DOE/ER-0442

Executive Summary

Atmospheric Radiation Measurement Program Plan

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Foreword

In 1978 the Department of Energy initiated the Carbon Dioxide Research Program to address climate change from the increasing concentration of carbon dioxide in the atmosphere. Over the years the Program has studied the many facets of the issue, from the carbon cycle, the climate diagnostics, the vegetative effects, to the societal impacts. The Program is presently the Department's principal entry in the U.S. Global Change Research Program coordinated by the Committee on Earth Sciences (CES) of the Office of Science and Technology Policy (OSTP).

The recent heightened concern about global warming from an enhanced greenhouse effect has prompted the Department to accelerate the research to improve predictions of climate change. The emphasis is on the timing and magnitude of climate change as well as on the regional characteristics of this change. The Atmospheric Radiation Measurement (ARM) Program was developed to supply an improved predictive capability, particularly as it relates to the cloud-climate feedback.

Scientists from the DOE National Laboratory community contributed to the preparation of the ARM Program Plan with input from members of the academic community, the private sector, and from scientists of other CES agencies. The Plan was subjected to an extensive peer review and the many helpful comments we have received have been incorporated into this document. We believe that ARM will serve the CES objectives in Global Change research and support the DOE mission of formulating a National Energy Strategy that takes into account the potential for global climate change.

Dr. Ari Patrinos, Acting Director
Atmospheric and Climate Research Division

Objective

In order to understand energy's role in anthropogenic global climate change, significant reliance is being placed on General Circulation Models. A major goal of the Department is to foster the development of General Circulation Models capable of predicting the timing and magnitude of greenhouse gas-induced global warming and the regional effects of such warming. DOE research has revealed that cloud radiative feedback is the single most important effect determining the magnitude of possible climate responses to human activity. However, cloud radiative forcing and feedbacks are not understood at the levels needed for reliable climate prediction.

The Atmospheric Radiation Measurement (ARM) Program will contribute to the DOE goal by improving the treatment of cloud radiative forcing and feedbacks in General Circulation Models. Two issues will be addressed: the radiation budget and its spectral dependence and the radiative and other properties of clouds. Understanding cloud properties and how to predict them is critical because cloud properties may very well change as climate changes.

The experimental objective of the ARM Program is to characterize empirically the radiative processes in the Earth's atmosphere with improved resolution and accuracy. A key to this characterization is the effective treatment of cloud formation and cloud properties in General Circulation Models. Through this characterization of radiative properties, it will be possible to understand both the forcing and feedback effects. General Circulation Model modelers will then be able to better identify the best approaches to improved parameterizations of radiative transfer effects. This is expected to greatly improve the accuracy of long-term, General Circulation Model predictions and the efficacy of those predictions at the important regional scale, as the research community and DOE attempt to understand the effects of greenhouse gas emissions on the Earth's climate.

The ARM Initiative and Field Experiment

The Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Program, is a key component of the Department's research strategy to address global climate change. The Program is a direct continuation of DOE's decade-long effort to improve General Circulation Models (GCMs) and provide reliable simulations of regional and long-term climate change in response to increasing greenhouse gases.

The ARM Program is a highly focused observational and analytical research effort that will compare observations with model calculations in the interest of accelerating improvements in both observational methodology and GCMs. During the ARM Program, DOE will continue to collaborate extensively with existing Global Change programs at other agencies, including the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA).

The objective of the ARM Program is to provide an experimental testbed for the study of important atmospheric effects, particularly cloud and radiative processes, and testing parameterizations of these processes for use in atmospheric models. This effort will support the continued and rapid improvement of GCM predictive capability.

The State of the Art

Over the past ten years, the research programs of DOE and other agencies have made significant progress toward understanding the potential for global climate change and the resulting consequences. Rising concentrations of greenhouse gases, primarily carbon dioxide have been well documented. Research programs are determining the relative roles of human activities and natural processes on the land, biosphere, and oceans. Models of the global climate system have advanced to include realistic geography, the annual cycle of the seasons, and varying cloud cover. Very recently, models have begun to include coupling of the ocean-atmosphere system. Results of climate models suggest that projected greenhouse gas emission patterns may lead to a global climate warming of 1.5 to 4.5 degrees Celsius and to significant changes in water availability during the next century.

However, this decade of research has also revealed that considerable uncertainties in model estimates remain. For example, although the 1980s have been especially warm, the extent of global warming over the past century may have been two to three times less than that estimated by current models. Further, when the results of different models are compared, there are substantial differences among their estimates of temperature and precipitation changes in response to doubled carbon dioxide. Significant climate change due to anthropogenic effects may be a plausible conclusion based on current GCMs. However, we do not know with sufficient accuracy how large the climatic changes will be, how rapidly the changes will occur, or how the changes will be distributed over the globe. We also know virtually nothing about the potential changes in the frequency of extreme climatic events.

U.S. Department of Energy Context for ARM

Greenhouse gases directly affect the radiation balance of the atmosphere. Theoretical models predict a net surface warming of the globe from the direct radiative forcing of these gases and, more importantly, the resulting series of feedbacks. These feedbacks directly affect many processes important to climate such as snow cover and sea ice melting, cloud formation, air-ocean interaction, and global circulation patterns. Consequently, a lack of understanding of the complex response of the atmosphere-ocean system to anthropogenic inputs allows much room for uncertainty about the future consequences of continued increases in the atmospheric concentration of greenhouse gases.

Decisions made in the next decade will determine the international response to projected anthropogenic global climate change. GCMs, are the best scientific tool to estimate global climate change and its regional distribution. The results from such models are being used as a basis for formulating national and international policies, which could greatly influence the economies of the United States and the world. Despite their weaknesses, the GCMs are the only tools available to provide the basis for policy formulation. It seems certain that GCMs will remain a part of the scientific basis for policy decisions during the 1990s and beyond. Therefore, it is urgent that the scientific community promote the rapid improvement of the accuracy and predictive capability of GCMs.

The DOE has responsibility for preparing a National Energy Strategy (NES) that fully considers the environmental effects of energy-related activities. The potential climatic and ecological changes that may result from the continuing emissions of carbon dioxide, methane, and other greenhouse gases will be important considerations in forming the most environmentally compatible energy policy.

To address these considerations, the DOE has proposed a three-fold initiative. One element will support the development of specialized GCM computing machines and another will promote the training of a new generation of climate scientists. The third, the ARM Program, will contribute to improved GCM predictions by improving the parameterization of model physics. All three will provide an improved scientific basis for the development of a responsible and appropriate national energy policy.

