# Recommendations for a U.S. Ice Coring Program

ad hoc Panel on Polar Ice Coring
Committee on Glaciology
Polar Research Board Commission on Physical Sciences, Mathematics
and Resources
National Research Council

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# Preface

This report presents recommendations from the ad hoe Panel on Polar Ice Coring. The panel was formed under the Polar Research Board's Committee on Glaciology to (1) assess the U.S. scientific capabilities in ice core drilling and core analysis from a national and international perspective; (2) recommend an appropriate balance between capabilities in shallow, intermediate, and deep drilling, based on the most compelling scientific opportunities and realistic assessments of technological problems and available resources; (3) recommend ice core analysis techniques that could advantageously be developed in the United States; (4) recommend an action plan for achieving the desired ice core drilling and ice core analysis capabilities; and (5) set guidelines for the development of policies for international agreements requisite for cooperative ice core programs, drill site selection, and science plan development.

The high scientific importance of ice core drilling and ice core analysis has been emphasized in previous National Research Council reports. The Polar Research Board report Snow and Ice Research: An Assessment (National Research Council, .1 983a) listed the following as highest priority in the field of Quaternary glaciology: a long-term program of ice core drilling in central Greenland for acquisition of long-term environmental and climatic records; a continuous ice core to bedrock at a site in Antarctica to determine the presence or absence of the West Antarctic ice sheet during past interglacials and to provide paleoclimatic data; the comparison of climatic and environmental information contained in ice cores with local or regional meteorological information and historical records of of climatic and environmental changes; and the development of analytical methods to extract information from ice cores related to global anthropogenic pollution, climatic and environmental history, absolute age, and the past configuration and motion of the ice sheet. The Polar Research Board report Research Emphases for the U.S. Antarctic Program (National Research Council, 1983b' juxtaposes polar ice coring against other research areas and recommends that highest priority be given to the extraction of the unique climatic record preserved in the Antarctic ice sheet; a priority reaffirmed in the recent Polar Research Board assessment of U.S. Research in Antarctica in 2000 A.D. and Beyond (National Research Council, 1986a). Similarly, National Issues and Research Priorities in the Arctic (National Research Council, 1985a) identifies ice coring as the first glaciological priority. Ice coring is identified as an important element in the report Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP (National Research Council, 1986b).

This report reaffirms these scientific priorities and makes specific recommendations for achieving a strengthened U.S. ice core drilling program. It assesses our current capabilities to drill and analyze ice cores, and attempts to outline elements of a plan that has the potential to strengthen significantly our ability to conduct scientifically exciting, resource-efficient ice core drilling and analysis.

Johannes Weertman
Chairman

ad hoc Panel on Polar Ice Coring
August, 1986

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# 1.
# Executive Summary

## SCIENTIFIC PROGRAM AND GOALS

Ice and climate are inextricably linked. The major climate variations of the past "ice ages" are characterized by vast advances of ice over the land and sea. Glaciers and ice sheets affect our current climate. In the future, human modification of climate, either purposeful or inadvertent (for example, by C02-induced warming) may cause major changes in the global ice volume and sea level. In addition to its active role in the climate system, ice also contains unique information about past climates. A clear reconstruction of climate history is an essential step toward understanding climate processes and testing theories that can predict future climatic changes.

Polar ice sheets and some ice caps contain ice layered in an undisturbed, year-by-year sequence. The isotopic composition of the ice, the enclosed air, and trace constituents including particles and dissolved impurities provide information about the composition, temperature, and circulation of the atmosphere. In turn these may provide information about other conditions (for example, biological and solar activity) that affect the atmosphere. The recent ice layers contain a record of anthropogenic pollutants such as carbon dioxide, other greenhouse gases, and heavy metals. Ice cores retrieved from depths down to 2000 m in the Greenland and Antarctic ice sheets have revealed variations in these climatic indicators over the last 150,000 years.

