergency power for the critical operational systems at Grover. Major improvements have already been made in the air-to-ground and ground-to-ground communications system. The new NHRE organizational structure (Fig. 17, p. 276), Field Management Organization (Fig. 18, p. 277), and Field Operations Organization (Fig. 19, p. 278), should also contribute to the solution of this problem by better focusing the responsibilities for all instrumentation efforts. A chief engineer has also been appointed to integrate all engineering support and to provide greater efficiency and flexibility in the assignment of engineers and technicians.

VI. General Plans and Budget

In the development of this revised NHRE plan, we have thoroughly reevaluated our current position. The revision thus takes advantage of lessons learned, and identifies and strengthens those parts of the program where our experience indicates that revised strategies and/or additional effort is essential. The overriding criteria in determining whether or not to include a particular item are that: (1) it be crucial to NHRE's goals and (2) the problem be tractable. Accordingly we have explicitly excluded those problems which are thought either to be only tangential to understanding and controlling hail growth or are unlikely to be soluble within the time and resources available to NHRE. For example, in microphysics, we shall concentrate on the effects of nucleation, rather than on the "how," because the fundamental physical chemistry of nucleation is unlikely to be solved for years to come. On the other hand, we omit a major attack on the storm electrification problems not because they are judged to be unimportant but because of the great difficulty of making revealing measurements within the storm environment.

In short we have used our experience to date to write a plan that is designed to give a high probability to the fulfillment of the NHRE objectives discussed in Section II.

In Section III we have discussed in brief the nature of the problems judged to be important and tractable. Our approaches and strategies are particularized and presented in depth in Section VII with special detail on the next two years. In this section, we highlight the major features and rationale of the revised plan, and present overall budgets for the remainder of the project. The following sections are organized according to the budget breakdown given at the end of this section.

The main components of the program are:

1. Suppression experiment
2. Societal utilization
3. Microphysics
4. Macrophysics
5. Numerical modeling

The key questions to which each of these components are addressed and their essential thrusts are described below. Note that there are many subsidiary questions which are not addressed in this section; these are discussed in Section VII, Detailed Plans and Budget. Similarly, only the essence of the attack toward each problem is given here with further details in Section VII, however, we do highlight major changes from the prior approach. Subsequently we present a list of the tasks under each of the major sub-programs and an indication of their priorities.

<u>Key Questions and Essential Thrusts</u>

1. Suppression Experiment:

Questions: a. Does seeding produce a statistically significant reduction in hailfall?

b. Does seeding produce a statistically significant change in rainfall?

c. What are the mechanisms by which seeding effects hail- and rainfall?

d. If hailfall reduction is feasible, how can we make it operationally effective?

e. Are the seeded and unseeded samples taken from a synoptically homogeneous set?

Thrusts:

a. In-depth critical review of experimental design by panel of experts and NHRE staff -- Fall, 1974.

b. Test measures other than total surface hail and rainfall, especially hail size spectrum or parameters thereof, radar reflectivity, dual wavelength radar 'hail signal,' and time-space trends of these measures in seeded and unseeded storms. Time space trends following the onset of seeding are also aimed in part at identifying the physical effects question (c. above).

c. Localize search for suspected major effects in restricted areas and time periods following seeding. Where possible, treat individual storms as test cases.

d. Procure electro-optical hail disdrometers for protected area.

e. Extend suppression experiment for two years (1977-78) to aim at attaining a minimum of 105 hail day samples sufficient to reach statistically significant conclusions on an average hailfall reduction of about 30%. The option of extending the protected area appears to be precluded by budgetary constraints.

f. The physical mechanisms by which seeding effects hail and rain are addressed under the sub-programs described below.

g. Study the synoptic and mesoscale settings conducive to hailstorms, identify differences between 'hail' and 'non-hail' days, and check for synoptic homogeneity between seed and no-seed days. Evaluate hailstorm predictability for ultimate operational use.

2. Societal Utilization:

Questions:

a. What are the economic benefits of various degrees of hail suppression in combination with varying effects on total rainfall?

b. What are the costs of a hypothetical but realistic operational suppression program?

c. What are the side-effects in terms of health hazards, downwind rainfall reductions, etc.?

d. What are the social and legal problems and risks?

Thrusts:

a. Crop damage functions are related to hailfall parameters and changes in hailfall within the PA are compared to damage on adjacent cooperating farms. Rainfall changes in the PA are related to crop yields. Results are converted to market value to deduce economic benefits of both hail reduction and rain enhancement.

b. A hypothetical operational hail suppression program is being evaluated in terms of cost/benefit ratios; costs are based in part upon estimates provided by commercial weather modifiers. Preliminary results indicate that a 10% hail reduction would be cost effective. Also the benefits of a 20% reduction in hail would be negated by a 5% associated reduction in rainfall at the critical part of the growing season.

c. Effects of silver iodide on insects, animals, and on the entire food chain are being studied under subcontract. Downwind effects of silver iodide and rainfall changes are under investigation.

d. Social response studies to the NHRE experiment and to a future operational program are in progress. Changes in existing laws and regulations necessary to permit a limited-risk operational program will be investigated.

3. Microphysics:

Questions: a. How and where do hailstones form?

b. What are the links between aerosols, cloud, and precipitation particle content?

c. What does the seeding material do to the microphysical structure of the storm and to the final precipitation products?

Thrusts:

a. Closely coordinated measurements between sailplane and T-28 penetrating aircraft to measure microphysics, drafts, and thermodynamic structure of storms and radar to observe and deduce embryo locations and particle growth rates, especially in new turrets and radar overhang.

b. Field and laboratory studies of cloud condensation and ice nuclei, their activation spectra and modes of activation, and their relations to cloud and precipitation types, sizes, and concentrations.

c. Laboratory evaluations of size, concentration, and nucleating ability of the seeding material.

d. Direct in-cloud measurement of the presence of seeding material and ice crystal and graupel products following seeding.

4. Macrophysics:

Questions:

a. What is the basic airflow in a hailstorm?

b. What is the hailstone trajectory from initial embryo to final appearance at the surface?

c. What is the trajectory of the seeding material and how does it diffuse?

d. What is the essential dynamics of a hailstorm and how does it differ from other thunderstorms?

e. What controls the precipitation efficiency of a thunderstorm and is the efficiency affected by seeding?

f. What, if any, effects on storm dynamics are produced by seeding?

g. Where and when should seeding be done, and in what amounts to maximize effects?

h. Is hail reliably detectable by dual-wavelength radar and can we deduce hailstone trajectories therefrom?

i. What are the 4-dimensional relationships between radar hail signals, reflectivities, and Doppler velocities and how do these relate to actual hail sizes and trajectories as deduced by aircraft and surface data?

Thrusts:

a. Coordinated aircraft circumnavigations with chaff releases as necessary and intense dual-Doppler radar observations to map both external and internal air motions and drafts. These are aimed at defining basic airflow in terms of the trajectories of both hailstones and seeding material and in identifying optimum locations (inflow, updrafts, new turrets) and times for seeding. The same methods will provide much of the basic information required in the studies of storm budgets and precipitation efficiency.

b. Dual wavelength radar observations first to validate hail detection capability and secondly to define hail trajectories in close coordination with surface observations and T-28 penetrations.

c. Three-dimensional mapping of the reflectivity, hail signal, and Doppler velocity fields of evolving storms in association with both surface and aircraft measurements aimed at a comprehensive model of the clouds, precipitation, and air motion and the manner in which hail grows in this environment.

5. Numerical Modeling:

Questions:

a. Can we simulate numerically the essential microphysical and dynamic processes of a hailstorm in an integrated model consistent with the observations?

b. Can we simulate numerically the microphysical and dynamic effects of seeding?

c. Where, when, and in what amounts should seeding be done to maximize effects, and what are the expected responses to various seeding materials and strategies?

Thrusts:

a. Develop limited models of individual processes.

b. Develop 1-D time dependent model with improved microphysics.

c. Develop a 2-D time dependent dynamic model with limited microphysics.

d. Blend the microphysical and dynamic models successively until the integrated model reproduces the observations realistically.

e. Numerical trials of different seeding materials and strategies with these models.

f. Conduct limited experiments with a 3-D model to the extent made possible by progress elsewhere.

Detailed descriptions of each of the sub-programs are presented in Section VII where we include primary and secondary objectives, background, specific relevance, approach, required resources, possible obstacles, key investigators, probable by-products, and a detailed budget. Section VII also presents details on the Research Support Program (Data Acquisition and Display, Data Management, Aircraft Calibration, Logistics) and Section VIII deals with Organization and Personnel.

Table 4 below summarizes the entire program and lists the priorities attached to each effort. By and large the priorities indicate both the emphasis and the scheduling of the study. Most priority 1 items are being addressed at the present time; some of them will continue to be attacked throughout the program. Under the seeding and societal utilization programs, all efforts will ultimately be undertaken regardless of priority. However, in the supporting research programs (Microphysics, Macrophysics, Numerical Modeling) we cannot guarantee that those efforts indicated as priorities 4 and 5 will receive adequate attention. These studies will be attacked only after satisfactory progress has been made on the higher priority investigations. Because most of the questions being addressed under supporting research are of a fundamental nature, it is not possible to provide well defined schedules for completion or indeed, to guarantee that definitive results will be achieved.

Table 4 also includes rough estimates of the FY 75 and 76 costs for each of the tasks; they are provided only as an indication of the magnitude of the effort. The costs are crude approximations at best because most of the tasks are overlapping and share supporting resources, and staff may be involved in two or more tasks simultaneously.

Table 4

NHRE Program Summary

		Estimated Funding Allocations			
		RANN		Non RANN	
	Priority	FY75	FY76	FY75	FY76
1. Suppression Experiment					
a. Review Design	1	10	5		
b. Related Operational Activities	1	530	550		
c. Statistical Analysis and Physical Effects Search					
(1) Statistical Analysis	1	135	135	20	20
(2) Reflectivity and Doppler	2	130	100	15	20
(3) AgI and Crystal Products	1	80	75	35	25
(4) Hail and Rain AgI Content	2	20	15	10	10
(5) Radar Structure in Seeded Areas	2	50	50		
(6) Numerical Tests of Seeding	3		15		
d. Synoptics					
(1) Synoptic seetings, differences between hail and non-hail days	2	25	25		
(2) Differences between seed and no-seed days	1	75	50		
(3) Hailstorm predictability	3	10	15		

	Priority	FY75	FY76	FY75	FY76
e. Operations Research					
(1) Feasibility and cost effectiveness of operational systems	3		15		
(2) Side effects	3		10		
f. Seeding Techniques					
(1) Operational evaluation of rockets/flares	1	20	15	10	10
(2) Alternative seeding methods	2	10	25		
(3) Variation of operational methodology with storm type	3		25		
Subtotals		1095	1125	90	85
2. Societal Utilization					
a. Direct and indirect benefits/disbenefits	1	85	90.5		
b. Costs of an operational suppression program	2	4	3.5		
c. Environmental side effects of AgI	1	39.5	32		
d. Social process model	3	29	30		
e. Legal and political problems	3	1	15		
f. Decision analysis model	4	6.5	9		
		165	180		
3. Microphysics Program					
a. Hail Embryo Problem					
(1) Role of liquid coalescence	1				
(2) Nature of initial embryos	1	150	150	80	80
(3) Region of embryo formation	1				
b. First Echo Studies					
(1) Particle growth rates in new storms	1	150	150	30	35
(2) Particle growth rates along hail trajectories in mature storms	1				

	Priority	FY75	FY76	FY75	FY76
c. Nucleation and Glaciation					
(1) Link between aerosols and ice particle content	4				25
(2) Nuclei climatology	4				25
d. Nucleant evaluation and In-cloud seeding effects					
(1) Laboratory studies of seeding material	1	55	60	55	45
(2) In-cloud tests of AgI and products	1	75	75	80	55
Subtotals		430	435	245	265
4. Macrophysics Program					
a. Air Motion and Dynamics					
(1) Ventillating effects of shear; entrainment, mixing, diffusion; boundary layer influences; steering and propagation	1	30	30	10	10
(2) Hailstone trajectories	1	40	30	15	15
(3) Dynamic effects of seeding	4				
b. Bulk transports and budgets					
(1) Precipitation efficiency	2	20	30	10	10
(2) Partition airflow into main branches	3		30		
(3) Differences between seeded/unseeded storms	2		30		
(4) Moisture budgets compared to radar estimates	4				
(5) Large scale interactions	5				
c. Anvil budget studies	3				
d. Dual-Wavelength Radar (DURAD) Studies					
(1) Evaluation of hail detection capability	1	75	25		
(2) Evaluation of DURAD for rainfall and LWC measurements	2	15	30		

	Priority	FY75	FY76	FY75	FY76
(3) Hail cross-sections as function of shape, roughness, wetness	5				
(4) Reflectivity profiles of melting hail	5				
(5) 4-D structure of reflectivity and hail signals	1		40		
(6) Reflectivity and hail data processing for all users	1	85	40		
e. Three-D dual Doppler velocity and Reflectivity Mapping					
(1) 3-D graphic displays of velocity and reflectivity	1	35	25		
(2) Relate reflectivity and hail signal fields to air motions and hail trajectories	1		30		
f. Vertical Doppler radar studies	3	30	25		
Subtotals		330	365	35	35
5. Numerical Modeling Program					
a. Comprehensive Models					
(1) 1-D time dependent, improved microphysics	1	40	25		
(2) 2-D time dependent, limited microphysics	1	45	45		
(3) 2-D, parameterized but realistic microphysics	2		35		
(4) Merger of (1), (2), and (3)	3				
(5) Full 3-D model	4				
b. Simple Models					
(1) Analytic or numerical treatments of various phases of hail growth and inhibition	1	20	25	20	25
(2) Evaluate role of electric fields in hail formation	4				
Subtotals		105	130	20	25

6. Other Elements

Logistics	125	136	----	----
Administrative	150	157	----	----
Sub Totals	275	293	----	----
Totals	2400	2528	390	410

Planned Staff Changes

Our experience in NHRE work thus far has exposed thinness in staffing that threatens the success of the experiment. The fact that key scientists currently on board must inevitably function in administrative, operational, and support roles has left us with an insufficient amount of key scientific energy to allow analysis to keep pace with the observational program. The lack of adequate programming and junior analytical staff is another cause of the analysis backlog, especially in the reduction, and analysis of the basic radar data and the hail/rain data for the seeding experiment. Concentration by engineering and support personnel on maintenance and calibration problems has similarly precluded the necessary attention to improving existing equipment and developing new ones. The absence of a chief scientist who, unlike the project leader, is free of administrative and management responsibilities, has led to serious deficiencies in integrating and guiding the multiplicity of individual studies carried out internally and by participating university groups. Accordingly, the current plans call for the following increases in staff:

<u>FY-75</u>

Program Integration	--	Add Chief Scientist (Dr. K. A. Browning)
Suppression Experiment	--	Add 1 Ph. D. Statistician
		Add 2 Ph. D. Meteorologists (1 vacancy due to resignation of senior consultant; transfer of Sartor)

	-- Add 2 M.S. Analysts (1 vacancy transferred from Microphysics; 1 new hire)
Microphysics	-- Transfer vacancy to Suppression Program
Macrophysics	-- Add 1 Ph. D. Analyst - Doppler air motion studies
	Add 1 Ph. D. Radar Meteorologist
Modeling	-- Add 1 Ph. D. Modeler
Research Support	-- Add 3 Programmers

FY-76

Modeling	-- Add 1 Ph. D. Modeler
Research Support	-- Add 1 Programmer

Schedule

This plan proposes a two year extension of the suppression experiment through the summer of 1978 in order to aim at attaining about 105 hail day samples, which is believed to be sufficient to reach statistically significant conclusions on a hail reduction effect of about 30%. This will provide 7 years of data.

In the summer of 1975, supporting research will comprise only a few intensive individual experiments (e.g., sailplane investigations and limited T-28 penetrations) and equipment trials. FY-75 will therefore be dedicated largely to the reduction and analysis of the backlog of past data, to equipment improvement, and to the redefinition and refinement of our hypothesis and approaches. We would then be much better prepared for returning to the field in the summers of 1976 and 1977 for an all-out attack.

The 1978 field season would be aimed at filling in the remaining gaps. All field work would terminate in August 1978.

The remainder of FY-79 (10 months) and all of FY-80 would be dedicated to data analysis, synthesis, and report writing. Considering the vast amount of data to be available by the mid-summer of 1978, 22 months of final analysis is not at all excessive. While initial results may be expected in the first half of this period, we may also predict with some degree of confidence that the initial analyses will raise more questions than they answer. Moreover, as in previous weather modification studies, it will surely be necessary to reexamine the data in various ways in order to answer the key questions implicit in the initial conclusions. Obviously, such interaction implies sequentiality and adequate time.

In addition to the multiplicity of scientific papers which may be expected throughout the program, by 30 June 1980 we propose to deliver at least two major reports:

(1) The Feasibility of Hail Suppression

(2) The Physics and Dynamics of Hailstorms and the Basis for Their Modification.

Budgets:

The overall budget for the program is presented in Table 5 at the end of this section. The budgets for 1970-73 are shown in Table 6 for comparison and completeness. While we have attempted to budget in some detail through 1980, readjustments in details will undoubtedly be necessary as the program proceeds. In the following paragraphs we summarize the main features underlying each year's budget with emphasis on the reasons for increases or decreases.

In examining the budget it should be noted that suppression experiment includes much more than indicated under Seeding Operations in Table 4 . If we include all the facilities and manpower associated with the suppression experiment (e.g., approximately four man years are dedicated each summer by scientists normally engaged in microphysics and macrophysics to the suppression operation; and the entire CP-2 radar team is similarly dedicated) we find that the estimated true costs of the suppression experiment for FY 1976 are as indicated in Table 7 below. In estimating these costs we have assigned reasonable fractions of the costs of each of the supporting research programs to suppression.

Table 7

Estimated Costs of the Suppression Experiment
FY76

	Total FY76 Request	Suppression Costs
Microphysics		
Precipitation Physics (50%)	163,000	81,500
Nucleation (100%)	41,000	41,000
SDSM (50%)	175,000	87,500
	379,000	210,000
Macrophysics		
Storm Dynamics (25%)	81,000	20,250
Mesoscale Network (100%)	41,000	41,000
Radar (75%)	187,000	140,250
Chicago (25%)	50,000	12,500
	359,000	214,000
Modelling		
Hailstorm Models (50%)	118,000	59,000

Societal Utilization		
ESIG (100%)	189,000	180,000
Suppression Program		
Seed and Analysis (100%)	588,500	588,500
Precipitation Network (100%)	100,500	100,500
Universities (77%)	130,000	100,000
	819,000	819,000
Project Management and Administration		
Management (50%)	140,000	70,000
Administration (50%)	70,000	35,000
	210,000	105,000
Research Support		
Programmers (50%)	126,000	63,000
Engineering and Mechanical Labs (50%)	24,000	12,000
Data Management (50%)	37,000	18,500
Data Acquisition (100%)	77,000	77,000
DRI (100%)	25,000	25,000
Aircraft Operations (50%)	38,000	19,000
Logistics (75%)	136,000	102,000
	463,000	316,500
TOTALS	2,528,000	1,903,500 (75% of total)

Main Thrusts - Year by Year

FY 1975: $2.4M (NSF - Assigned Level)

Critical review of design of suppression experiment. Procurement and installation of electric-optical hail size sensors. Major enhancement of suppression experiment analysis staff through reasignments, new hires, and an expert statistical consultant. Reorganized data base management system. Intensive analysis effort to overcome data backlog. Additional Ph. D. radar meteorologist and programmer for radar studies to solve radar data processing problems and accelerate analyses. Start up numerical modeling program. Appoint Chief Scientist. Hire Ph. D. scientist for air motion studies.

Summer of 1975 will be primarily for the suppression experiment and limited supporting research mainly with the T-28 and sailplane; the prime goal is to measure direct seeding effects. Support of South Dakota School of Mines and Technology will be increased over FY-74 levels. Other supporting research will be minimal. Effort will be concentrated on data reduction and analysis of past data, equipment improvements, retooling, and refinements of hypotheses. CHILL radar, Wyoming Queen Air, and DRI precipitation silver studies eleminated due to budgetary constraints. Small contracts to be initiated with University of Arizona (Dr. Young) for modeling and Clemson University (Dr. Ulbrich) for suppression data analysis.

FY-76: $2.5M (NSF - Assigned Level)

Except for CHILL radar, Wyoming Queen Air, and DRI precipitation silver studies, the summer of 1976 will be a full field operation with both the suppression experiment and supporting research. The full complement of NCAR research aircraft will again be used. The NCAR C-band (CP-3) Doppler radar will provide vertical Doppler coverage and will operate with the Grover CP-2 radar to provide dual-Doppler velocity mapping. Participation of NOAA and University of Arizona Doppler radars is dependent upon external funding. Emphasis of supporting research will continue to be the crucial questions related to the suppression experiement (i.e. nature of hail embryos, airflow and hail trajectories, evaluation of seeding material, direct seeding effects in clouds, and capability of dual wavelength radar for hail detection).

FY-77: 3.1M

The summer of 1977 will be a full research season with the return of the CHILL radar, Wyoming Queen Air, the DRI precipitation silver studies, the full complement of NCAR aircraft, CP-2 and CP-3 radars, and other participating groups dependent upon their own funding. Research emphasis will be on an <u>integrated</u> observational and numerical model of a hailstorm and the mechanisms by which seeding affects hailstone growth. Intensive statistical analysis of the suppression experiment continues. Results of first 5 years of suppression experiment to be available by 30 April 1977.

FY-78: 3.2M

The summer of 1978 is the last field season and includes a full supporting research program with same facilities as in FY-77. However, the research effort will be focused on remaining gaps required to be filled in order to arrive at a comprehensive model (or models) of a hailstorm. All analysis efforts intensified.

FY-79: 2.2M

Last field season terminates in August 1978; final analysis begins. Major reductions in operational and instrumentation support staff. Initial statistical results of suppression experiment to be available by 30 June 1979. Drafts of final reports commence.

FY-80: 1.3M

Final analysis and report writing. All non-analytical staff phased out.

Table 5

OVERALL BUDGET SUMMARY

	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Suppression Experiment	$ 503,000	$ 823,000	$ 819,000	$1,020,000	$1,056,000	$ 474,000	$ 302,000
Societal Utilization	170,560	165,000	180,000	225,000	238,000	228,000	105,000
Storm Microphysics	430,000	439,000	379,000	434,000	443,000	291,000	168,000
Storm Macrophysics	397,000	277,500	359,000	557,000	583,000	446,000	228,000
Numerical Modeling	-0-	49,500	118,000	127,000	144,000	149,000	154,000
Project Management	162,000	203,000	210,000	225,000	238,000	235,000	141,000
Research Support	400,000	443,000	463,000	484,000	516,000	370,000	148,000
Total	$2,062,560	$2,400,000	$2,528,000	$3,072,000	$3,218,000	$2,193,000	$1,246,000

Table 6

FUNDING LEVELS FROM FY 70 THROUGH FY 73

	70	71	72	73
Storm Microphysics	$ 42,605	$ 584,942	$ 732,089	$ 698,660
Storm Macrophysics	205,764	528,270	651,396	718,940
Modeling	0	0	0	0
Seeding Experiment	25,808	19,705	352,512	597,500
Societal Utilization	0	0	128,941	171,000
Project Management	53,377	73,592	121,325	144,500
Research Support	27,326	421,758	485,095	506,400
Totals	$ 352,880	$1,628,267	$2,471,358	$2,837,000

Comment:

The budgets given above represent the best available estimates of funding required to achieve the goals of NHRE. They are based on experience that now provides a clearer view of the tasks to be accomplished, and the resources required, than was possible at the outset of NHRE.

The budgets given exclude all activities except those required to maximize the probability that (1) the statistical results of NHRE will be powerful; (2) the physical understanding of both natural and seeded hailstorms will be sufficient to give the scientific community and the decision-makers confidence in the conclusions reached, whether positive or negative; and (3) if positive, the results will be useful in designing operational hail suppression programs on the Great Plains and elsewhere.

In various past discussions with the NHRE Advisory Panel, the UCAR Board of Trustees, the staff of the National Science Foundation, and others, the cost and advisability of a pure-and-simple statistical suppression experiment have been examined. With respect to cost, it has been shown that the suppression experiment alone would require about 70% of the total funds.

With respect to the advisability of a pure statistical experiment, we must reiterate that it cannot achieve the objectives of NHRE. It will not produce the physical evidence required to establish the credibility of the statistical results; it will not allow us to generalize to other storm types or to prescribe how to mount optimum operational programs; it will not allow us to establish the societal benefits and disbenefits to be obtained from operational programs. In short, the usefulness of the product of a pure-and-simple statistical experiment would be severely limited.

VII. Detailed Plans and Budgets

NHRE plans and budgets are organized along disciplinary lines, but it is obvious that the goal of understanding hailfall in sufficient detail to develop effective hail suppression techniques requires a synthesis among the different studies. In a very real sense, such a synthesis is the most important research goal of NHRE, and often the connections between these studies are more important than new knowledge within each sub-program itself.

This is particularly clear in the relations between cloud microphysical processes and the airflow. Neither is particularly useful independent of the other. A hailstone's growth history in a storm is a consequence of its microphysical history and its trajectory. The trajectory determines the growth rate of a hailstone by determining its growth environment, and the growth rate determines the trajectory by determining the hailstone's terminal velocity as a function of time. The two can hardly be thought of separately. Therefore, while the microphysics plans, for example, do not emphasize dynamics, it is of first priority importance that those aircraft making microphysical measurements also make simultaneous dynamics measurements, particularly updraft velocities, and that the flights be coordinated with Doppler radar and other measurement systems whenever possible. Therefore, although the detailed plans given in this section may appear to be separate, it will also be noted that interdependence among the various lines of research is also emphasized.

The detailed research plans presented here reflect the two major objectives outlined in Section II. The individual plans are so presented as to be reasonably self-sufficient, with a concise description of objectives, background, approach, and so forth. As just emphasized, however, the interdependence among the various lines of research is quite evident.

In developing these detailed plans of programs and sub-programs, particularly for FY 1975-76, a careful reexamination of priority within NHRE was conducted. Studies that are judged to be concerned with the key questions of hail formation were given first priority and placed at the earliest possible date in the NHRE schedule. Some areas of investigation are suspected to be important in the hail process, but cannot be effectively studied until some other issues are resolved; these were placed later in the project schedule. A group of candidate sub-programs were deemed to be not of potential importance for the NHRE goals or to have a probability of success sufficiently low (in the NHRE time frame), that they were eliminated from the plan. Some of these subjects may well be studied in NHRE if they occur as natural by-products of the core studies and can be accomplished at no additional cost; and in the case of those few important-but-intractable-in-the-NHRE time-frame programs pragmatic approaches have been designed to bridge our lack of knowledge and have been included in the plan.

Each program description which follows includes some detail on the problem and approach, its relevancy to NHRE goals, schedule phase, and a mention of the type of resources (not explicitly included in earlier long range plans) needed to accomplish the task.

A. Suppression Program

The purpose of the Suppression Program is to determine whether hail suppression is feasible and the extent to which it can be made operationally effective. It is recognized that while the most scientifically justifiable arguments with respect to suppression are physical in nature, the high variability in the natural processes and the difficulty of measuring and evaluating these processes make the probability of obtaining a clear assessment of the suppression concept from physical observations unlikely. Therefore, a statistical experiment is being conducted, which, in principle, is capable of detecting any substantial seeding effects with a high degree of confidence in a reasonable amount of time (see Preliminary Results of Suppression Experiment, Section IV). The seeding approach that has been chosen is the one assessed to have the highest probability of success among the alternatives available in light of knowledge at the program outset (see Experiment Design, Section III).

In addition to the statistical experiment the suppression program is involved in establishing parameters of the storm other than hailfall to assist in analysis of hail data using controls and partitioning. Intensive case studies are also being conducted to search for seeding effects.

In order to fully address the objective of the Suppression Program, operations research studies are being conducted with respect to operational alternatives, side effects and cost/effectiveness implications. Various seeding systems are considered in these studies as well as alternative seeding approaches.

1. Suppression Program - The Statistical Experiment

a. Objective: To analyze from a statistical point of view the effect of seeding on hail measured at the ground by the study of results from a randomized-target statistical design experiment.

Sub-objectives:

(1) Statistical analysis of hail, rain and other measures at the ground.

(2) Development of evidence for the similarity or dissimilarity of the behavior of the seeded and non-seeded samples or various stratifications thereof.

b. Background: The NHRE Suppression Program is statistical in nature. Based on the great variability among thunderstorms, particularly with regard to their hail production, it appeared at the outset that a case study approach to the suppression experiment would be unconvincing (Swinbank, 1970). As a result, a statistical design related to a physical hypothesis of hail suppression was established. The hypothesis being tested was, among others, that of the Soviets: that damaging hail at the ground could be reduced by the injection of ice-forming nuclei into the storm just beneath the radar-detected "overhang" thought to characterize the hail growth zone (Sulakvelidze, et al., 1967). Fundamental to the Soviet method was the introduction of the nucleating agent directly into the heart of the storm, rather than allowing it to be carried in by the updrafts at cloud base. Underlying these attempts at hail suppression was the fundamental idea that an increase in the number of ice particles would force competition for the available supercooled water, thus producing a larger number of hailstones that were smaller in size and could consequently melt during their fall to the ground. With these concepts in mind, the primary measure of seeding effect for the statistical experiment was chosen to be the total mass of hail measured at the ground over a target area (the so-called Protected Area). Other variables, such as hail size, duration, hail-to-rain ratio, and radar reflectivity are also being evaluated. In addition, surface wind-field studies were established to determine whether seeding influenced the magnitude of the surface wind, and programs concerned with the small-scale variability of hailfall were set up to consider, among other things, the influence of network density and collection methods on the data.

In the evaluation of the statistical experiment it is necessary to consider the possibility of biases caused by meteorological inequalities of the natural setting. While it is hoped that one would get a "fair draw," with seeded and non-seeded days having, on the average, the same hail potential, it is desirable to have some way of determining whether or not this occurred. To this end, part of the Synoptic Analysis effort (see Part 5 of Suppression Experiment) is devoted to a search for synoptic parameters and indices suitable for characterizing hail potential. It is anticipated that simple numerical hailstorm models (using pre-storm initial conditions) will also be helpful in this regard. In addition, the storm radar structure at the time of the hail day declaration will be used as an indicator of hail potential.

c. Relevancy and schedule priority: The statistical experiment is the backbone of the Suppression Program which in turn is an indispensable activity throughout the NHRE.

d. Approach:

Sub-objective (1): The two systems that address this sub-objective are the precipitation and mesoscale meteorological networks. The precipitation network was designed and established primarily to support the Suppression Experiment, although it provides time-dependent hail and rain data useful to all areas of research within the NHRE. The basic precipitation network consists of 240 hail separators in the approximately 600-square-mile target area. This instrument measures mass of hail and rain with one-minute time resolution. One hundred and twenty stations with standard Belfort weighing raingauges and hail impactors designed by NOAA personnel to estimate the time-resolved hail size distribition are spread over the target area and a fifteen mile zone around the area. All instrument sites contain styrofoam hailpads designed to provide time-integrated hail size distribitions. These instruments provide data critical to the Statistical Experiment and to detailed case studies of specific seeding effects. As previously noted, we propose to deploy 100 to 130 electro-optical hail-size sensors throughout the protected area in the summer of 1975 because hail size is the fundamental parameter which seeding aims to affect and it is the one to which all other measures may be related.

The mesometeorological network was established primarily as a research tool to assist in detailed studies of the air motion associated with thunderstorms. However, the mesonet also provides data for statistical analysis of the possible effect of suppression efforts on parameters other than precipitation. In particular, wind fields at the ground will be carefully studied for variations attributable to seeding.

Sub-objective (2): The program includes an effort to determine, after the fact, to the degree possible, that the sample taken for seeded and unseeded days is not biased. Derived thermodynamic parameters such as the cloud buoyant energy, based on adiabatic ascent, maximum temperature excess in the cloud, cloud top heights and temperatures as well as surface and upper air variables will be used to establish similarity or dissimilarity of the samples. For instance, comparisons of the mean soundings for seeded and non-seeded samples in 1972 showed virtually no differences between them. One of the stratification schemes will involve the use of a one-dimensional model in a manner similar to that of Chisholm (1973).

Use of the Grover radar data to classify storm type and intensity before the declaration of a hail day will be very valuable for assessing possible biases between the two sets of days. Such classification will also assist in partitioning events for analysis.

e. Resources required: Basic requirements for this program involve the operation, data handling, and quality control of the precipitation network. Instrumentation is required for the purpose of improving time-dependent hail size measurements ($65,000 - FY75). Adequate on-going analysis of the data necessitates the addition of significant staff (see General Plans, Schedule, and Budget, Section VI).

f. University and other agency participation: Student support provided by Metropolitan State College; upper-air network operated by Air Force personnel.

g. Possible obstacles and chances for success: The primary obstacle to assessing the effects of seeding is the weather itself. If the weather is uncooperative, it is possible that an insufficient number of samples will be accumulated in the NHRE experimental period to arrive at any conclusive results. Studies prior to the beginning of the program (Schickendanz and Changnon, 1971), were based on expected numbers of hailstorm days. These mathematical expectations derive from highly skewed distributions in which the 95% probability of success point, for example, is considerably greater than the expectation. With the two year extension of the program proposed herein we can expect a total of about 105 hail days in the protected area at the end of 1978; this should be sufficient to reach a statistically significant conclusion at the 95% confidence level on average hailfall reductions of about 30%.

h. Schedule: The installation of the precipitation and mesoscale networks begins six weeks prior to the summer's operations. One week prior to the start of field operations, the precipitation network starts providing data for checkout and shakedown purposes. Instrument development is an on-going process without schedule limitations. While the basic instruments are presently operational, new electro-optical hail size sensing instruments are currently being developed to improve time-dependent measurements of hail size distributions. 100 to 130 of these instruments should be ready for field use in 1975.

The final analysis of the basic statistical experiment will, of course, not be done until the end of the field program. However, the data from each summer are available in September, and analyses of progress, data quality, and operational impacts, as well as attempts to assess the sufficiency of the present network density and to relate other measurements to the precipitation data are conducted each year.

i. Investigators: Dr. C. C. Lovell, Dr. J. D. Sartor, Mr. T. R. Nicholas, Mr. A. C. Modahl, Mr. M. E. Solak, and two vacancies, NCAR.

j. Probable by-products: Precipitation monitoring instruments may find substantial utility outside of NHRE in many applications. Seeding techniques and data collection techniques as well as a possible objective method for determining hail damage are potentially valuable by-products related to this program.

k. References:

Chisholm, A. J., 1973: Alberta hailstorms, Part I: Radar case studies and airflow models. Meteor. Monogr., 14, 1-36.

Schickedanz, P. T. and S. A. Changnon, 1970: A study of crop-hail insurance records for northeast Colorado with respect to the design of the National Hail Experiment. Illinois State Water Survey project report, 47 pp.

Sulakvelidze, G. K., N. Sh. Bibliashvili and V. F. Lapcheva, 1967: Formation of precipitation and modification of hail processes. Israel Program for Scientific Translations, Jerusalem, 208 pp.