Science Context for ARM

The interagency Committee on Earth Sciences (CES) has identified cloud-climate interactions as the highest research priority within global change research to produce the needed improvements of GCMs. The ARM Program seeks to supplement ongoing cloud climatology and satellite cloud-radiation projects by contributing critical data and analyses from an intensive measurement and modeling program.

Changes in cloud cover and cloud characteristics, because of their intimate relationship with infrared and solar radiation, are a major factor in determining the magnitude of potential warming resulting from increased concentrations of green-house gases. Also, the accuracy of radiative calculations, including the treatment of clouds, affects the accuracy of estimates of climate sensitivity. Together they control the radiative forcing that drives some of the key feedbacks of the global climate system.

Recent satellite measurements have revealed the magnitude of the effects of clouds on solar and infrared radiation (Ramanathan et al. 1989). The measurements indicate that the global effects of clouds are large. The size of these effects is important in the following sense. Clouds affect both the incoming (solar) and outgoing (infrared) radiation in the atmosphere. Clouds affect the solar radiation by changing the amount of solar radiation that is reflected back to space, an effect which is currently thought to lead to a net cooling. On the other hand, clouds can trap infrared radiation, (the greenhouse effect) and an increase in cloudiness could cause a heating of the troposphere. Current models suggest that the absolute magnitude of these two feedback effects is individually about 10 times the size of the direct radiative forcing due to a doubling of the atmospheric carbon dioxide concentration. The net effect, their difference, is about three times the magnitude of the direct radiative forcing. Small uncertainties in the modeling of cloudiness or cloud properties could produce predicted effects comparable to or larger than the relatively better understood anthropogenic radiative perturbation. Therefore, inferred changes in cloud distribution or properties are critical to understanding the temperature response of the entire system due to increased greenhouse gas concentrations.

Predictions of climatic response to changing greenhouse concentrations are also ambiguous because of uncertainties in estimating radiative forcing. There is a range of about 20% in the estimates of the radiative flux change at the tropopause from a doubling of carbon dioxide concentration among the different radiation models used in GCMs (Luther et al. 1988). There are other significant inaccuracies and disagreements due to inadequate modeling of specific effects within GCMs. Estimates of radiative perturbations due to changing water vapor concentrations and distribution are particularly uncertain. These uncertainties along with uncertainties in our understanding of clouds contribute directly to the differences among GCM estimates of climate sensitivity (Cess et al. 1989; Gates 1987; Wang et al. 1988) and the consequent lack of confidence in GCM predictions at all levels, but particularly on the regional scale.

Limits to the current understanding of radiation and cloud interactions also contribute to many other uncertainties in estimating climate change. Radiative processes create the temperature differences that drive convective cloud-forming processes. These processes generate warm season precipitation, important for agriculture, and much of the cirrus cloud cover that can trap additional infrared radiation. Gates (1987) points out the necessity of properly characterizing major energy fluxes in climate models. This becomes even more critical as model grid resolution is increased to levels needed for regional prediction (~50 km) and when such features as coupled atmospheric and ocean processes are added. As model parameters change, through the addition of new effects or changes in scale, the model physics needs to be modified as well. This is particularly true for radiation and clouds, because of their intimate relationship to the overall energy budget.

Model and data intercomparisons suggest a definite focus for future GCM research. Grotch (1988) has compared GCMs with historical regional climatology and demonstrated that future GCM research needs to improve regional prediction. The failure of the current generation of GCMs to converge on accurate regional predictions is not surprising. Other studies point out that the treatment of the surface energy balance and its relationship to the hydrologic cycle (Wang et al. 1988) and radiative transfer (Luther et al. 1988) are still not adequate. Both of these studies show discrepancies among the models several times larger than the projected anthropogenic radiative forcing functions. In short, the models do not agree among themselves at climatologically significant levels in their treatment of the energy balance. Most importantly, Cess et al. (1989) show that there are significant disagreements among models in their estimates of cloud radiative forcing under closely controlled experimental conditions for the model intercomparisons.

The state of the lowest few kilometers of the atmosphere is the most crucial to determining the surface climate. It is this part of the atmosphere that contains most of the air, water, vapor, clouds, and other critical constituents, and into which man-made pollutants are directly injected. The direction of climate change, cooling or warming, and the degree of change caused by anthropogenic gases in the atmosphere, depends upon the detailed absorption and emission characteristics of the atmosphere. However, the radiative characteristics of the lower atmosphere have never been measured with any great detail; certainly not with the resolution and precision required to assist the development of accurate climate predictions on the regional scale needed from GCMs. The ARM Program results will be combined with results of other DOE programs; NOAA, NFS and NASA programs; and interagency programs, such as the First ISCCP Regional Experiment (FIRE); and others, to specifically meet this important scientific need.

ARM Program Requirements

A decade of research on the performance of GCMs, including several model intercomparison programs, has highlighted important areas of scientific need associated with the understanding and prediction of global climate change. Some of the most important needs fall in the general area of the treatment of physical processes that are not resolved in GCMs, particularly radiative transfer and cloud formation. In these two areas, the following scientific requirements emerge as the most critical for a program designed to remedy key weaknesses of current models:

1. A quantitative description of the spectral radiative energy balance profile under a wide range of meteorological conditions must be developed. Such descriptions must come from field measurements and must be quantified at a level consistent with climatologically significant energy flows of 1 to 2 W/m2

2. The processes controlling the radiative balance must be identified and investigated. Validation of our understanding of these processes must come from a direct and comprehensive comparison of field observations with detailed calculations of the radiation field and associated cloud and aerosol interactions.

3. The knowledge necessary to improve pa-rameterizations of radiative properties of the atmosphere for use in GCMs must be developed. This requires intensive measurements at a variety of temporal and physical scales. A major emphasis must be placed on the role of clouds, including their distribution and microphysical properties.

The above requirements are direct consequences of the sensitivity of atmospheric equilibrium to changes in the radiation field. Current models indicate that if carbon dioxide were to instantaneously double, the outgoing longwave radiation leaving the atmosphere (more precisely, the troposphere) would be temporarily reduced by about 4 W/m2, until the climate system adjusted to restore the balance. Most GCMs suggest that, under these conditions, the globally averaged surface temperature would warm by about 1.5 to 4.5 degrees C before a new climatic equilibrium would be reached.