Results from ice core analyses have recently revolutionized our thinking about the mechanisms of climatic change. For example, they have revealed that major changes in climate may have occurred very abruptly, perhaps in time scales of only a few decades. This remarkable new information was, and is, obtainable only from ice cores because they can provide high time resolution together with the unique possibility of directly sampling prehistoric atmospheres. These newly discovered rapid oscillations in climate have important relevance to the prediction of our future environment. The relative timing and amplitude of changes in temperature (indicated by oxygen isotopes), atmospheric aerosols (from particulates and soluble impurities), and greenhouse gases (from trapped air) may hold the key to establishing cause and effect in climatic changes.

Climatic changes involve feedbacks between various regions of the globe. Sampling the unique climatic indicators found in ice outside the polar regions in high-altitude ice caps can add to an understanding of the globally coupled climate system. For example, analyses of ice cores from Peru show that El Nino-Southern Oscillation events are recorded in the ice, thereby enabling the reconstruction of El Ni-x1o history. The time interval that can be sampled at such locations is limited to the last several thousand years, but extremely high time resolution allows the seasonal cycles to be determined. Sampling to these ages requires coring down to shallow or intermediate depths of several hundred meters or less.

The ice cores and access to ice sheet interiors provided by drill holes, have also yielded information about the physical properties of the ice. Such knowledge is essential for predicting the future response of the ice sheet to changing climate.

The cores taken to date have barely tapped the potential information that is available. Ice much older than 150,000 years, perhaps approaching one-million years, can be found in Greenland and Antarctica. This very old ice can extend ice paleoclimatic data over several ice age glaciation cycles. Ice cores from additional high-altitude, low-latitude locations can provide an expanded geographical coverage back to one to two thousand years before the present. Improved geochemical measurement techniques, such as dry gas extraction and accelerator mass spectrometry, are expanding the range of measurements that is possible. We can be sure that future developments in laboratory techniques will open new horizons.

Ice coring in both polar regions and available low-latitude sites has been identified as a scientific priority in previous recommendations from the Polar Research Board, primarily because of the major scientific results obtained from ice coring and because of the potential for dramatically advancing them (National Research Council, 1983a, 1983b, 1985a, 1986a).

**This report-endorses these scientific priorities and strongly recommends that the United States**

- **initiate a program of ice coring and analysis over a period of at least 10_years;**
- **obtain high resolution climatic time series, with wide geographical coverage over the last several thousand years by analyses of cores from various depths at many locations in both polar regions and nonpolar regions; and**
- **obtain long-period climatic time series of several hundred thousand years from both polar regions.**

The report examines the current status of ice core research in the United States and recommends specific steps to implement an ice coring and analysis program. Successful execution of such a program requires a number of elements, which must be individually successful and interact with one another with positive feedback loops. The elements may be divided into two groups. The first concerns management to mobilize a talented personnel base and to create a mode of operation that allows personnel to focus their energies productively. The second concerns scientific and technical requirements. The report addresses both of these groups, but gives special attention to the first.

# MANAGEMENT ELEMENTS

## Scientific and Technical Personnel

Requirements: The most essential requirement for a successful ice coring program is talented and capable personnel. Their tasks include arduous field work, complex equipment design, scientific planning, recognition of new scientific problems and their creative solutions, as well as synthesis of the results. Long-term stability of research support is needed in order that personnel can fully commit themselves and focus on the program objectives.

Current Status More than 20 U.S. laboratories have an interest in ice core analysis. They provide a personnel base with substantial technical and scientific strength. In contrast, there are only a few experienced scientists committed to participation in field work to ensure the successful execution of this central step of a coring program. Lack of funding continuity militates against the mobilization of an experienced personnel resource focused primarily on ice core research.

Recommended Steps:

- **Ensure reasonable long-term support for the key scientific and technical elements of ice core research.**
- **Ensure retention of the most capable personnel active in ice core research and promote entrance of new talent.**
- **Promote active participation of senior scientific personnel in the field work when critical ice cores are obtained.**

## Management and Organization

Requirements: A successful ice coring and analysis program requires positive coupling between scientists, engineers, and field personnel to promote development of optional scientific strategies, advanced interpretation techniques, balance between scientific requirements and technical limitations, and wide utilization of ice core data by the scientific community.