2. Suppression Program - Physical Effects

a. Objective: To search for seeding effects, with emphasis on those relevant to hail suppression, by relating the seeding event to specific physical observations on a case-study rather than a statistical basis.

Sub-objectives:

(1) Develop case studies utilizing Doppler radar and aircraft estimates of the wind field as well as reflectivity structure and in-cloud particle measurements to relate the seeding event to the character of precipitation measured at the ground. Emphasize the search for possible localized effects.

(2) Examine the effectiveness of silver iodide in producing ice particles, by making direct, in-cloud measurements (see the Storm Microphysics Program plan).

(3) Analyze hail and rain samples collected at the ground for silver content.

(4) Examine the radar structure in the vicinity of expected seeding effects, using reflectivity, hail signal, and liquid water content information (see the Storm Macrophysics Program plan).

(5) Conduct numerical modeling experiments to help guide the search for physical effects and to aid in the interpretation of the observations (see the Numerical Modeling Program plan).

b. Background: While the emphasis for testing the efficacy of AgI seeding for hail suppression is being placed on the Statistical Experiment, there is still a need for examining physical effects (including but not limited to hail on the ground) on a detailed, case-study basis. Given the past history of weather modification experiments, particularly the problems of getting a fair seed/no-seed draw and obtaining enough cases to establish statistical significance, the possibility is apparent that the results of the NHRE statistical experiment may fail to give a definitive answer. The aim of the present program is to bolster the statistical results by providing additional corroborative evidence of the effects produced by seeding. While neither the Physical Effects study nor the Statistical Experiment may be wholly convincing by itself, the combination of the two, the one complementing the other, should lead to greater confidence. Of course, ultimately the final result of the seeding program, be it a positive or a negative statement of seeding efficacy, must be understood in terms of the basic physics involved in natural hail formation and in AgI seeding. Indeed, if this understanding of the physical processes is not forthcoming, then the suppression results will always be doubted by some. This pursuit of a better physical understanding is a major part of the NHRE Microphysics, Macrophysics, and Modeling Programs.

c. Relevancy and schedule priority: This program is clearly essential to the goals of the NHRE and must receive continuous attention.

d. Approach: The general approach to these objectives is covered in the other Programs. Individuals dedicated to the suppression analysis will be coordinating results and helping in the design of specific experiments. In particular, seeding and sampling experiments using the rocket and the flare systems will be coordinated in 1974 with the sailplane operation. Other experiments will be conducted in 1975 and 1976.

The analysis of silver in precipitation, and where and when it occurs, is being conducted by Dr. J. Warburton of the University of Nevada.

Wind data collected from the Doppler radars and instrumented aircraft will be integrated, when it is available, with the reflectivity data from the Grover radar, and with seeding events. Attempts to trace the seeding material forward and hailstones back into the storm will be made. Integration of these phenomena will hopefully lead to insights into the effects of seeding. Attempts to retrace hailstones back through the storm will be made on non-seeded cases also, and compared with seeded cases. Diffusion rates will be inferred from turbulence studies, and will be used to help trace the trajectory of the seeding agent.

e. Resources required: The major systems contributing to this phase of the Suppression Program are described in other sections. They include the Grover radar, CHILL radar, NOAA dual-Doppler radar, University of Arizona Doppler radar, NCAR C-band radar, M33 tracking and acquisition radar from DRI, the South Dakota School of Mines and Technology T-28 and the NCAR aircraft.

f. University and other agency participation: University of Chicago, NOAA (1974), University of Arizona (1974), University of Nevada, University of Wyoming, and South Dakota School of Mines and Technology.

g. Possible obstacles and chances for success: The probability of achieving useful results in the microphysical area of in-cloud seeding effects is high. Similarly, the search for silver in precipitation should prove fruitful. The attempts to look for localized effects based on estimates of particle trajectories, and the radar and wind-field studies will be confounded to an unknown degree by the natural variability of storm behavior. The use of the dual-wavelength radar hail signal may be of great help, but the *a priori* probability of success here is thought to be only moderate.

h. Schedule: Rocket and cloud base seeding experiments will be conducted in 1974. Specific tests of the rocket nucleating efficiency under environmental conditions will be completed in 1974. The sailplane will be used to evaluate seeding effects in cumulus congestus and small storms in 1974 and 1975. The T-28 will be used for this purpose in larger storms in 1975-77. Other schedules are presented in the Storm Macrophysics and Microphysics sections.

i. Investigators: Dr. C. C. Lovell, Mr. M. E. Solak, M. S. Scientist (to be hired). Other scientists involved in specific studies contributing to this overall effort are identified in other sections.

j. Probable by-products: Hopefully inferences about other seeding methods also addressed in previous sections will be gained and use of the radar to identify and evaluate seeding effects will be developed, applicable to future work. Any unequivocal physical test of seeding efficacy found would obviously be of immeasurable value in any future weather modification programs by reducing or eliminating the need for extensive and costly statistical trials.

3. Suppression Program - Seeding Techniques

a. Objective: To investigate the relative merits of various seeding methods with respect to effectiveness, operational feasibility and adaptability and, if indicated, to consider new approaches.

Sub-objectives:

(1) Operational evaluation of the rocket/flare system.

(2) Evaluation of alternative seeding methods.

(3) The study of physical variations in storm processes implying the possible requirement for different operational methods.

b. Background: At the outset of the NHRE, the Soviets were making the most credible claims of success in hail suppression. Their approach was to fire artillery shells or rockets into the storm to inject the nucleant directly into the storm, in the vicinity of the high reflectivity zone (Sulakvelidze, et al., 1967). Based on analysis by the NHRE staff, with the assistance of consulting experts, it was decided that development of a vertically launched rocket for use at cloud base was the best way to duplicate this approach in the USA, and a development program was undertaken. However, development problems prevented its use during the first two operational years and conventional cloud base seeding was used instead. The rocket system is now operational and will be integrated into the seeding experiment in 1974.

Other systems have been considered, and tests and evaluations of such systems are intended. One interesting alternative to the NHRE rocket system based on other experiences is droppable flares. The Alberta program has used this approach for four years and its history is well documented (e.g., Renick, et al., 1972). Their seeding is accomplished by dropping flares into the young growing turrets rather than the mature updraft. The idea is that ice particles forming in the young turrets probably have the longest lifetime in the cloud; hence, growing the largest, they may be the embryos for natural hail formation. Thus, hail suppression might be best effected by trying to produce embryos in the same location that nature does. The argument has some appeal, but a number of uncertainties are involved. Of course, seeding of these new turrets could also be attempted with cloud-base flares and rockets.

Another technique that appears worthwhile from the standpoint of the suppression hypothesis is direct seeding in the updraft with the T-28 at about the -5C level. While there are many problems with this approach on an operational basis, it seems to have substantial merit in terms of studying the basic hypothesis. This <u>in situ</u> seeding has been done and more experiments are planned.

c. <u>Relevancy and schedule priority</u>: Many questions remain with regard to the most appropriate seeding method for hail suppression. Answers to these questions and determination of an optimal seeding method, if indeed any seeding methods turn out to be useful, should have high priority. Sub-objective (1) should receive prompt attention; (2) and (3) will follow later in the schedule.

d. <u>Approach</u>:

Sub-objective (1): The primary seeding technique chosen by the NHRE is the rocket launched vertically from cloud base, dispensing about 100 grams of AgI in the updraft near the -5C isotherm. This method was chosen because it best approximates the Soviet method within the constraints of FAA regulations, and it thus satisfies the requirements of the physical hypothesis deemed most appropriate at the program outset. Further, it minimizes problems of deactivation at the warmer temperatures and places the seeding event closer in time to the outcome at the ground making the establishment of physical cause and effective relationships more likely. The rockets are now considered to be operational, and are intended for use through the duration of the program.

Cloud-base seeding has been used for two years and will be integrated with the rockets in 1974. The integration of the two systems is to provide continuity from the first two years to the third. The basic rationale is that any effects of cloud-base seeding should be carried over, and effects of the rocket made additive until experience and results are attained. Further, cloud-base seeding will be used in the advent of a failure in the rocket system or if situations occur in which use of rockets would be in violation of FAA regulations. Careful studies of the operational feasibility of the rocket will be conducted with respect to location variabilities affecting the ability to locate the aircraft for firing.

Sub-objective (2): Other systems have been considered, and testing on a case study basis will be conducted. In particular, in situ seeding of thunderstorms with the T-28, the use of flares dropped from above into the new growth regions, and propane seeding experiments have or will be conducted within the program. Tracer experiments to help evaluate proper seeding approaches have also been attempted and additional tracer work is planned. Because of the inability to conduct extensive field trials of alternate seeding methods without affecting the sample size or the homogeneity of the statistical experiment, the testing of alternate methods will also be attempted using the numerical models discussed earlier.

Sub-objective (3): It is conceivable that meteorological conditions may preclude a given seeding technique at certain times, and also that different storm characteristics may imply different approaches to seeding. Intensive studies, particularly of radar data, are being conducted against operational experiences gained both by the staff and by other groups to assess the applicability of particular seeding methods for the variety of storm conditions that exist.

e. Resources required: The principal resources required by this effort are the seeding aircraft, droppable flares, and rockets. The primary additional resources required will be development of a modified rocket to deliver tracer materials.

f. University and other agency participation: Atmospherics, Inc., under contract to NHRE, has provided seeding pilots, technicians and aircraft. The rockets are manufactured by MBAssociates.

g. Possible obstacles and chances for success: The possibility that the seeding techniques now used may be superseded by some new system suggested by research results exists. While the operational feasibility of various methods can be established in a fairly straightforward way, determination of the over-all effectiveness would require a program on the scale of the NHRE Statistical Experiment for each method. Since this is not practical, the methods outlined in the Physical Effects Program and the use of numerical simulation have been adopted. Chances for determining the effectiveness of alternate procedures for suppressing hail will probably be low until progress is made in the physical understanding of hail processes.

h. Schedule: Rockets and flares will be used in 1974 and a decision on continuation of both systems will be made prior to the summer of 1975. Droppable flare experiments are planned for the summer of 1975 or 1976 and *in situ* experiments with the T-28 will resume as soon as it returns to the field. Consideration of tracer experiments is in progress.

i. Investigators: Dr. C. C. Lovell, Mr. M. E. Solak, two additional scientists (to be hired).

j. Probable by-products: The benefit of reliable, operational seeding techniques as well as evaluation techniques to future weather modification efforts is obvious. Further, the applicability of the NHRE vertically-launched rocket to other areas is substantial both in the meteorological sciences and elsewhere. It has possible application to any requirements to place a payload 2 1/2 kilometers vertically above an aircraft position.

k. References:

Renick, J. H., A. J. Chisholm and P. W. Summers, 1972: The seedability of multicell and supercell hailstorms using droppable pyrotechnic flares. Unpublished manuscript. Third Conference on Weather Modification, Amer. Meteor. Soc., Boston, 272-278.

Sulakvelidze, G. K., N. Sh. Bibliashvili and V. F. Lapcheva, 1967: Formation of precipitation and modification of hail processes. Israel Program for Scientific Translations, Jerusalem, 208 pp.

4. Suppression Program - Operations Research

a. Objective: To determine, assuming hail suppression can be accomplished, the feasibility and basic cost effectiveness for operational hail suppression for various systems and operational situations, and to assess the possible side effects.

b. Background: One of the most critical parts of a suppression program is the proper conduct of the actual seeding operations. The efficiency with which seeding aircraft, for example, are dispatched, properly located, and the delivery is conducted are all equally important in this regard. Furthermore, differing meteorological conditions may dictate different approaches and perhaps different basic seeding methods. Assessment of all of these situations and systems is important to the development of an optimal operational program.

It is well known that the "hail season" moves geographically with time and is relatively short lived, three months or so, in a given geographic region. This phenomenon tends to make localized programs inefficient. Further, in the case of localized programs, extended squall line conditions might be more efficiently dealt with within cooperative unions between adjacent regions in much the same way that regional fire districts support one another.

Suppression of hail on an operational basis will also depend on the relative benefits of suppression to the cost of operations. Included in costs are any detrimental effects or losses that may accrue. The Societal Utilization Program covers the ecological, economic, legal and societal studies relevant to this problem. Studies of downwind effects of seeding are being conducted under an NSF grant to Colorado State University.

The Operations Research efforts are intended to integrate these problems and assess the operational possibilities for hail suppression on a cost/effectiveness basis, assuming that hail suppression is demonstrated to be feasible. This assessment will cover details from radar type and manpower to large-scale trade-offs such as a mobile system that moves with the season.

Finally this effort provides a continual reappraisal of the operational conduct of the NHRE Statistical Experiment.

c. Relevancy and schedule priority: This phase of the suppression program is potentially valuable to persons considering carrying out future operational programs and should be a primary legacy of the NHRE, but these studies can wait until late in the program.

d. Approach: Questions associated with the development of operationally feasible hail suppression operations are the primary thrust of this objective. The first and most obvious of these is positive control of the operational delivery system.

The data display and control of the operational seeding system is important both to the conduct of the experiment and to the development of an overall operational system. Careful analyses of radar data with integrated aircraft information are being conducted to assess optimal direction and control of the seeding aircraft. This information will be related to the results of studies conducted under previous objectives to obtain an optimal approach with respect to maximizing effect.

Studies will also be conducted on a larger scale to look at variations in storm systems with respect to scale. The frequency of hail producing squall lines of hundreds of miles in extent and systems necessary to affect such lines will be assessed. These will be compared for feasibility of suppression with small-scale efforts. The implications of the possible requirement for multiple seeding approaches will be integrated into this assessment.

Alternative radar systems for operational programs are being assessed, to a great extent based on the various displays available to the NHRE operations. Range and mobility considerations are being taken into account in both radar and seeding system assessments. Other operational variables such as aircraft staging and airfield facilities availability will be considered when operational cost assessments are made.

Further side effects such as silver in the precipitation and downwind effects on scales of 150 miles are being studied. These data will be integrated with the feasibility studies in developing cost/effectiveness estimates for hail suppression and to determine if more expansive testing programs are necessary.

e. Resources required: Staff and systems for this effort are available.

f. University and other agency participation: FAA, Atmospherics, Inc., Colorado State University (funded separately by NSF).

g. Possible obstacles and chances for success: This work is totally dependent on the success or failure of the suppression efforts to affect hail. No apparent obstacles other than the failure of the current techniques to suppress hail are apparent.

h. Schedule: While preliminary work in this area is underway, intensive effort is not planned until 1975.

i. Investigators: Dr. C. C. Lovell, Dr. P. J. Eccles, Dr. L. Grant (CSU), Mr. W. J. Carley (Atmospherics, Inc.).

j. Probable by-products: A design for a severe storm detection warning, and suppression control system is considered a probable outgrowth of this effort. Optimal large-scale program design and possible new approaches to the seeding problem should be an outgrowth of operational studies.

5. Suppression Program - Synoptic Analysis

a. Objectives: To understand better the synoptic and mesoscale settings conducive to hailstorms, identify differences between 'hail' and 'non-hail' thunderstorms, to determine the synoptic homogeneity of seed and no-seed days, and to evaluate hailstorm predictability for use in an operational hail suppression program.

Sub-objectives:

(1) Complete a synoptic climatology for describing the hail setting using synoptic and meso-scale upper-air and surface data.

(2) Investigate the interaction of synoptic, mesoscale, and cloud-scale environments.

(3) Categorize seed and no-seed days by synoptic features.

(4) Provide observed mean conditions and other baseline data to the groups involved in numerical modeling, dynamics and mass budgets, cloud physics, and seeding technique analysis.

(5) Determine why hail occurrence is at a maximum in northeast Colorado rather than elsewhere.

(6) Develop and test improved forecasting methods, including objective prediction techniques.

(7) Generalize forecasting methods for use in other areas.

2. <u>Background</u>: Present understanding of the generating conditions for hail is severely limited by the lack of an adequate description of the hailstorm environment. The occurrence of hail in an environment which oftentimes lacks the usual synoptic indices for severe weather is a perplexing problem. The influences of local topographic features, possible convection-induced airmass contrasts and mesoscale fields of surface convergence, and the role of water

vapor distribution are largely unknown at present, as is reliable knowledge of how these depend on synoptic scale influences. Many techniques of meso-meteorological analyses have been presented by Fujita (1963). Exploitation of the large sample of data being amassed by the NHRE offers the opportunity of deriving a much more reliable model of the hailstorm environment than that presently available.

In order to determine that the seed days were drawn from a homogeneous sample of hail days having essentially similar synoptic conditions to those of no-seed days, it is necessary to compare the soundings and synoptic conditions on both seed and no-seed days.

A crucial problem involving forecasting is the requirement, assuming the advent of a successful hail suppression method, for determining the probable time and location of hailstorms with several hours notice in order that suppression forces may be efficiently deployed.

c. Relevancy and schedule priority: In addition to establishing the fairness of the seed, no-seed sample improved understanding of the hailstorm synoptic setting and increased capability for reliably forecasting hail occurrence are inherently germane to the suppression experiment and the overall goals of NHRE. The latter is crucial to the economic feasibility of future operational hail suppression programs.

Sub-objectives (1), (3), (4) and (6) will receive prompt emphasis while sub-objectives (2), (5), and (7) will be included as the opportunity permits.

d. Approach:

Sub-objectives (1) and (3): Stratify the synoptic and mesonetwork surface and upper air data into regimes based on cloud types, weather phenomena, and synoptic setting for hail and non-hail days and seed and no-seed days. Produce statistics based on the stratifications and introduce a normalization for the effect of the seasonal march of temperature and humidity. Departures from moving 15-day averages will be tested for this purpose. Seasonal and diurnal variations will also be studied. While latitudinal variation is not a major factor in the NHRE study area, knowledge of this aspect is desirable for the pursuit of sub-objectives (5) and (7).

Sub-objectives (2) and (3): Using data from the NHRE surface meso-meteorological network and the NHRE upper-air networks, perform case studies of seeded and non-seeded hail occurrences as well as non-hail events.

Sub-objective (4): Collaborate with NHRE staff and contractors in order to produce the most effective and comprehensive team effort directed at achieving NHRE overall goals.

Sub-objective (5): Re-examine hail climatologies from projects in other areas of the world in the light of expertise and information achieved in the pursuit of sub-objectives (1), (2), and (3). Prepare cross sections centered on northeast Colorado showing latitudinal and seasonal variations of appropriate variables.

Sub-objective (6): Inasmuch as summertime pressure gradients on the synoptic scale are frequently small in the eastern Colorado region, emphasize testing of streamline analysis techniques for identifying mesoscale wind convergence regions which may be the location of subsequent storm formation. Preliminary work has shown the promise in this approach (e.g., Foote and Fankhauser, 1973; Modahl, 1973). The distribution of potential and equivalent potential temperatures will also be investigated. Anderson and Uccellini (1973) have shown some positive correlation between the equivalent potential temperature distribution and storm formation. In addition to improved subjective forecasting skills a statistical approach will also be followed. Examination of possible correlations between meteorological variables or groups of variables and hail events will identify promising predictors, and, where appropriate, derivation of multiple regression relationships will be performed.

Sub-objective (7): Work performed for sub-objectives (5) and (6) will be extended in consideration of varying climatic conditions.

e. Resources required: In order that answers be found for the problems and objectives outlined not only herein, but in support of virtually all other areas of endeavor in NHRE, it is essential that the NHRE mesoscale surface and upper-air networks be continued for the remaining years of the experiment. Although it would be desirable to increase the coverage and density of the surface network over that of past years, it is adequate for presently planned research. While the 1974 coverage of an upper-air station at Grover and at Sterling (dictated by budgetary constraints) will suffice for climatological purposes, it is not adequate for detailed case studies and should be expanded back to the 1973 level of five stations in 1977 and 1978.

One to two student assistants will be needed.

f. University participation: Hail event data from the Colorado State University Cooperative Hail Reporting Network (now operated by Professor Lewis O. Grant, formerly under Professor P. C. Sinclair). This network of cooperating citizens, although biased toward population distribution, covers a much larger area of northeast Colorado than does the NHRE precipitation network. Additional hail event information is highly useful for stratification purposes.

g. Possible obstacles and chances for success: No major obstacles to performing the work outlined are expected. Chances of achieving modest, perhaps marked, improvement in the reliability of limited area hail forecasts are good, considering the extent of smaller-scale information to be incorporated into forecasting schemes.

h. Schedule: While several of the interim steps toward the sub-objectives will be completed prior to the end of the observational program, refinement and continuing analysis will extend beyond the observational program. Testing of forecasting schemes will begin in 1975.

i. Investigators: Mr. Alf C. Modahl, Mr. James C. Fankhauser, Dr. G. Brant Foote, Dr. J. Doyne Sartor, and Dr. Clifton C. Lovell, NCAR.

j. Probable by-products: The mesoscale analysis and forecasting methods developed for hail studies will have application to the study of other thunderstorm-associated phenomena, such as high winds, heavy rains, and tornadoes.

The software for data handling and statistical studies will similarly find application in other observational programs.

k. References:

Anderson, C. E. and L. W. Uccellini, 1973: Studies of meteorological factors involved in the formation of severe local storms in the northeast Colorado region. Unpublished manuscript. 8th Conference on Severe Local Storms, Amer. Meteor. Soc., Boston, 84-89.

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Fujita, T., 1973: Analytical mesometeorology: A review. Meteor. Monogr. 5, 77-125.

Modahl, Alf C, 1973: Meso-scale surface flow features on 22 July 1972. Unpublished manuscript. 8th Conference on Severe Local Storms, Amer. Meteor. Soc., Boston, 149-154.

6. Schedules

Gant charts depicting the development program, expected availability of measurement systems, field test and calibration periods and field observation period are shown as follows:

a. Seeding Rocket, figure 6 .

b. Precipitation Network, figure 7 .

Figure 6

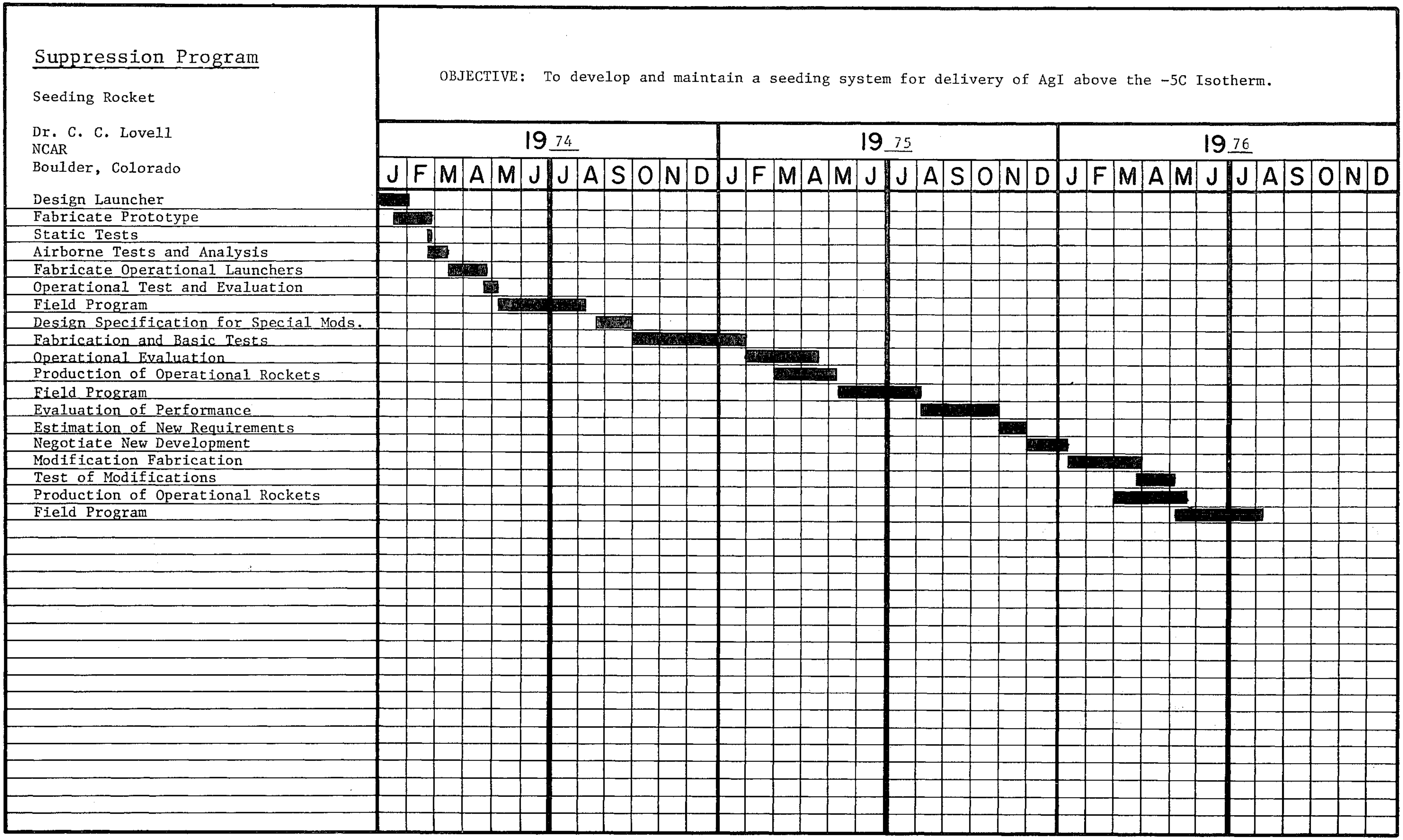
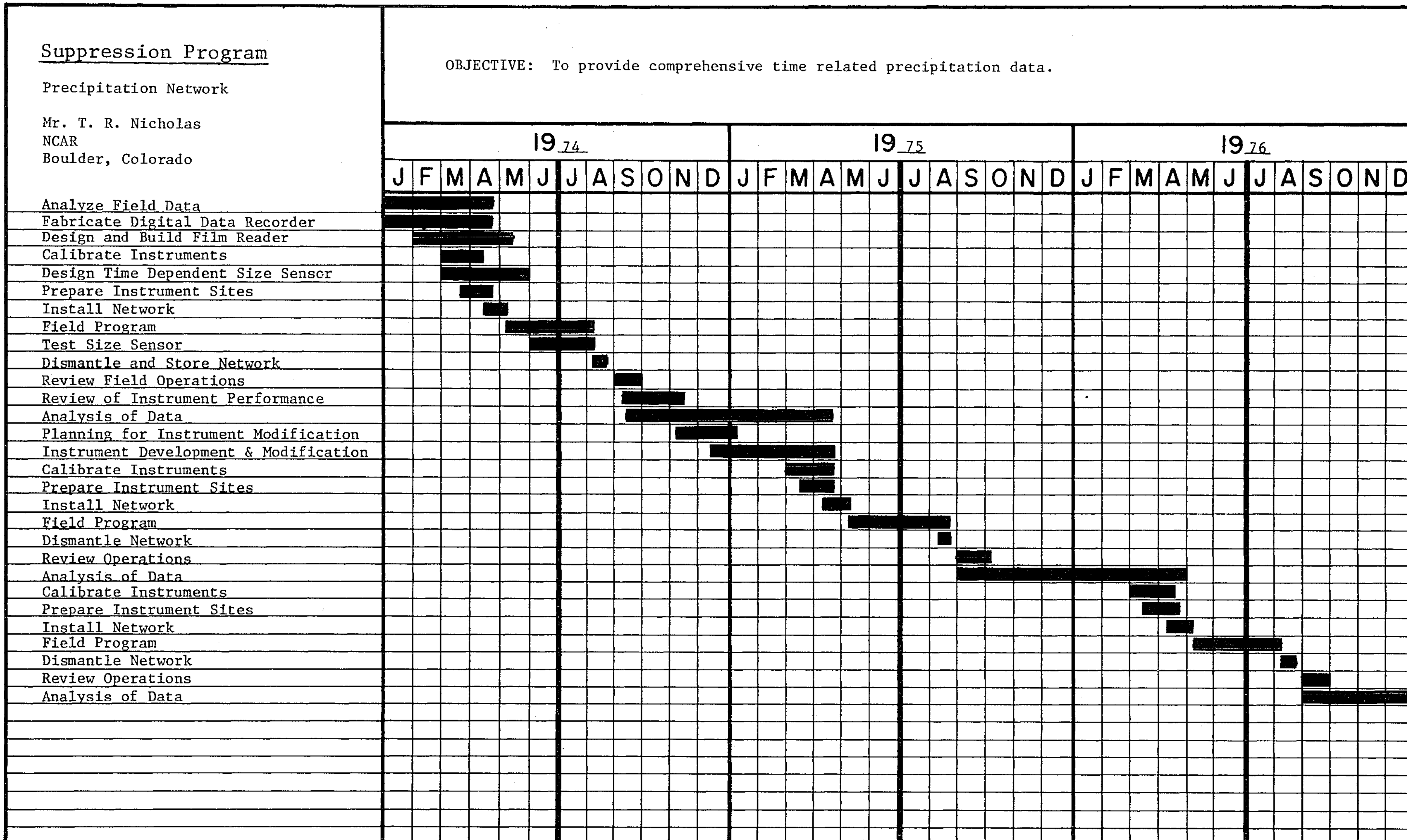

Suppression Program
Seeding Rocket
Dr. C. C. Lovell
NCAR
Boulder, Colorado
OBJECTIVE: To develop and maintain a seeding system for delivery of AgI above the -5C Isotherm.
1974
1975
1976
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Design Launcher
Fabricate Prototype
Static Tests
Airborne Tests and Analysis
Fabricate Operational Launchers
Operational Test and Evaluation
Field Program
Design Specification for Special Mods.
Fabrication and Basic Tests
Operational Evaluation
Production of Operational Rockets
Field Program
Evaluation of Performance
Estimation of New Requirements
Negotiate New Development
Modification Fabrication
Test of Modifications
Production of Operational Rockets
Field Program

Figure 7


Suppression Program
Precipitation Network
Mr. T. R. Nicholas
NCAR
Boulder, Colorado
OBJECTIVE: To provide comprehensive time related precipitation data.
1974
1975
1976
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Analyze Field Data
Fabricate Digital Data Recorder
Design and Build Film Reader
Calibrate Instruments
Design Time Dependent Size Sensor
Prepare Instrument Sites
Install Network
Field Program
Test Size Sensor
Dismantle and Store Network
Review Field Operations
Review of Instrument Performance
Analysis of Data
Planning for Instrument Modification
Instrument Development & Modification
Calibrate Instruments
Prepare Instrument Sites
Install Network
Field Program
Dismantle Network
Review Operations
Analysis of Data
Calibrate Instruments
Prepare Instrument Sites
Install Network
Field Program
Dismantle Network
Review Operations
Analysis of Data

SUPPRESSION EXPERIMENT PROGRAM

Seeding and Analysis	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Salaries & Benefits		$121,500	$141,000	$152,000	$ 164,000	$177,000	$125,000
Materials & Supplies							
Rockets/Flares		125,000	40,000	135,000	140,000		
Miscellaneous		5,500					
Subtotals, Materials & Supplies		$130,500	$ 40,000	$135,000	$ 140,000		
Purchased Services							
Consultant		8,000	5,000	5,000	5,000	5,000	
Seeding Aircraft		200,000	210,000	220,000	225,000		
Tracer Payload Development			30,000				
Radiosondes		60,000	60,000	60,000	60,000		
Subtotals, Purchased Services		268,000	305,000	285,000	290,000	5,000	
Travel		2,000	2,500	3,000	4,000	3,000	2,000
Subtotals, Seeding and Analysis	$267,000	$522,000	$588,500	$575,000	$ 598,000	$185,000	$127,000
Precipitation Network							
Salaries & Benefits		60,000	64,500	69,000	74,000	60,000	45,000
Materials & Supplies		5,000	5,000	5,000	6,000	2,000	
Purchased Services		10,000	9,000	9,000	10,000	4,000	
Travel		16,000	17,000	17,000	18,000	10,000	
Equipment							
Time/Size Hail Sensor		65,000					
Miscellaneous		5,000	5,000	5,000	5,000	3,000	
Subtotals, Precipitation Network	$132,000	$161,000	$100,500	$105,000	$ 113,000	$ 79,000	$ 45,000

SUPPRESSION EXPERIMENT PROGRAM cont.

University Participation	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
University of Wyoming		100,000	75,000	225,000	225,000	100,000	50,000
Clemson University		20,000	25,000	35,000	40,000	40,000	40,000
Colorado State University	43,000	20,000	30,000	35,000	35,000	40,000	40,000
Desert Research Institute	61,000			45,000	45,000	30,000	
Subtotals, University	$104,000	$140,000	$130,000	$ 340,000	$ 345,000	$210,000	$130,000
Totals, Suppression Experiment	$503,000	$823,000	$819,000	$1,020,000	$1,056,000	$474,000	$302,000

B. Societal Utilization

1. The NCAR Environmental and Societal Impacts Group (ESIG)

a. Objectives: The ultimate objective of the Societal Utilization study in NHRE is to answer the following question: Should operational hail suppression program(s) be undertaken in the northern Great Plains utilizing the knowledge gained and techniques developed during NHRE? That is, will the benefits of such program(s) exceed the costs and disbenefits? The terms "benefits" and "costs" have been given the broadest possible definitions, and include environmental and social, as well as economic, considerations. The results of this study are intended to complement the results of NHRE and to provide decision makers in the public and private sectors with information that they will need to make rational judgments regarding the implementation of operational hail suppression programs. This study is being carried out by the NCAR Environmental and Societal Impacts Group (ESIG).

More specifically, this study involves an assessment of the impacts and implications of a hypothetical operational hail suppression program in the northern Great Plains.

Sub-objectives:

(1) To estimate the direct and indirect economic benefits and disbenefits of the hypothetical operational hail suppression program.

(2) To estimate the direct costs of an "efficient" hail suppression program in the hypothetical operational area.

(3) To assess the effects of the silver iodide used in hail suppression activities upon important components of the biosphere.

(4) To develop a realistic social process model to describe and predict the reactions of individuals and organized groups to the information, events, and situations that they can expect to encounter in the course of an extensive hail suppression program .

(5) To evaluate the set of legal and political problems that may arise in connection with the application of hail suppression technology.

(6) To formulate and utilize a decision analysis model to quantify the relevant impacts and uncertainties, to integrate the results of the several tasks, and to develop rational and internally consistent information and recommendations regarding alternative courses of action.

b. Background: Hail damage to crops alone in the U.S. exceeds $500 million annually when valued at the price levels prevailing in 1972 (Boone, 1973), and estimates of the annual property damage due to hail generally exceed ten percent of the crop losses (Changnon, 1972). While hail suppression appears to be a promising adjustment to the hail hazard, the many direct and indirect effects of applying this technology on an operational basis need to be considered, and quantified where possible, within the framework of a comprehensive analysis of its impacts and implications.