In addition to the basic sensitivity of the climate system to radiative forcing, the intercomparison studies identify two other important needs for effective modeling of the terrestrial radiation field. First, clouds play a critical role in regulating the flow of both longwave and shortwave radiation within the troposphere. Changes in the distribution and physical characteristics of clouds can have major effects on climate sensitivity. Therefore, it is essential to account for the interaction of clouds and radiation for reliable prediction of climate change.

Secondly, the radiative transfer problem is not simply an energy balance problem. The greenhouse effect is a spectral redistribution process, in which the radiation absorbed by carbon dioxide and other radiatively important trace species is absorbed in particular parts of the spectrum. Carbon dioxide is particularly important in the greenhouse warming process because it absorbs near the peak of the blackbody radiation curve for the atmosphere. The energy absorbed heats the atmosphere, which redistributes the radiation to other wavelengths.

These considerations suggest that a comparison between the radiation field calculated in a model and actual observations of the spectral dependence radiation would constitute a sensitive test of the efficacy of the modeling process. As illustrated in Figure 1, ARM is best viewed as a hypothesis testing approach.

This approach has three elements: a set of measurements of meteorological and other physical conditions that can be used as inputs to a radiative model or a cloud parameterization model; the models being tested, which predict atmospheric features, such as the direction and spectral dependent radiation field or the cloud type and distribution; and a set of measurements designed to confirm the model predictions.

The goals of ARM are two-fold. First, it will attempt to improve the treatment of radiative transport in GCMs for the clear sky, general overcast, and broken cloud cases. Second, it will provide a testbed for cloud parameterization models used in GCMs. The measures of the quality of the models will include their ability to reproduce observed wavelength and direction-dependent fluxes of longwave and shortwave radiation and the time-varying distribution of cloud type and amount. Figure 1 illustrates the ARM experimental approach to the study of the radiation field. That approach, based on meteorological measurements made both to drive models and to confirm their predictions, will use those results to guide improvements in both the measurements and the models.

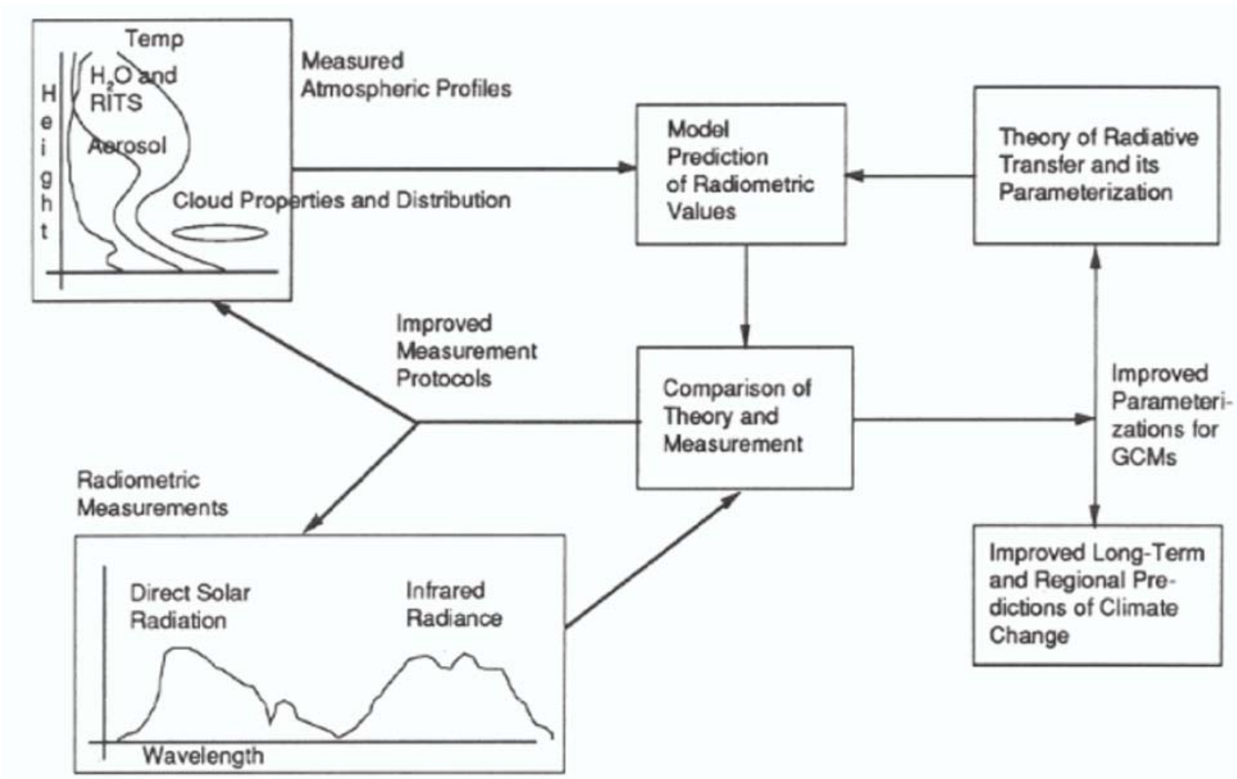

Figure 1. The ARM approach to systematic integration of theory, measurement, and parameterization is shown for the special case of testing models of the radiation field. An analogous approach will be employed by ARM for the study of clouds and cloud models.

Experimental Approach

ARM is an observational program driven by the theoretical and modeling requirements. The ARM Program must provide data that can improve and test the GCM parameterizations of clouds and their microphysical composition. The smallest domain explicitly represented in a GCM is the single grid cell. A GCM cell is orders of magnitude larger than the scale associated with important cloud characteristics. It is possible that over the next decade model resolution will increase substantially so that single grid cells will have dimensions of a few tens of kilometers (comparable to an ERBE pixel). Even so, since clouds can have dimensions less than a kilometer, subgrid parameterization will remain necessary.

Of all the subgrid-scale characteristics that may affect radiation, cloud inhomogeneities and surface albedo variations are most important. Uncertainties in climate models will be reduced substantially when a reliable cloud parameterization is developed that will consistently apply under important mean climate conditions. Data that characterizes the statistics of clouds on a subgrid-scale is necessary for the development of improved cloud models.

In response to the nature of the problem of studying subgrid phenomena, the experimental equipment will be deployed at a series of field settings. These settings will be chosen on the basis of their climatological significance and ability to support a systematic exploration of the performance of radiation cloud parameterization and cloud formation models under a wide range of climatologically significant conditions.