Current Status: Funding, operations, and scientific coordination of U.S. ice core research are concentrated in the Division of Polar Programs (DPP) of the National Science Foundation (NSF). Although there is usually coordination through a science plan, research is initiated by proposals from individual institutions operating more or less independently at widely separated geographical locations, In comparison, the strengths of the principal European laboratories arise partly because each has been able to concentrate diverse aspects of ice core research in one unit with strong scientific leadership and positive feedback between capable and committed personnel. There is no standing scientific body responsible for setting directions on ice coring research at either the national or international level in the United States.

**<u>Recommended Steps:</u>**

- **Establish formal organizational connections, between key institutions by encouraging multi-institutional proposals.**
- **Support lead institutions willing to commit themselves to excellence in ice core research and to lead in initiation of multi-institutional efforts.**
- **Locate ice core drill inventory, develop new drills, and store ice core at laboratories with strong scientific programs.**
- **Establish a formal structure such that scientific direction within the United States and negotiation of international programs are determined by a representative segment of the U.S. scientific community.**
- **Promote rapid interactive communication and data transfer between researchers through modern computer-based communication systems and a data management program.**

## SCIENTIFIC PLANNING AND TECHNICAL ELEMENTS

<u>Requirements:</u> <u>Ice coring should proceed in the context of a global scientific strategy that encompasses both polar regions and lower latitudes.</u> This is needed so (that each coring operation adds to the goals of broad geographical coverage and refined or extended time history in an optimum way consistent with available resources.

<u>Current Status:</u> There is an excellent scientific plan for a deep coring program in central Greenland. As yet there are no accepted global or regional strategies, and there is no mechanism to create them with input from a representative segment of the scientific community.

<u>Recommended Steps:</u>
- **Establish responsibility for preparation of global and regional coring strategies, with input from the scientific community.**

### Ice Coring Techniques

<u>Requirements: A dependable and efficient technological base for obtaining ice cores is essential to ice core research.</u> Three classes of ice cores are needed in order to achieve the geographical coverage and time scales required for the scientific programs. These classes are shallow (to about 50 m depth), intermediate (to about 50 m depth), and deep (to 3000 m. or greater depth).

<u>Current Status:</u> The United States has good coring capability to about 300 m depth, but acceptable quality cores cannot be obtained from depths corresponding to pre-Holocene ice, which lies at more than 1000 m in the major ice sheets.

Recommended Steps:

- **Maintain and update the current shallow and intermediate depth core drill inventory.**
- **Modify an existing or build a new intermediate core drill that can operate in a fluid filled hole to improve core quality and extend the accessible depth coverage.**
- **Build a deep drill based on the most current technology.**

## Ice Analysis Techniques

Requirements: Essential laboratory measurements on ice cores include isotope ratios, ionic impurities, microparticles, trace greenhouse gases, and trace elements, as well as various physical properties of the ice. New technologies and new environmental studies undoubtedly will lead to new kinds of measurements. Capacity for large numbers of samples is required to exploit the high time resolution available from ice cores. Onsite processing and analysis of cores are essential first steps before cores are transported to laboratories and repositories.

Current Status: Most of the important ice analysis techniques can be carried out in the United States. However, available capacity is limited and could be easily saturated by successful ice coring. The techniques of dry gas extraction so important for sampling the prehistoric atmosphere are missing in the United States. Onsite core handling and analysis techniques are weakly developed.

Recommended Steps:

- **Maintain current breadth in laboratory capability.**
- **Increase efficiency and through-put rate especially for accelerator mass spectrometry.**
- **Develop dry gas extraction techniques to advance measurement of climatically active gases including carbon dioxide.**

## Related Needs

Requirements: Ice core procurement and interpretation must be supported by thorough ice dynamic and geophysical measurement and analysis for site selection and assessment of ice flow effect on stratigraphy, by a strong logistical base for transport to and from remote locations, and by procedures for storage and distribution of ice cores.

Current Status: The United States has adequate capabilities in these areas.