Briefly, with regard to the economic benefits and disbenefits, the problem is to trace the direct effects of a hail suppression program in a Hypothetical Operational Area (HOA) from the damage and production functions, relating crop and property damage and crop production to hail-fall, precipitation, and other relevant variables, through the response of farmers, in terms of crop production, to changes in these variables as a result of the suppression program. Further, crop production changes initiate a chain of events leading to indirect economic effects, including possible changes in employment, consumption spending, and income distribution in the HOA. Changnon (1971) and Summers and Wojtiw (1971) have estimated damage functions for crops in Illinois and Alberta, respectively, while initial attempts have been made to assess the direct economic effects of precipitation augmentation on crop production in the northern Great Plains (e.g., Stroup and Townsend, 1973). However, no detailed assessment of the direct and indirect economic effects of a hail suppression program in this area has been undertaken. Such an assessment should also include an evaluation of the economic benefits and disbenefits associated with changes in production, employment, etc., due to any extended area effects of seeding to suppress hail in the HOA.

With regard to the hail suppression program itself, the HOA must be delineated, an "efficient" operational program must be designed for this area, and the costs of such a program must be estimated. Experienced commercial weather modifiers and NCAR and university personnel involved in NHRE can provide much of the information required to accomplish this task.

Studies of the disposition and environmental effects of silver iodide in connection with several cloud seeding programs including NHRE (e.g., Teller, 1972; Teller and Klein, 1973) have failed to find significant increases in silver concentrations in the target areas. However, considerable variability exists among sampling sites and among time periods, and silver concentrations in terrestrial samples are to date just at the level of detectability. In order to be able to assess the implications of long-term seeding activities at operational levels, the monitoring of silver concentrations in, and downwind of, the NHRE target area and the studies of the uptake of silver by plants and animals are expected to continue throughout the course of the ESIG study.

The insights provided by analyzing the in-depth interviews of citizens in northeastern Colorado are essential in structuring a social process model to describe and predict public attitudes, reactions, etc., to a hail suppression program such as NHRE. This series of interviews, which was initiated prior to NHRE's first operational season, also serves to monitor public opinion concerning NHRE operations and activities. Furthermore, the latest series of interviews (Haas and Krane, 1973) has provided useful information regarding the organization and financing of an operational hail suppression program.

The development (and potential application) of a new technology such as hail suppression raises legal and political questions relative to, for example, claims for damages, conflicts of interest, and institutional arrangements (Taubenfeld and Taubenfeld, 1972). Since these considerations are expected to have important implications for the organization of, and constraints placed upon, future operational programs, the legal and political alternatives and constraints need to be investigated.

Finally, the ESIG study should be conducted within a framework which provides for the quantification, where possible, of the relevant impacts and uncertainties and for the integration of the results of the several tasks. The methodology of decision analysis (e.g., Howard, Matheson, and North, 1972; Keeney, 1973; Raiffa, 1968) represents such a framework. Specifically, this methodology provides a means of taking account of the uncertainties associated with hailfall and other variables under natural and seeded conditions and of estimating the value of conducting additional seeding experiments to reduce these uncertainties.

c. Relevance and priority: While the degree to which NHRE will be successful in developing an effective hail suppression technology is not yet known, the need for a detailed investigation of the impacts and implications of applying this technology on an operational basis is evident. If the results of NHRE suggest that significant reduction in hailfall can be achieved, then individuals in the public and private sectors can be expected to advocate that this technology be used operationally. However, until a comprehensive assessment of benefits, costs, and disbenefits has been completed, operational programs may be undertaken with unforeseen and perhaps undesirable consequences, or the programs may have to be delayed for several years until an assessment is completed. Such an assessment should be initiated at the same time as the physical experiment, since the former will depend in part upon certain baseline and other data (e.g., silver concentrations in the experimental area, "matched" hailfall and damage data) obtained during the experiment.

On the other hand, if the results of NHRE are inconclusive and consideration is being given to an additional period of experimentation, then such an assessment can, when conducted within an appropriate framework, provide estimates of the benefits which can be expected from such experimentation.

This study is underway and should receive continuous emphasis.

d. Approach: Sub-objective (1): The economic aspects of the study require certain data, some of which have been obtained from insurance companies and associations, from the Federal Crop Insurance Corporation (FCIC), from studies conducted by agricultural experiment stations, and from reports in the agricultural and meteorological literature. However, these data are neither sufficiently extensive nor entirely appropriate for the purpose of formulating satisfactory relationships between hailfall parameters (e.g., mass of ice, size distribution) and hail damage in the geographic area of concern. Therefore, a cooperative network of farmers has been established in the NHRE protected area to provide information about the occurrence, size, and intensity of hail and the extent and severity of hail damage to cultivated fields and/or to structures and chattels located near NHRE instrument sites. This information will be used to estimate the functional relationships between damage to crops and to property and a number of meteorological variables such as mass of hail. Specific relationships will be developed for different crops and for different periods within the growing season, while property damage will be estimated as a separate task.

Another set of variables for which data will have to be obtained from a variety of sources is that related to "downwind effects." The change in total precipitation in the downwind area, for example, may be different from that experienced in the experimental area. Basic data on the extended area effects of NHRE are being collected and analyzed by a study team from Colorado State University.

An effective program of hail suppression will reduce the individual farmer's unit costs of production by increasing the output which can be obtained from given inputs. Since the price effect of even large increases in the output of a single multi-county region will be small, an incentive to expand production will be created. This expansion of production will reinforce increases in output resulting directly from damage reductions. The net market value of such increased output is the principal component of the set of direct economic benefits and will be estimated with the aid of a computer model run with yields applicable to the situation prior to the operation of a hail suppression program and then rerun with yields anticipated to result from such a program. The model utilizes the techniques of separable linear programming.

The process of estimating the damage reductions which can realistically be anticipated under actual operating conditions and constraints is extremely complex. The ESIG staff is seeking the assistance of agricultural experts in the field to obtain and verify information concerning such items as typical crop budgets for various representative farm operations; customary rotation cycles across the 35-county HOA; and the extent to which farmers in the region are likely to alter or adapt their operations to changes in production costs which would result from the implementation of a "successful" program of hail suppression.

The direct economic impacts discussed in the preceding paragraphs initiate a chain of events. Changes in output produce changes in the use of a wide variety of goods and services for such operations as harvesting and hauling, and changes in farm income imply changes in consumption spending by regional households. The nature and extent of these secondary impacts will be estimated by utilizing input-output (I-O) techniques. The I-O analysis will also be used as one method of assessing income distribution effects, particularly as these effects relate to transfers between functional economic groups.

Sub-objective (2): The determination of the scale and structure of an "efficient" operational program is proceeding through consultations with experienced commercial weather modifiers whose experience and advice was carefully considered in delineating the boundaries of the 35-county "target area" over which the hypothetical operational suppression program extends. These firms have provided itemized breakdowns of actual costs for various functional categories of expense which will be compared with each other and with appropriate cost information obtained from NHRE personnel.

Reliable estimates of the total direct costs of an "efficient" operational program will permit assessment of the feasibility of a number of mechanisms by which such programs might be financed. Certain methods of cost-sharing will be more desirable in some respects than on others, and a weighting system will be employed to identify those schemes which score well on specified criteria. In completing this task an important element of objectivity will be provided by the availability of the information being collected by the ESIG staff as part of their cooperative research project with the Economic Research Service (ERS) of the U.S. Department of Agriculture.

Sub-objective (3): The work being carried out under these tasks includes the following subtasks:

(1) Estimation of baseline values for specified major terrestrial and aquatic components of the NHRE experimental area and subsequent monitoring of the area during the entire time span of NHRE in order to identify any significant changes.

(2) Analysis of silver uptake by plants in greenhouse conditions.

(3) Evaluation of silver effects on soil microbial processes in soils located in the NHRE experimental area and also adjacent to ground generator sites.

(4) Investigation of the possible movement of silver from corn grown in specially treated soils to grasshoppers consuming that corn.

(5) Developing a sequence of oxidation and reduction reactions in the laboratory to trace transformations of silver iodide ignition products into other forms of silver.

Sub-objective (4): The strategy adopted for this part of the work has been to set up three sample groups of Colorado citizens over which both inter-group and inter-temporal comparisons are being made. One group consists of almost the entire population of the NHRE protected area. The second group resides along the southern and eastern boundaries of the NHRE experimental area, and the third (control) group lives well to the south. A data base was established by holding the initial interviews prior to NHRE's first operational season. In each subsequent year to date, in-depth interviews have been conducted prior to and/or immediately after the spring-summer period of NHRE field activities. Insights provided by analyzing this series of interviews are essential in structuring a social process model.

Sub-objective (5): In the first year of the NHRE, legal and political research included investigation into such matters as the existing political regimes, relevant statutory and case law, alternative strategies for resolving conflicts of interest, methods for avoiding interference between seeding operators, and the implications of seeding effects across state lines. Personal interviews with elected political officials and responsible government administrators were conducted during and after the period of field operations and close attention was given to the development of a weather modification control bill passed by the Colorado Legislature in January 1972.

With this benchmark information on the NHRE research region in hand, attention was turned to specific, current issues in 1972. Subtasks undertaken in this area included:

(1) Analyzing the weather modification statutes of Colorado and the adjoining states, paying particular attention to their legal consequences for NCAR and NHRE.

(2) Conducting a case study of the legal and political results of applying the Colorado statute in a licensing matter in the San Luis Valley.

(3) Assessing the functioning to date of the NHRE Citizens' Council on Hail Research, particularly as the latter bears on the likelihood of suits being filed against UCAR for damages or injunctive relief.

(4) Evaluating the liability problems generated by NHRE and by other federally sponsored programs of research in weather modification. Special attention is being paid to appropriate distinctions between "research" and "operational" programs and to the role of liability insurance.

In addition to these studies of legal and political questions involved in NHRE, members of the ESIG staff have examined the available options in public policy and procedure applicable to the problems posed when liability for damage is an issue and causation is impossible to prove. Clear-cut answers to the broader issues suggested by these investigations are not yet apparent, but NCAR has been able to develop a set of operating policies with regard to potential claims of damage resulting from hail suppression research.

Sub-objective (6): A decision analysis model for the ESIG study has been formulated. This model is being used in a "demonstration run" using proxy data. As soon as initial estimates of the probability distributions for the relevant hailfall and other variables under natural and seeded conditions are available from NHRE and preliminary estimates of the "utility" of the relevant benefits, costs, and disbenefits have been made, an initial assessment of hail suppression technology will be undertaken. This initial assessment, as well as the decision analysis model itself, will be revised as additional data and information become available from the other tasks in the ESIG study.

e. Resources required: Funding budgeted for FY1976 is expected to be adequate for projected requirements, except for additionals that may be needed to support a proposed investigation into uptake of silver by primary consumers. The work would be done by Colorado State University in cooperation with the University of Wyoming as an expanded part of studies already being done for ESIG on the environmental effects of silver from cloud seeding. Additional funding may also be needed in FY1976 to support an expanded surface network in the NHRE downwind area in connection with the CSU extra-area effects study. An augmented network may be required to enhance the ability to detect seeding effects in the downwind area. The basic extra-area effects study is presently funded directly by NSF.

f. University and other agency participation: The environmental and sociological studies are being carried out under subcontract by Colorado State University and the University of Colorado, respectively. The ESIG staff maintains close laison with the study team at CSU conducting the extended area effects study. In addition, the ESIG staff has been working with the Economic Research Service of the U.S. Department of Agriculture on a study of the organizational and operational characteristics of hail suppression programs.

g. Possible obstacles and chances for success: A significant difficulty in obtaining accurate data from the crop damage network lies in the problem of determining the track of hail storms through the network within twelve hours of their occurrence. Hail damage appraisers are deployed from Sterling by message from Boulder as quickly as possible after storms strike the NHRE network but network data has not been immediately available from service personnel due to the time required to service the network. As automation of the network increases, this problem will become more severe. The other principal method of obtaining storm tracks, radar, has proved almost useless since many storms pass through the area at night after the radars are shut down.

Other obstacles include the difficulty in detecting and analyzing silver deposited by cloud seeding because of the low levels of concentrations involved, and the familiar problem of determining downwind effects from seeding with sufficient certainty for inclusion in a decision analysis model.

h. Schedule: Studies related to all of the six sub-objectives are presently underway, and these studies will be completed by the end of the

NHRE program. See Work Plan in Summary.

i. Investigators: The principal investigator for the ESIG study is A.H. Murphy. S.W. Borland and W.J.D. Kennedy are the other principal ESIG staff members involved in the study. D.A. Klein (CSU) and E.J. Haas (CU) are the principal investigators for the environmental and social studies, respectively, being conducted under subcontract to NCAR. L.O. Grant and G.W. Brier, both of CSU, are co-principal investigators for the extended-area effects study, which is funded directly by NSF.

j. Possible by-products: The by-products of the ESIG/NHRE study are expected to include the following:

(1) Improvements in decision analysis methodology resulting from the application of the procedures to this particular problem;

(2) Additions to the literature on supply responses in agriculture to decreases in unit costs of production;

(3) Extensions of existing models for quantifying risk aversion and the value of insurance;

(4) Extensions of social behavior theory derived from longitudinal studies of attitudes towards weather modification on the part of residents of the NHRE experimental area;

(5) Useful insights into effective legal provisions governing conduct of operational and research oriented weather modification activities; and

(6) Conclusions with regard to the value of regular and extensive communication between scientific researchers in the field and citizens perceiving themselves as effected

by the field operations.

k. References:

Boone, L.M., 1973: Estimating crop losses due to hail. Lincoln, Nebr., U.S. Department of Agriculture, Economic Research Service, unpublished report.

Changnon, S.A., 1971: Hailfall characteristics related to crop damage. Journal of Applied Meteorology, 10, 270-274.

____, 1972: Examples of economic losses from hail in the United States. Journal of Applied Meteorology, 11, 1128-1137.

Haas, J.E., and S. Krane, 1973: Social implications of the National Hail Research Experiment. Loveland, Colo., Human Ecology Research Services, Inc., unpublished report.

Howard, R.A., J.E. Matheson, and D.W. North, 1972: The decision to seed hurricanes. Science, 176, 1191-1202.

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Stroup, R.L., and S. Townsend, 1973: Impacts of induced rainfall on the Great Plains of Montana - Section 5 - Economics. Bozeman, Montana State University, Agricultural Experiment Station, Research Report 42, 86 pp.

Summers, P.W., and L. Wojtiw, 1971: The economic impacts of hail damage in Alberta, Canada, and its dependence on various hailfall parameters. Preprints, Seventh Conference on Severe Local Storms (Kansas City, Mo.). Boston, Mass., American Meteorological Society, 158-163.

Taubenfeld, R.F., and H.J. Taubenfeld, 1972: The National Hail Research Experiment - Legal and political aspects and implications. Dallas, Tex., Southern Methodist University, unpublished report.

Teller, H.L., 1972: Current studies in the ecological effects of weather modification in Colorado. Preprints, Third Conference on Weather Modification (Rapid City, S.D.). Boston, Mass., American Meteorological Society, 226-231.

____, and D.A. Klein, 1973: Disposition and environmental impact of silver iodide in the National Hail Research Experiment. Fort Collins, Colorado State University, Operations Report No. 2, 88 pp. and three appendices.

SOCIETAL UTILIZATION PROGRAM

Societal Utilization	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Salaries & Benefits		$ 88,954	$ 95,003	$128,000	$138,000	$149,000	$100,000
Materials & Supplies		1,582	1,676	2,000	2,500	4,000	500
Purchased Services		2,142	2,270	2,000	3,000	5,000	1,500
Travel		3,822	4,051	5,000	5,500	6,000	3,000
Subtotals, Societal Utilization	$110,776	$ 96,500	$103,000	$137,000	$149,000	$164,000	$105,000
University Participation							
Human Ecology Research Service		29,000	30,000	30,000	30,000	30,000	
Colorado State University		29,500	32,000	32,000	32,000	34,000	
Legal Studies			15,000	13,000	12,000		
University of Wyoming		10,000		13,000	15,000		
Subtotals, University	$ 54,224	$ 68,500	$ 77,000	$ 88,000	$ 89,000	$ 64,000	
Other							
Department of Agriculture	5,560						
Subtotals, Other	5,560						
Totals, Societal Utilization	$170,560	$165,000	$180,000	$225,000	$238,000	$228,000	$105,000

C. Storm Microphysics Program

The NHRE microphysics effort is concerned with the processes that form hailstones in northeast Colorado thunderstorms. These processes range from the initial condensation at cloud base, through diffusive growth and ice nucleation, to the growth of large hail in strong updrafts. The priorities are set, by the emphasis on hail suppression, on the portions of the processes that are most susceptible to artificial influence and on the physics of cloud seeding itself.

The Microphysics Program is divided into four portions. First, and most straightforward, is the effort to determine how and where hailstones form within the storms. This applies particularly, because of the priority mentioned above, to hailstone embryos. Next, radar aspects of the first-echo investigations are elaborated. Third, and scientifically most difficult and obscure, comes the subject of ice nucleation and cloud glaciation. Included in this category is the subsidiary and more straightforward subject of condensation nucleation. Fourth is laboratory characterization of the seeding material and direct evaluation of effects of seeding in the field.

1. Storm Microphysics Program - Hail Embryo Problem

a. Objectives: Determine the basic processes and rates of hailstone embryo formation.

Sub-objectives:

(1) Determine whether liquid coalescence is involved at all, and if so, to what extent.

(2) Determine the character and size of the initial ice particles upon which embryos grow. How fast do the embryos form?

(3) Determine the region of hail embryo formation. Do they need to form outside the main updraft and then be transported into it? If so, is this a systematic process?

b. Background: Previous work on hailstorms has been confined almost completely to four methods: radar, visual observation, hailstone study, and external wind-field analysis. The hailstones carry some information about processes in the storm interior, but they are complicated and non-uniform and the evidence is rarely clear-cut. Radar gives general information about storm contents, but the reflectivity is ambiguous about the most important distinctions; are there many small particles or a few big ones?--are they liquid water or ice? In view of the nature of the evidence that has been available, it is not surprising that there are several competing concepts of hail formation in thunderstorms.

By way of example, the Soviets (Sulakvelidze et al., 1967) envisage hail formation to require large accumulations of supercooled water by means of the Langmuir chain process. Other models do not require liquid or condensed water contents in excess of adiabatic. Danielsen's (1972) model procuces 4-cm diameter hail in a simple up-and-down trajectory, while English's (1973) model relies upon injection of embryos into a strong updraft to make large hail. Chisholm (1973) postulates 100-micron drops freezing in the updraft to start the hailstones. Direct justification of any of these models by field measurement has been lacking because of the difficulty of making reliable measurements within the storms.

c. Relevancy and schedule priority: Each of the several conceptual and numerical hail models implies different procedures for effective hail suppression. For instance, according to the Soviet model, the ice nucleant should be added just below the zone of accumulation of supercooled water (identified with the maximum radar reflectivity) to glaciate this zone and eliminate the "fuel" for rapid hail growth. If the embryo-injection process is dominant, one needs to find where the embryos come from and seed there, some place outside the main updraft, probably in a place with little or no radar reflectivity. (This is if the seeding concept is to supply competing embryos so that only small hailstones form.) The seeding of feeder clouds as has been done in Alberta may be an example of this.

The point is that until it is known which model represents reality, it will not be known with certainty where to seed the storms so as to suppress the hail. The relevance of obtaining an answer to this question, of obtaining, in other words, a verified hail model, is clear, and it must have a first priority in NHRE.

Our schedule calls for intensified work on the embryo stage of hailstones. Work toward a detailed understanding of the subsequent growth mechanisms and growth rates of large hail is less important and will not receive early emphasis, since it seems likely that once large hail is growing in a very strong updraft, it is probably too late for suppression.

d. Approach: NHRE brings a far more powerful set of tools to attack the problem of hail formation than has been available heretofore. Excellent radar coverage at 10-cm wavelength is now routine, and three aircraft--the South Dakota School of Mines and Technology T-28, the NOAA-NCAR sailplane, and the University of Wyoming Queen Air--have operated successfully within storms. The main advantage that NHRE has over previous studies is this combination: detailed, quantitative radar histories of the storms combined with aircraft penetrations giving *in situ* measures of cloud content. The close coordination of radar with aircraft measurements of particle types and concentrations should enable the testing of storm models in considerable detail, and will give inputs to numerical modeling efforts and provide verification data. Other NHRE measuring systems--the precipitation network, the mesonet and radiosondes, dual-wavelength radar, single and co-plane Doppler radars, and hailstone structure analysis, will be combined when possible with the radar and aircraft measurements.

Thunderstorms are complex and difficult to anticipate, so that field work must be designed flexibly, to take best advantage of whatever circumstances arise. Detailed plans will be thwarted in many cases. Nevertheless, the two major measurement objectives are clear: (1) to explore the microphysical content and the processes occurring in the vicinity of first radar echoes of developing storms; and (2) to explore the content and processes in the main updrafts of severe storms, the lower parts of which are commonly the areas identified by radar as the Weak Echo Regions (WER).

The first-echo study is very important because the first precipitation-sized particles that a storm produces may very well be those that stay the longest and grow to hail size as the storm increases in intensity. This study is a sailplane-radar coordinated effort. The radar aspects of this program are discussed in more detail in the next section. The sailplane instruments are already partly adequate for the job, with the Cannon camera now having an increased sample volume and serving as the primary microphysical instrument, backed with actual particle collections. A cloud droplet sizing instrument that is trustworthy in supercooled clouds is to be added.

The WER study is more directly relevant to hail formation. This includes study of the strong radar echo that is above the WER but is still presumably within the updraft. The primary platform, for study of this region is, because of safety, the T-28. Present instrumentation includes a foil impactor that has a large sample volume and detects and characterizes the larger particles. Instruments in existence but not completely tested include the Kyle disdrometer (range 40-microns to 3-mm radius) and a formvar replicator. Instruments anticipated for the future are (1) a simple, wing-mounted version of the Cannon camera to check interpretation of the foil impactor data, and (2) possibly a disdrometer for the smaller drop sizes. The first item, the camera, is proposed for FY1975. The second will be evaluated very carefully, balancing scientific interest against price and reliability of various possible instruments. A hail detector and spectrometer which is being developed at South Dakota, may be a key instrument for measuring the rare larger particles above the WER because of its very large sample volume. It should be pointed out that the major difficulty in deciding the correct instrument complement beforehand is that the needed sample volumes and size sensitivities will not be known until the measurements actually start.

The Wyoming Queen Air* and the sailplane will operate in the lower portions of the WER when safety permits, and measure cloud physics parameters. In this part of the storm the larger cloud droplet size range is very important, and a Knollenberg optical-array probe (about 5- to 75-microns radius sensitivity) is planned. A foil impactor, Cannon camera, or formvar replicator is indicated to detect the extreme, large-size tail of the spectrum that may be important for hail formation. The sailplane instruments are fairly adequate now, with the exception of size spectrum measurements of cloud droplets in supercooled clouds.

The approach to putting together the aircraft data with the radar data will probably involve both numerical modeling and laboratory experiments. The

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* The present plan calls for the use of this aircraft in 1977 and 1978.

WER observations (including vertical velocity measurements from the aircraft) will be used to model graupel (or drop) growth, and the model will then be tested directly against radar data by attempting to predict the reflectivity gradient under the overhang. The modelers may very well need new data on collection efficiencies of ice crystals for cloud droplets, and if so, this will be measured in the laboratory.

Another place where laboratory work may be necessary to support modeling to interpret radar data is in hail melting: what sizes of drops are shed, and what are the melting rates of various types of hail? Information on these questions may be needed to interpret radar data on precipitation below the freezing level.

Smaller efforts are planned to attempt to evaluate the importance of electric fields and turbulence on precipitation particle growth.

e. Resources required: Addition of a Cannon camera system and other improved instrumentation for the SDSMT T-28.

f. University participation: South Dakota School of Mines & Technology (T-28), University of Wyoming (Queen Air)*and University of Chicago and the Universi of Illinois (CHILL radar)*.

g. Obstacles and chances for success: There is no question but that this work will greatly increase knowledge of precipitation formation in northeast Colorado, both in cumulus congestus and in thunderstorms, during the time period of NHRE. Since small hail is surely just a small extension of the usual rain-forming processes in the area, this is included in the above. Large hail is so rare in northeast Colorado that any increase in understanding

* In 1977-78 only.

by direct observations in-cloud will be very fortunate. Nevertheless, the advances in understanding of general thunderstorm microphysics and dynamics will surely be a great help in understanding large-hail formation as well. Given adequate funding, chances for success here are high.

h. Schedule: More than six well-documented first-echo studies with sailplane and radar coordination are to be accomplished in 1974 and 1975 and analyzed before the 1976 field season, along with a more extensive radar "climatological" first-echo study.

Weak-echo region explorations with the sailplane during 1974 and 1975 will be attempted, but operations and safety make it difficult to predict what can be done in detail. Results will be used for further planning.

Results from the T-28 penetrations in 1975 will provide information to start modeling WER processes. Some data are already available, from the sailplane and Queen Air in previous seasons. See Work Plan in Summary.

i. Investigators: Dr. C. A. Knight, Dr. J. E. Dye, Dr. T. W. Cannon, Dr. T. G. Kyle, Dr. P. J. Eccles, Mrs. I. R. Paluch, Mrs. N. C. Knight, NCAR; Dr. E. A. Mueller, University of Illinois, Dr. D. J. Musil and Mr. W. R. Sand, South Dakota School of Mines & Technology; and Dr. R. Srivastava of University of Chicago.

j. Probable by-products: Studies such as these are important not only for hail suppression research, but for understanding rain augmentation problems as well. It is anticipated that important new information relating to the rain formation process will be forthcoming.

k. References:

Chisholm, A. J., 1973: Alberta Hailstorms, Part I: Radar case studies and airflow models. Meteor. Monogr., 14, 1-36.

Danielsen, E. F., R. Bleck and D. A. Morris, 1972: Hail growth by stochastic collection in a cumulus model. J. Atmos. Sci., 29, 135-155.

English, M., 1973: Alberta Hailstorms, Part II: Growth of large hail in the storm. Meteor. Monogr., 14, 37-98.

Sulakvelidze, G. K., N. Sh. Bibliashvili and V. F. Lapcheva, 1967: Formation of Precipitation and Modification of Hail Processes. Israel Program for Scientific Translations, Jerusalem, 208 pp.

2. Storm Microphysics Program - First-Echo Studies

a. Objective: The measurement of particle growth rates in the real environment (1) at the beginning of a storm (the first echo), and (2) within an established storm (in the overhang above the weak echo region).

b. Background: The sequence of events involving the initiation of a persistent storm, the subsequent development of a severe storm, the airflow within such a storm, and the sizes and growth rates of particles within it are all subjects of intense interest to meteorologists. Within NHRE the Explorer sailplane has been flown repeatedly into cumulus congestus and small cumulonimbus clouds to sample particle sizes, and measure temperature and updraft speeds. Some studies of first radar echoes have accompanied this effort (Dye, *et al.*, 1974). Radar first echoes have been investigated in the past by Workman and Reynolds (1949), Battan (1953), Braham (1958), Ackerman (1960), Battan (1963), and Browning and Atlas (1965).

Radar studies allow particle-growth estimates to be made beyond that available from *in situ* sensors such as the Cannon camera, because the radar samples the entire storm and can use data from the *in situ* sensors to extrapolate locally measured conditions through the growing turret. Even in the absence of *in situ* sensors, Browning and Atlas (1965) derived growth rates and liquid water content estimates from rate of echo intensification, echo movement, and local soundings. Clearly a cooperative effort is necessary to supersede these earlier studies.

c. Relevance and schedule priority: Coordinated aircraft/radar studies of phenomena in the vicinity of the first echo (with the idea that the lower part of the familiar radar overhang may be considered a first echo) are of primary importance since all numerical simulations show the great sensitivity of later storm growth to the nature of the droplets early in the storm history. This area will receive early emphasis.

d. Approaches:

(1) Attain maximum sensitivity of the Grover dual-wavelength radar system (DURAD) by frequency hopping, increasing the pulse length, removing attenuating hardware, increasing peak pulse power and using long averaging times. Support sailplane when it is in echo by a thorough but fast raster scan of the cloud of interest.

(2) Fine tune radar as above. The radar will normally be scanning hailstorms and no special procedures are required except that storm scan times be kept to a minimum (less than 120 sec). The T-28 will be vectored through the lower edge of the radar-detectible overhang to provide *in situ* measurements. The sailplane may be vectored through the lower-outer edge of the overhang in those cases for which flight conditions are believed to be safe.

Post-analysis will consist of use of *in situ* measurements and co-plane Doppler velocity measurements (from NOAA radars) to yield the necessary inputs for calculating the local radar reflectivity factor growth rate by consideration of particle growth (along streamlines) and hailstone (or hail embryo) transport or migration across streamlines.

Occasionally these studies will be attempted with the Grover DURAD in a Doppler velocity measurement mode where there will be some small sacrifice in sensitivity.

e. Resources required: The radars for this study are available but need to be coordinated for this experiment. The T-28 and sailplane will yield the *in situ* measurements with the instruments presently planned for them (see previous Section).

f. University participation: The University of Chicago and the University of Illinois will be involved with the CHILL radar*. Dr. K. Haman of the

* In 1977-78 only.

University of Warsaw will participate in both phases of this program. The South Dakota School of Mines and Technology operates the T-28.

g. Possible obstacles and chances for success: Frequency agility of the Grover 10-cm radar transmitter has not been achieved as yet--despite efforts over the past two years. We do not see any problems for the latest attempt at this modification--but it is untested.

Safe maneuvering of the sailplane in the vicinity of a mature storm is a serious problem. We are not sure, at present, of our ability to give adequate vectoring information from the ground.

Operational requirements of the Grover radar may make the concentration on individual cumulus congestus clouds impossible at some times.

h. Schedule: Radar observations will be taken in 1974, 1975 seasons in conjunction with aircraft observations. Analysis of observations from 1972 and 1973 will continue. Intensive observations with all systems in operation will be made in 1976-1978 field season. See Work Plan in Summary.

i. Investigators: Dr. C. A. Knight, Dr. J. E. Dye, Dr. T. G. Kyle, Dr. D. Atlas, Dr. P. J. Eccles, Mrs. I. R. Paluch, NCAR; Professor K. Haman, University of Warsaw; Dr. E. A. Mueller, University of Illinois; and R. Srivastava, University of Chicago.

j. References:

Ackerman, B., 1960: Orographic convection as revealed by radar. Physics of Precipitation, Geophys. Monogr. No. 5, Washington, D. C., Amer. Geophys. Union.

Battan, L. J., 1953: Observations on the formation and spread of precipitation in convective clouds. J. Meteor., 10, 311-324.

_____, 1963: Relationship between cloud base and initial radar echo. J. Appl. Met., 2, 333-336.

Braham, R. R., Jr., 1958: Cumulus cloud precipitation as revealed by radar. Arizona, 1955. J. Meteor., 15, 75-83.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. J. Atmos. Sci., 21, 634-639.

_____, and D. Atlas, 1965: Initiation of precipitation in vigorous convective clouds. J. Atmos. Sci., 22, 678-683.

Dye, J. E., C. A. Knight, V. Toutenhoofd, T. W. Cannon, 1974: The mechanism of precipitation formation in NE Colorado cumulus - III. Coordinated microphysical and radar observation and summary. Manuscript submitted to J. Atmos. Sci.

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Knight, C. A., and N. C. Knight, 1974: Hailstone embryo recirculation. Manuscript submitted to J. Atmos. Sci.

Ludlam, F. H., 1962: Airflow in convective storms. Quart. J. Roy. Meteor. Soc., 88, 117-135.

Workman, E. J., and S. E. Reynolds, 1949: Electrical activity as related to thunderstorm cell growth. Bull. Amer. Meteor. Soc., 30, 142-144.

3. Storm Microphysics Program - Nucleation and Cloud Glaciation

a. Objectives:

(1) To understand the link between aerosols and the ice particle content of cumulus clouds, particularly thunderstorms.

(2) To learn the climatology of Cloud Condensation Nuclei (CCN) in NE Colorado during the hail season and relate the CCN to cloud droplet concentrations and size spectra.

b. Background:

(1) Ice nucleation and cloud glaciation. These subjects are very complicated and poorly understood, and are frought with controversy. The recent state of the art of ice nucleus measurement is best summarized in the Proceedings of the Second International Workshop on Condensation and Ice Nuclei held at Fort Collins, Colorado, in 1970 (Grant, 1970). To quote from the summary article by Bigg (see pp. 97 and 98), "...the scatter in individual estimates [of ice nucleus concentration] is appalling. ...While high accuracy is not required for many purposes, it certainly needs to be better than this!" Recent suggestions to resolve some of the problems have been made (e.g., Langer, 1973) but the scientific community is far from agreement on ice nucleus measurement still. Not only do different instruments not agree with each other, but in some instances none of them give nuclei counts which are even within several orders of magnitude of measured ice concentrations in clouds. The discrepancy, when it exists, is always such that the nucleus counters predict far fewer ice crystals than are found. This problem has been studied most extensively by Mossop over the past several years, and it is not resolved whether on the one hand

all of the nucleus counters are incorrect for some unknown reason, or, on the other hand, there exists an ice multiplication mechanism in clouds. Theories and hypotheses abound, but this is also a subject in which consensus is not yet in sight.

(2) Condensation nuclei. The subject of CCN measurement and how CCN relate to drop concentration and size spectra is relatively well understood. Shallow thermal diffusion chambers properly operated give quite consistent results--consistent with each other and with cloud droplet concentrations measured in clouds. The Nucleation Workshop referred to above is the best recent reference on the state of the art of CCN measurement.

c. Relevancy and schedule priority:

(1) The formation of ice crystals in hailstorms, and the ice budgets of hailstorms, are obviously of fundamental importance to both natural hail formation and to hail suppression by seeding with artificial ice nuclei. Nevertheless it must be recognized that this is a basic problem, and the state of ignorance is such that it is not possible to state a specific approach that has a high certainty of success. Work on this subject is still a matter of testing hypotheses and perhaps finding them to be inadequate. Work on this problem will therefore proceed, opportunistically, mostly later in the schedule.

(2) While the CCN determine the droplet concentrations and sizes, and these in turn determine the modes and rates of ice growth in the clouds, the information of direct relevance to NHRE's goals in cloud droplet spectra and concentrations near cloud base, not the CCN themselves.

Therefore, the CCN spectra should be determined in coordination with cloud droplet measurements during one NHRE field season. Measurements to determine the concentration of giant nuclei at cloud base will be made by at least two independent methods (e.g., slides and filters). If giant nuclei are commonly present at cloud base, they may act to initiate hailstones.

d. Approach: Two groups are involved in this work: Dr. Rosinski's at NCAR and Dr. Vali's at the University of Wyoming. The problem is a difficult one, and the approach cannot be specified closely. The two groups between them measure ice nucleus concentrations at least five different ways: by drop freezing, by the NCAR counter, by developing filter samples in diffusion chambers, and by other methods. Nuclei are collected in the air at the ground, in the air at cloud base, in liquid water at the ground and in-cloud, and in hail.

The approach is to find and study systematic features of the measurements and correlations of the measurements with each other and with rainfall intensity, hailstone number and size, and other factors. Both groups either measure or plan to measure aerosol size distribution and concentrations in precipitation and in the air, and to correlate these with nucleus concentrations and other factors to determine sources of nuclei.