The ARM experiment will consist of coordinated sets of instruments at each of four to six permanent base sites. These sites are the primary experimental resource of CART. Each ARM site will have three closely associated components. Figure 2 shows an artist's conception of an ARM site. Each component is briefly described here:

- **The Central Facility**. A critical experimental task of ARM is to make intensive measurements of the radiation field and the physical conditions that control the radiative transfer. Therefore, ARM will field two classes of equipment at the central facility: those for measuring the radiation field directly and those intended to characterize the local radiative circumstances, such as surface and cloud properties. In general, the base site complement of instruments will include more expensive pieces of equipment, some of which will be experimental in nature. The focus of the observations at the central facility will be the detailed characterization of the atmospheric column above the facility and high spectral resolution radiometric instruments.

- **The Three-Dimensional Mapping Network**. A series of auxiliary stations will surround the central facility within a 20-km radius (this radius was derived from consideration of the scale height of the atmosphere). These stations will contain instrumentation designed to measure the three-dimensional structure of the atmosphere near the base site and will make use of fundamental profiling equipment, as well as basic radiometric and meteorological equipment. A focus of the specialized stations will be the reconstruction of the cloud geometry surrounding the base site using state-of-the-art photogrammetric methods. This cloud "visualization system" will be supplemented with a system of wind profilers capable of measuring large-scale vertical velocities. These observations are critical to the study of cloud parameterization and cloud formation.

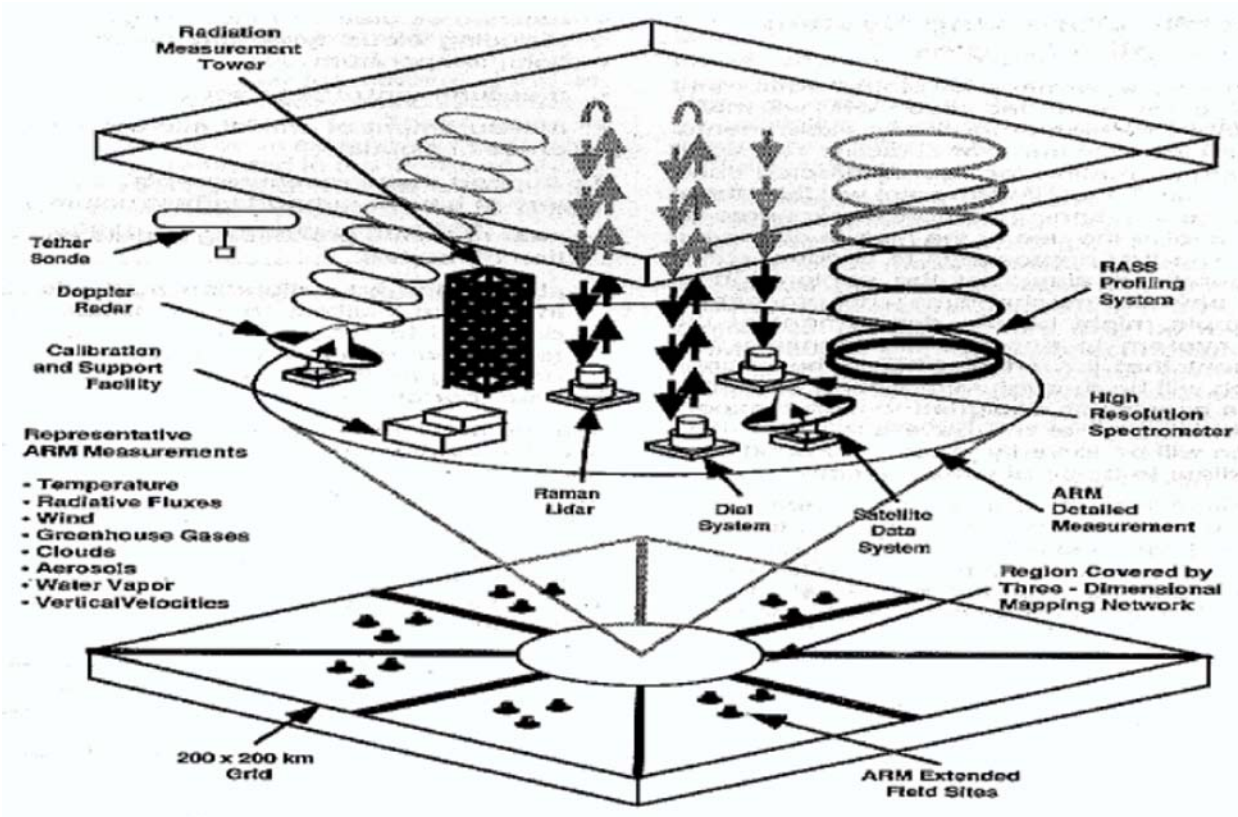

Figure 2. The ARM Experimental Configuration.

An ARM site will have three components as described in the text. The central facility, for which representative equipment is shown, will be supported by a system for mapping the three-dimensional distribution of meteorological variables. In addition, 16 to 25 sets of instrumentation will provide critical data for understanding how to generalize the results to the 200 x 200 km GCM grid size.

- **Extended Observing Network**. Surrounding the central facility and the mapping network will be 16 to 25 extended observing stations. These stations will support the development and study of methods used to generalize detailed atmospheric models for use in GCMs and related models through the process of parameterization.

  The extended observing area of a base site will include a region of the order of magnitude expected for GCM grid cells in the near future, approximately 200 x 200 km. The instrumentation at these stations will be less extensive, less specialized, and capable of more autonomous operation than that at the base sites. The instruments at the extended stations will be designed to collect the basic radiometric information and conventional meteorological data needed to characterize the radiative transfer throughout the extended area. Only limited vertical information will be collected, with the more extensive and demanding profiling equipment reserved for the base sites and mapping stations. Wind profilers will, however, be employed on this scale as well to observe the general vertical motions associated with mesoscale phenomena.

Mobile Observing System and Campaign Studies

In addition to the permanently placed equipment at the base and extended sites, ARM will maintain a mobile version of the basic experimental equipment found at the central facility and additional instrumentation for use in directed campaign studies. The ARM Program will take three approaches to planning campaign experiments that will involve the use of the mobile observing system. The first approach is to conduct short-term operations aimed at the exploration of specific physical mechanisms and processes. An example might be the deployment of the mobile system to support an intensive field experiment that is part of FIRE. The second approach will be through longer-term operation and data acquisition designed to reveal experimental anomalies at the base sites. The third approach will be to verify models for conditions intermediate to those of the base sites.