Recommendations:

- **Update geophysical and ice dynamic measurement methods as new technologies become available.**
- **Promote ice dynamic analysis directed specifically to1ce core research.**

- **0ptimize field operations to minimize transport weight and field time to hold logistical requirements as low as possible.**
- **Adhere to explicit procedures for ice core distribution.**

## RECOMMENDATIONS FOR IMPLEMENTATION

- **The National Science Foundation (NSF), through ''its Division of Polar Programs (DPP), should be the lead agency in funding a new ice Coring and Analysis Program (11CAP),and should manage the program on behalf of the scientific community.**

**The responsibility for providing NSF with scientific and technical Planning and advice in its role as manager Of ICAP should be vested in a new U.S. national body, the Ice Core Working Group (ICWG), composed of active and committed U.S. investigators with multi-institutional representation.** The activities of ICWG must provide the scientific direction and the driving force t-o execute ICAP and include the following specific tasks:

- Develop a global strategy and coring plans for the Arctic, Antarctic, and low-latitude geographical regions.
- Plan for drill development.
- Recommend an appropriate balance between: capabilities in shallow, intermediate and deep drilling.
- Plan for development of advanced geochemical techniques.
- Represent U.S. scientific interests in international planning.
- Interface with other disciplines.

- **The NSF should sequester funds for the support of U.S. ice coring, and seek funds from other agencies concerned with impacts from climatic change.**

- **The United States should coordinate its own effort with those of other nations through a formally constituted international advisory body.**

## ACTION PLAN

<u>Within the first year</u>, the Ice Core Working Group (ICWG) should be established and funding identified within NSF/DPP for a new program of ice core drilling analysis (ICAP). The ICWG should develop the plans identified in its tasks. A call from the NSF for proposals should go out.

<u>During the second year</u>, scientific programs should be started with existing drill technology. Drill development for future scientific programs should also begin.

Beginning in the third year and continuing on a yearly basis, ongoing scientific research and drill technology development should be reviewed by ICWG, with the goal updating the science and engineering plans.

## 2.
## Scientific Motivation for Ice Coring

Ice is a major component of the global climate system. The cycles of glaciations and interglacials arc among the most spectacular and intriguing climatic changes in the history of the Earth. Aside from the age-old scientific quest to understand the causes of ice ages and to predict the next glaciation, the current ice areas are an important part of today's climate. How they were formed, whether they are shrinking or growing, and how they will interact with the coming century's climatic forcings are key questions being asked by those active in the attempt to formulate a quantitative theory of climate.[1]

An understanding of present and future climate will come about only with accurate documentation of the natural experiments of the past. The physical, mechanical and geochemical properties of ice cores provide one of the most detailed and quantitative sources of information for the reconstruction of climate history (Dansgaard and others, 1971, 1984; Oeschger and others, 1984; Lorius and others, 1985).

As snow accumulates on the surface of an ice sheet it preserves information related to atmospheric temperature, which is revealed by measuring oxygen and hydrogen isotopic ratios (Dansgaard and others, 1971). The snowfall also incorporates within its layers solid dust and pollen particles (Thompson and Mosley-Thompson, 198. Petit and others, 1981), ionic components (Davidson and others, 1981; De Angelis and others, 1984; Herron and Langway, 1985), and trace metals (Wolff and Pcel, 1985). The concentrations of these components are related to the wind pattern and conditions on the land and ocean surfaces. For example, these impurities record debris peaks resulting from significant volcanic eruptions (Hammer, 19801, Radioactive isotopes produced by cosmic rays (e.g. 14C, Be,

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[1] Numerous national and international groups have issued statements on the importance of these issues, including many private businesses or foundations (Electric Power Research Institute) agencies of the U.S. government (DOE/EV/10098-5; EPA 230-09-007), and other national governments and international bodies including the United Nations, the International Council of Scientific Unions, International Climate Research Program (ICRP), the World Meteorological Organization, all of which indicate the societal need to understand the ice-covered parts of the Earth.

NAI, and Cl) also become embedded in snow deposits at concentrations that depend on solar activity and geomagnetic variability (Stuiver and Quay, 1980; Oeschger, 1982; Elmore and others, 1982 and 1984). Atmospheric gases are entrapped naturally in glacier ice as air bubbles, providing the only known source of prehistoric samples of atmospheric gases (Stauffer and others, 1985; Rasmussen and Khalil, 1984, Craig and Chou, 1982). The variations in concentration of greenhouse gases such as $C0^2$, methane, and others are of special importance in developing theories of climatic change. All of these many components are deposited and preserved in annual layers and provide a detailed record book of the past.