Laboratory experiments usually play a large part in testing hypotheses relating to either ice nucleation or ice multiplication. Most ideas about processes are much more easily tested in the laboratory than in the field. For instance, Rosinski thinks that the high, transient ice supersaturation in the near vicinity of drops freezing in clouds can activate enough ice nuclei to explain some ice nultiplication. Such ideas are best tested in the laboratory or by numerical modeling.

e. Resources required:

(1) Continuing, modest funding for ice nucleus and aerosol particle measurement system development is indicated. Support for laboratory work and field sampling and operation of various nucleus and aerosol counters is also indicated.

(2) It is planned that CCN work will be done entirely on contract to one of several universities or other organizations that have proven capability in this area. It would be best to have the instrument mounted on an NCAR Queen Air or the Wyoming Queen Air.

f. University participation: University of Wyoming; as yet unknown university or other contractors.

g. Possible obstacles and chances for success:

(1) The importance of this area of research and the splendid framework offered by NHRE makes it mandatory to carry on this work at a stable, moderate level, in spite of the fact that it is a gamble whether answers of practical importance will be forthcoming during the period of NHRE.

(2) Apart from always-possible disasters, success in characterizing CCN is quite certain.

h. Schedule:

(1) Measurements of aerosols and of various types of ice nuclei by various methods are planned to proceed routinely to provide a large data base with which to work.

(2) Field measurements to be made in 1976. See Work Plan in Summary.

i. Investigators: Dr. J. Rosinski, Mr. G. Langer, Dr. J. E. Dye, NCAR; Dr. G. Vali, University of Wyoming.

j. Probable by-products: Again, the role of nucleation in the atmosphere is central to the whole field of cloud physics, and not just to the hail problem.

k. References:

Grant, L. O., 1970: The second international workshop on condensation and ice nuclei. Compiled by L. O. Grant, Colorado State University, pp. 1-149.

Langer, G., 1973: Analysis of results from second international ice nucleus workshop with emphasis on expansion chambers, NCAR counters, and membrane filters. J. Appl. Meteor., 12, 991-999.

4. Storm Microphysics Program - Nucleant Evaluation and In-Cloud Seeding Effects

a. Objectives:

(1) Laboratory characterization of the seeding material used.

(2) Direct, in-cloud testing of the results of seeding with the material.

b. Background:

(1) Laboratory characterization of the seeding material used in cloud seeding efforts has often been done. The method is to burn (or somehow disperse) the material, collect the aerosol produced and test its effectiveness with any of several ice nucleus counters. This always has been subject to at least all of the uncertainties encountered in measuring natural ice nuclei (see Microphysics Program Plan 2).

(2) Most cloud seeding evaluation has proceeded by attempting to correlate precipitation amount or type with the presence or absence of seeding. In this approach the physical processes that lead from cause to effect remain inscrutable. Attempts to correlate the cloud microphysical content with seeding are one step better, in that the number of links in the chain between cause and effect are fewer. Such attempts have been made in the past, particularly by the MRI group working at Flagstaff, Arizona. But the ice content of cumulus clouds is variable and poorly understood (e.g., Braham, 1964; Mossop, 1970), and results of such attempts must be treated with care.

c. Relevancy and schedule priority:

(1) Part of the legacy that NHRE must leave behind, to enable people to assess and further improve seeding methods in the light of knowledge to be gained in the future, is as complete as possible a physical characterization of the seeding material used (for example, the size distribution of particles, and the behavior of ice and condensation nuclei by various methods), with the results and the methods used to get the results described in very complete detail. This is therefore a difficult problwm which must receive early emphasis.

(2) While an extended statistical experiment is needed to test the effects of seeding upon precipitation, it seems feasible to detect direct effects of seeding with aircraft measurements in-cloud. A substantial effort will be mounted to attempt to do this. If successful, it will demonstrate one link in the chain of cause-and-effect between seeding and the alteration of the precipitation, and buttress the statistical result. Continuous emphasis will be given throughout the field program.

d. Approach:

(1) The nucleant material is to be tested in all of the same ways that both the NCAR and Wyoming groups test natural ice nuclei, as well as a comprehensive test in the large cloud chamber at Colorado State University. The size distribution of the nucleant aerosol must be determined with great care because this importantly affects scavenging and contact processes. The condensation nucleation behavior is to be tested by the same group that contracts to measure CCN (see Microphysics Program Plan 2). The ice nucleation tests particularly will be carried out in such a way that reproducibility of results

will be evaluated and comparison of results between NCAR and Wyoming, with the same and with different measurement techniques, will be evaluated.

(2) There are three approaches here, corresponding to the three aircraft to be used in attempting to detect seeding effects directly. For the sailplane, the procedure will be for the sailplane to ascend in the updraft of a cumulus congestus or small cumulonimbus to about the -10C level or higher. Then while it circles in the updraft at approximately constant level, either the tow plane will seed the cloud base with the same AgI flares that are used in the hail suppression operation, or seeding rockets will be fired into the cloud to seed a region several thousand feet below the sailplane. Soon after seeding starts, two sailplane instruments will be activated: the Cannon camera to characterize the microphysical content of the updraft and a moving filter device invented by G. Langer of NCAR to collect aerosol with a time resolution of between 30 and 60 seconds. If a burst of ice crystals caused by the seeding does occur, the camera will record the crystals and at the same time that the camera sees crystals the filter should be collecting AgI. Langer will analyse the filter for ice nucleus content, which should be a sensitive test for significant amounts of AgI. If a sequence of no crystals to crystals to no crystals is found, and correlates with a sequence of no AgI to AgI to no AgI, then a seeding effect has been found without the need for a statistical test. Quantitative analysis of results in terms of such things as ice crystal growth rates and AgI dispersion, will be most valuable for optimizing cloud seeding.

The T-28 is to be used in a somewhat similar effort in larger thunderstorms. It is not feasible for it to circle in the updraft, so the operation would involve successive penetrations at about the -15C level, with the penetrations being done with as rapid a repetition rate as possible. The instrument for characterizing the microphysical content will be a formvar replicator (continuous variety) and the instrument for detecting AgI with time resolution will be a low pressure impactor with a moving impactor slide, capable of collecting aerosol particles down to 0.01-micron radius, designed by Langer. The impactor slides are examined for ice nuclei, rather than AgI directly. With this flight plan, the verification of seeding effect must be primarily to correlate AgI content with ice crystal content in space, and only secondarily in time. This flight plan could be used to evaluate rocket seeding as well as cloud base seeding.

A third platform for evaluating seeding is the Sabreliner, flying in the anvil. Some cloud models predict large changes in the content of ice crystals blowing out in the anvil as a result of seeding. The Sabreliner can be flown in the anvil with, possibly, a Knollenberg imaging probe to measure ice crystal concentrations and a Langer impactor or the NCAR counter (which is excellent for this purpose, but will not fit on the sailplane or the T-28) to detect AgI. This is a less direct test because it is farther "downstream" than the other two.

If possible, the Wyoming Queen Air* will participate in some of these tests also. Operationally, it will be best for the aircraft to

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* 1977-78 only.

be prepared to do either these tests or other research flights, and do which ever is most appropriate in each particular situation.

e. Resources required: No large, new items are required for this portion of the program, with the exception of a Knollenberg probe for the Sabreliner (funds listed in Macrophysics Program).

f. University participation: South Dakota School of Mines & Technology, and University of Wyoming (1977-78).

g. Possible obstacles and chances for success: If it is possible to correlate AgI content with microphysical content, then the experiment (b) is a success. If not, then either (1) AgI is found but does not correlate with ice crystal concentration, or (2) no AgI is found. The first eventuality is a result, albeit discouraging; the second means an operational failure, either because the AgI detection scheme did not work (it has not yet been thoroughly tested) or because the aircraft did not encounter the AgI. It is very hard to estimate beforehand the chances for success in this experiment, but it is well worth attempting and will be attempted with considerable perseverance.

h. Schedule:

(1) This effort is already in progress; barring new developments in ice nucleus testing, initial results should be available in 18 months, with the exception of the evaluation of the seeding material as CCN. Additional experiments will be done in 1977-78 when the Wyoming Queen Air is again available.

(2) The sailplane efforts along these lines begin in summer 1974; the T-28 in 1975. See Work Plan in Summary.

i. Investigators: Dr. J. Rosinski, Mr. G. Langer, Dr. J. E. Dye, Dr. T. W. Cannon, Dr. C. A. Knight, NCAR.

j. Probable by-products: Again, many of the same questions addressed here are important for rain enhancement programs using silver iodide.

k. References:

Braham, R. R., Jr., 1964: What is the role of ice in summer rain showers? J. Atmos. Sci., 24, 640-645.

Mossop, S. C., 1970: Concentrations of ice crystals in clouds. Bull. Amer. Meteor. Soc., 51, 474-479.

6. Schedules

Gant charts depicting the development program, expected availability of measurement systems, field test and calibration periods and field observation period are shown as follows:

a. Schweizer SGS 2-32 Sailplane, figure 8.

b. SDSM T-28, figure 9.

c. T-28 Instrumentation, figure 10.

d. Nucleation Studies, figure 11.

STORM MICROPHYSICS PROGRAM

Precipitation Physics	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Salaries & Benefits		113,000	121,000	130,000	141,000	152,000	100,000
Materials & Supplies		13,500	10,000	10,000	5,000	5,000	
Purchased Services		17,500	10,000	5,000	10,000	10,000	
Travel		11,500	12,000	12,000	10,000	2,000	2,000
Equipment							
Particle Camera T-28		25,000					
Turbulence Meter T-28		5,000					
Static Pressure T-28		3,000					
Accelerometer T-28		3,000					
Miscellaneous		7,500	10,000	15,000	15,000	3,000	
Subtotals, Equipment		43,500	10,000	15,000	15,000	3,000	
Subtotals, Precipitation Physics	$167,000	$199,000	$163,000	$172,000	$181,000	$172,000	$102,000
Nucleation							
Salaries & Benefits		6,000	6,000	7,000	7,000	7,000	7,500
Materials & Supplies		5,000	5,000	5,000	5,000	2,000	1,500
Purchased Services		8,000	10,000	10,000	10,000	5,000	5,000
Travel		7,500	5,000	5,000	5,000	3,000	2,000
Equipment							
CCN Counter		8,500					
Ice Nucleus Counter		5,000					
Aerosol Generator		1,500					
Coulter Counter		14,000					
Data Recorder		3,000					
Membrane Unit		2,000					
Miscellaneous		4,500	15,000	10,000	10,000	2,000	
Subtotals, Equipment		38,500	15,000	10,000	10,000	2,000	
Subtotals, Nucleation	$ 27,000	$ 65,000	$ 41,000	$ 37,000	$ 37,000	$ 19,000	$ 16,000

STORM MICROPHYSICS PROGRAM cont.

University Participation	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
University of Wyoming	106,000						
South Dakota School of Mines	130,000	175,000	175,000	225,000	225,000	100,000	50,000
Subtotals, University	$236,000	$175,000	$175,000	$225,000	$225,000	$100,000	$ 50,000
Totals, Storm Microphysics	$430,000	$439,000	$379,000	$434,000	$443,000	$291,000	$168,000

Figure 8

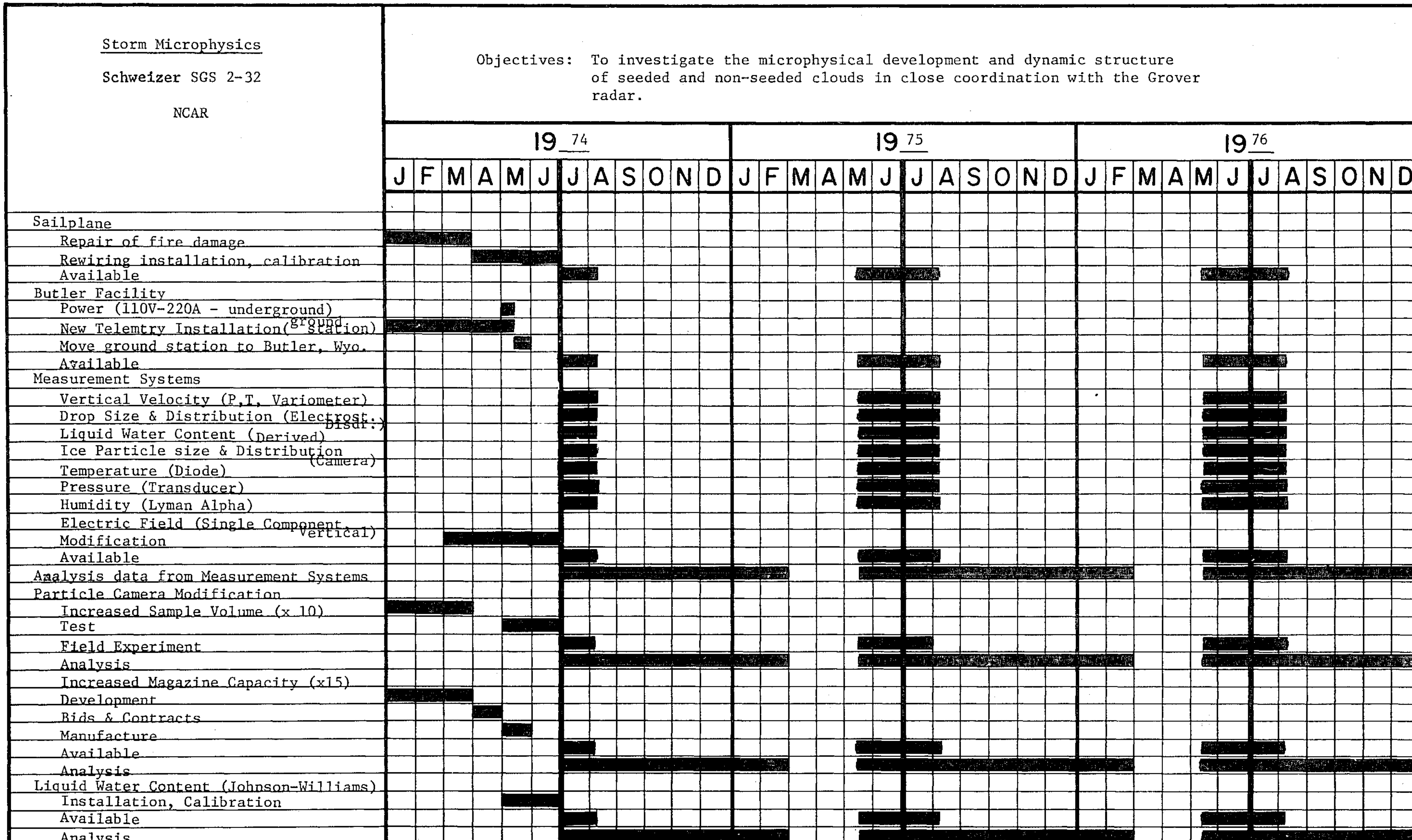

Storm Microphysics
Schweizer SGS 2-32
NCAR
Objectives: To investigate the microphysical development and dynamic structure of seeded and non-seeded clouds in close coordination with the Grover radar.
19 74
19 75
19 76
J F M A M J J A S O N D
Sailplane
Repair of fire damage
Rewiring installation, calibration
Available
Butler Facility
Power (110V-220A - underground)
New Telemtry Installation(ground station)
Move ground station to Butler, Wyo.
Available
Measurement Systems
Vertical Velocity (P.T. Variometer)
Drop Size & Distribution (Electrost. Distr.)
Liquid Water Content (Derived)
Ice Particle size & Distribution (Camera)
Temperature (Diode)
Pressure (Transducer)
Humidity (Lyman Alpha)
Electric Field (Single Component, Vertical)
Modification
Available
Analysis data from Measurement Systems
Particle Camera Modification
Increased Sample Volume (x 10)
Test
Field Experiment
Analysis
Increased Magazine Capacity (x15)
Development
Bids & Contracts
Manufacture
Available
Analysis
Liquid Water Content (Johnson-Williams)
Installation, Calibration
Available
Analysis

Figure 8 (cont.)

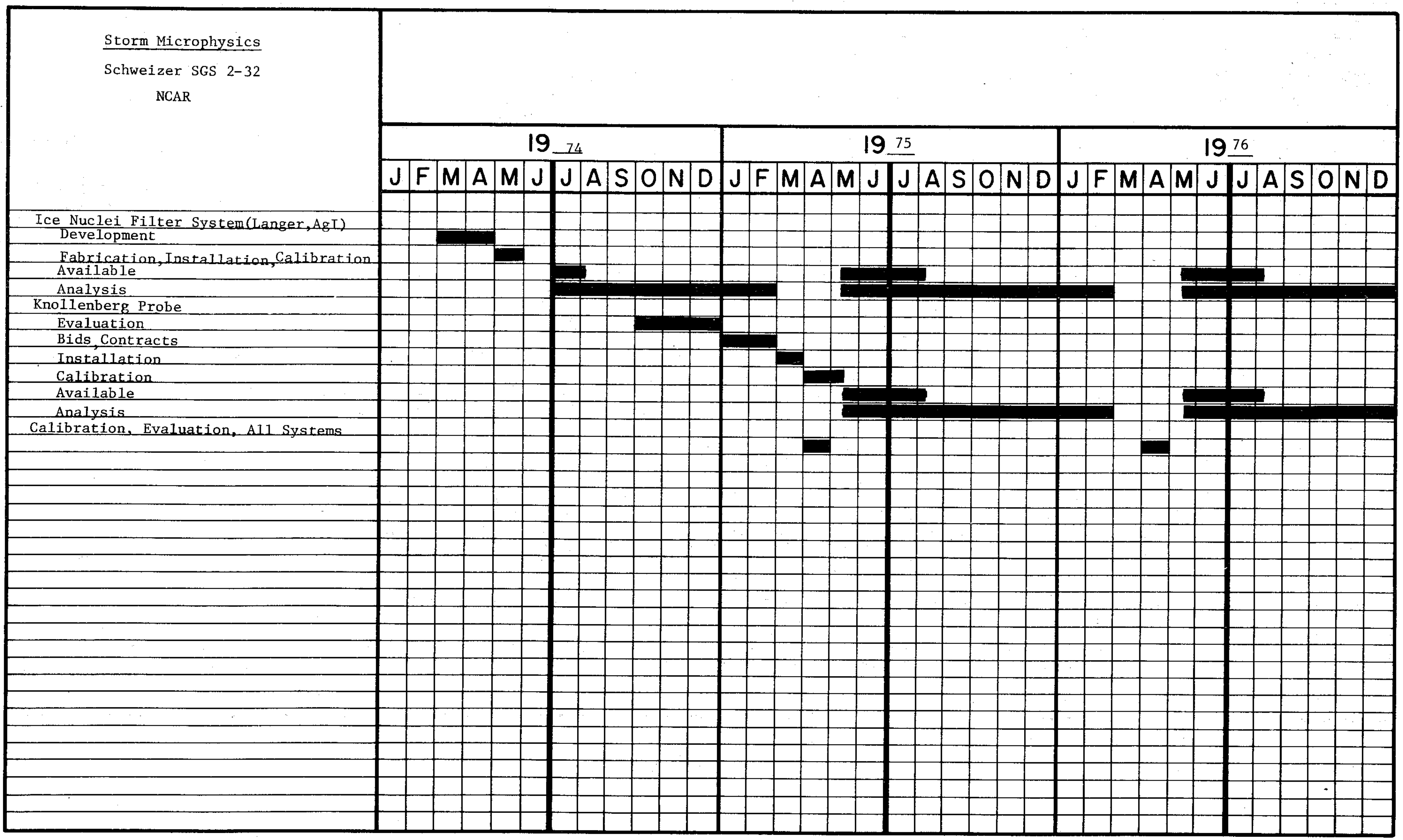
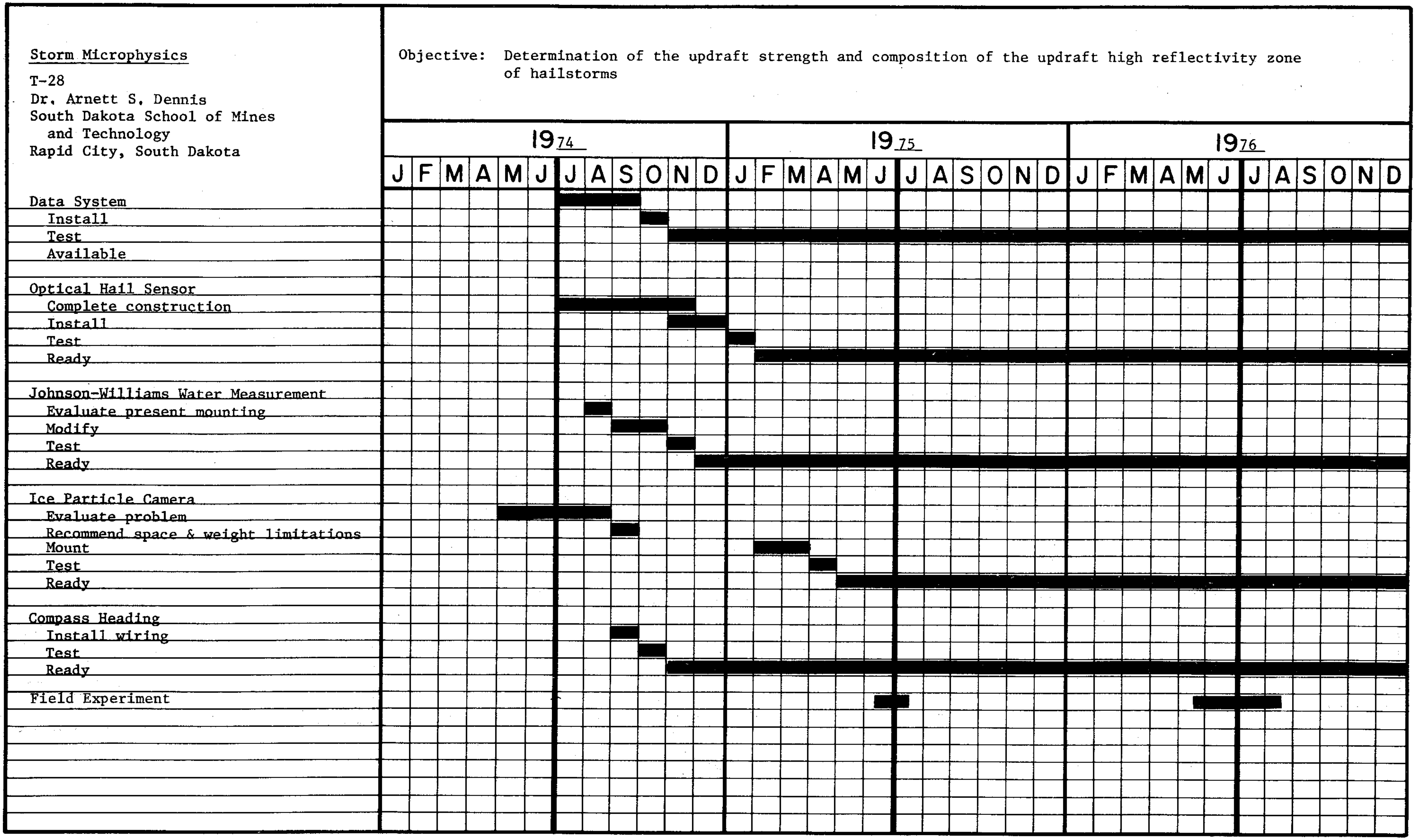


Figure 9


Storm Microphysics
T-28
Dr. Arnett S. Dennis
South Dakota School of Mines
and Technology
Rapid City, South Dakota
Objective: Determination of the updraft strength and composition of the updraft high reflectivity zone of hailstorms
1974
1975
1976
J F M A M J J A S O N D
J F M A M J J A S O N D
J F M A M J J A S O N D
Data System
Install
Test
Available
Optical Hail Sensor
Complete construction
Install
Test
Ready
Johnson-Williams Water Measurement
Evaluate present mounting
Modify
Test
Ready
Ice Particle Camera
Evaluate problem
Recommend space & weight limitations
Mount
Test
Ready
Compass Heading
Install wiring
Test
Ready
Field Experiment

195

Figure 10

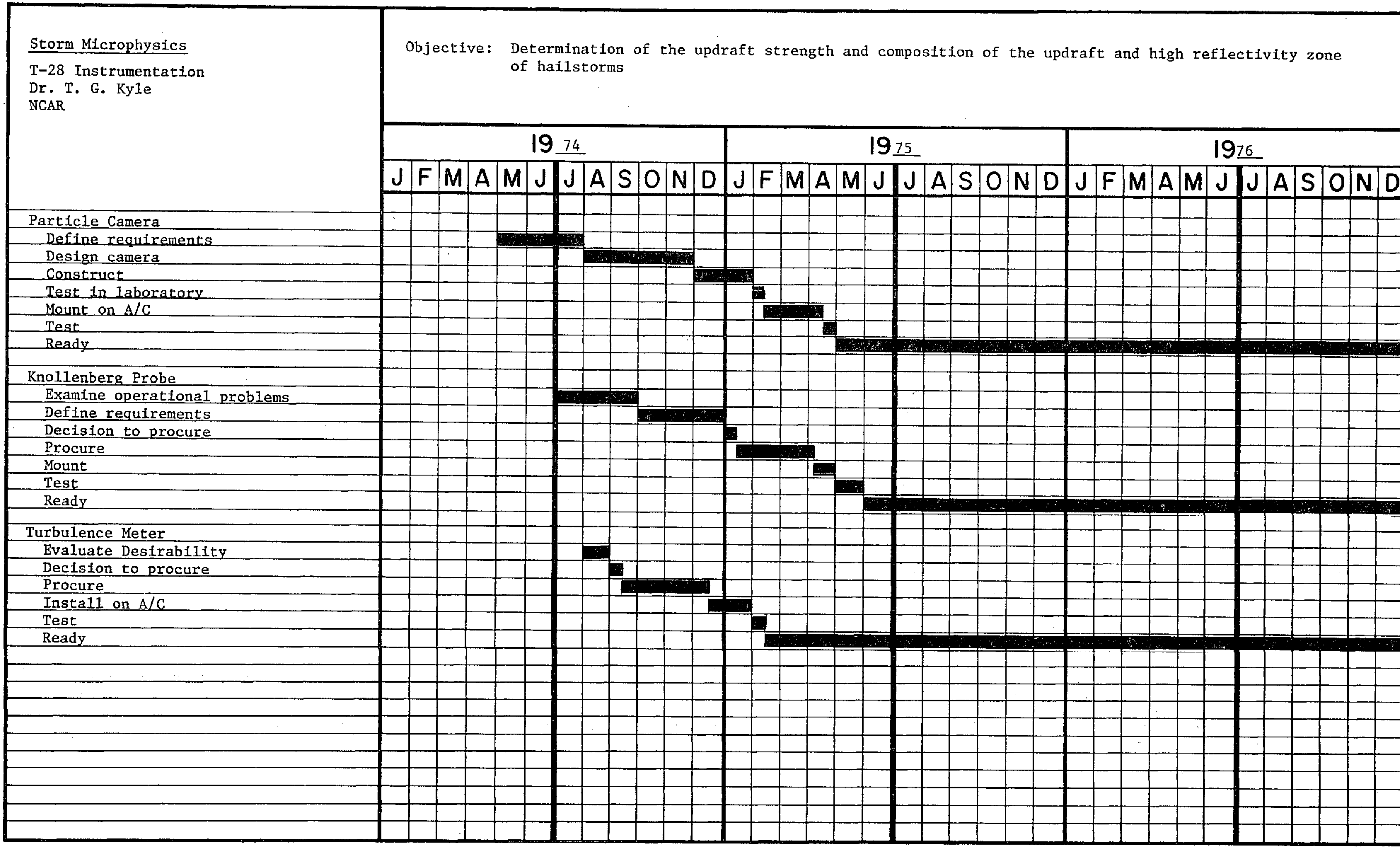

Storm Microphysics
T-28 Instrumentation
Dr. T. G. Kyle
NCAR
Objective: Determination of the updraft strength and composition of the updraft and high reflectivity zone of hailstorms
1974
1975
1976
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Particle Camera
Define requirements
Design camera
Construct
Test in laboratory
Mount on A/C
Test
Ready
Knollenberg Probe
Examine operational problems
Define requirements
Decision to procure
Procure
Mount
Test
Ready
Turbulence Meter
Evaluate Desirability
Decision to procure
Procure
Install on A/C
Test
Ready

Figure 10 (cont.)

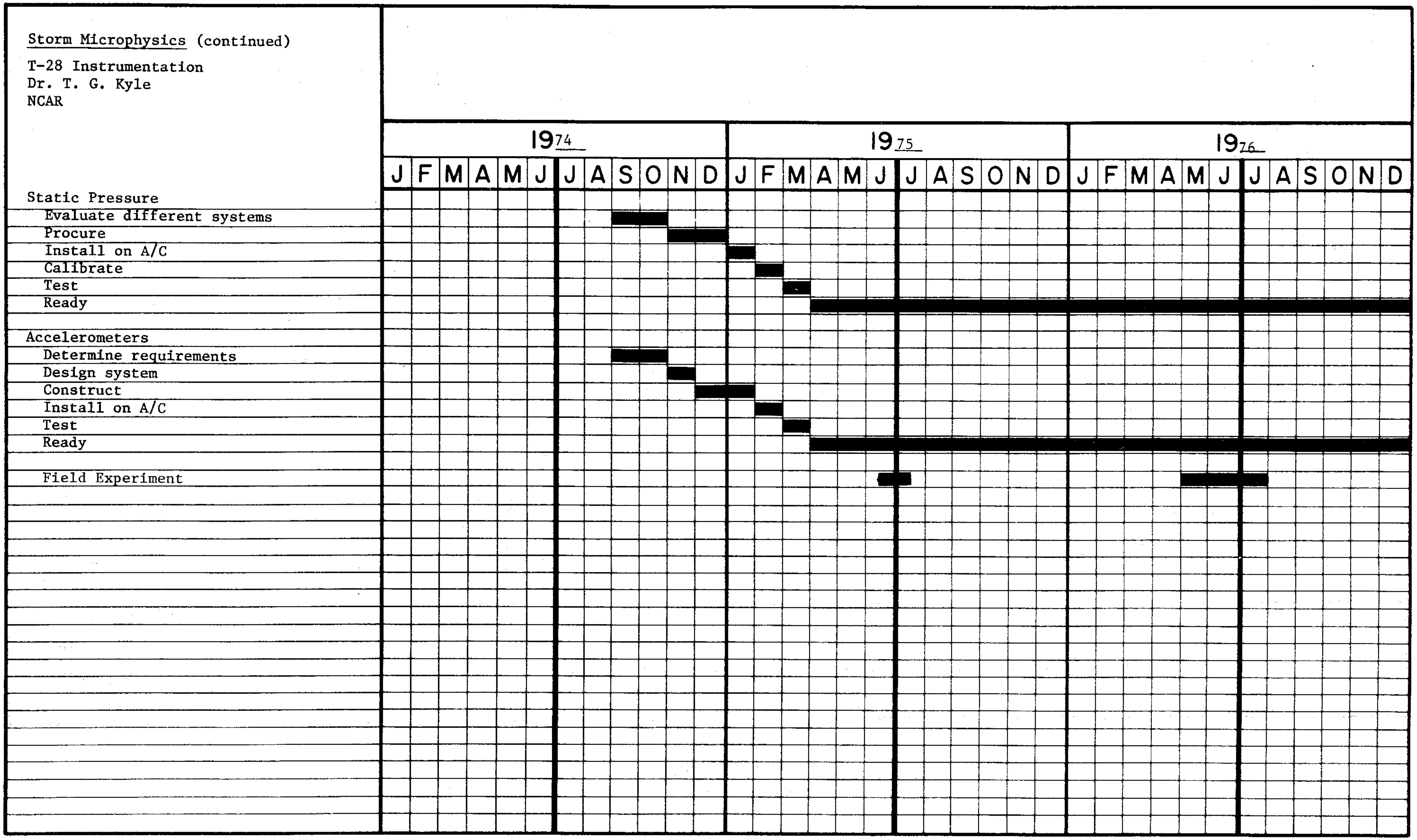
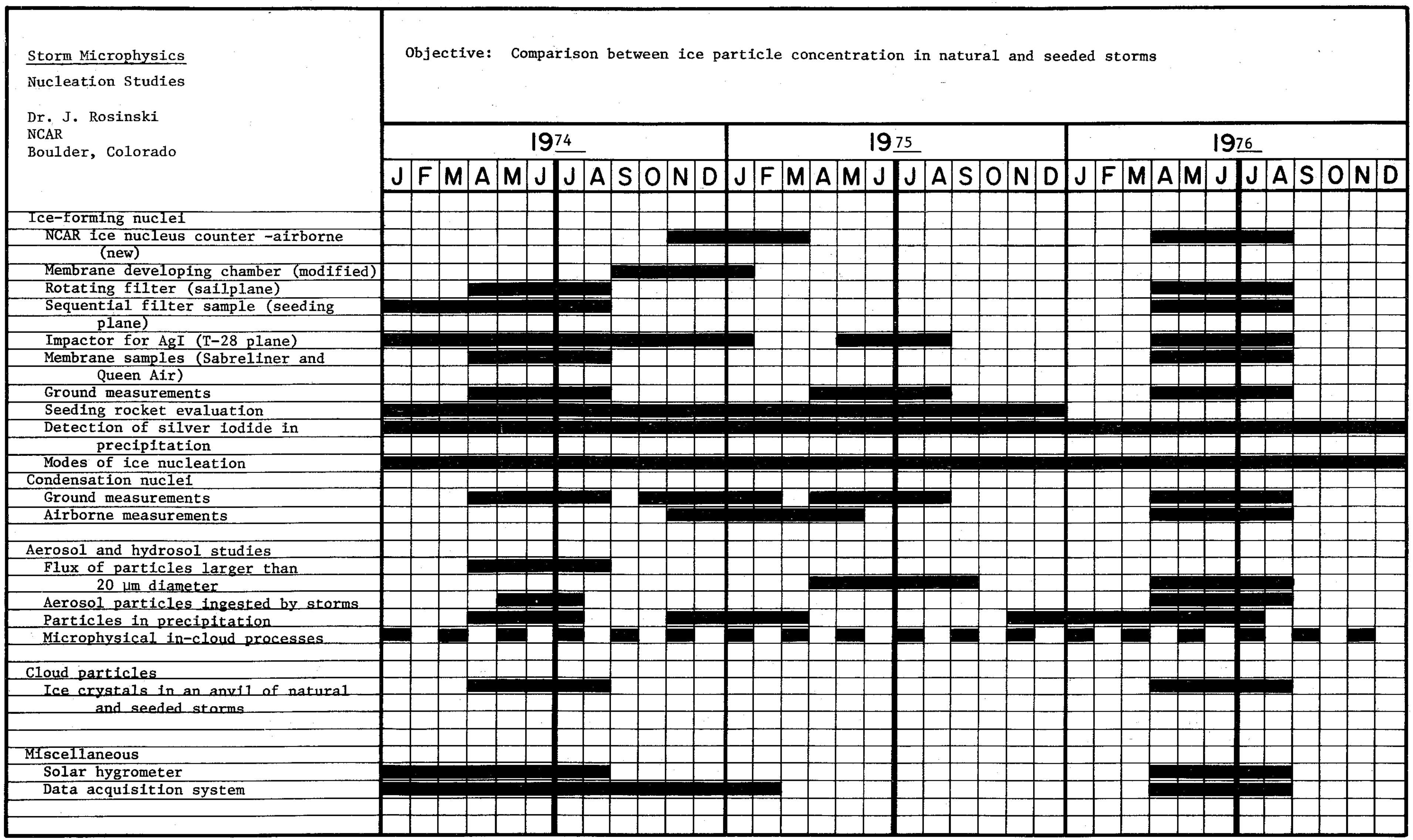


Figure 11


Storm Microphysics
Nucleation Studies
Dr. J. Rosinski
NCAR
Boulder, Colorado
Objective: Comparison between ice particle concentration in natural and seeded storms
1974
1975
1976
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Ice-forming nuclei
NCAR ice nucleus counter -airborne (new)
Membrane developing chamber (modified)
Rotating filter (sailplane)
Sequential filter sample (seeding plane)
Impactor for AgI (T-28 plane)
Membrane samples (Sabreliner and Queen Air)
Ground measurements
Seeding rocket evaluation
Detection of silver iodide in precipitation
Modes of ice nucleation
Condensation nuclei
Ground measurements
Airborne measurements
Aerosol and hydrosol studies
Flux of particles larger than 20 μm diameter
Aerosol particles ingested by storms
Particles in precipitation
Microphysical in-cloud processes
Cloud particles
Ice crystals in an anvil of natural and seeded storms
Miscellaneous
Solar hygrometer
Data acquisition system

D. Storm Macrophysics Program

As mentioned previously, the main NHRE objectives require a search for hail formation mechanisms. In order to make progress on the hail problem one must know a good deal more about the natural modes of embryo formation and the characteristic air motion patterns that determine the stone trajectory and its growth time. Emphasis in the Macrophysics Program is on determining these air circulation patterns and relating them to both the hailstone growth and the convective dynamics of the storm itself. The studies involved with reconstructing the hailstone trajectories are pursued in conjunction with the Microphysics Program. Similarly, various aspects of the internal circulation patterns (including, for example, the interaction of the precipitation with the storm dynamics, and the role of non-hydrostatic pressure forces) are most profitably examined with the aid of numerical models, and close coordination with the modeling program is being maintained.