A campaign may also involve the addition of instruments to the basic instrument suite, for a finite time, in order to achieve a specific scientific objective. Throughout its duration, ARM will encounter a variety of circumstances in which it will be desirable to operate other instruments at the site to specifically supplement the routine data. This might be desirable, for instance, to perform a comprehensive calibration experiment on an experimental instrument or to take advantage of an extraordinary transient climate condition.

Measurement Strategy and Instrument Selection

In order to meet the goals of ARM, the instrument selection must support:

- the measurement of key aspects of the radiation field under a range of climatologically significant meteorological conditions sufficient to constrain detailed radiative calculations
- detailed studies of atmospheric trace gas, aerosol, and water-vapor distributions
- detailed studies of meteorological variables, including cloud type and distribution, wind field, temperature, etc.
- measurement of large-scale vertical velocities
- measurement of critical microphysical properties of clouds.

To support these measurements, it will be necessary to have a support infrastructure with:

- near real-time processing of data and execution of models
- state-of-the-art calibration methods, including onsite calibration at facilities explicitly designed to support the measurement systems and redundant measurement suites providing near real-time evaluation of instrument performance.

The intent of the measurements in ARM is to test the predictive power of the models. The instrumentation will be improved continuously. Specialized research instruments, either developed through this program or by others, may be brought to an operational state and then added to the complement of instruments. Observing protocols may also be changed to increase the quality of the tests. All critical measurements will be systematically replicated. The Science Team will have a critical role in the selection of instruments and their evolution at particular sites. The instrument complement for a specific site may be tailored to individual site characteristics. In spite of these caveats, it is expected that the complement of instruments will look something like the following.

Central Facility Instrumentation

The primary mission of the central facility is the simultaneous measurement of the radiation field and the physical conditions that might control the radiative transfer. The instrument selection emphasizes redundant measurements and varied observing strategies.

In the longwave radiometric regime, four spectrometers have been tentatively identified as likely instruments. These include two inter-ferometers, a grating spectrometer for measuring atmospheric emission and a much higher resolution interferometer for measuring the solar infrared spectrum. The specific list of instruments is shown in Table 1. These types of spectrometers have been extensively field tested and thoroughly presented in the literature and at numerous meetings (e.g., Kunde et al. 1987; Brasunas et al. 1988; Murcray et al. 1984; Murcray 1984; Revercomb et al. 1988).

Table 1. The Spectrophotometric Recommendations for ARM

Instrument	Spectral Range	Resolution
Interferometer #1	5-15 mm	0.02 cm-1
Interferometer #2	4-16 mm	0.3 cm-1
Solar Interferometer	2-20 mm	0.002 cm-1
Grating Spectrometer	8-25 mm	0.5 cm-1

In the visible region, a spectrophotometer will be used for the spectrally resolved observations. If a shadowband spectrometer can be field proven, it will be included in the instrument complement. An automated filter photometer will also be employed to provide a moderate resolution measurement comparable to that obtained using hand-held sunphotometers. It would also be particularly useful if radiometers were included with spectral sensitivity similar to those chosen for use on the Earth Observing System (EOS).

The strategy for the broad-band radiometric instrumentation is to duplicate exactly at the base site the complement of instrumentation selected for the extended sites. This instrumentation will support calibration and facilitate quality control. The radiometric instrumentation at the extended stations are discussed below.

Measurement of the meteorological conditions associated with radiative transfer is one of the principal tasks of ARM. Previous radiation studies have had to rely upon radiosonde or air-craft measurements of temperature, humidity, cloud, and aerosol profiles. However, the atmosphere is sufficiently dynamic that such profiles are rarely compatible with the requirements for modeling radiative processes. Radiation properties change with the instantaneous state of the atmosphere.

Fortunately, recent advances in surface-based profiling technology during the past decade have produced instruments capable of near-instantaneous measurement of vertical profiles. These are generally possible for important variables to altitudes of at least 5 km. In some cases, profiles to 10 km or more may be measured. ARM needs to employ those technologies which have been field-proven and that give the best possible vertical resolution and accuracy.

The proposed complement of profiling systems is as follows:

- Raman Lidar and Differential Absorption Lidar (DIAL): These technologies are chosen to provide humidity distribution data required by the ARM program to parameterize cloud formation and radiation balance (Grant 1990; Wilkerson et al. 1986). They have undergone significant field tests, including ground-based measurements using Raman lidar (Melfi et al. 1989; Melfi and Whitemen 1985), and both ground-based (Browell et al. 1979; Cahen et al. 1982; Grant et al. 1987) and airborne (Browell 1983) studies using DIAL. Both techniques have comparable measurement accuracies for water vapor, i.e., 5 to 10%, for acquiring data from the ground during nighttime, with ranges extending to roughly 7 km. DIAL technology presently is able to produce a profile in about 10 seconds at nighttime, and in about 15 seconds in daytime with roughly the same accuracy and resolution. At night, Raman systems have demonstrated the ability to acquire concentration profile data in several minutes. Practical implementation of daytime Raman lidar, expected in the near term, awaits planned experiments utilizing solar-blind detection combined with powerful XeCl excimer lasers. This system also will speed up nighttime Raman data acquisition. The expected values are roughly several minutes in the daytime and about 5 seconds at night. Both Raman and DIAL systems can achieve desirable range resolutions of about 100 to 200 m.

- Radio Acoustic Sounding System (RASS): The RASS provides good measurement of **virtual temperature**. It is also possible to get **actual temperature** by combining RASS data with humidity data from Raman lidar. ARM plans to field a 400 MHz system with a 300 m to 3 km altitude range and a 50 MHz system with a 2 to 7 km range. The vertical resolution of these systems is 150 meters, with an accuracy better than 0.55C when the vertical wind component is below 0.25 m/sec. Otherwise the system accuracy is 15C. The RASS will also be used in a wind profiling mode to obtain measurements of **wind field and turbulence** information with the same vertical resolution.

- Lidar: The Wave Propagation Laboratory of NOAA and NASA Langley have developed a wide variety of lidar systems for **aerosol and cloud measurements**. At present it is clear that a 10 mm carbon dioxide lidar would be highly desirable. Measurements from this instrument will eliminate the need to extrapolate aerosol properties from the visible wavelength spectra collected by most lidars.