At many locations, some properties vary on an annual cycle, the variation of which identify the annual ice layers (Hammer and others, 1978, 1985; Thompson and others, 1979; Herron 1982a, b). This imprint may last for thousands of years in some locations. It enables the glacial archives to be read with fantastic detail and provides a means for dating akin to tree rings. On longer time scales the information contained in annual layers is smoothed out, but resolution on the order of decade or century time scales may still persist at ages of more than 100,000 years.

The high time resolution has revealed startling indications of dramatic climatic changes occurring abruptly in the course of a few decades (Stauffer and others, 1985). This possibility has important implications for human activity.

Current theories of climatic change place great importance on the role of anthropogenic pollutants in the atmosphere. Most important are trace greenhouse gases such as CO and methane. It is also important to monitor pollutants such as sulfates and toxic heavy metals (Boutron and Paterson, 1983; Wolff and Peel, 1985). The dispersal of these pollutants through the atmosphere can be studied in the ice sheets and ice caps. Even the very recent ice layers are of interest, because they catalogue the deposition of pollutants in remote places where there are no observing stations. Similarly the ice provides old samples needed to establish natural background levels and variations existing before intervention by major human activity.

Carbon dioxide is now considered to be an especially important anthropogenic pollutant that could affect climate. The well-known rise in $C0^2$ concentration caused by industrialization in the last few centuries is recorded in the ice (Delmas and others, 1980; Neftel and others, 1982, 1985; Raynaud and Barnola, 1985). An important discovery is that a major natural increase in $CO_2$ concentration occurred at or possibly preceding the end of the last glaciation (Stauffer and others, 1985). This observation is important in the quest to predict the climate impact of anthropogenic $C0_2$. Knowledge of the relationship between C02, sea level, climatic conditions, glacier sizes, and other environmental variables is essential to any comprehensive, credible theory of climate.

Methane also has a greenhouse effect. It is produced by biological processes (Rasmussen and Khalil, 1981; Khalil and Rasmussen, 1983a). Analysis of the gas extracted from ice cores has shown that methane concentration started to increase markedly about 200 years ago (Rasmussen and Khalil, 1984). The cause may be related to agricultural practices and population growth. Were there significant natural variations in the past? What were they? These are questions ice coring can answer. Research frontiers exist in the measurement of many other climatically important gases such as the oxides of nitrogen (Khalil and Rasmussen, 1983b) and chlorofluorocarbons.

Extremely old ice lies deep within the Greenland and Antarctic ice sheets. Analyses of core from Vostok, East Antarctica, are currently under way by the French (Lorius and others, 1985). The ice only midway through the total ice thickness is about 150,000 years old. Much older ice can be reached in both polar ice sheets to extend the glacial time series of climatic indicators back over more than one glacial cycle, thus opening the opportunity to make detailed interhemispheric comparisons complementary to those from ocean cores.

Climatic changes occur in a globally coupled system that involves feedbacks on various geographical and time scales. An understanding of climate processes requires a broad geographical picture that can be reconstructed for the past only by means of a wide spectrum of paleoclimatic indicators in the terrestrial, marine, and ice environments. The unique spectrum of geochemical indicators found in ice can be exploited in high-altitude ice caps at lower latitude locations. The ice at these locations is probably limited to a few thousand years old (Swithinbank, 1974; Thompson and others, 1984a), but holds opportunity for contributing to a geographically broad definition of climate fluctuations operating over the shorter time scales, which are of most immediate concern to human activity. Analyses of ice cores from the Quelccaya Ice Cap in Peru have shown that El Nino-Southern Oscillation events are recorded in the ice and a multicentury history of occurrence can be reconstructed (Thompson and others, 1984b, 1985).