A portion of the Synoptic Analysis research in support of the Suppression Program will be complementarily related to the Storm Macrophysics Program. See Suppression Program Section VII, A., 5.

1. Storm Macrophysics Program - Air Motion and Dynamics

a. Objective: To describe the thermodynamic structure and airflow pattern in and around the variety of hailstorm types occurring in northeast Colorado, with emphasis on Doppler radar and instrumented aircraft measurements, to give an integrated picture of the storm circulation pattern, particularly those features relevant to hailstone growth, and to give an improved understanding of the processes responsible for establishing that circulation.

Sub-objectives:

(1) In order to understand the circulation, the following storm-environment interactions must be evaluated:

(a) Ventilating effects of wind shear, particularly with regard to the mid-level flow;

(b) Entrainment, turbulent mixing and diffusion processes;

(c) Boundary layer influences;

(d) Storm steering and propagation mechanisms.

(2) Given an airflow pattern and some idea of the region of hail embryo formation (work being pursued by the cloud microphysics group), estimate hailstone trajectories through the storm.

(3) Investigate the possible effects of seeding on the storm's dynamic structure.

b. Background: Theories of thunderstorm structure involving the depiction of mean streamlines date to at least the late 1800's (see, e.g., Ludlam, 1963). The first attempt at making systematic, direct measurements was that of the Thunderstorm Project (Byers and Braham, 1949), involving storms of small to moderate intensity. Modern theories of the severe storm structure rest heavily on the work of Newton (1950), Newton and Newton (1959), Browning, 1964, 1965), and Newton (1966). This work relied almost completely on the interpretation of rawinsonde, radar, and surface meteorological data. Basic circulation features included a sloping updraft situated next to but distinctly separated from a downdraft, with this organization leading to a quasi-steady state flow. The updraft was pictured as originating from a horizontal inflow in the moist boundary layer, with the downdraft air coming principally from the potentially cold mid-level region. The role of wind shear in promoting this organization was of paramount importance. Radar analysis showed a rather dramatic echo-weak region thought to coincide with the region of maximum updraft, the argument being that large particles did not have time to form there, and the high updraft speed prevented anything from falling back through. Recirculation of hailstones through the tilted updraft became part of Browning and Ludlam's (1962) and others' theory of large hail growth.

Subsequent work by a number of investigators, generally involving the use of instrumented aircraft or the radar tracking of air motion tracers, has tended to support the general features of the above description and has added considerable further detail (Fujita and Grandoso, 1968; Fankhauser, 1971; Marwitz, 1972; Barnes, 1972; Chisholm, 1973; Marwitz, 1973; Foote and Fankhauser, 1973; Grandia, 1973). Some of the more recent findings include: the blocking effect of the storm on the ambient, mid-level flow; direct confirmation of the collocation of the updraft and weak-echo region (WER); the smooth nature of the updraft at cloud base, and the deterioration of this smooth flow into a rather chaotic, turbulent regime higher up in the WER; the existence of cold updrafts at cloud base, associated with the arrival of air parcels that could be traced to near the surface; radar tracking of chaff packets that reveal updraft maxima (though not necessarily the primary maxima) rather low in the cloud, only 2 to

4 km above cloud base in most cases, apparently requiring a high degree of turbulent mixing and entrainment for an explanation, and the subsequent finding that such entrainment is apparently taking place; the cloud base aircraft data and chaff-track data indicating that the updraft is essentially always sloped; and detailed studies of the sub-cloud wind structure showing the complexities that can occur there.

While the general description of the flow in terms of a tilted up-draft adjacent to a downdraft appears to have a good deal of direct confirmation, the picture may be so over-simplified as to bring its general usefulness for the hail problem into serious question. In particular, while a single large updraft dominates the picture at cloud base, data from penetrating aircraft (e.g., Musil, Sand and Schleusener, 1973), dropsondes (Bushnell, 1973), and vertically-pointing pulsed-Doppler radar (Battan and Theiss, 1966, and others) indicate strongly that the picture is much more complicated aloft with much fine-scale structure being observed in both the motion field and the condensed water (e.g., Kyle and Sand, 1973).

Progress on the hail problem demands that more of the details be understood. With the advent of Doppler radar as a wind-finding tool, and the development of reliable aircraft air motion-sensing equipment, we are now in a position to make a quantum jump in our understanding of the internal air motion structure and how it is coupled to the environment.

c. Relevancy and schedule priority: The motivation for the present work is essentially two-fold. First to gain a better understanding of the storm itself as a convective element--to understand what factors are important for the storm genesis, and what factors contribute to the maintenance of long-lived, traveling storms and to the winds and occasionally tornadoes that can occur at the ground.

Second, the internal flow has to be a major factor controlling hailstone growth. All theories of hailstone growth, for example, regardless of other peculiarities, involve a vigorous updraft. Definition of the storm motion field and the associated hailstone trajectories are thus essential to an understanding of the hail problem, and of the utmost importance to any program interested in hail suppression. In addition, this work interacts in fundamental ways with the formulation and verification of numerical modeling endeavors.

Sub-objective (2) will be emphasized immediately, sub-objective (1) will be held for later emphasis, since progress may be made on the hail problem without a complete understanding of why the circulation evolves as it does; sub-objective (3) has only a moderate chance of obtaining significant results and so will be studied as a by-product.

d. Approach: The key instrumentation for pursuing the objectives here include Doppler radar, instrumented aircraft, and a surface mesometeorological network, precipitation network, and an upper-air network (see Section 5, below, for more detail).

Main objective and sub-objective (1): The approach, quite simply, is to coordinate the field activities so that a maximum number of the key systems are concentrated on a particular storm at a given time. Flight plans for the powered NCAR (non-penetrating) aircraft will be similar to those flown in past years in NHRE, involving the circumnavigating mode, flight patterns concentrating on the inflow region, and a cloud base aircraft monitoring the updraft properties. An inertial navigation system currently available on one of the Queen Airs will make possible for the first time the routine acquisition of high quality vertical and horizontal wind field data at cloud base. The Sabreliner will concentrate in 1974 on the mid-level flow in an attempt to observe directly the entry of cold mid-tropospheric air into the storm circulation (a ventilation-entrainment effect). In 1976 and 1977 it will concentrate again on the anvil region to investigate the air motion and water budget there. The three NOAA Doppler radars will be so situated in the field that each pair can do co-plane scanning through a storm located over the third radar, while is is pointing vertically. The NCAR C-band and the University of Arizona* vertically-pointing Doppler systems will also be placed in regions covered by the dual-Doppler scans, the mesonet, and a dense surface rain and hail network. The radar aspects of this program are discussed more fully in the Macrophysics Programs 6 and 7.

The concentrated case study approach to the data analysis will be continued, in an attempt to bring together all relevant information on the most significant storm cases. It is expected that no more than 1 to 3 such cases per year will be analyzed in great depth, and this number appears to be adequate for these purposes.

Studies of the turbulent diffusion rates inside the storm will be continued, using estimates of the kinetic energy spectrum obtained from storm-penetrating aircraft. Knowledge of such diffusion rates is extremely important for determining whether proper seeding agent dispersion is taking place.

Boundary layer processes and their influence on storm genesis are currently being investigated at Oregon State University, utilizing data from the NHRE mesometeorological network.

Sub-objective (2): The NHRE Cloud Microphysics group is particularly interested in the region of hail embryo formation, and is pursuing research aimed at identifying the characteristics of that region. For those instances in which both groups have collected useful data, attempts will be made to estimate, given the airflow pattern and the initial stone location, the subsequent hailstone trajectory through the cloud.

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* Funded directly by NSF.

Sub-objective (3): An attempt will be made to look for dynamic effects of seeding in the aircraft and dual-Doppler wind data near the location and time of the seeding event. While the natural variability will be such that effects resulting from AgI seeding may be difficult to discern, it nevertheless is important to try.

e. <u>Resources required</u>: The key instrumentation is already in existence, and includes the NOAA dual-Doppler radar system, the NCAR and CHILL DURAD radar (1977-78), the NCAR C-Band Doppler, the University of Arizona* vertically-pointing Doppler, the NCAR aircraft (two Queen Airs and Sabreliner in 1974) and the surface mesometeorological network and upper-air network. With the addition of the South Dakota T-28 and the Wyoming Queen Air (1977-78 only) as storm-penetrating aircraft, the dual-Doppler systems will be augmented by more detailed, direct measurements of the internal airflow structure. Of particular value will be the measurements of thermodynamic parameters and turbulence levels by the penetrating aircraft.

f. <u>University and other agency participation</u>: The NOAA Wave Propagation Laboratory, Boulder, the University of Arizona* on a limited basis, with a vertically-pointing Doppler radar, the University of Wyoming with an instrumented aircraft (1977-78 only), the South Dakota School of Mines and Technology, with armored T-28 aircraft, Oregon State University (through FY 75) conducting boundary layer studies. Rawinsonde support provided by U. S. Air Force personnel.

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* Funded directly by NSF.

g. Possible obstacles and chances for success: The key equipment has, with few exceptions, already been developed and tested, and the main obstacle will probably be the weather itself--having storms in the right location for optimum coverage by the fixed networks (particularly the mesonet, the precipitation network, and the vertically-pointing Dopplers). The dual-Doppler radars and the aircraft have a greater areal coverage and will no doubt observe many more storms. It is expected that data will be collected, on the average, from 10 to 20 storms per year, of which possibly 3 to 6 will be well observed by the aircraft and scanning Doppler radars, and perhaps 1 to 3 will be well observed by all the key systems. Chances for success are high.

h. Schedule: See Work Plan in Summary.

i. Investigators: Dr. G. B. Foote, Dr. K. A. Browning, Mr. J. C. Fankhauser, Mr. C. G. Wade, Dr. T. G. Kyle, and Dr. P. J. Eccles, NCAR; Dr. E. Gossard, Mr. R. Strauch, and Mr. J. Miller, NOAA; Dr. J. D. Marwitz, University of Wyoming, Dr. A. S. Dennis, South Dakota School of Mines and Technology; Dr. L. J. Battan, University of Arizona; Dr. L. Mahrt, Oregon State University; Dr. Ramesh Srivastava, University of Chicago, and Dr. E. A. Mueller, University of Illinois.

j. Probable by-products: A knowledge of the storm flow pattern has relevance to a much wider range of phenomena than just the hail problem, for example: the study of tornado genesis; the interaction of convection with the general circulation, including effects of momentum and energy transfer and radiative effects; the essential contribution to numerical modeling efforts, including the specification of initial and boundary conditions and the verification data.

k. References:

Barnes, S. L., 1972: Morphology of two tornadic storms: an analysis of NSSL data on April 30, 1970. Unpublished manuscript. 15th Radar Meteorology Conference, Amer. Meteor. Soc., Boston, 69-76.

Battan, L. J. and J. B. Theiss, 1966: Observations of vertical motions and particle sizes in a thunderstorm. J. Atmos. Sci., 23, 78-87.

Browning, K. A., 1964: Air flow and precipitation trajectories within severe local storms which travel to the right of the winds. J. Atmos. Sci., 21, 634-639.

____ , 1965: The evolution of tornadic storms. J. Atmos. Sci., 22, 664-668.

____ and F. H. Ludlam, 1962: Airflow in convective storms. Quart. Jr. Roy. Meteor. Soc., 88, 117-135.

Bushnell, R. H., 1973: Dropsonde measurements of vertical winds in the Colorado thunderstorm of 22 July 1972. J. Appl. Meteor., 12, 1371-1374.

Byers, H. R. and R. R. Braham, 1949: The Thunderstorm. U.S. Government Printing Office, Washington, D.C., 287 pp.

Chisholm, A. J., 1973: Alberta hailstorms, Part I: Radar case studies and airflow models. Meteor. Monogr., 14, 1-36.

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____ and H. Grandoso, 1968: Split of a thunderstorm into anticyclonic and cyclonic storms and their motion as determined from numerical model experiments. J. Atmos. Sci., 25, 416-439.

Grandia, K. L., 1973: Aircraft observations within the weak echo region of high plains thunderstorms. Master's Thesis, University of Wyoming, 92 pp.

Kyle, T. G. and W. R. Sand, 1973: Water content in convective storm clouds. Science, 180, 1274-1276.

Ludlam, F. H., 1963: Severe local storms: a review. Meteor. Monogr., 5, 1-30.

Marwitz, J. D., 1972: The structure and motion of severe hailstorms. Parts I, II, and III. J. Appl. Meteor., 11, 166-201.

____, 1973: Trajectories within the weak echo regions of hailstorms. J. Appl. Meteor., 12, 1174-1182.

Musil, D. J., W. R. Sand and R. A. Schleusener, 1973: Analysis of data from T-28 aircraft penetrations of a Colorado hailstorm. J. Appl. Meteor., 12, 1364-1370.

Newton, C. W., 1950: Structure and mechanism of the prefrontal squall line. J. Meteor., 7, 1364-1370.

____, 1966: Circulations in a large sheared cumulonimbus. Tellus, 18, 699-713.

____ and J. C. Fankhauser, 1964: On the movements of convective storms with emphasis on size discrimination in relation to water-budget requirements. J. Appl. Meteor., 3, 651-668.

____ and H. R. Newton, 1959: Dynamical interactions between large convective clouds and environment with vertical shear. J. Meteor., 16, 483-496.

2. Storm Macrophysics Program - Bulk Transports and Budgets

a. Objective: To estimate the bulk transports and budgets of air mass and water vapor accompanying the variety of northeast Colorado hailstorms.

Sub-objectives:

(1) Compute precipitation efficiency by comparing moisture influx to precipitation measured at the ground.

(2) Identify and partition the airflow into the primary branches of the circulation.

(3) Attempt to identify possible differences between seeded and unseeded storms.

(4) Compare moisture budgets with radar estimates of liquid water content.

(5) Determine the two-way interaction between storm entities and larger-scale circulations.

b. Background: Fankhauser (1971) and Foote and Fankhauser (1973) demonstrate the coordinated involvement of a broad observational base in pursuit of the main and sub-objectives. Fankhauser (1971) introduces the technique of using aircraft measurements of horizontal wind for determining thunderstorm moisture budgets, and Foote and Fankhauser (1973) refined this basic approach in considerable detail. Auer and Marwitz (1968) and Dennis et al. (1970) present air mass and moisture flux estimates for High Plains thunderstorms based on cloud-base measurements.

c. Relevancy and schedule priority: The evaluation of air mass and water vapor budgets obtained for a spectrum of storm types is necessary to:

(1) provide a general framework for interpreting more refined but often sporadic measurements from diverse observational sources.

(2) Define the benchmarks required for verification of cloud models.

(3) Establish a physical framework for interpreting the statistical results of the hail suppression experiment.

All sub-objectives require prompt emphasis except (5) which appears as a possible by-product of the experiment.

d. Approach: Achievement of the specific objectives requires the coincident involvement of the complete observational base available in the NHRE. Of the currently available facilities, the extra-cloud measurements by aircraft, the radar reflectivity and air motion observations, and detailed surface records are the most essential aspects of the measurement program. The need for a coordinated set of observations concentrated on a particular convective element dictates a case study approach in the analyses.

The primary observational mode involves flying patterns that encircle a storm, at selected constant pressure altitudes ranging from near the surface to 12 km (MSL), by at least three instrumented aircraft. For an isolated and persistent storm this mode ensures recurrent passage through important branches of the storm's circulation and provides information concerning the detailed structure and evolution of the air motion in inflow and outflow sectors.

In treating the data, individual aircraft tracks are adjusted to compensate for storm motion, and the cross-track wind component is used to compute horizontal air mass and moisture flux. Interpolation between observed levels provides a flux convergence profile which may be integrated in the vertical to obtain budgets for the storm as a whole, as often as closed circuits are made.

c. Resources required: A large volume of data pertinent to the central and sub-objectives already exists in the NHRE data archives. Time is required to integrate the data from diverse sources and accumulate case studies which will ultimately lead to general interpretations. To add significantly to the present data base requires the involvement in coming field seasons of all the NCAR aircraft.

Surface network data such as that projected from the NCAR Portable Automated Mesonet is essential for defining the lower boundary conditions where the roots of the convection lie, and both dense surface precipitation records and radar estimates of the storm water content are necessary to complete the water budget calculations.

f. University participation: No direct university contributions toward this goal are foreseen; however, the operations of the University of Wyoming aircraft and South Dakota School of Mines T-28 contribute to the overall interpretation of the results.

g. Possible obstacles and chances for success: The work of Foote and Fankhauser (1973) is an example of achievable results. What is needed are a number of similar studies covering the spectrum of phenomena in northeast Colorado. The complexity of thunderstorms and the limitations in our observational tools restrict the odds of obtaining coordinated investigations. We hope for, at the most, a few well observed situations per season. In view of the complex task of integrating the data, this is also about the number that can be adequately analyzed per year.

h. Schedule: Continued field investigations and analyses through the NHRE program with analyses continuing beyond the termination of the field observational schedule. See Work Plan in Summary.

i. Investigators: Mr. J. C. Fankhauser, Dr. G. B. Foote, and Mr. C. G. Wade, and Dr. K. A. Browning, NCAR.

j. Probable by-products: Results should have direct relevance to the role that thunderstorms play in the general circulation of the atmosphere and future modeling efforts both at the cloud and larger scales will undoubtedly benefit from results obtained here. Knowledge gained with regard to moisture budgets will be pertinent to understanding the role of convection in the hydrologic cycle. Obviously, such results will also have important implications with respect to the efficacy and methodology of seeding thunderstorms of varying types and in different environmental conditions.

NHRE aircraft calibration and intercomparison procedures have already been adopted as models for other field programs and have established the validity of using airborne Doppler wind-finding systems in thunderstorm airflow studies.

k. References:

Auer, A. H., Jr. and J. D. Marwitz, 1968: Estimates of air and moisture flux into hailstorms on the High Plains. J. Appl. Meteor., 7, 196-198.

Dennis, A.S., C. A. Schock and A. Koscielski, 1970: Characteristics of hailstorms of western South Dakota. J. Appl. Meteor., 9, 127-135.

Fankhauser, J. C., 1971: Thunderstorm-environment interactions determined from aircraft and radar observations. Mon. Wea. Rev., 99, 171-192.

Foote, G. B. and J. C. Fankhauser, 1973: Airflow and moisture budget beneath a northeast Colorado hailstorm. J. Appl. Meteor., 12, 1330-1353.

3. Storm Macrophysics Program - Anvil Budget Study

a. Objective: To study the airflow and water budget of the storm anvil region.

b. Background: Various investigators have shown that the water mass deposited in the anvil of thunderstorms is lost to the surface precipitation. The overall precipitation efficiency is inversely related to the environmental wind shear (Marwitz, 1972; Foote and Fankhauser, 1973) in that the larger the shear the greater is the ice crystal mass blown downwind aloft and not returned to earth. Such losses may amount to greater than 50% of the water vapor entering the storm in the updraft. While the key objective of seeding hailstorms is to reduce damaging hail, economic studies have already demonstrated that the benefits of hail suppression may be negated if, at the same time, the surface rainfall is reduced. Because the seeding is intended to produce more ice crystals than would exist naturally, it is possible that the increased number of small crystals may be carried up into the anvil, thereby decreasing the overall precipitation efficiency. Therefore, there may be some optimum seeding rate which would produce a maximum net benefit in terms of both decreased hail damage and (hopefully) increased rainfall or minimally acceptable decreases in rainfall. Thus, studies of the water budget of the anvil region are of importance in determining the effects of seeding on overall precipitation efficiency. At the same time, studies of the air mass and moisture flux out of the anvil region are significant indicators of divergence and updraft velocities (see, e.g., the section here on Bulk Transports and Budgets).

c. Relevance and schedule priority: This is basic to the understanding of the precipitation efficiency of both natural and seeded storms and to the determination of optimum seeding rates to reduce hail damage without reducing rainfall but must await instrumental improvements, on the Sabreliner, and the assembly of sufficient radar capability to study storm details while seeding.

d. Approach: The NCAR Sabreliner will be used to circumnavigate storms, penetrating the anvil at least on the downwind side. Ice crystal sizes and concentrations will be measured by the new Knollenberg imaging probe and air motions measured by the wind-finding system. The flux of condensed water will then be estimated. In addition, to extend the aircraft measurements in both time and space, a relationship will be developed between radar reflectivity and the ice crystal mass concentration in the manner of Heymsfield (1973). Radar reflectivity measurements in the anvil region should then permit conversion to realistic estimates of ice crystal mass. At the same time, Doppler radar observations with the sensitive 10-cm CHILL* and Grover radars, and with the NOAA 3-cm dual-Doppler radars, supported by airflow measurements by the Sabreliner, should permit reasonably accurate measurements of the net mass flux in the anvil. This will be done in both seeded and natural storms. It is also of interest to assess the rate at which ice crystals evaporate upon being carried out into the dry environmental air around the storm and below the anvil. This can be evaluated from the net flux at the radar-detectable anvil boundaries.

e. Resources required: Knollenberg particle size probe.

f. University participation: This problem is an ideal one for a Ph.D. student from any one of the participating universities. University of Chicago or Colorado State University are probable candidates.

g. Possible obstacles and chances of success: No serious obstacles are envisioned. The key to realistic estimates of mass flux from radar data will be a reasonably stable and unique relationship between reflectivity and ice crystal mass. Chances for success are very good because of the backup air-truth data from the Sabreliner.

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* In 1977-78 only.

h. Schedule: Initial observations in 1976; detailed observations to be made in both 1977 and 1978 field experiments.

i. Investigators: Drs. D. Atlas and P. J. Eccles, NCAR; probably Professor R. C. Srivastava, University of Chicago.

j. Probable by-products: The most important by-product which may result from this study would be a set of curves for the rate of seeding as a function of wind shear to provide enhanced rainfall at the surface. Well defined relationships between anvil reflectivity and ice crystal mass would also be of considerable benefit in a variety of research and operational contexts; e.g., estimating how much water is pumped up into the upper troposphere and lower stratosphere over the globe from climatological radar data.

k. References:

Foote, G. B. and J. C. Fankhauser, 1973: Airflow and moisture budget beneath a northeast Colorado hailstorm. J. Atmos. Sci., 12, 1330-1353.

Heymsfield, A. J., 1973: The cirrus uncinus generating cell and the evolution of cirroform clouds. Ph.D. Dissertation, University of Chicago, 269 pp.

Marwitz, J. D., 1972: Precipitation efficiency of thunderstorms on the High Plains. Unpublished manuscript. 3rd Weather Modification Conference, Amer. Meteor. Soc., Boston, 245-247.

4. Storm Macrophysics Program - Dual-Wavelength Radar Studies

a. Objective: To deduce the evolution and trajectories of hail and the nature of the in-storm environment from radar observations, to evaluate the efficacy of suppression techniques, and to contribute to the study of the storm water budget.

Sub-objectives:

(1) Complete the evaluation of the dual-wavelength radar (DURAD) system for hail detection.

(2) Evaluate the dual-wavelength radar for quantitative measurements of rainfall at the surface and of liquid water content and median-volume diameter aloft and provide quantitative data on the storm water budget and the hail-water budget.

(3) Measure the radar cross-sections of hailstones of varying shape, roughness, and surface wetness as a means of determining the limitations of the radar hail detector and the feasibility of deducing estimates of hail size and concentration.

(4) Measure the changes in radar cross-section and fallspeeds of melting hail, and model the radar reflectivity profiles associated therewith as a means of deducing the changes in hail size (during melting) from radar measurements and, similarly, the rainfall resulting from melting hail.

(5) Relate the four-dimensional radar reflectivity, hail and liquid water maps to the synoptic situation.

(6) Provide operational reflectivity and hail mapping capability for control of research and seeding functions, and for later use by other NHRE investigators. In all the above it is implicit that this will be done in both natural and seeded storms.

b. Background: Eccles and Atlas (1973) provide the basic theory and design of the dual-wavelength radar (DURAD) hail detector. Eccles and Mueller (1971), Carbone (1971), and Srivastava and Carbone (1971) discuss the false alarm problem associated with the DURAD system. Carbone et al. (1973) and Eccles (1973) report preliminary successful results in hail detection. Eccles and Mueller (1971) discuss the possibility of using the attenuation measurements available by DURAD to deduce liquid water content in rain, and discuss the possible accuracy of the procedure. Atlas and Ulbrich (1974) demonstrate theoretically how estimates of rainfall rate, liquid water content, and median-volume diameter may be deduced with greatly improved accuracy from measurements of attenuation and reflectivity with the DURAD. Atlas and Wexler (1963) provide the only measurements of the back-scatter cross-sections of smooth oblate hailstones; there are no corresponding measurements of the cross-sections of the rough distorted stones which are commonly the largest.

c. Relevancy and schedule priority: Understanding the evolution and trajectories of hail is critical to the development of the chain of evidence required to support the hail suppression experiment. Also, if the radar hail detector is proven to be reliable, the presence or absence of hail signals may become the fundamental measure of the efficacy of suppression. The latter is especially vital because of the great technical, economic, and logistic problems in establishing and servicing a surface hail detection network of sufficient density.

All sub-objectives except (3) and (4) will receive immediate emphasis; (3) and (4) will be included as the opportunity permits.

d. Approach:

Sub-objective (1): Compare hail signals observed by both the Grover (NCAR) and Fort Morgan (CHILL) DURAD systems with the hail patterns recorded by the ground network.

An initial rough test will compare integrated "far side" negative range-derivative hail signatures, at one degree elevation or lower, with observed swaths. The hail display will then be modified, after computer analysis, to indicate the hail signal itself--not the range derivative of it. This new procedure involves subtracting a fitted X-band attenuation from P_{10}/P_3 to obtain a better hailshaft signal. (P_{10} and P_3 are the received powers at the 10- and 3-cm wavelengths, respectively; see the above-mentioned references for further details.)

Testing of this signal against <u>in situ</u> sensors will be more useful than similar testing of its range derivative. This signal should be a measure of the P_{10}/P_3 "hump" caused by a hailshaft, not merely an indication that the hump is there. The height of the hump is dependent on hail mass per unit volume and hail size.

Determine from hailpad data minimum hail sizes and concentrations, and, where possible, concentration gradients detectable by the DURAD. Also compare locations of DURAD hail signals to hail locations observed by the T-28 penetrating aircraft. Artificial hailstones of various sizes and concentrations may also be dropped from aircraft to test the DURAD system in clear air. Once confidence is gained in the significance of the hail signals, prepare time sequences of three-dimensional maps of hail signals and play them back in time-lapse fashion to follow the evolution and trajectories of hail in space. Relate the latter to the storm wind fields as observed by dual-Doppler radar to determine the consistency of the hail trajectories with the field of motion.

Sub-objective (2): Use the smoothed X-band attenuation, ρ, the reflectivity at low elevation angles, and the rain parameter diagram of Atlas and Ulbrich (1974) to deduce rainfall, liquid water content, and median-volume diameter. Similarly use attenuation and the expression $M = 2.2\rho^{0.8}$ (see Eccles and Mueller, 1971) to deduce liquid water content at low elevation angles. Check measurements against isohyetal patterns over the surface raingage network and against point samples of drop size spectra measured with the Joss drop spectrometer. Similarly, compare DURAD estimates of the liquid water content and median-volume diameter against drop size and water content measurements made by the T-28 aircraft. Extending these measurements to smaller rainfall rates and water contents and improving the accuracy would require the addition of a 1.5 cm radar; this is not possible at present budget levels.

Obtain Vertically Integrated Liquid water content (VIL), the total water mass in the active region of the storm, and investigate the horizontal distribution of VIL (a parameter used by the National Weather Service in describing storms).

Sub-objective (3): Measurements of the cross-sections of artificial hailstones of varying shape, roughness, and surface wetness will be made on a radar range using the NCAR-3 cm PPS-4a pseudo-Doppler radar, and a 10-cm radar modified for pseudo-Doppler operation. The model stones will be rotated into the radar beam at velocities equal to their natural fall speeds using a rotating arm and string-supported hailstones. A standard calibration sphere supported from the other end of the rotating arm will provide an accurate, calibrated reference on each rotation.

Sub-objective (4): Several approaches will be used to assist in the interpretation of reflectivity profiles associated with melting hail. First, individual model hailstones will be observed on the PPS-4a pseudo-Doppler radar range throughout their melting history. Secondly, individual stones, some containing asymmetric radar reflectors, will be dropped from aircraft and observed during melting by the FPS-6 or TPS-40 rapid scan RHI radar belonging to the Air National Guard at Greeley, Colorado. In addition, numerical calculations will be made of the melting and wind-sorting effects of an assumed distribution of hailstones aloft and of the resulting raindrops produced from melting. Wind tunnel observations may also be required to measure the raindrop distribution of the melt water. Analysis of echoes from stones containing radar reflectors should allow computation of rotation rates and axis of rotation.

Sub-objective (5): Real-time PPI and RHI displays of the DURAD hail signals will be developed to locate the hailswaths both for control of research strategies and control of the seeding aircraft. These should be ready during the 1975 season. The Data Acquisition and Display System (DADS) will be improved to display the hail signals in an unambiguous color superimposed upon a reflectivity display. The data will also be tape recorded for quick time-lapse playback for monitoring the evolution and track of a hailswath.

A new radar signal averager, to handle 2040 range gates, with 0.33 microsecond resolution and 1 to 4 multiplexed video inputs, will be completed by fall 1974.

We plan to feed the resulting averaged data to computer-compatible magnetic tape and subsequently, 3 milliseconds later, to read it off and display it. In this way we will have an almost foolproof method of checking the quality of recorded data. We expect to increase our data taking rate by a factor of ten and also, at the same time, to decrease our absolute error rate from 1973 by at least two orders of magnitude.

We do not consider setting up the various displays to be a serious problem since we have had two years of experience in this area.

Our scanning mode is a total raster scan through a storm in about 120 seconds as compared with 120 to 300 seconds in the past. We will achieve this by increasing the azimuth velocity, decreasing the averaging time and increasing the elevation step (the gap between each scan of the raster) with increase in solid angle subtended by a storm. We even plan to approximate a 120-second scan through a storm vertically overhead (actually it will be 180 sec but will include 12 sec of a vertically-incident sounding).

Sub-objective (6): Using these techniques we plan to satisfy the needs of about fifty UCAR-related scientific users requiring PPI and RHI maps of radar reflectivity factor for their research.

e. Resources required: The NCAR and CHILL*DURAD systems, which are basic to all experiments, are available. Significant computer time will be required to process the NCAR DURAD signals until the real-time signal processor is completed. Funds required for the latter processor amount to $20,000. Joss raindrop spectrometers (available) will be operated by the University of Wyoming staff. Improvements to DADS are covered elsewhere. One additional Ph. D. scientist.

f. University participation: University of Chicago and Clemson University for radar analyses. University of Wyoming for operation and data analysis of Joss spectrometers. South Dakota School of Mines and Technology for T-28 measurements of water content and hail aloft.

* 1977-78 only.

g. Possible obstacles and chances for success: No major obstacles are expected. Directions are fairly straightforward and engineering does not require new state of the art developments. The major programming job is the mapping of 3-D evolution of hail signals. Chances of success are high.

h. Schedule: Hail detection evaluation is in progress, operational display and the new averager are near completion. Evaluation of DURAD liquid water signals will commence in 1975. See Work Plan in Summary.

i. Investigators: Dr. P. J. Eccles, Dr. C. A. Knight, Dr. G. B. Foote, NCAR, Professor R. C. Srivastava, University of Chicago, Dr. E. A. Mueller, University of Illinois.

j. Probable by-products: It is likely that the DURAD system will ultimately provide operational hail detection and warnings for aircraft hazard avoidance. Also, the DURAD will probably provide the basis for future remote quantitative measurements of rainfall and flood warning. The use of DURAD should also permit discrimination and tracking of chaff within precipitation and the discrimination of lightning and clear air echoes from precipitation echoes.

k. References:

Atlas, D. and C. W. Ulbrich, 1974: The physical basis for attenuation-rainfall relationshiops and the measurement of rainfall parameters by combined attenuation and radar methods. Manuscript submitted to *Journal de Recherches Atmospheriques*.

____ , and R. Wexler, 1963: Backscatter by oblate ice spheroids. *J. Atmos. Sci.*, 20, 48-61.

Carbone, R. E., 1971: One dimensional numerical simulation of a dual-wavelength radar hail detector. Laboratory of Atmospheric Probing, Department of Geophysical Sciences, University of Chicago, Tech. Rep. No. 24, 43 pp.

____, D. Atlas, P. Eccles, R. Fetter and E. Mueller, 1973: Dual-wavelength radar hail detection. Bull. Amer. Meteor. Soc., 54, 921-924.

Eccles, P. J., 1973: Dual-wavelength observations of a hailstorm. Unpublished manuscript. 8th Conference on Severe Local Storms, Amer. Meteor. Soc., Boston, 52-56.