- Tethersonde and tower system: These will provide for in situ **pressure, temperature, humidity, and ozone** measurements up to 2 km. Remote sensing systems are “blind” to the region just above the surface. Most of the radiation in the more opaque spectral bands will be coming from this near-field region. Tower- and sonde-based measurements will be invaluable for filling this data gap and for providing calibration points for the Raman lidar and RASS.

- Satellite data: Since surface based and radiosonde profiling accuracy declines with altitude, satellite retrievals of temperature, humidity, and ozone will be relied on for information above the mid-troposphere.

- In addition to the radiation and related meteorological measurements of ARM, a variety of other measurements will be taken at the central facility. Some of the additional equipment provisions necessary for these are described here.

- Trace gas concentrations: Trace-gas concentrations will be determined from a combination of flask samples and direct real-time sampling using commercial nondispersive infrared analyzers. The solar spectrometer data can be used to infer trace-gas column amounts.

- Surface aerosol concentration: Knollenberg counters, or equivalent, can provide the aerosol data needed to impose an important boundary condition on the aerosol profile. Aerosol lidars, like other profiling systems, have a blind region near the surface.

- Aerosol optical depth and water vapor column amount: A variety of methods will be used to infer these important column densities. One risk associated with these methods, which include sunphotometers and radiometers, is that they rely on knowledge of radiative transfer for calibration and interpretation. Nevertheless, despite the question as to whether these are quantities that should be inputs to the radiative models or predicted by them, the measurements will have very useful corroborative value.

- Routine surface weather observations: It is particularly crucial to have routine data of surface pressure to calibrate the satellite data, which are expressed in pressure coordinates. The central site will duplicate the basic meteorological information available at the extended observing sites, adding appropriate other measurements as required.

Three-Dimensional Mapping Instruments

There are no well-established systems for mapping the three-dimensional structure of the atmosphere in a reasonably automated fashion. An important part of ARM will be an equipment development activity, a major portion of which will focus in this area. The Cloud Lidar and Radar Exploratory Test (CLARET) experiment at the NOAA Wave Propagation Laboratory may provide some guidance for the development of this system. The most desirable solution would be a system based on imaging arrays of devices like charge-coupled devices (CCDs), scanning DIAL systems, dual doppler radar, and wind profilers. A system of this type offers far more automatic data processing options and should be able to take advantage of the many years of development of advanced photogrammetric techniques that have been applied to aircraft and satellite imagery. The quality of instrumentation in this area will have a direct effect on the ARM Program's ability to contribute to the understanding of parameterized cloud formation models.

Extended Observing Station Instrumentation

The extended station instruments will be less extensive than the central facility equipment and must be capable of more autonomous operation. The primary mission of these instruments will be to collect basic radiometric information and conventional meteorological data. There will be only limited vertical information collected.

The ARM selection of extended station instrumentation is motivated by the desire to make the instrument complement as compatible as possible with that of the Global Baseline Surface Radiation Network (GBSRN), a program being designed by John DeLuisi of NOAA for the World Climate Research Program (WCRP).

Instrumentation for the ARM extended observing network will include the basic instrumentation listed for a GBSRN station. The ARM Program will attempt to coordinate its final instrument selection with GBSRN, matching their choice of specific instruments to the greatest extent possible. The only exception is that a rotating shawdowband radiometer will be substituted for the sunphotometer, pending comparison operation and calibration studies. The basic measurements and instrumentation for the extended sites are listed below.

Radiometric measurements and instrumentation will be:

- pyranometers and tracking pryheliometers (several of each, some unfiltered and some filtered)

- pyrgeometer and low-resolution thermal infrared radiometer to cover both sides of the 9.6 mm ozone band (latter provides direct monitoring in the atmospheric “window” regions)

- upward and downward components of solar and longwave infrared radiation (includes longwave net radiometer)

- rotating shadowband radiometer for flux ratios (rotating shadowband spectrometer would be preferred and will be substituted for some of the radiometers if development is successful)

- spectral ultraviolet measurements.

Other instrumentation at the extended sites will be:

- normal complement of weather station measurements such as surface temperature, relative humidity, winds, etc.

- micrometeorological instrumentation for measuring the ratio of latent to sensible heat fluxes

- whole-sky cameras for automatic measurement of cloud amount in coordination with satellite observations

- lidar for measuring cloud ceiling at the site.

Other measurements to be conducted in conjunction with the operation of the network will be:

- routine measurement of surface reflectivity surrounding the sites
- regular soil moisture sampling.

Aircraft-Borne Operational and Campaign Measurements

In addition to the complement of fixed instruments that will be placed at the permanent sites, the ARM research program will require additional instruments that will be used on both an operational and a campaign basis. An important activity at the permanent sites will be the routine overflight of airborne sensors for measuring cloud microphysical properties. As has been described previously, this data will be central to the ARM mission.

The aircraft cloud-microphysics measurements of ARM can be subdivided into two types: primary and secondary. Primary measurements are those that pertain to cloud-physics features that directly influence radiative transfer. Secondary variables are those quantities that directly influence the primary features, but influence radiative transfer only indirectly. ARM will concentrate on the primary cloud-microphysics measurements, and will perform selected secondary measurements as necessary. Key primary and secondary measurements are summarized in Table 2.

Table 2. Aircraft-Based Measurement Systems

Quantity Measured	Candidate Techniques
Part I: Primary Measurements	
liquid water content	heated wire, integrated size spectrum (see below), virtual impactor (see Part II, below)
solid water content	integrated size spectrum (see below), virtual impactor (see Part II, below)
cloud-droplet size distribution	optical probe
raindrop size distribution	optical probe
ice morphology and size distribution	optical array probe, Formvar replicator, foil impactor
Part II: Secondary Measurements*	
thermodynamic properties: temperature, aircraft pressure, humidity (1)	standard research package: resistance thermometer, piezoelectric transducer, mirror hygrometer
aerosol loading and size distribution (2)	optical probe, optical particle counter, electrostaticmobility analyzer
cloud condensation nucleus count (3)	controlled humidity chamber-optical counting device
ice nucleus count (4)	controlled supercooled chamber device
aerosol chemical content (3)	low-pressure impactor
cloud-water chemical content (3)	counterflow virtual impactor

*Flagging convention for secondary measurements is as follows: (1) important and easy to perform; (2) important but moderately difficult or expensive to perform well; (3) important but very difficult to perform well; (4) relatively unimportant. Categories (1) and (2) are recommended for routine application; category (3) is recommended for intensive campaigns, as deemed advisable to specific campaign objectives.