Ice cores are needed by glaciologists to understand the dynamics of ice flow based on the physical properties of the ice column and the interface with the bed beneath. Concerns about the stability of ice sheets and the rapidity with which they might change have recently been brought to the forefront in relation to the potential response to C02-induced climatic warming and sea level change (National Research Council, 1985b). Knowledge of the ice flow also contributes to the dating of ice obtained at different levels in a drill hole (Dansgaard and Johnson, 1969) and to interpretation of layer thicknesses in terms of past accumulation rates (Paterson and Waddington, 1985). A parallel effort to model the dynamic history of ice caps and ice sheets is needed to provide a clear reading of the ice core record book.

It is important to note that ice coring activities need to interface with many other disciplines in order to provide the most cost-effective use of research resources across the earth sciences. This is essential to achieve the comprehensive geographic and time coverage that is needed, but also to strengthen interpretation through use of a variety of indicators. For example, in order to prove the tentative identification of a rapid climatic change event in the past (Stauffer and others, 1985), it is important to have evidence for such an event in more than one location or proxy method. A local match of ice core stratigraphy or chemical records with that of a nearby set of offshore deep sea cores could prove invaluable to the interpretation of both sets of proxy records. Lake sediments, deep-sea sediment cores, prehistoric beaches, and glacier moraines are all examples of other sources of proxy information, which are currently used to study the earth's climatic history.

All major efforts to advance the knowledge and predictive capacity of climate-related disciplines have stressed the importance of understanding the active role of ice and of unraveling the extraordinary history of past environments contained in them. Ice coring is the principal means to advance our collective knowledge in these areas.

A new carefully preplanned, comprehensive, and integrated ice core drilling and analysis program is essential. The recent successfully completed Greenland Ice Sheet Program (GISP) at Dye 3, Greenland, is a prime example of what can be accomplished when the full force of modern day glaciological technology is unified into a field and laboratory team effort, as was done by the State University of New York (SUNY), Buffalo, the University of Copenhagen, and the University of Bern (Langway and others, 1985b).

## 3.
## State of Current Effort

### ORGANIZATION

Arctic and antarctic field research is funded primarily through the Division of Polar Programs (DPP) o the National Science Foundation (NSF). Proposals from research institutions are evaluated through peer review, and must be compatible with logistical operations organized by DPP.

The Polar Ice Coring Office (PICO), located at the University of Nebraska-Lincoln, operates under contract from DPP. It conducts shallow and intermediate depth ice( core drilling in Antarctica, Greenland and other high-alpine locations. It is also responsible for providing U.S. logistical support to NSF-sponsored research projects in Greenland. The DPP also supports under contract an ice core storage facility at SUNY, Buffalo, and supports under a research grant a facility for oxygen isotope ratio measurements at the University of Washington, Seattle.

Although the main part of NSF support comes through DPP, additional support for ice core research is possible from other NSF sources when specific goals are directed toward the research of these other NSF programs (for instance, Climate Dynamics in the Division of Atmospheric Sciences). Cold regions research is supported by the U.S. Army Corps of Engineers through the Cold Regions Research and Engineering Laboratory (CRREL) at Hanover New Hampshire. The CRREL was instrumental in the drilling of earlier cores (Camp Century, Greenland, and Byrd Station, Antarctica) but is currently not involved in ice sheet drilling operations. The National Aeronautics and Space

Administration supports a limited number of activities related to remote sensing. Polar research is also supported by the Office of Naval Research (ONR), but no ONR funds have been directed toward ice coring.

Advisory input to DPP/NSF and other agencies may come, upon request, from internal advisory committees and from the National Academy of Sciences/National Research Council (NAS/NRC), through its Polar Research Board (PRB) and Committee on Glaciology. These sources have also provided oversight of specific projects, such as the Greenland Ice Sheet Program (GISP 1) and the Ross Ice Shelf Project (RISP). Scientific input also is received from ad hoc panels set up by DPP, such as the Greenland Ice Sheet Program (GISP-II) panel. However, no standing national body of scientists is responsible for planning and executing an integrated long-term ice coring program.