____, and D. Atlas, 1973: A dual-wavelength radar hail detector. J. Appl. Meteor., 12, 847-854.

____, and E. A. Mueller, 1971: X-band attenuation and liquid water content estimation by a dual-wavelength radar. J. Appl. Meteor., 10, 1252-1259.

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5. Storm Macrophysics Program - Dual-Doppler Radar Studies and Three-Dimensional Reflectivity Structure

a. Objective: To describe the evolution of the structure and internal airflow of a hailstorm from the time history of the three-dimensional field of reflectivity, hail, and winds and to relate this evolving structure to the development of hail.

Sub-objectives:

(1) Develop graphic three-dimensional computer routines to display reflectivity and dual-Doppler radar wind observations and time-lapse computer movies thereof.

(2) Using multiple-Doppler techniques, determine the three-dimensional wind fields in severe storms, and interpret the results in terms of storm dynamics and hailstone growth.

b. Background: All significant efforts aimed at understanding the mechanisms of severe storms end with a three-dimensional conceptual model of the essential geometric structure and flow field (Ludlam, 1963; Browning, 1964). Modern methods of computer processing and displaying quantitative radar data (e.g., Boardman and Smith, 1974) and playing them back in time-lapse provide opportunities for obtaining new insights into the evolution of storms, including the development of new cells and turrets, the trajectories of rain and hail shafts, propagation effects, and the interactions between adjacent storms. The advent of dual-Doppler radars for the mapping of the wind field in three-dimensions now adds an important new capability to our diagnostic tools (e.g., Lhermitte, 1970; and Miller, 1972). The combination of three-dimensional reflectivity, hail detector signals, and wind data in a graphic motion picture display is expected to provide an unprecedented view of the evolving storm structure, the interactions between precipitation and airflow, and new understanding of how hail develops in this complex field. Time-lapse playback of the 3-D reflectivity, hail, and wind field is also the most likely way to observe the physical effects of seeding although at this time this must be considered a hope rather than a reality.

c. Relevancy and schedule priority: This effort is crucial to the ultimate aims of NHRE in developing both conceptual and numerical models of hailstorms and in finding means of observing the physical effects of seeding, and these must have prompt emphasis. (See also the discussion in the Air Motion and Dynamics section.)

d. Approach: The NOAA dual-Doppler radar system uses two radars separated by a fixed baseline to rapidly scan a common volume of space. They simultaneously scan common planes (COPLAN scan) beginning with the zero elevation plane, stepping upward through perhaps 8 to 15 such planes. At present, 24 range gates are sampled over perhaps 16 beams in each plane, taking 128, 256, 512, or 1024 samples, as desired, in each volume increment. The time required to sample the whole volume is typically between 1.5 and 6 minutes depending on the number of samples in each volume increment and the number of coplanes sampled. Spectra of the samples are computed off-line by FFT*, providing both radial velocity and velocity variance information. The two radial components are then combined to give the total velocity field in each coplane. Next, the divergence is computed in the coplanes and the velocity component normal to the planes is computed by integration of the equation of continuity. Finally, the total velocity field is transformed and interpolated from the cylindrical coordinate system into the more convenient Cartesian system.

Three-dimensional graphic displays have been developed successfully by the NCAR Computer Facility. These methods will be extended to provide for the 3-D

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* FFT stands for Fast Fourier Transform.

mapping of the evolving reflectivity field with superimposed hail detector signals in a distinct color. Vector winds obtained by the NOAA dual-Doppler radars will also be superimposed in a variety of forms as will contour maps of divergence and vorticity. The combined 3-D display of reflectivity, hail signature, and winds will be available in time-lapse form for studying the evolving geometric structure, the rain and hail development and trajectories, and precipitation interaction with the wind field.

e. Resources required: At NCAR the key new requirement is for a talented programmer to develop the graphic routines to display the available reflectivity, hail, and wind data from the various radars in the NHRE program. A Ph.D. meteorologist is required to guide the data handling and interpret the results.

f. University and other participation: NOAA Wave Propagation Laboratory and University of Chicago.

g. Possible obstacles and chances for success: Close coordination is required between the NOAA dual-Doppler and the NCAR DURAD systems to ensure highest quality and frequent observations on the same storm. Graphic displays of combined data fields are likely to require extensive experimentation before all three data sets can be presented for satisfactory unambiguous interpretation. The chances for success are high.

h. Schedule: By spring 1975, display 3-D reflectivity and hail signature fields. By fall 1975, add wind fields.

i. Investigators: Dr. P. J. Eccles, NCAR; Dr. E. E. Gossard, Mr. J. Miller, Mr. R. Strauch, NOAA; Dr. R. C. Srivastava, University of Chicago.

j. Probable by-products: It is highly likely that this work will lead to new insights into the mechanisms of formation of the meso-scale vortex circulations and possibly also tornadoes. Tornado detection techniques are also likely to evolve. Hopefully a short-range severe storm prediction method will also result.

k. References:

Boardman, J. H. and P. L. Smith, Jr., 1974: A computer-generated "four-dimensional" graphic display for weather radar data. Bull. Amer. Meteor. Soc., 55, 16-19.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. J. Atmos. Sci., 21, 634-639.

Lhermitte, R. M., 1970: Dual-Doppler radar observation of convective storm circulation. Unpublished manuscript. 14th Radar Meteorology Conference, Amer. Meteor. Soc., Boston, 139-144.

Ludlam, F. H., 1963: Severe local storms: a review. Meteor. Monogr., 5, 1-30; Amer. Meteor. Soc., Boston.

Miller, L. J. (1972), Dual-Doppler radar observations of circulation in snow conditions, Preprint Vol., 15th Rad. Meteor. Conf., Am. Meteor. Soc., Boston, Mass., 309-314.

7. Storm Macrophysics Program - Vertically-Incident Doppler Radar Studies

a. Objective: To measure and model the field of vertical air motion and the associated fields of particle size and concentration as deduced from vertical-incidence Doppler radar observations, aircraft measurements, and numerical modeling.

b. Background: Doppler radar observations at vertical incidence have provided some important insights into the field of vertical air motion and the associated patterns of reflectivity and particle fallspeeds in convective storms. Atlas (1966) introduced the concept of the balance level, the level at which the mean vertical Doppler velocity is zero, and above which the particles are effectively sorted into the small rising ones and larger falling ones. He also showed that a quasi-steady balance level could only occur in close juxtaposition to a maximum (not necessarily the primary one) in the updraft profile. Such a maximum provides the means of separating the particle size spectrum into rising and falling groups of comparable reflectivity. The layer surrounding the balance level is one of major growth because of the long durations spent by the particles near turn around. Moreover, the balance level is shown to be a pseudo-generating level because precipitation trails appear to be released there.

Using either of two approaches (the so-called Rogers method, or the lower spectral bound method), it is possible to estimate the field of vertical motion to accuracies of about $\pm$ 2m sec^{-1} or better. Given this motion field, one can estimate the particle size distribution from the Doppler spectra. In this way, a reasonable picture of the evolution of the particle size spectra is obtained. Among other things, Battan and Theiss (1966) and others have shown that the updraft may continue to increase with height above the balance level and secondary updraft maximum to a primary maximum which is not infrequently close to the storm top. Precipitation particles are unloaded from the updraft to produce a reflectivity maximum just below and to one side of the draft maximum; updraft maxima and reflectivity maxima are thus closely correlated. In his most recent work, Battan (1974) has shown that regions of large variance of the Doppler spectra (i.e., greater than about 10 $m^2 sec^{-2}$) can only be interpreted in terms of the coexistence of fast falling hailstones and smaller particles in a broad spectrum. Regions of large variance occur in well defined narrow sheaths and are well correlated with hailfalls at the ground. He also showed the coexistence of two tilted updrafts joining to become one major draft at the upper levels with shafts of precipitation and hail falling from one draft into the other. These observations of multiple drafts and multiple shafts of hail falling from one to the other and thence to the ground provide the most detailed picture of airflow and precipitation development yet obtained.

Browning et al. (1968) used both a vertically pointing and an RHI Doppler radar simultaneously to study a shower. They found the precipitation growth to occur only in a small region of gently rising air within which the vertical and horizontal air velocities relative to the cell rarely exceeded 1 m sec^{-1}. Ice crystals within the draft were balanced by it; graupel particles developed during descent through it. Growth was consistent with cloud water contents about half the adiabatic values. The use of two Doppler radars in this mode is thus capable of revealing vital features of both the airflow and precipitation growth. Obviously, a third radar scanning in a direction normal to the other two would eliminate most remaining ambiguities.

While "air-truth" measurements made by a penetrating aircraft are required to assist in the validation of the deductions made by a vertically-pointing Doppler radar, aircraft samples suffer from severe restrictions in volume sampling size and are incapable of providing a 'snapshot' of the events at all altitudes. The Doppler observations must be used to extend the aircraft measurements to otherwise unobserved regions. Although such vertical-incidence radar observations suffer from ambiguities between time and space variations, including the effects of sidewise penetration of tilted drafts and precipitation streaks into and out of the radar beam, they nevertheless provide much greater detail and reality than can be obtained by any other means. Moreover, it is now possible to use two or more vertically-pointing Doppler radars, 3-D reflectivity mapping radars, and dual-Doppler radars (or to employ the methods of Browning et al., 1968) to control the interpretation of the vertical-incidence observations.

If we are ultimately to be able to provide both conceptual and numerical models of the evolution of a hailstorm, we must obtain a realistic and detailed picture of both the field of vertical motion and the size distribution of precipitation elements. The vertical Doppler observations are thus important in providing basic inputs to the numerical models, and also must be used in validating those models.

c. Relevancy and schedule priority: Observations of the pattern and intensity of vertical motion and the associated size and concentration of precipitation elements is critical to the understanding of the basic mechanisms of hailstorms.

This effort however will be delayed somewhat because we shall probably not be able to proceed intensively with this effort with the existing competition for radar activities.

d. Approach: The NOAA Wave Propagation Laboratory operated three Doppler radars simultaneously in 1974. Two were generally used in the wind mapping mode while the third (whichever is directly under the storm) was used in the vertical mode. In addition, the NCAR Field Observing Facility (FOF) operated a new 5.5-cm vertically-pointing Doppler radar, and Professor Battan of the University of Arizona deployed a 3.2-cm vertical Doppler. The latter radars were within 4 km of each other to permit relationships between the records to be drawn.

As a test of the validity of the various methods of correcting vertical Doppler observations for particle fallspeeds to obtain air motions, the deduced draft will be compared to those computed from the dual-Doppler convergence measurements. In addition, whenever storms are overhead, the T-28 penetrating aircraft (and the Wyoming Queen Air in 1977-78) will overfly the radar to determine particle types and size spectra and updraft velocities. This will provide the "air-truth" data alluded to earlier.

Several raindrop spectrometers and hail spectrometers will also be deployed around the vertical Dopplers to validate and extend the deductions made from the radar data. For example, the mean Doppler fallspeeds of the particles at the surface will be known and need not be deduced. Also the Doppler spectral variances computed from the particle size spectra measured at the surface will be used to validate the interpretations made from variance measurements aloft.

The vertical incidence and scanning Doppler data will provide important inputs to the numerical models currently being developed. At the same time, the modeling group will be predicting, among other things, the field of mean

Doppler velocity and Doppler spectral characteristics to aid in the interpretations of the radar observations. The observations will also be used to validate the numerical models.

e. Resources required: The basic Doppler radars are already available. Doppler signal processing equipment is being developed by the NCAR Research Systems Facility and Field Observing Facility. It is expected that the vertical Doppler observations will provide dissertation material for two or three Ph. D. students and that such students would do much of the analysis.

f. University and other agency participation: NOAA Wave Propagation Laboratory; University of Chicago; University of Arizona (funded directly by NSF); Clemson University.

g. Possible obstacles and chances for success: The data taking and reduction are tedious and somewhat complex, but methods are well established and no difficulties are anticipated. The key problem is in the interpretation which requires imagination and insight. The possibility also exists that the most interesting portion of a storm may not pass directly overhead of any one radar, but the joint probability of such an event is reduced with 4 or 5 radar sites. Chances for success are high.

h. Schedule: Radar observations will be taken intensively in the 1974 field season without data from the T-28 aircraft. Analysis will start in the fall of 1974 and preliminary results on one or two cases can be expected in the spring of 1975. Intensive observations with all systems in operation will be made in the 1976-1978 field seasons.

i. Investigators: Drs. D. Atlas and P. J. Eccles, NCAR; Professor R. C. Srivastava, University of Chicago; Professor L. J. Battan, University of Arizona; Dr. E. E. Gossard, NOAA; Professor C. Ulbrich, Clemson University.

j. Probable by-products: In addition to fundamental understanding of thunderstorm airflow and precipitation mechanisms, the basic data processing and interpretive techniques will contribute importantly to the broad research use of Doppler radar techniques in meteorology. It is also likely that the work will lead to simple and economical CW Doppler techniques to measure hailfall and rainfall particle size spectra remotely from unattended stations. Doppler radar sensing of vertical drafts and turbulence in convective storms will also contribute to aviation safety. The Doppler methodology will surely contribute to the ultimate development of an operational Doppler weather radar system which is clearly on the horizon.

k. References:

Atlas, D., 1966: The balance level in convective storms. J. Atmos. Sci., 23, 635-651.

Battan, L. J. and J. B. Theiss, 1966: Observations of vertical motions and particle sizes in a thunderstorm. J. Atmos. Sci., 23, 78-87.

____________, and ____________, 1974: Doppler radar observations of a hailstorm. Sci. Report 28, Inst. of Atmos. Phys., University of Arizona, 25 pp.

Browning, K. A., T. W. Harrold, A. J. Whyman, and J. G. D. Beimers, 1968: Horizontal and vertical air motion and precipitation growth within a shower. Quart. J. Roy. Meteor. Soc., 94, 498-509.

9. Schedules

Gant charts depicting the development program, expected availability of measurement systems, field test and calibration periods and field observation period are shown as follows:

a. NCAR Grover Radar, figure 12.

b. NCAR Aircraft, Queen Airs 304D and 306D and Sabreliner 307D, figures 13, 14, and 15.

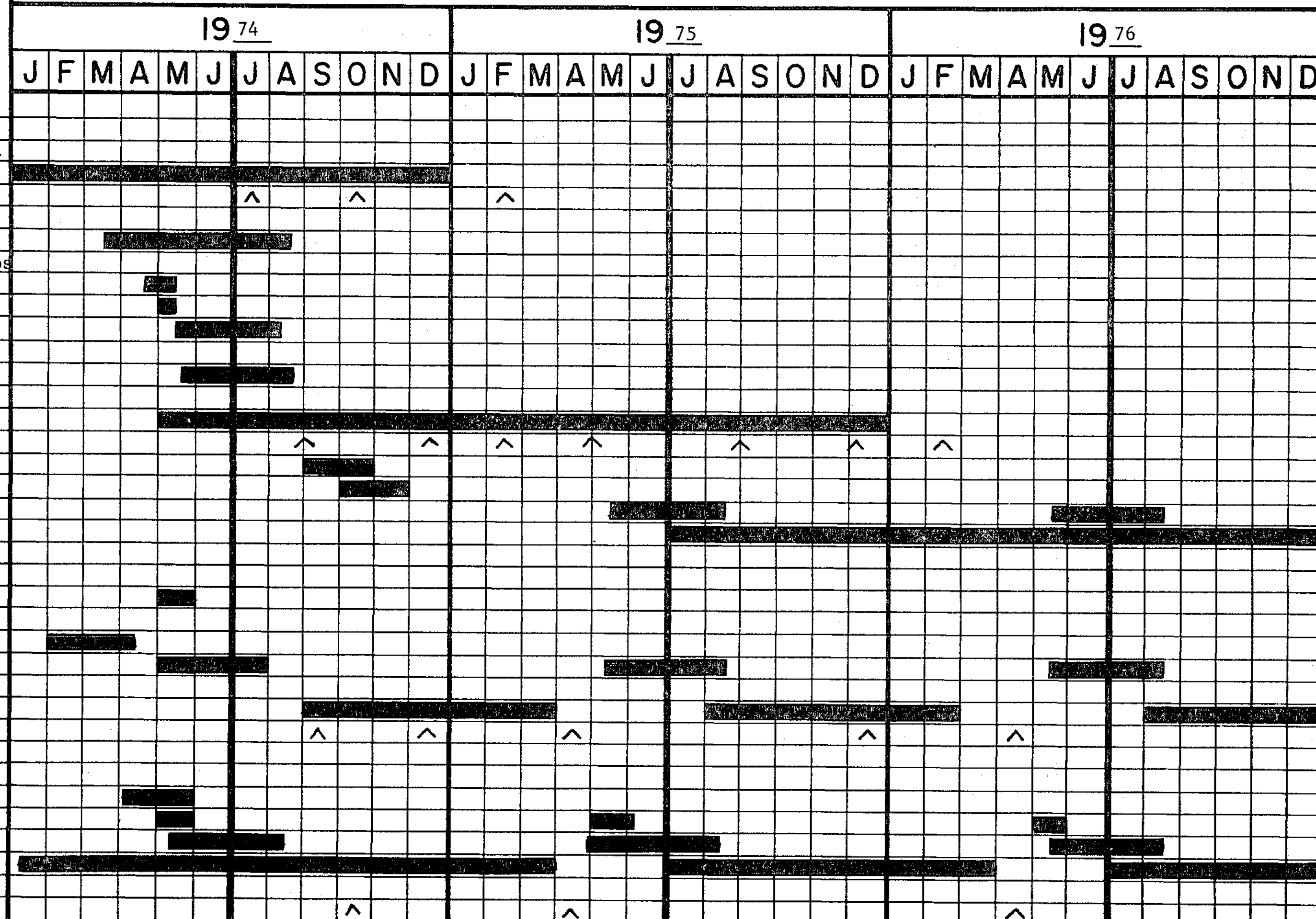
c. Mesoscale Networks, figure 16.

Figure 12

Storm Macrophysics

NCAR Grover Radar
Dr. Peter Eccles
NCAR
Boulder, Colorado

OBJECTIVE: To Provide Measurements of the Storm Interior, for Research, for Use in Directing Research Aircraft Measurements and in Control of Seeding Operations.



1973 Field Experiment
- Generate 7600 Computer Programs to Compress the Analytical Data
- Report

1974 Field Experiment
- Integrate with Field Computer, Field Ops Room
- Field Check Out, Detailed Calibrations
- Observations
- 9-track to 7-track magnetic tape Conversion (in field)
- 7600 Computer Programs to Compare Analysed Data
- Report
- Evaluate
- Budget Review

1975-76 Field Experiment
- Compression, then Analysis

Velocity Processor - Lhermitte Type
- Installation and Test
- Velocity Processor Display Circuits, Design, etc.
- Observations using Velocity Processor
- 7600 Programs, Analysis, Evaluation of Velocity Data
- Reports

Hail Real Time Processor
- Installation, Interface, Test
- Calibration
- Observations
- 7600 Programs, Analysis, Evaluation of Hail Data
- Report

Figure 12 (cont.)

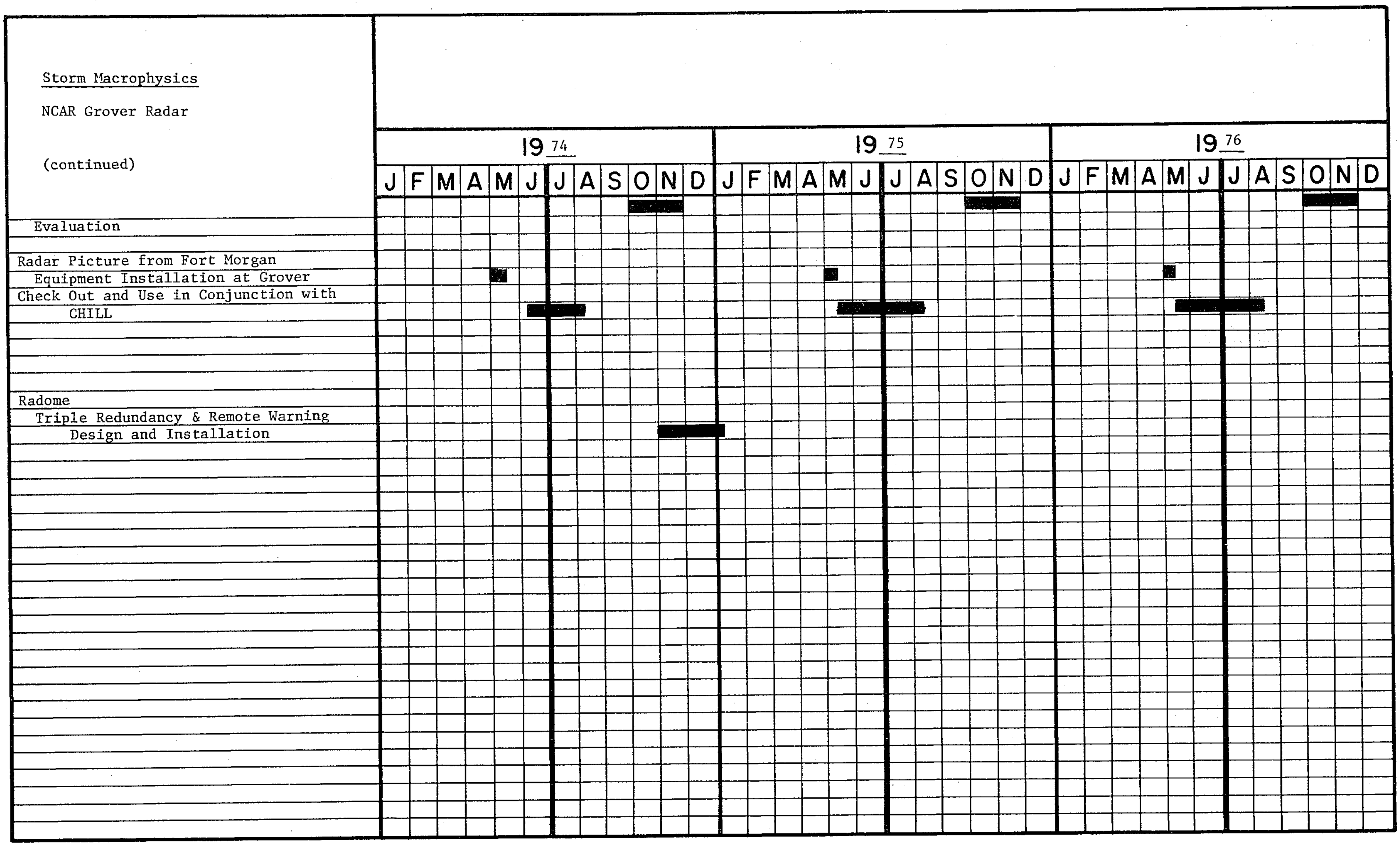


Figure 13

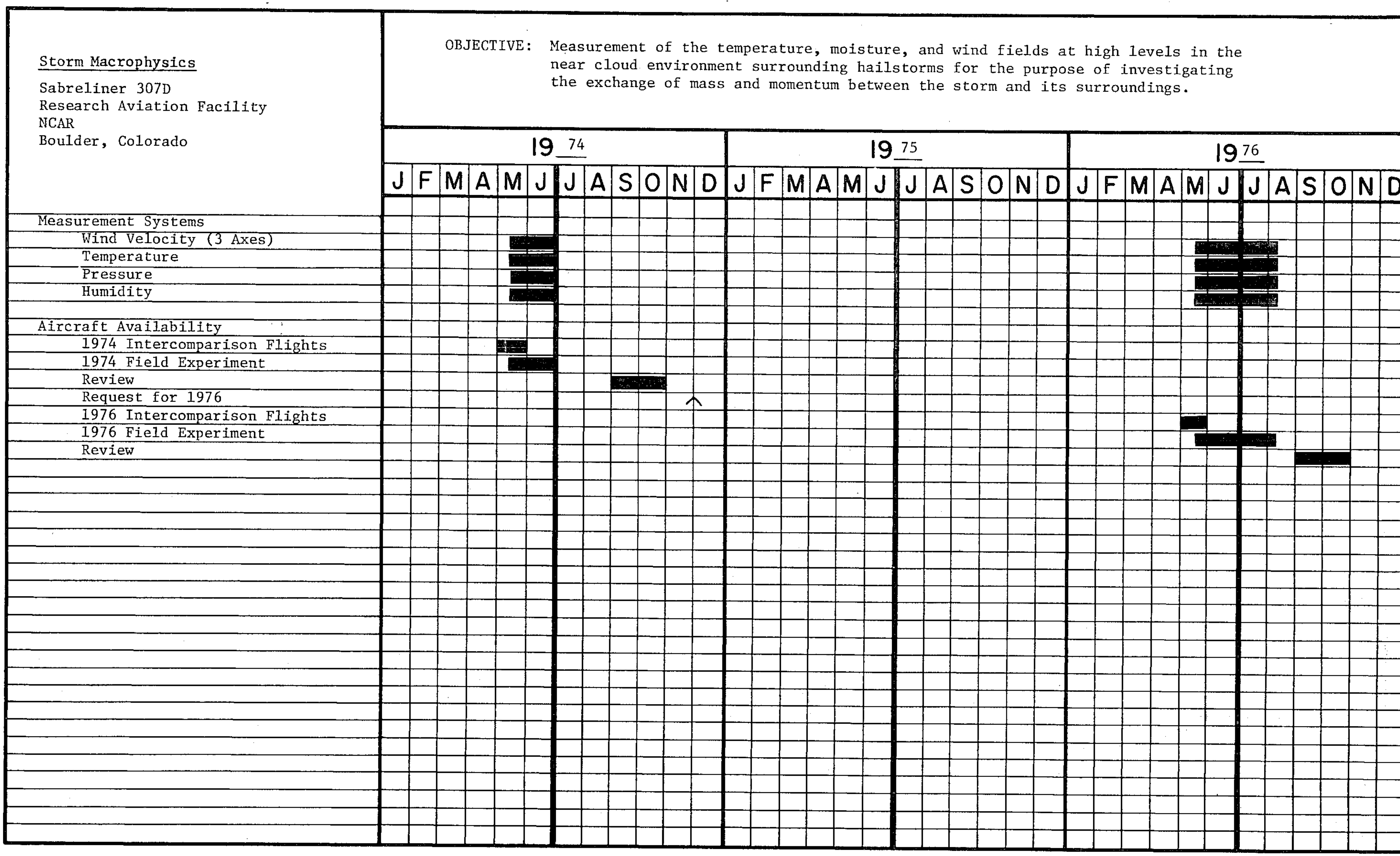

Storm Macrophysics
Sabreliner 307D
Research Aviation Facility
NCAR
Boulder, Colorado
OBJECTIVE: Measurement of the temperature, moisture, and wind fields at high levels in the near cloud environment surrounding hailstorms for the purpose of investigating the exchange of mass and momentum between the storm and its surroundings.
19 74
19 75
19 76
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Measurement Systems
Wind Velocity (3 Axes)
Temperature
Pressure
Humidity
Aircraft Availability
1974 Intercomparison Flights
1974 Field Experiment
Review
Request for 1976
1976 Intercomparison Flights
1976 Field Experiment
Review

Figure 14

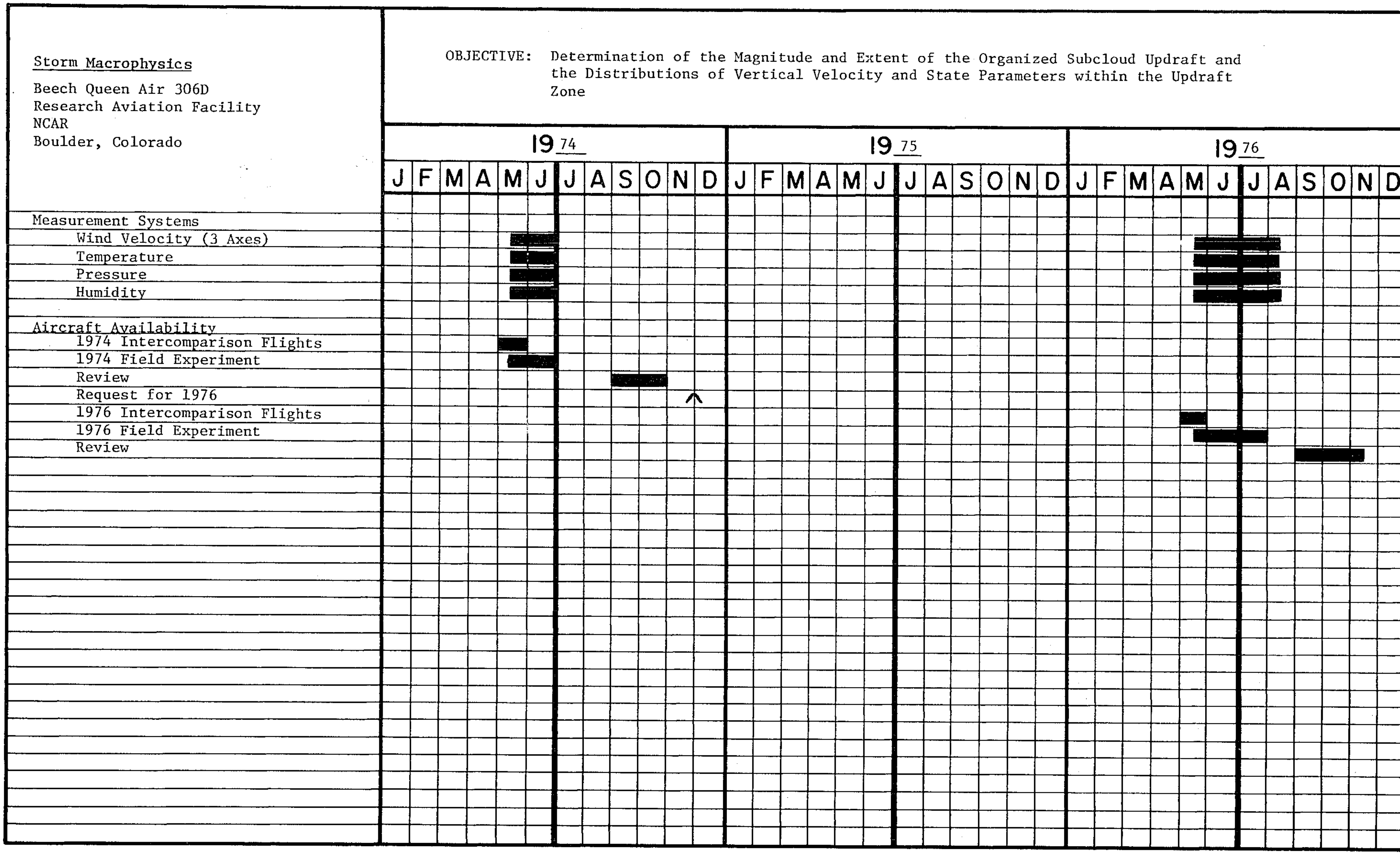

Storm Macrophysics
Beech Queen Air 306D
Research Aviation Facility
NCAR
Boulder, Colorado
OBJECTIVE: Determination of the Magnitude and Extent of the Organized Subcloud Updraft and the Distributions of Vertical Velocity and State Parameters within the Updraft Zone
19 74
19 75
19 76
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Measurement Systems
Wind Velocity (3 Axes)
Temperature
Pressure
Humidity
Aircraft Availability
1974 Intercomparison Flights
1974 Field Experiment
Review
Request for 1976
1976 Intercomparison Flights
1976 Field Experiment
Review

Figure 15

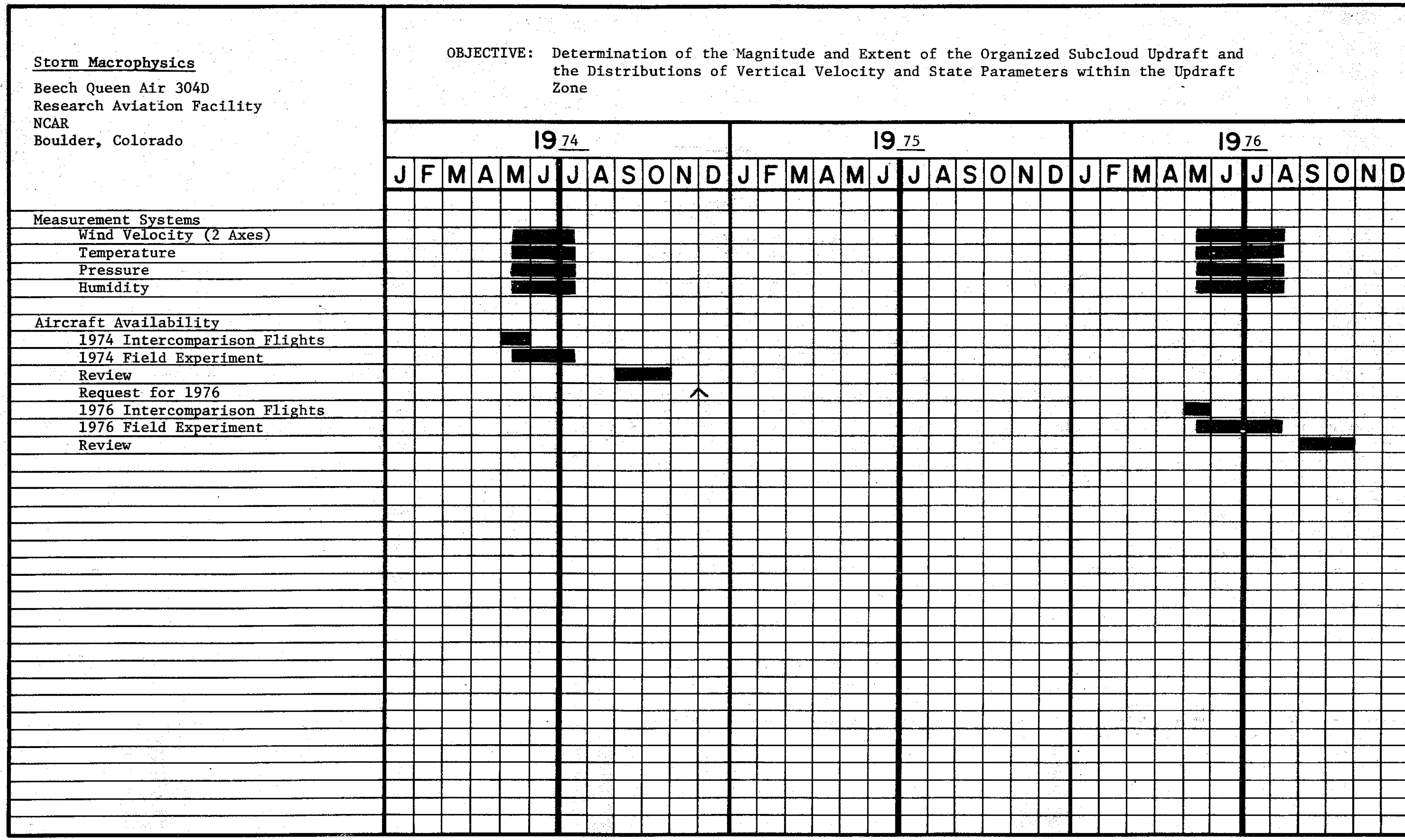
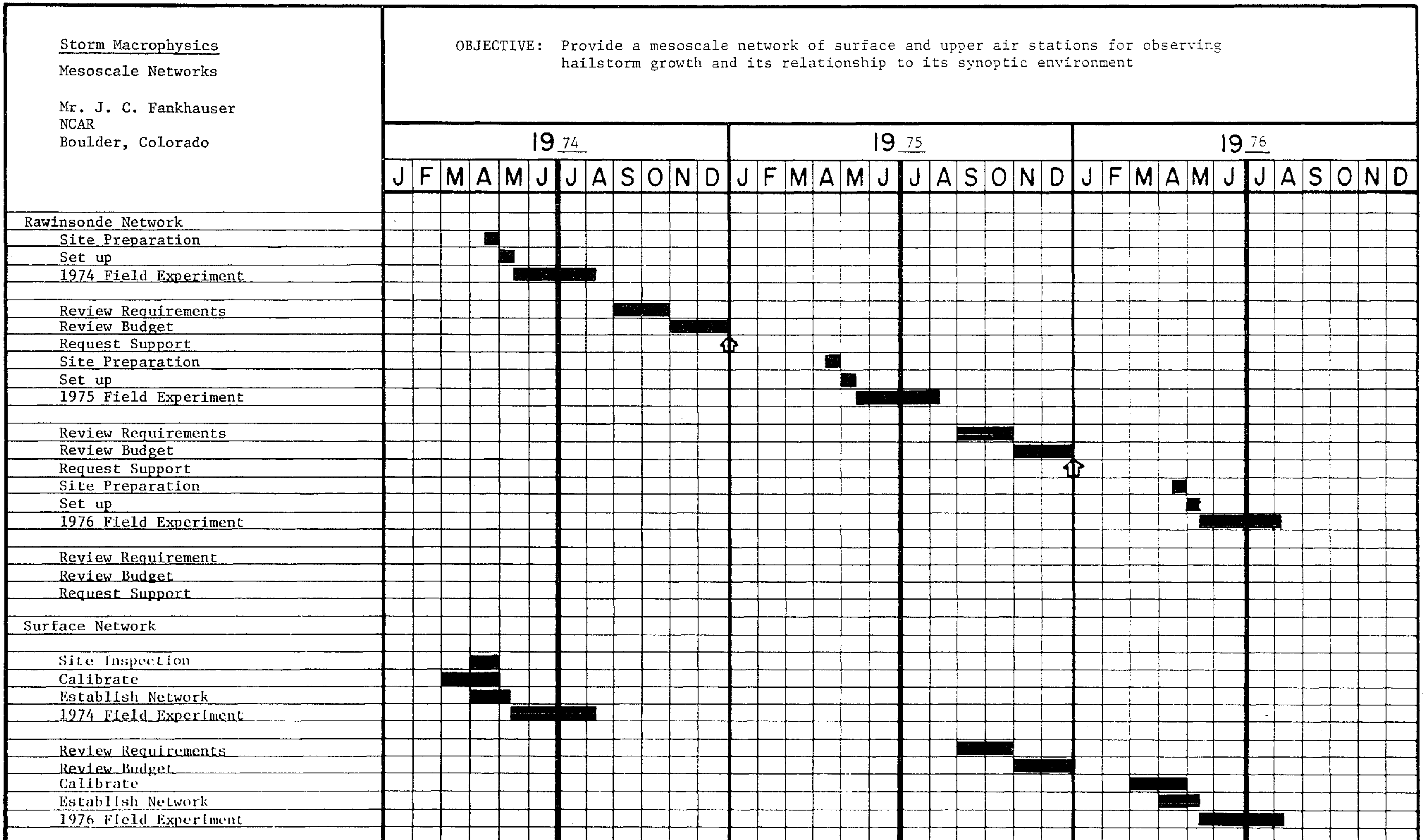