Site Selection

Finally, the site-selection process for ARM will be complicated. The choices must incorporate the optimal combination of characteristics in several areas. The general groupings of the criteria are: climatic significance, appropriate climatic sampling, synergistic potential with other programs, scientific viability, and logistical viability.

The focus of the ARM measurements is the basic physics of GCMs. However, the physics of the atmosphere are not immutable, as in the sense of a physical law. GCMs integrate elements from theory, basic physics, and observation. They are computational tools and, as such, only approximate reality. This approximate treatment is very much at issue in the discussion of the parameterizations used in the models. Therefore, the use of ARM data is not only to confirm the details of the basic physical processes, but to understand what physical processes and effects must be preserved as the problem is solved in the highly unresolved GCM case.

The application of the first two criteria for site selection, climatic significance, and climatic sampling clearly show that multiple sites will be required. The parameterization of clouds in GCMs is so important that it is absolutely necessary to confirm observationally the correctness of those parameterizations in those regions of the globe that are important to climate modeling. More than one region is important. Further, there is sufficient diversity among the climatically important parameters at different sites that no single site can be thought to adequately explore the meteorological envelope and ensure proper parameterization for GCMs.

The critically important choice of sites will be carried out by the Science Team under direction of the ACRD.

Management of ARM

The planned management and organizational structure for the program appears in Figures 3 and 4. The major features of the program's organization are four-fold:

1. Direct management of the Program by the Atmospheric and Climate Research Division (ACRD) of DOE's Office of Health and Environmental Research supported by an Interagency Working Group to ensure close coordination with other agency-led programs such as FIRE, GEWEX, and TOGA.

2. A strong Science Team will set the scientific and intellectual direction of the program. It is made up of two groups. The first, the project scientists, will be selected based on peer review proposals to conduct specific scientific programs with the ARM facilities and data. The second group will be selected by DOE to provide an interface with existing programs both within DOE and other agencies.

3. The Cloud and Radiation Testbed (CART) will serve as the experimental framework and infrastructure within ARM. CART will include fixed experimental sites, a mobile complement of instrumentation, and a series of focused campaigns aimed at particular scientific issues. All elements will be drawn together by a shared data system that will provide ready access to major experimental results for the Science Team and other investigators.

4. An Instrument Development Program will support ARM and the CART in two significant ways, as a place for new and innovative instrumentation to be developed in response to the needs of ARM and as a pathway for instruments developed outside of ARM and DOE to be introduced into the operational ARM environment.

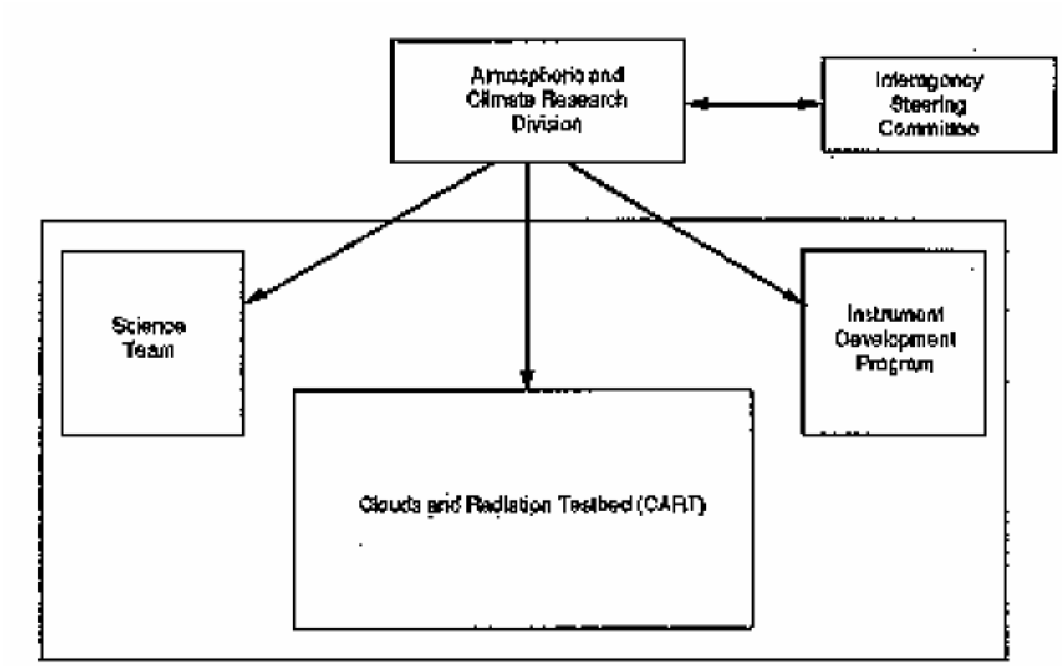

Figure 3. DOE Management Oversight of ARM.