Storm Macrophysics
Beech Queen Air 304D
Research Aviation Facility
NCAR
Boulder, Colorado
OBJECTIVE: Determination of the Magnitude and Extent of the Organized Subcloud Updraft and the Distributions of Vertical Velocity and State Parameters within the Updraft Zone
1974
1975
1976
J F M A M J J A S O N D
J F M A M J J A S O N D
J F M A M J J A S O N D
Measurement Systems
Wind Velocity (2 Axes)
Temperature
Pressure
Humidity
Aircraft Availability
1974 Intercomparison Flights
1974 Field Experiment
Review
Request for 1976
1976 Intercomparison Flights
1976 Field Experiment
Review

Figure 16


Storm Macrophysics
Mesoscale Networks
Mr. J. C. Fankhauser
NCAR
Boulder, Colorado
OBJECTIVE: Provide a mesoscale network of surface and upper air stations for observing hailstorm growth and its relationship to its synoptic environment
1974
1975
1976
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Rawinsonde Network
Site Preparation
Set up
1974 Field Experiment
Review Requirements
Review Budget
Request Support
Site Preparation
Set up
1975 Field Experiment
Review Requirements
Review Budget
Request Support
Site Preparation
Set up
1976 Field Experiment
Review Requirement
Review Budget
Request Support
Surface Network
Site Inspection
Calibrate
Establish Network
1974 Field Experiment
Review Requirements
Review Budget
Calibrate
Establish Network
1976 Field Experiment

STORM MACROPHYSICS PROGRAM

	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Storm Dynamics							
Salaries & Benefits		64,000	74,000	82,000	88,500	90,000	75,000
Materials & Supplies		1,500	2,000	3,000	3,500	3,000	
Travel		4,500	5,000	5,000	5,000	3,000	1,500
Subtotals, Storm Dynamics	$ 53,000	$ 70,000	$ 81,000	$ 90,000	$ 97,000	$ 96,000	$ 76,500
Mesoscale Surface Networks							
Salaries & Benefits			14,000	15,000	16,000	7,500	
Materials & Supplies			10,000	10,000	10,000	2,500	
Purchased Services							
Miscellaneous			10,000	10,000	7,500		
Travel			5,000	5,000	6,000		
Equipment							
Miscellaneous			2,000	5,000	2,500		
Subtotals, Mesoscale Networks	$108,000		$ 41,000	$ 45,000	$ 42,000	$ 18,000	
Radar Program							
Salaries & Benefits		97,500	120,000	140,000	151,000	163,000	100,000
Materials & Supplies		20,000	20,000	15,000	15,500	5,000	
Purchased Services		12,000	15,000	10,000	15,000	5,000	
Travel		6,000	7,000	7,000	7,500	4,000	1,500
Equipment							
Hail Signal Processor		5,000					
PPI Displays		5,000					
Miscellaneous		15,000	15,000	10,000	15,000	5,000	
Subtotals, Equipment		25,000	15,000	10,000	15,000	5,000	
Subtotals, Radar Program	$136,000	$160,600	$187,000	$182,000	$204,000	$182,000	$101,500

STORM MACROPHYSICS PROGRAM cont.

University Participation	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Oregon State	7,000	7,000					
University of Illinois	12,000			120,000	120,000	75,000	
University of Chicago	40,000	40,000	50,000	120,000	120,000	75,000	50,000
Colorado State University	41,000						
Subtotals, University	$100,000	$ 47,000	$ 50,000	$240,000	$240,000	$150,000	$ 50,000
Totals, Storm Macrophysics	$397,000	$277,500	$359,000	$557,000	$583,000	$446,000	$228,000

E. Numerical Modeling Program

Numerical models of convective cloud systems may be characterized as to being theoretically or observationally based. Traditionally, there has been a significant gap between the highly simplified, observational models and the generally unrealistic, theoretical models. Under NHRE, we hope to close this gap. Part 1 describes the program plan for theoretically based models. Part 2 describes the program plan for observationally based models.

1. Numerical Modeling Program - Comprehensive Models

a. Objective: To formulate a series of numerical models, firmly based on theoretical understanding and verified, to the extent possible, by field observations, capable of (1) identifying environmental variables which have a strong effect on hail formation and growth, (2) identifying probable hail formation and growth regions within the hailstorm, (3) simulating changes in the microphysical and dynamical structure of the cloud induced by AgI-seeding with regard to hail formation and growth and (4) optimizing the seeding variables to maximize the joint economic benefit of hail suppression and rain enchancement by simulating a variety of seeding modes.

Sub-objectives:

(1) Development of a one-dimensional, time-dependent (z,t) model along the lines of Danielsen *et al.*(1972) but with significantly improved treatment of the microphysical processes (Young-Foote).

(2) Development of a two-dimensional, time-dependent dynamical model (x,z,t) with limited microphysics (Takahashi).

(3) Parameterization or simplification of the microphysical processes developed under (1) to the extent made necessary by time/storage limitations

of the two-dimensional model while retaining the basic realism of (1) (Young-Foote).

(4) Merging the dynamical framework developed under (2) with the microphysical treatment developed under (3) (Young-Foote-Takahashi).

(5) Concurrent development of a dynamically sophisticated three-dimensional time-dependent model (by Lilly-Klemp in another part of NCAR).

b. Background: The complexity of numerical models of cloud processes and cloud systems has been closely related to the speed and size of available computers. Hence, the degree of realism attained by cloud models has improved in recent years to the point where fairly complex microphysical interactions or fairly complex dynamical interactions may be handled (but not both).

Two-dimensional, time-dependent dynamical models such as those developed by Ogura and Takahashi (1971) or Wisner, Orville and Myer (1972) are capable of simulating up- and down-draft structures, hailstone trajectories and precipitation at the ground (including hail) in a qualitative sense. However, the highly parameterized treatment of the microphysical processes is inherently incapable of simulating the basic physics involved in the formation of hail embryos under natural conditions (nucleation of the ice phase followed by diffusional and accretional growth of the ice particle to the graupel stage), or in simulating the changes induced in this process by AgI-seeding. In addition, these models are incapable of modeling the upper-level environmental flow around the storm (part of which is entrained into the cloud, forming the downdraft) or the interaction between the storm circulation and the meso-scale circulation which is important in maintaining the storm.

The development of equivalent complexity in microphysical models has lagged behind the development of dynamical models. The model developed by Danielsen et al. (1972) represents a significant improvement in the treatment of the microphysical processes important in hail growth but neglects almost entirely ice-phase nucleation which governs hail embryo formation. Since enhancement of the nucleation process is the basis for hail suppression, this is a serious deficiency. However, by introducing large cloud droplets into the bottom of the updraft, Danielsen et al. (1972) were able to realistically simulate the radar structure, and, presumably, the hailstone growth rates. These simulations showed that, given their assumed initial conditions, it is not necessary to postulate the existence of liquid water "accumulation zones" in order to account for the growth of large hailstones. While being limited to a one-dimensional, time-dependent framework, these results produced radar reflectivity profiles in (z,t) which were remarkably similar not only to observed (x,t) profiles, but also to (x,z) profiles. This suggests that such a treatment may be capable of describing, in a limited sense, a two-dimensional (x,z) profile of a steady-state storm.

c. Relevancy and schedule priority: Numerical simulation is highly relevant to the goals of the NHRE in three ways. First, it provides the integration of field observations, laboratory observations and theory necessary to proper understanding of hailstorms. In this, understanding implies the ability to explain field observations in terms of accepted theory in a step-wise, quantitative fashion. Second, numerical simulation can demonstrate the physical chain of cause-effect relationships which can lend credence to the findings of the statistical experiment (either positive or negative). Third, numerical simulation is necessary to address the question of optimizing seeding methods in lieu of adequate time and money to investigate more than one such seeding method. In this, improved seeding methods may be suggested and the relative importance of variables such as AgI particle size and concentration can be defined.

All of these sub-objectives are new in the NHRE and will begin immediately. The three-dimensional modeling work must necessarily lag the simpler model, both for logical development and to mesh with available computer power.

d. Approach: The program of numerical modeling under the auspices of NHRE is necessarily open-ended since it is anticipated that a significantly larger/faster computer will be available at NCAR between 1978 and 1980. This will make it possible to combine the improved microphysical treatment under sub-objectives (1) and (3) with the three-dimensional model. It is anticipated that this combined model will overcome a number of inherent limitations in describing the three-dimensional flow field which are recognized defects in the models proposed for development under NHRE.

The program as outlined envisions three parallel lines of development, ranging from predominantly microphysical to predominantly dynamical modeling efforts.

(1) Young-Foote: Responsibility is the development of a detailed, non-parameterized, microphysical treatment of cloud processes in a one-dimensional, time-dependent framework. This comprehensive model will be used as the standard against which to compare simplifications/parameterizations which may be necessary before combining the microphysical treatment with the more sophisticated dynamical treatments.

The dynamical framework developed by Danielsen et al. (1972) will be improved somewhat and combined with the improved microphysical treatment based on that of Young (1973, 1974). This model will include the following:

(i) Liquid and ice phase nucleation including contact and immersion freezing nucleation and deposition nucleation. The model will provide for a size spectrum of natural and AgI aerosol particles with an ice nucleating ability based on laboratory observations and field measurements provided by Drs. Rosinski and Vali. The ice nucleating ability will be defined in terms of size, temperature and ice supersaturation. Contact nucleation and aerosol (in particular, AgI) scavenging rates will be calculated from Brownian motion, thermo- and diffusiophoresis and inertial capture, made possible by an iterative calculation of supersaturation.

(ii) Diffusional growth of particles including ice crystals of variable habit and calculation of supersaturation. Ice crystals are allowed to grow in two dimensions (a and c axes) with an axial ratio and density determined by the ambient temperature and supersaturation in accordance with observations of ice crystal growth habits (Kobayashi, 1957, and Ono, 1969). The diffusional growth equations are expanded to include the release of latent heat on ice crystals accreting water drops. The mass and heat balance equations are solved iteratively to provide an accurate determination of ambient supersaturation which enters directly into calculations regarding the nucleation processes. The melting of ice particles includes heat transfer by conduction and sublimation.

(iii) Collection processes of liquid-liquid coalescence and liquid-ice accretion, drop breakup and shedding of liquid water from hailstones. The collection processes are formulated according to a "discrete" treatment (which is virtually identical to a proper "stochastic" treatment). Drop breakup is based on the disintegration of large drops following Srivastava's (1971) treatment and a collisionally-induced breakup based on the theory and observations of Brazier-Smith _et al_. (1973). This treatment has been shown to produce a Marshall-Palmer raindrop spectrum (Young, to be submitted for publication). Collection efficiency data for the ice crystal accretion process and details of the process whereby liquid water is shed from hailstones (due to melting and/or accretion) may require new laboratory work.

(iv) Updrafts computed with a simple entrainment law, and initiation and sustenance of downdrafts through water-loading and injection of potentially cold, mid-level air included. As the updraft becomes loaded with water, downward motions are induced. The environmental air at this level is potentially very cold and observationally the air which forms the downdraft. An attempt will be made to model this second branch of the circulation. As with other aspects of the modeling program, the computed updraft structure will be tested against the best available field data.

(2) Takahashi: Responsibility is the development of a two-dimensional, time-dependent framework, concentrating on the dynamics with a more limited, but hopefully still realistic, microphysical treatment than that of Young-Foote. This model will be based in part, on the work of Ogura and Takahashi (1971), and initially will be used to study particle trajectories. Three-dimensional extensions of this work may be attempted, in collaboration with Prof. Y. Ogura of the University of Illinois. Eventually this framework will be merged with the Young-Foote microphysical treatment.

(3) Lilly-Klemp: Working in another part of NCAR, they intend to develop a three-dimensional, time-dependent model of the cloud dynamical processes with highly parameterized microphysics. Much of the effort in this line of development is in formulating a highly efficient computing scheme, both in terms of storage and computational time requirements. Major problems include moving vast amounts of data around in the computer, the proper handling of sub-grid scale processes such as turbulent mixing, and the accurate calculation of advective changes. While it is not expected that this model will be fully developed within the time scale of NHRE, limited experiments of use to NHRE will be conducted.

These programs will be pursued in parallel. The numerical formulations will be compatible, thereby facilitating the eventual incorporation of the Young-Foote microphysics into the Takahashi two-dimensional model and eventually into the Lilly-Klemp three-dimensional model.

This approach is designed not only to produce a relatively sophisticated and comprehensive hailstorm model within the time-frame of NHRE, but also to provide tentative answers to the stated objectives in a continuous sense, i.e., answers will be available prior to and independent of the development of the full combined model that is envisioned. For example, the Young-Foote one-dimensional model will be able to evaluate the relative efficiency of AgI-seeding at cloud base and with rockets internal to the cloud as a function of AgI nucleus size; the Takahashi two-dimensional model will provide knowledge regarding hailstone trajectories, including the possibility of re-cycling, and knowledge relating to formation and growth regions for hailstones within the cloud.

The validity of these models can only be demonstrated through adequate field observations. In this regard, in-cloud sampling of particle spectra, in particular, ice particle spectra resulting from AgI-seeding, are of primary importance. Measurements of CCN activity spectra and ice nuclei spectral data obtained in the inflow region of the hailstorm are required input to the microphysical model. Radar observations such as reflectivity profiles and velocity fields within the cloud will be useful in verifying many aspects of the models.

Verification of the microphysical models will rely largely on comparison with aircraft observations concentrating on certain regions and processes in the cloud. The ability to simulate processes in the cloud regions where they are dominant lends credence not only to the validity of the overall model predictions but also confirms our understanding of the applications (and relative importance) of the theoretical equations involved. A less specific verification of the microphysical treatment can result from calculations of the mean Doppler velocity and its variance. These will be compared to the vertical-incidence and scanning Doppler data which will be available.

e. Resources required: The numerical simulation will require considerable use of the NCAR computers. The complexity of the models to be developed is related to the availability of computer resources; however, an accurate assessment of such resources is difficult to make at this time. A single run of the full two-dimensional model envisioned under NHRE will likely require 2 to 10 hours of CPU time on the CDC 7600. By late 1975, such time requirements will be realized and 10 hours of CPU 7600 time per week is estimated.

In terms of personnel, Dr. Takahashi **joined** the NHRE staff in July 1974. In addition, another Ph.D. position, specializing in cloud microphysics is required. The services of an expert programmer are required to deal with problems associated with data handling and storage, display of model results and related areas. Major tasks would be to design improved numerical techniques to improve the efficiency of the models being developed, allowing the physicists more time to concentrate on physics rather than programming problems. Professor Y. Ogura will serve as a consultant.

f. University and other agency participation: Modeling work will be carried out by Dr. K. C. Young, University of Arizona. Dr. Takahashi plans to consult frequently with Dr. Y. Ogura of the University of Illinois.

g. Possible obstacles and chances for success: The two main obstacles are (1) the development of a realistic model of ice phase nucleation which can be field-verified (both in terms of natural and AgI nucleation) and which depends on laboratory and field measurements in addition to a coherent formulation of these measurements in a theoretical framework and, (2) storage/time limitations on the complexity of the model which may seriously limit the ability to treat the necessary microphysics or dynamics in sufficient detail to be realistic.

To the first of these, the needs of the modeling group are being coordinated with plans of the groups involved with nucleation measurements and observations. The findings of the nucleation groups will have direct input to the formulation of ice phase nucleation processes in the model. Advice as to the relative importance of various nucleation processes will be actively sought.

The basic objectives will, no doubt, be attained over a wide range of credibility. While certainty on all the important points will, no doubt, not be at hand in the next several years, nevertheless, it is felt that the modeling effort will produce useful results pertaining to some or all of these objectives.

h. Schedule:

By July 1975 -- The one-dimensional and two-dimensional, time-dependent models will be operational.

By December 1975 -- Field measurements of ice crystals concentrations produced by AgI-seeding will be available and compared against the microphysical model predictions. It is anticipated that a number of other observations of cloud microstructure will be available for verification purposes.

By July 1976 -- A working, two-dimensional, time-dependent model (x,z,t) will be operational, incorporating the Takahashi dynamical framework with the Young-Foote microphysics.

i. Investigators: Drs. T. Takahashi, G. B. Foote, D. Lilly, and J. Klemp, NCAR; Professor Y. Ogura, University of Illinois*; and Dr. K. C. Young, University of Arizona.

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* Not funded through NHRE.

j. Probable by-products: The one-dimensional model, developed under sub-objective (1) in conjunction with meso-scale and boundary layer models being developed, can and is intended to be used in studying the effects of such things as urban centers, nuclear power plants, smelters, and alteration of land surfaces through strip-mining, in modifying the microphysical structure of convective clouds.

The modeling effort under NHRE can serve as direct input to advanced three-dimensional models incorporating detailed dynamical and microphysical treatments made possible with the next generation of computers, scheduled at NCAR for 1978. Indeed, the formulation of the detailed, one dimensional microphysical model is an essential basis for such an advanced model.

For operational hail suppression, these models can be used to identify the important environmental parameters and prepare nomograms giving the optimal seeding strategy (type and properties of seeding agent and location of injection) as a function of these parameters and based on climatological studies of their magnitude and range for the region of interest. Thus, seeding strategies might be derived for regions other than northeast Colorado.

The two- and three dimensional models are potentially useful in predicting severe storm development such as those producing tornadoes. These, in conjunction with boundary layer and meso-scale models, may also be used to evaluate the dynamical effects of anthropogenic modification of such storms.

k. References:

Brazier-Smith, P. R., S. G. Jennings and J. Latham, 1973: Raindrop interactions and rainfall rates within clouds. Quart. J. Roy. Meteor. Soc., 99, 260-272.

Danielsen, E. F., R. Bleck and D. A. Morris, 1972: Hail growth by stochastic collection in a cumulus model. J. Atmos. Sci., 29, 135-155.

Kobayashi, T., 1957: Experimental researches on the snow crystal habit and growth by means of a diffusion chamber. J. Meteor. Soc. Japan, 35, 38-47.

Ogura, Y., and T. Takahashi, 1971: Numerical simulation of the life cycle of a thunderstorm cell. Mon Weather Rev., 99, 895-911.

Ono, A., 1970: Growth mode of ice crystals in natural clouds. J. Atmos. Sci., 27, 649-658.

Srivastava, R. C., 1971: Size distribution of raindrops generated by their breakup and coalescence. J. Atmos. Sci., 28, 410-415.

Wisner, C., H. D. Orville and C. Myers, 1972: A numerical model of a hailbearing cloud. J. Atmos. Sci., 29, 1160-1181.

Young, K. C., 1973: A numerical simulation of wintertime orographic precipitation under natural and seeded conditions. Ph.D. dissertation, University of Chicago, 202 pp.

__________, 1974: A numerical simulation of wintertime orographic precipitation. Part I. Description of model microphysics and numerical techniques. (Submitted to J. Atmos. Sci.)

2. Numerical Modeling Program - Simple Models to Test Specific Hypotheses

a. Objective: To provide mathematical models which permit the evaluation of conceptional explanations of observational data.

Sub-objectives:

(1) Seek those components of cloud models useful in predicting observed dynamical and microphysical processes in hail and precipitation growth, and their modification or inhibition.

(2) Isolate those simplifications of the physical processes in hail clouds that can eliminate or simplify calculations.

(3) Evaluate the role of electric forces in storm development.

b. Background: A considerable variety of models have been formulated to describe various processes within convective clouds. Pertinent to NHRE are: (1) the axi-symmetric kinematic model of Cannon and Sartor (1973) which shows how particle growth and sedimentation in a prescribed circulation field can lead to high concentrations of ice particles, and (2) the studies of thunderstorm electrification by Paluch and Sartor (1973a,b). In essence, these are examples of the type of models to be developed in response to the objectives listed in (1).

c. Relevancy and schedule priority: These objectives are relevant to the NHRE in helping to understand the role and relative importance of the spatial and temporal variations in cloud microstructure. This pertains directly to proper understanding of hailstorm microphysical processes and is considered to require an early start.

The complex, theoretical models being developed will not normally include such effects as electrical forces, and sub-grid scale variations in dynamical and microphysical structure, but these models can be modified later in the project to examine these effects separately, or less comprehensive models developed to evaluate particular processes.

d. Approach: The approach is essentially theoretical in all of the listed sub-objectives. The theoretical approach, however, will be firmly based on observational fact obtained within the NHRE structure and elsewhere, and will include the results of laboratory studies which have clear extensions to the real atmosphere.

The NHRE observations provide the synoptic, meso-scale and immediate environmental background to complement the cloud data obtained through the use of the sailplane, the T-28 and the radar observations. The present sailplane system does not obtain particle charge and electric field data required for sub-objective (3), but it should be possible to obtain some useful first-order estimates of the role of electric forces from past laboratory and theoretical work.

e. Resources required: The major resource required is the continued support of the present measuring systems, including improved instrumentation. Continued NHRE data collection on the synoptic, meso-scale and vertical scales are also necessary. The availability of computer and programming support is also required.

f. University participation: Interactions with the University of Wyoming and the South Dakota School of Mines and Technology would be desirable, as these organizations are obtaining the type of data which is needed as a basis for the models.

g. Possible obstacles and chances for success: The main problems are the time lag between theoretical advances and corresponding instrumentation and data analyses.

h. Principal investigators: Dr. J. D. Sartor, Dr. T. W. Cannon, Dr. T. G. Kyle, Ms. I. R. Paluch, and Dr. T. Takahashi, NCAR.

i. Probable by-products: The understanding of charge separation mechanisms and cloud electrification will be useful in understanding lightning and its suppression.

Studies of turbulent interactions and sub-grid scale variations in the cloud structure will be useful in evaluating these effects for a wide variety of cloud models.

j. References:

Cannon, T. W., and J. D. Sartor, 1973: Ice phase propagation in developing continental clouds. Proc. Int'l Conf. Nucleation, Leningrad, 24-29 September.

Paluch, I. R., and J. D. Sartor, 1973a: Thunderstorm electrification by the inductive charging mechanism: I. Particle charges and electric fields. J. Atmos. Sci., 30, 1166-1173.

____________, and ____________, 1973b: Thunderstorm electrification by the inductive charging mechanism: II. Possible effects of the updraft on the charge separation mechanism. J. Atmos. Sci., 30, 1174-1177.

NUMERICAL MODELING PROGRAM

Hailstorm Models	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Salaries & Benefits		25,000	54,000	60,000	66,000	72,000	78,000
Materials & Supplies		500	500	500	500		
Travel		2,000	1,500	1,500	2,500	2,000	1,000
Subtotals, Hailstorm Models		$ 27,500	$ 56,000	$ 62,000	$ 69,000	$ 74,000	$ 79,000
University Participation							
South Dakota School of Mines			40,000	40,000	45,000	45,000	45,000
Arizona		22,000	22,000	25,000	30,000	30,000	30,000
Subtotals, University		$ 22,000	$ 62,000	$ 65,000	$ 75,000	$ 75,000	$ 75,000
Totals, Numerical Modeling		$ 49,500	$118,000	$127,000	$144,000	$149,000	$154,000

F. Research Support Program

1. Research Support Program - Data Acquisition and Display System

a. Objective: To provide real-time display of radar data necessary for directing and evaluating research and seeding operations, and to provide storage and subsequent retrieval and reproduction of the data for early analysis.

Sub-objectives:

(1) Complete the programming of the real-time display system that will provide contoured reflectivities of PPI and downrange RHI cuts of storm cells with aircraft track and chaff overlays.

(2) Develop a system for instant time-lapse replay of displays.

(3) Implement the ability to differentiate elements in the displays by color coding.

(4) Provide displays of wind field information from the Doppler radar. (Task already accomplished in Summer, 1974 by new NCAR F.O.F. false color display.)

(5) Provide capability to display hail signals.

(6) Develop software for topographic maps of storm tops.

b. Background: Boardman and Smith (1974) and Suomi (1972) describe meteorological display systems with time-lapse playback. Proposals for prototypes of computer display systems of the current type are described by Chisholm (1970), and an early working model is described by Pranger and Chisholm (1970).

c. Relevancy and schedule priority: PPI contours with aircraft track overlays provide operations directors with a tool for directing seeding and research aircraft to optimum locations in storms. The PPI contour mode of display also assists those making hail day declarations. RHI contour displays with chaff track overlays help locate the echo-free vault and provide information about the trajectory and speed of the updraft. Time-lapse replay is important in observing the past history of a storm for purposes of predicting its future course and obtaining an insight into its development. Time-lapse replays are also an effective means for presenting complex displays such as three-dimensional perspective views of data fields. Hail signal display in real-time will help locate hailshafts and permit the observer to follow their course and possibly predict their future trajectory. Wind field and storm top displays provide further tools for observing the evolution of a storm for aircraft direction and seeding effectiveness. Differentiating different data fields in a display by color is necessary when many different fields are superimposed on one another to form a complex picture. This support is scheduled for early implementation.

d. Approach:

Sub-objective (1): 10 cm signals from the CP-2 radar and aircraft track signals from the DRI M-33 radar are processed through a minicomputer and stored on a disk and on magnetic tape. A second computer retrieves the data from disk, contours it or calculates an aircraft trajectory, converts it to analog signals and sends it to scan converters that make it available to remotely located TV monitors.

Sub-objective (2): Record on video tape or disk relevant displays of storm events. The time history of the events may then be played back through a TV monitor to give a time-lapse view of the process of interest.

Sub-objective (3): Install one or more color TV monitors and superimpose signals from two or more scan converters to different color guns on the monitor.

Sub-objective (4): The mapping of Doppler velocities was successfully accomplished by the NCAR Field Observing Facility in the Summer of 1974 with the installation of a false color display.

Sub-objective (5): Design a radar-computer interface and data base to process hail signal information. Develop software for the hail signal presentation.

Sub-objective (6): Incorporate into existing software a new data base structure that will allow ease in retrieving the necessary data for storm top topographic maps.

Sub-objective (7): Develop the software necessary to integrate the data fields from the hail signal calculator and the 10-cm radar reflectivities into a single coherent display that is amenable to time-lapse playback.

e. Resources required: For the time-lapse replay a video tape or disk system will be necessary ($3,000). For color displays one or more color TV monitors must be added ($1,000 each). The increased rate at which data must be displayed will require a speed up in processing time which can only be effected by a floating point processor ($4,000). New I/O interfaces that must be designed for hail signal inputs will require additional hardware components ($4,000).

f. Other agency participation: Coordination with the DRI M-33 system for aircraft track inputs.

g. Possible obstacles and chances for success: Technology for time-lapse playback and color displays is proven and readily available. The engineering for interfacing with the hail signal processor or 3-cm radar will involve a major effort but will not involve any methodology not already known. The effort will be in evaluating the maximum rate at which data can pass through the computer to determine whether it will be saturated by the massive amount of data if a new computer is not obtained. Programming will also require a large effort. With an additional central processing unit, reflectivity and hail signal displays can probably be achieved.

h. Schedule: For hail signal display, analysis of computer capacity to begin at the start of FY 75. Detailed planning to be completed no later than start of 1975. For color displays and time-lapse playback, implementation to begin end of 1974 field season. Topographical map software to begin start of 1975. Study of implementing 3-D multiple field displays to begin end of 1974 field season.

i. Investigators: Mr. D. A. Morris, Mr. J. H. Merrill, Mr. A. C. Smith; Dr. H. Jordan, University of Colorado.

j. Possible by-products: Technology for a severe storm detection and warning system.

k. References:

Boardman, J. H. and P. L. Smith, Jr., 1974: A computer generated "four-dimensional" graphic display for weather radar data. Bull. Amer. Meteor. Soc., 55, 16-19.

Chisholm, J., 1970: Study of the NECHE Communication and Data Processing System. Progress Reports Nos. 1 and 2. Desert Research Institute, University of Nevada.

Pranger, M., and J. Chisholm, 1970: Digital computer processing of radar reflectivity data. Final Report. Desert Research Institute, University of Nevada.

Suomi, V. E., 1972: MCIDAS - An Interim Report on the Development of the Man-Computer Interactive Access System. Space Science and Engineering Center, University of Wisconsin.

2. Research Support Program - Data Management

a. Objective: To provide a comprehensive integrated multivariate data base of all research and operational data relevant to the analysis of the Suppression Research goals; and to provide associated retrieval and analysis software necessary to meet the analysis requirements of the program.

Subobjectives:

(1) To provide data quality control for mesonet, rawinsonde, aircraft and precipitation data (radar quality control will be maintained within the radar group), basic data processing (mesonet, rawinsonde, precipitation, aircraft and radar data, inventory (all project data), and archival services (all project data).

(2) To develop and maintain with the collaboration of the other scientific personnel an efficient scheme for acquiring, reducing and formatting data and to implement this scheme throughout the field collection periods.

(3) To promote wider use of project data and facilitate data retrieval within a variety of alternative parameter specifications by (a) maintaining up-to-date, thoroughly documented, and readily accessible automated records; (b) by developing software to allow for multidimensional data retrieval combinations, (c) by providing thorough documentation on data availability; and (d) by providing retrieval and analysis assistance for data requested as rapidly and completely as possible.

(4) To develop and maintain a near-real-time multivariate statistical summary and analysis system compatible with all relevant research data.

b. Background: The Data Management Program began in April 1971 with the objective of "cataloging the data." The program gradually evolved to include data quality control, data processing and the responsibility for answering requests for NHRE data. The program is now evolving further toward the development and maintenance of a comprehensive automated system of all relevant research data with the ability to retrieve and perform basic analysis as required.

c. Relevancy and schedule priority: Research is strongly dependent on data accessibility and interchange. If research is to be timely and thorough, taking advantage of all the multidimensional possibilities in the data, retrieval systems must be established and maintained that facilitate the use of the data in as many ways as possible. An aggressive data management program helps ensure maximum and timely research results.

All sub-objectives are receiving immediate emphasis in order to improve the use of research data throughout the program.

d. Approach:

Sub-objective (1): Mesonet charts from the field will be examined weekly by the Data Management group and reduced to digital form compatible with the overall data system. Quality control and edits will be performed routinely. Rawinsonde data will be handled using the scheme outlined by Robitaille and Haagenson (1972). Precipitation data will be recorded on strip charts or 35 mm film and transported to NCAR at regular intervals for digitizing and computer processing. Data inventorying, formatting, and archiving will be performed continually during the field program and cross-referecing of strip charts, punched cards, magnetic tapes, and microfilm containing the same or related data sets will be maintained. Aircraft data will be edited by the Aviation Facility and the participating scientists prior to integration with the other data. All radar data will be put into compressed tape format by the radar group prior to integration.

Sub-objective (2): Data Management staff will be trained to assume full responsibility for the conversion of mesoscale and precipitation data to digital form. Wind charts will be taken to Denver at regular intervals during and immediately after the field program where they will be microfilmed in a standard format. Procedures for the integration of other data into the central data base will be established and managed from this office.

Sub-objective (3): The on-going Data Report series will include a Calendar of Events, an Index of Available Data, and a description of available software. Work on the Calendar will begin during the field program to allow publication and distribution by October of each year. Information about all facets of the data gathering process, formatting and retrieval capability will be maintained for inclusion in the Data Reports.

Standard formatting will not be imposed on the various data collection efforts, but will be a software function. Common data parameters such as location and time are now an integral part of essentially every NHRE data collection system. Retrieval programs will be developed that can merge data from multiple sources and select and accumulate over such parameters as time and spacial location.

Sub-objective (4): Statistical summary programs that are capable of producing the fundamental statistics from any of the data sets such as means, standard deviations, probability estimates for the occurrence of an event, histograms, correlation coefficients for paired data, and elementary regressions and time series analysis are extremely useful and powerful tools for answering preliminary questions in analysis and for checking on instrument and system performance. Comprehensive packages of such programs exist already (e.g., the UCLA BioMed series) and most of the desired routines can probably be modified to NHRE's specific requirements with some ease. Special use programs or analysis programs peculiar to NHRE's needs will have to be developed in-house. However, this is expected to be minor when compared with the overall effort.

e. Resources required: The primary resource required will be programming support. An estimated 3/4 man year of programming support is estimated to bring the data information and retrieval system on line. However, this system when operational will eliminate a large number of singular and frequently redundant efforts. Considerable support from the NCAR Computer Facility Keypunch Group will be needed to process rawinsonde data. A great deal of time on the Bendix Datagrid will be needed to handle mesonet and precipitation network data. Estimates run to 20 man-hours per week for six to eight months.

f. Possible obstacles and chances for success: No major obstacles are expected. The cooperation of project staff and support groups is required for the rapid documentation of experimental events and availability of data sets. Given proper programmer resources the multivariate data base approach should be in operation in six to nine months.

g. Schedule: Reassessment of the total data collection program and the identification of key data elements within each data set to establish a generalized data structure within the fundamental parameters of time and physical location of the event will be accomplished during FY 75. The design of generalized retrieval routines will be started during early FY 75; development of specific data retrieval routines will follow.

A survey of statistical and transgeneration routines will be made in early FY 75 such that the marriage of the various system components should be in the testing stages by the third quarter and available for general use with data from the 1975 field data. Near-real-time data processing will be conducted at NCAR during the summer periods FY 76 through FY 78. This data should be ready at the end of each field system for use within the integrated data system.

h. Investigators: Dr. C. C. Lovell, Mr. F. E. Robitaille, Mr. T. R. Nicholas, Miss B. A. Horner, Mr. C. G. Mohr, Mr. R. L. Coleman, NCAR.

i. References:

Harslem, E. F. and S. Landa, 1973: VIEW: A distributed system for graphical analysis of large data bases. No. P-4972, The RAND Corporation, Santa Monica, California.

Levien, R. E. and M. E. Maron, 1966: A computer system for inference execution and data retrieval. No. RM-5085-PR, the RAND Corporation, Santa Monica, California.

Robitaille, R. E. and P. L. Haagenson, 1972: Catalogue of select 1971 National Hail Research Experiment rawinsonde data. NHRE Data Report No. 71/2, NCAR, Boulder, Colorado.

Sweetland, A. and F. Finnegan, 1969: The RAND/TAC information and analysis system. Volume I--Data collecting and editing, No. RM-5666-PR; Volume II--The analysis programs and procedures, No. RM-5667-PR; Volume III--The analysis design and methods, No. RM-5668-PR; Volume IV--The system software, No. RM-5669-PR. The RAND Corporation, Santa Monica, California.

3. Research Support Program - Aircraft Field Calibration and Intercomparison Program

a. Objective: To provide a means of checking and controlling the quality of aircraft data, and establishing the relative accuracy of the research data among the NHRE aircraft.

b. Background: Proper airborne measurements are very difficult to make. Procedures for the calibration of the instrumentation must include tests under the dynamic conditions of flights. It is well known that previous experiments involving instrumented aircraft have suffered from the lack of such tests. In an experiment such as the NHRE, with several aircraft making similar measurements, it is important for the sake of compatibility to establish the relative accuracy of the observations among the aircraft (Biter *et al.*, 1974).

c. Relevancy and schedule priority: The accurate measurement of temperature, humidity and winds by research aircraft in the vicinity of convective storms is a fundamental part of the NHRE program. Past experience here clearly indicates the high value of the calibration procedures, which fortunately require little additional flight time. Continuous emphasis is required.

d. Approach: Aircraft tower fly-bys are conducted at the beginning, middle and end of the field experiment. Parameters checked by the tower are temperature, moisture (dewpoint), and static pressure. Static pressure is a particularly important measurement because it affects the aircraft true airspeed, which in turn affects the temperature and wind computations. Following the successful completion of the tower fly-bys the aircraft are intercompared at the altitude ranges corresponding to their normal operation in NHRE. Formal intercomparisons are conducted along prescribed tracks with

M-33 radar tracking of the aircraft itself, and chaff released from the aircraft. Routine intercomparisons are conducted among the aircraft on a non-interference basis during actual research missions. A time history of the behavior of the instruments is thus established throughout the summer. The aircraft data is compared by way of means and standard deviations for selected time periods. If an error is detected in the aircraft data an immediate effort is made to correct the problem.

e. Resources required: Aircraft instrumentation and data processing procedures are the same as for standard NHRE dynamics missions. An M-33 tracking radar at Grover is utilized during formal intercomparisons. A 15-m tower (NCAR-owned) located 10 km south of Grover is utilized for tower fly-bys. Tower instrumentation involves a standard Assman-type wet bulb/dry bulb psychrometer and a precision aneroid barometer. Some past difficulties with the reduction of the tower psychrometric data may require other means of measuring dewpoint there (such as a portable frost-point hygrometer, $5,000). All the aircraft data are computer processed.

f. University participation: The University of Oklahoma was funded from 1971-1973 to assist NHRE in the development of the above procedures. NHRE now conducts the aircraft calibration program entirely in-house.

g. Possible obstacles and chances for success: No major obstacles are expected. The importance and value of the program have been demonstrated in the past. Chances of success are high, based on past experience.

h. Schedule: Tower fly-bys at beginning, middle and end of each field experiment. Formal intercomparisons at beginning of each summer, with routine intercomparisons on each dynamics mission throughout the summer.

i. Investigators: Mr. C. J. Biter and Mr. C. G. Wade, NCAR.

j. Probable by-products: The NHRE aircraft calibration program has already demonstrated that not only is it possible to establish the relative accuracy of mreasurements taken from a number of research aircraft, but also that the accuracies can actually be improved through the elimination of biases uncovered in such a program. (Confidence is gained when these biases are shown to arise from demonstrable equipment or calibration problems.) This should have a significant impact on future field experiments in which a number of research aircraft are involved.

k. References:

Biter, C. J., C. G. Wade, A. R. Rodi, 1974: Field calibration and intercomparison of aircraft meteorological systems. Manuscript to be submitted to J. Appl. Meteor.

PROJECT MANAGEMENT AND ADMINISTRATION

	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Project Management							
Salaries & Benefits		$115,000	$123,000	$132,000	$142,000	$143,000	$100,000
Materials & Supplies		1,000	1,000	1,000	1,000		
Travel		16,000	15,000	15,000	15,000	10,000	5,000
Equipment		1,000	1,000	1,000	1,000		
Subtotals, Project Management	$116,000	$133,000	$140,000	$149,000	$159,000	$153,000	$105,000
Administration							
Salaries & Benefits		35,000	37,000	40,000	43,000	46,000	35,000
Materials & Supplies		1,000	1,000	1,000	1,000	1,000	500
Purchased Services							
Insurance		27,000	27,000	30,000	30,000	30,000	
Legal Fees		5,000	3,000	3,000	3,000	3,000	
Other		2,000	2,000	2,000	2,000	2,000	500
Subtotals, Purchased Services		33,000	32,000	35,000	35,000	35,000	500
Subtotals, Administration	$ 46,000	$ 70,000	$ 70,000	$ 76,000	$ 79,000	$ 82,000	$ 36,000
Totals, Project Management and Administration	$162,000	$203,000	$210,000	$225,000	$238,000	$235,000	$141,000

RESEARCH SUPPORT PROGRAM

	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Programming Support							
Salaries & Benefits		$115,000	$125,000	$135,000	$146,000	$157,000	$125,000
Materials & Supplies		500					
Travel		1,000	1,000	1,000	1,000	1,000	
Subtotals, Programming Support	$ 80,000	$116,500	$126,000	$136,000	$147,000	$158,000	$125,000
Engineering and Mech. Labs							
Salaries & Benefits		18,500	20,000	21,500	23,000	10,000	
Materials & Supplies		1,000	1,000	1,000	1,000		
Purchased Services		1,000	1,000	1,000	1,000		
Travel		1,000	1,000	1,000	1,000		
Equipment		1,500	1,000	500	500		
Subtotals, Eng. & Mech. Labs		$ 23,000	$ 24,000	$ 25,000	$ 26,500	$ 10,000	
Data Management							
Salaries & Benefits		31,000	21,500	24,000	26,000	28,000	20,000
Materials & Supplies		4,500	4,500	4,500	5,000	2,500	1,500
Purchased Services		9,500	9,500	7,500	7,500	2,500	1,500
Travel		1,500	1,500	1,000	1,000	500	
Subtotals, Data Management	$ 48,000	$ 46,500	$ 37,000	$ 37,000	$ 39,500	$ 33,500	$ 23,000
Data Acquisition & Display							
Salaries & Benefits		42,200	45,000	48,500	52,500	35,000	
Materials & Supplies		4,300	4,500	4,500	5,000	3,000	
Purchased Services		12,500	14,500	8,000	7,500		
Travel		3,000	3,000	3,000	4,000	3,000	

RESEARCH SUPPORT PROGRAM cont.

Data Acquisition & Display cont.	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Equipment							
Floating Pt. Processor		4,000					
I/O Bus/Switch		2,000					
Video Disc		3,000					
TV Monitor, Color		1,000					
Miscellaneous			10,000	15,000	15,000		
Subtotals, Equipment		10,000	10,000	15,000	15,000		
Subtotals, Data Acquisition & Display	$ 59,000	$ 72,000	$ 77,000	$ 79,000	$ 84,000	$ 41,000	
University Participation							
Desert Research Institute	28,000	24,000	25,000	27,000	28,000	30,000	
Subtotals, University	$ 28,000	$ 24,000	$ 25,000	$ 27,000	$ 28,000	$ 30,000	
Aircraft Operations							
Salaries & Benefits		21,500	23,000	24,500	26,500	15,000	
Materials & Supplies		2,500	2,500	1,500	1,500	1,000	
Purchased Services		10,000	10,000	10,000	12,000	10,000	
Travel		1,500	1,500	1,000	2,000	1,000	
Equipment							
Miscellaneous			1,000	1,000	1,000		
Subtotals, Aircraft Operations	$ 53,000	$ 35,500	$ 38,000	$ 38,000	$ 43,000	$ 27,000	

RESEARCH SUPPORT PROGRAM cont.

Logistics	FY 74	FY 75	FY 76	FY 77	FY 78	FY 79	FY 80
Salaries & Benefits		43,000	46,000	49,500	53,000	29,000	
Materials & Supplies		18,000	18,000	18,500	19,000	10,000	
Purchased Services							
Communications/Utilities		28,500	33,000	35,000	37,000	10,000	
Motor Vehicle Leases		14,000	18,000	18,000	18,000	10,000	
Building and Land Lease		9,000	9,000	9,000	9,000	3,000	
Maintenance		2,500	3,000	3,000	3,000	1,000	
Other		5,000	5,000	5,000	5,000	2,000	
Subtotals, Purchased Services		59,000	68,000	70,000	72,000	26,000	
Travel		1,500	1,500	1,500	1,500	1,000	
Equipment		4,000	2,500	2,500	2,500		
Subtotals, Logistics	$132,000	$125,500	$136,000	$142,000	$148,000	$ 66,000	
Totals, Research Support	$400,000	$443,000	$463,000	$484,000	$516,000	$370,000	$148,000

VIII. Organization and Personnel

A. Organization

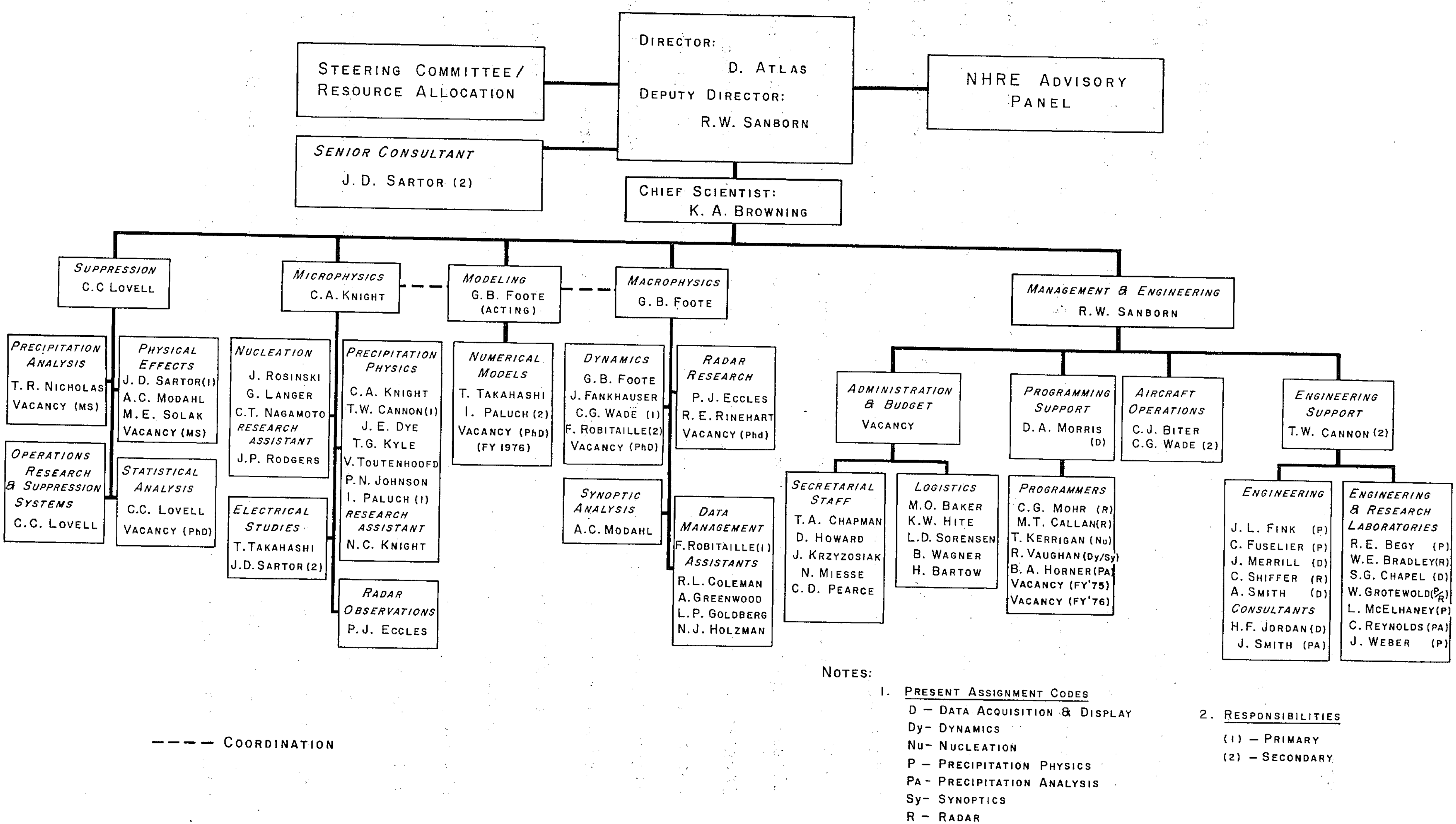
The function of the NHRE management is clearly set out in the NECHE Plan (p. 24). Essentially, it is to plan and direct a large cooperative experiment in hail research involving the participation of a number of university groups, government agencies, private research institutes and industry. In preparation for discharging this function, it has been necessary to appoint scientific, technical and administrative personnel.

The detailed organization of the NHRE staff is presented in Figure 17. This chart shows the names of each staff member along with their assignment in NHRE. This vertical structure was adapted because it provides for closer supervision and review of the various NHRE research and development programs. The pooling of programmers, engineers and technicians provides the means for periodically reviewing work assignments and allows for flexibility in reassigning people to meet high priority demands, thus making more efficient and effective use of these limited resources.

In addition to the staff organization, three other organization charts are included. These depict the NHRE Field Management Organization, Figure 18; the NHRE Field Operations Organization, Figure 19; and the NHRE Coordination and Liaison Responsibilities, Figure 20.

The field management organization chart shows the basic NHRE field management responsibilities for the summer operational period. It shows who is responsible for each major observing system and for those other functions essential to meet the field research objectives.

Figure 17



NHRE STAFF ORGANIZATION

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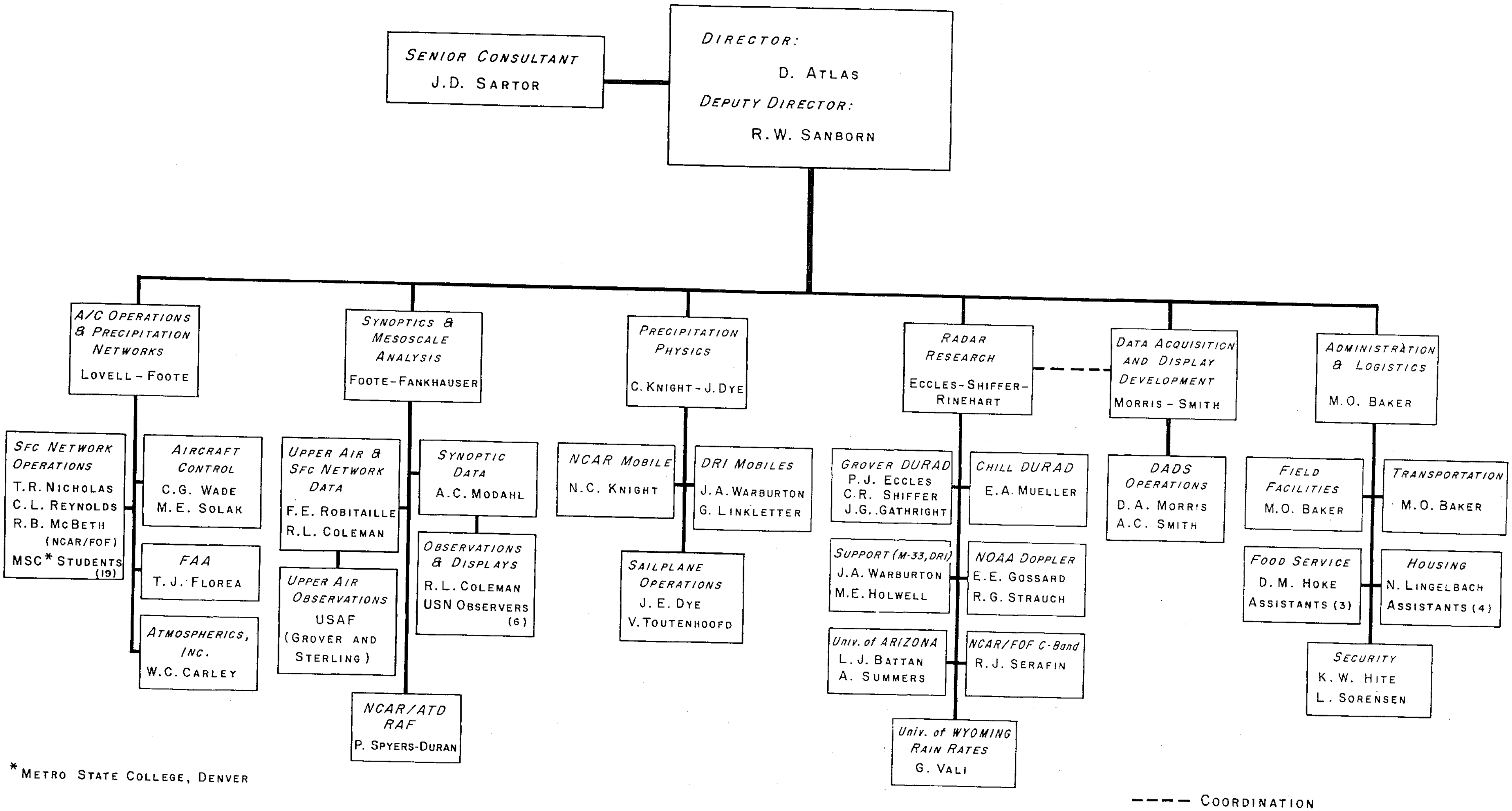
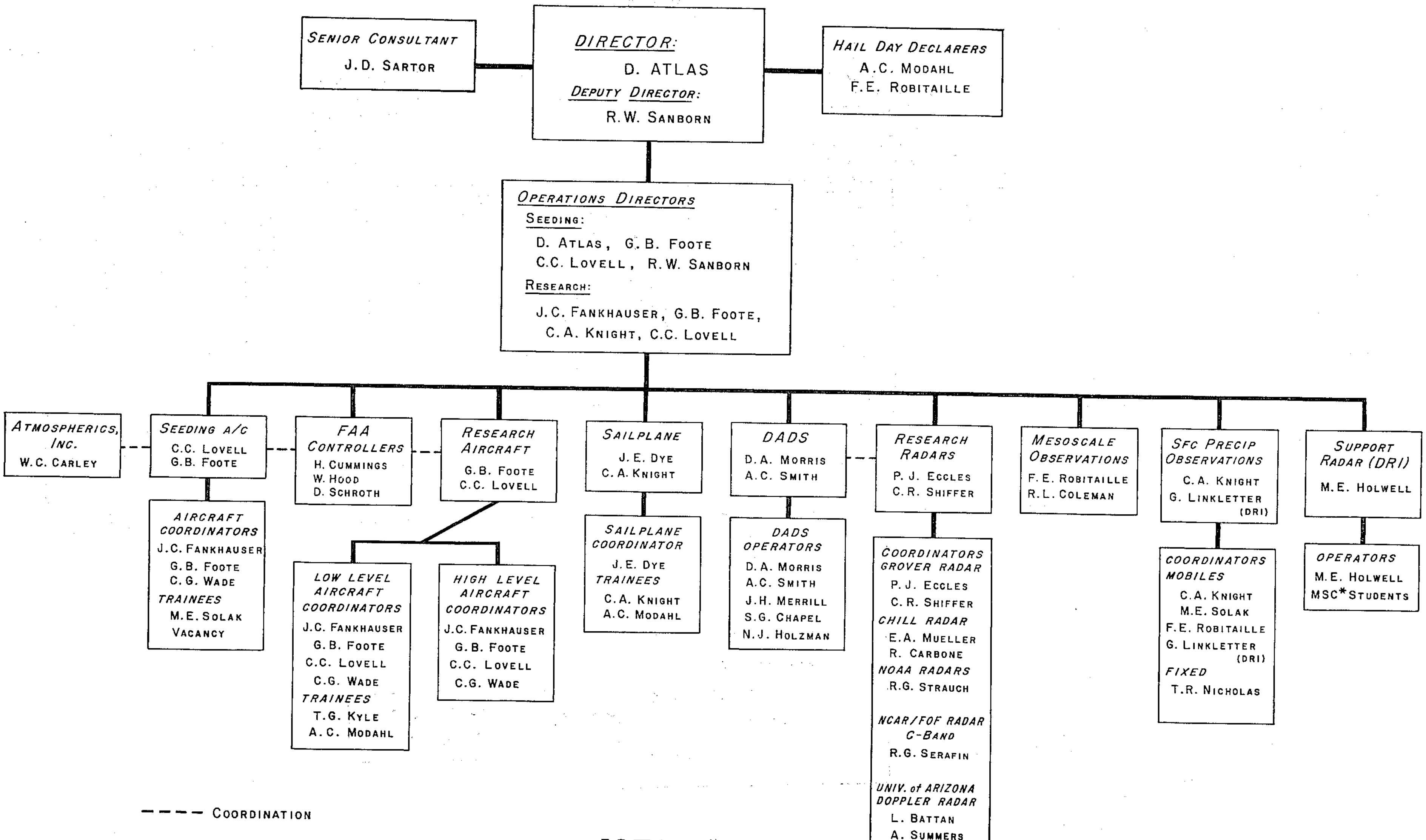
Figure 18



1974
NHRE FIELD MANAGEMENT ORGANIZATION

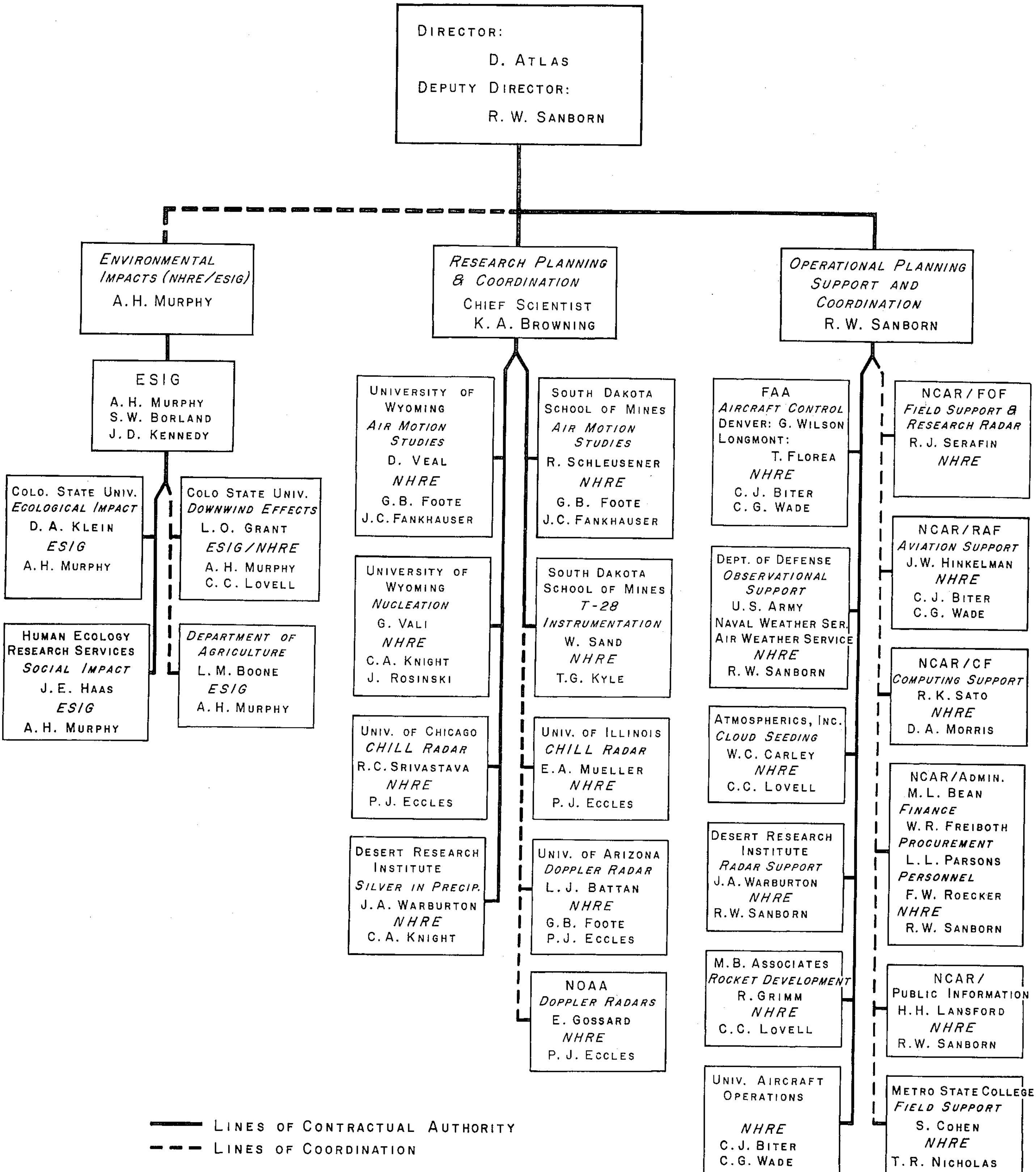
Figure 19



1974

NHRE FIELD OPERATIONS ORGANIZATION

Figure 20



1974

Organization Chart for NCAR, NHRE, Universities, Government Agencies and Commercial Contractors

Figure 19, the Field Operations Organization chart, shows the line of responsibilities during the actual conduct of operations. The direction of operations is carried out from the Grover field site.

The last organization chart, Figure 20, shows the lines of contractual authority and coordination. The NHRE personnel responsible for maintaining contact with the supporting or participating groups is also shown. Table 8 is a list of the key participating university personnel and their areas of contribution to NHRE.

Several committees have been set up to assist the Project Director in assessing how well NHRE is meeting its goals, and to advise him on these and other matters. For example, the purpose of the Citizens' Council on Hail Research is to provide for the exchange of information and a "listening mechanism" by which NHRE can get an assessment on how the residents of northeast Colorado feel about NHRE and hail suppression.

The terms of reference and the present membership of these committees are shown in the paragraphs that follow:

The NHRE Advisory Panel -- Terms of Reference: The function of the Advisory Panel is "to review the current status and future plans for the National Hail Research Experiment, as reported from time to time by the Director, and to make appropriate recommendations."

Membership: Dr. Walter F. Hitschfeld, Dean
Faculty of Graduate Studies and Research
McGill University
P. O. Box 6070
Montreal 101, Quebec, Canada
(514-392-5106)

Dr. Ronald L. Lavoie
NOAA
Room 727, WSC #5
6010 Executive Blvd.
Rockville, Maryland 20852
(202-496-8108)

Dr. Paul B. MacCready, Jr., President
AeroVironment Inc.
660 South Arroyo Parkway
Pasadena, California 91105
(213-449-4392)

Dr. Joanne Simpson, Director
Experimental Meteorology Laboratory
NOAA
P. O. Box 8044
University of Miami Branch
Coral Gables, Florida 33124
(305-350-4498)

Dr. Patrick Squires, Director
Laboratory of Atmospheric Physics
Desert Research Institute
Sage Building, Stead Facility
Reno, Nevada 89501
(702-972-1676)

Statistician (not filled)

Steering and Resource Allocation Committee -- Terms of Reference: The function of the Steering and Resource Allocation Committee (STRAC) is to (1) assist the Director in the critical review of NHRE, (2) specify research objectives, (3) to review the proposed allocation of NHRE resources, including personnel, and (4) to review new research plans and to recommend priorities in case of conflict.

Membership: Dr. D. Atlas
Dr. K. A. Browning
Dr. Peter J. Eccles
Dr. G. Brant Foote*
Dr. Charles A. Knight*
Dr. Thomas G. Kyle
Dr. Douglas K. Lilly
Dr. Clifton C. Lovell*
Dr. Chester W. Newton
Mr. Richard W. Sanborn*
Dr. J. Doyne Sartor

*Group heads are permanent members; remaining positions are rotated between other NCAR personnel.

Table 8

Current University Participants and Their Contributions

University of Wyoming:

D. L. Veal: Direction of University of Wyoming participation.
J. D. Marwitz: Hailstorm dynamics.
G. Vali: Role of ice nuclei in precipitation processes.

South Dakota School of Mines and Technology:

A. S. Dennis: Direction of SDSM participation.
D. Musil: Verification of numerical storm model.
W. R. Sand: Hailstorm structure.

Colorado State University:

P. C. Sinclair: Cloud dynamics and modeling (subcontract ends 30 June 1974).
L. O. Grant: Downwind effects (funded by separate NSF grant).

University of Chicago:

R. C. Srivastava: Application of radar measurements to cloud physics and modeling.

Illinois State Water Survey: (funded by separate NSF grant)

E. A. Mueller: Development of dual-wavelength and Doppler radar and use in the study of thunderstorms for measuring liquid water content and detecting hail.

G. M. Morgan, Jr.: Modeling.

Desert Research Institute:

J. Hallett: Microphysics of hailgrowth (subcontract ends 30 June 1974).
J. Telford: Cloud dynamics (subcontract ends 30 June 1974).
J. Warburton: Operational aircraft tracking radar.
J. Warburton: Precipitation samples and analysis for AgI.

NCAR Environmental and Societal Impacts Group (ESIG):

J. E. Hass, University of Colorado: Social implications of the NHRE.
H. L. Teller, Colorado State University: The disposition and possible environmental impact of silver iodide in the NHRE.
H. J. and R. Taubenfeld, Southern Methodist University (not participating in 1975): Legal and political implications of the NHRE.

Citizens' Council of the NHRE -- Terms of Reference: To provide a channel for the dissemination of factual information and value perspectives to the residents of the area, and to serve as a collection mechanism to funnel information about citizen interest and concerns to NHRE personnel, a "listening mechanism" for NHRE. To be a point of personal contact with the NHRE to the area residents.

Membership: Sherman Blach
Yuma, Colorado 80759
(303-741-2728)

Robert Fritzler
Route 2
Sterling, Colorado 80751
(303-522-1376)

Lester Garner
Great Western Sugar Co.
Box 870
Sterling, Colorado 80751
(303-522-2281)

Clifford Herboldsheimer
Potter, Nebraska 69156
(308-879-4493)

Lloyd Hodges
Julesburg, Colorado 80737
(303-474-2320)

Clarence Jones
Box 617
Fort Morgan, Colorado 80701
(303-867-8276)

Daniel Kinnison
215 East Second Street
Kimball, Nebraska 69145
(308-235-4797)

Ivan Liljegren
1031 10th Street
Sidney, Nebraska 69162
(308-254-4963)

Delmar Nelson
Peetz, Colorado 80747
(303-334-2280)

James Read
Logan County Extension Agent
Federal Bldg., Box 950
Sterling, Colorado 80751
(303-522-3200)

Dale Reimer
Holyoke, Colorado 80734
(303-854-2231)

Dr. Richard Simmons
Box 148
Fort Morgan, Colorado 80701
(303-867-7137)

Walter Younglund
New Raymer, Colorado 80742)
(303-437-2242)

B. Proposal Review Process

Proposals for participation in the NHRE project are encouraged from all members of the university community as well as other groups in NCAR. Such proposals are carefully reviewed on the basis of their potential contribution to the NHRE objectives.

To assess this potential, proposals are examined by members of the NHRE staff, or other NCAR personnel, who have expertise in the study area addressed in the proposal. These reviewers provide the Director of NHRE with their recommendations. After further scrutiny, those university proposals for which NHRE recommends funding are sent to the NHRE Advisory Panel for review and comments, and depending on these, the final decision on acceptance is made.

Proposals which do not satisfy the criteria mentioned above for support by NHRE, but nevertheless have relevance towards further understanding of hailstorms, should be submitted to the NSF.

C. Personnel

A summary of the NHRE staff positions categorized by program is contained in Table 9. The increases for FY 1975 and FY 1976 are discussed in the appropriate parts of Section VI. We have also attempted to reflect in this table reduction in staff as presently planned for FY 1979 and FY 1980. These reductions are reflected in the budgets included in Section VI.

STAFFING COMPARISON BY ACTIVITY

RANN Support Only

	FY 1974	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980
Microphysics	3.5	3.5	3.5	3.5	3.5	3.0	2.0
Macrophysics	6.0	8.0	8.0	8.0	8.0	8.0	5.0
Numerical Modeling	0	1.0	2.0	2.0	2.0	2.0	2.0
Suppression Experiment	4.0	7.0	7.0	7.0	7.0	7.0	4.0
Societal Utilization (ESIG)	4.5	4.5	4.5	4.5	4.5	4.5	3.0
Research Support	12.0	15.0	16.0	16.0	16.0	13.0	5.0
Project Management/Administration	5.5	6.5	6.5	6.5	6.5	6.5	4.0
TOTALS	35.5	45.5	47.5	47.5	47.5	44.0	25.0