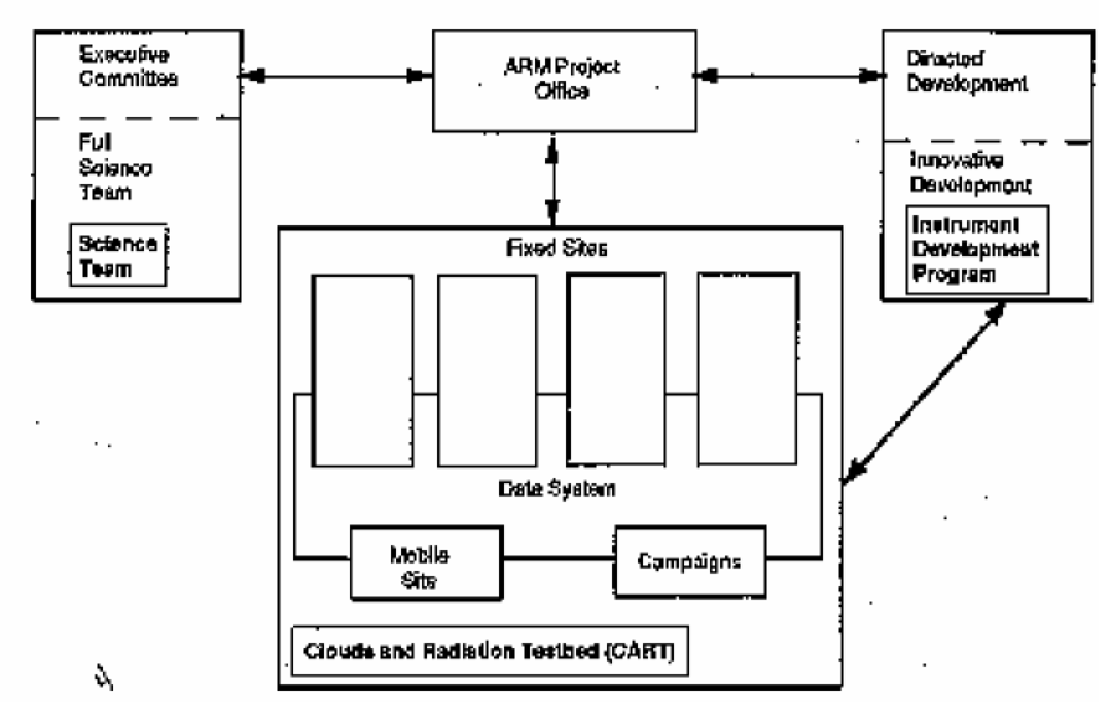

Figure 4. Internal Management of ARM

The three internal elements of ARM, the Science Team, CART, and the Instrument Development Program, will by managed on a day-by-day basis through a project office which will be responsible for the general coordination and scheduling of major ARM activities. Final approval, oversight, and funding authority will be retained by ACRD.

The three elements of ARM will be funded independently by ACRD using a combination of competitive proposals, interagency transfers, and funding to the DOE laboratories. All Science Team research will proceed through a competitive peer review process regardless of the status of the institutional affiliation of the principal investigator, be it university, private industry, DOE laboratory or non-DOE laboratory. The Instrument Development Program will be funded through several processes, including the review of unsolicited proposals, directed development and interagency transfer of funds to obtain the unique capabilities of other government agencies. The funding of the CART will follow a similar plan with overall management provided through the DOE laboratory system. However, individual sites or campaigns may well be operated by universities, other laboratories, or private contractors. The budget for ARM and the associated schedule is shown in Figure 5.

The project office will employ several basic functions to meet its responsibilities.

Specifically these functions will be organized into a series of teams with specific tasks and charters.

- The modeling team will be responsible for the development and maintenance of a set of models to be used for data quality assurance and to serve as a set of “community models” for the Science Team. The selection and design of these models will be conducted under the guidance of the Science Team.

- The instrument teams will be formed by the project office around particular parts of the experimental program. These teams will be formed to ensure integration of particular parts of the experimental program within the program objectives and with the Instrument Development Program. There will be teams associated with the meteorological remote sensing, the radiometric instrumentation, the extended site instrumentation, and data management. The coordination of these teams will be managed by the project office. The goal of these teams is to develop, deploy, and research sites and provide a smooth transition to the groups responsible for operation of the equipment and the data system. The final instrument complement will be approved by ACRD following recommendations from the Science Team and appropriate reviews.

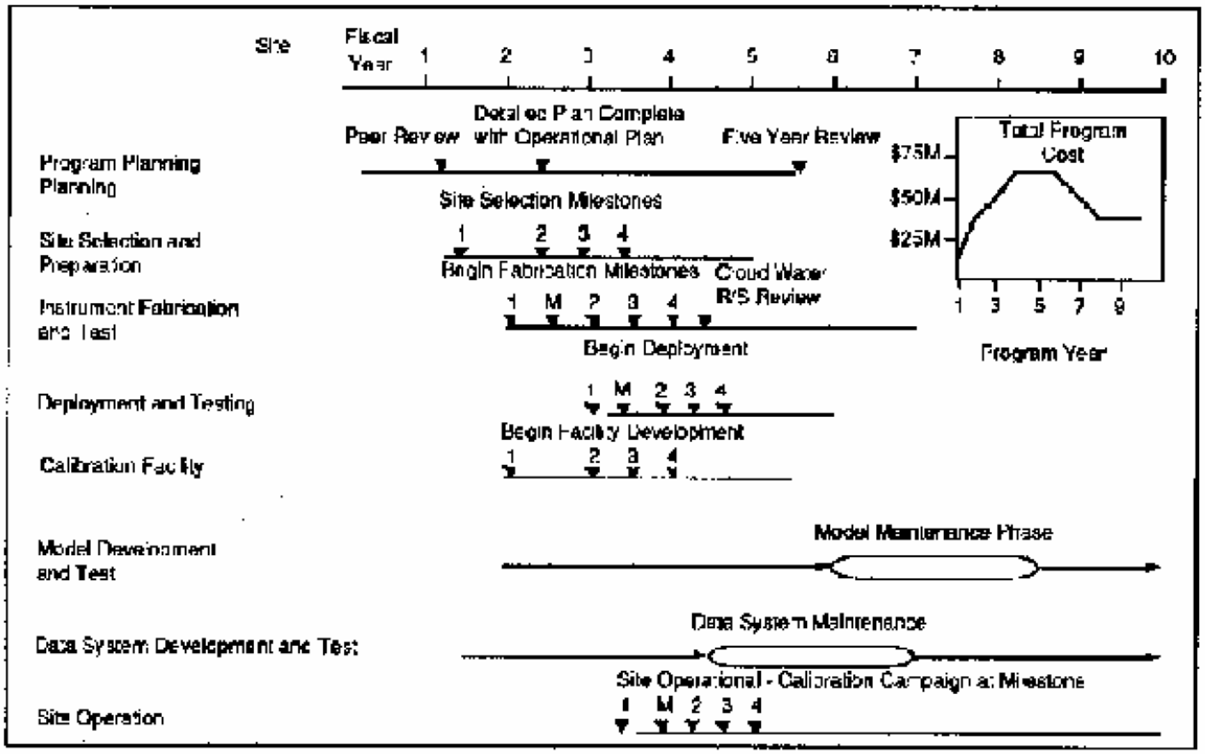

Figure 5. Atmospheric radiation measurement program schedule and budget for four (1 to 4) fixed sites and one mobile (m) site.

- The data management team will be responsible for the design, development, and deployment of the data management and analysis system for the Program. Unlike the operations team, which will be organized around the operation of a particular site, the data management team will have program-wide responsibility.

- The operation teams will be formed by the project office around the management and operation of each individual site and the mobile system. The goal of these teams is to provide for the operation of the individual sites. Responsibility for the operation of individual sites will be determined on the basis of logistical considerations and could be contracted, assigned to a DOE laboratory, or operated by another federal agency.

- Campaign teams will be formed on an ad hoc basis around the conduct of a particular campaign or coordinated activity with another program. The campaign team will be responsible for the development and maintenance of liaison with the operational teams as required to support campaign activities.

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