International organizations, including the Scientific Committee on Antarctic Research (SCAR), the International Council of Scientific Unions QCSU), and the international Commission on Snow and Ice (ICSI), are charged with identifying scientific programs of circumpolar scope and significance. International guidance and advice in areas of drilling and core studies in Antarctica was provided to the United States by SCAR and associated groups, particularly by the International Antarctic Glaciology Program (IAGP) for operations in East Antarctica and through a SCAR subcommittee on Ice Core Drilling. The IAGP, composed of scientific and logistic experts from seven countries, has developed a series of international glaciological research programs in Antarctica. An international program for Glaciology of the Antarctic Peninsula (GAP) has also been encouraged (Swithinbank, 1974). All of these bodies have been concerned with ice coring, but no standing international group advises on the scientific and logistical aspects of ice core drilling.

## ICE CORE DRILLING

Ice core drilling began primarily as a U.S. initiative during the International Geophysical Year (IGY). These efforts culminated in the successful penetration to the bed beneath Camp Century, Greenland (1390 in), in 1966 and Byrd Station, West Antarctica (2164 in), in 1968. These successes initiated the growth of research programs in other countries and the modern era of ice core analysis. The early drills were developed at CRREL (a brief history is given in Appendix A). The deep drill used in the 1960s was irretrievably jammed near the base of the West Antarctic Ice Sheet. In the early 1970s, there was an attempt to replace the lost deep drilling capability with a unique wire-line core drill system. However, this was not successful.

Subsequent development in the United States of coring technology and hardware for drilling to shallow (less than 50 m) and intermediate depths (less than 300 m) has continued with emphasis on light weight and efficiency. These systems have been used advantageously to expand geographical coverage. Unfortunately, the equipment for reaching greater depths has not been replaced in the United States. The current inventory of U.S. ice drills is detailed in Table 2 of Appendix B. These drills are designed, constructed and operated by PICO at the University of Nebraska.

In the last decade, ice drills for all depth ranges have been built in other countries (Holdsworth and others, 1984). At present, drills capable of penetrating ice to depths corresponding to pre-Holocene ice in the interior of big ice sheets exist only in Denmark, France, and the USSR. These drills have been used successfully in Greenland at Dye 3 (Langway and others, 1985b) and in Antarctica at Dome C (Lorius and others, 1979) and Vostok (Lorius and others, 1985). Australia and France are assembling equipment to reach 4000 m depth. These drills include both electrothermal and electromechanical drills, with a variety of design features incorporated in response to the unique requirements of ice drilling. Table I of Appendix B details the current international inventory of ice coring systems as it is presently known to the ad hoc panel.

Ice drilling is an engineering art confronted by conditions not encountered by the rock drilling technology used in hydrocarbon exploration and extraction (Appendixes A and B). Of principal importance is the close proximity of the ice to its melting point with consequences for ice melt, adhesion and creep. This condition makes it possible to use rather simple thermal corers that penetrate by melting the ice. The meltwater must be removed or mixed with a freezing inhibiting fluid. Accumulated experiences, nevertheless, indicate that mechanical techniques of ice drilling are faster and lighter, require less power, and produce higher quality core. The main problem is efficient removal of ice cuttings, which tend to adhere to each other and drill parts.

An important component of ice coring is introduction of fluid into a hole as it is drilled. This provides a pressure balance with the weight of the ice. One purpose is to increase core quality by suppressing fracturing, which is a serious problem in dry hole coring below a few hundred meters depth. Fracturing is fatal for some studies, especially gas measurements. A second purpose is to oppose creep closure of the hole walls. Depending on ice temperature, penetration of a dry hole beyond depths of a few hundred to a maximum of about one-thousand meters is impractical because of rapid closure.

The U.S. CRREL developed the first fluid-filled hole drilling technique in 1958-59 at Little America V. Yet, ice core drills in the current U.S. inventory can be used only in dry holes. Although the intermediate-depth drills could easily penetrate deeper, their useful depth range is limited to about 300 m because of the poor quality of cores from below this depth. Similarly, the restriction to dry-hole coring is a barrier to a stepped development of capability for deep coring below 1000 m depth. The advances in other countries have depended on adopting techniques for fluid-filled holes.

Although there is a variety of core drills fitting into the shallow, intermediate, and deep descriptions, the proven international inventory does not currently meet all the drilling requirements in Greenland and Antarctica. Without modification, existing core drills cannot penetrate to the greatest depths of the ice sheets (e.g., 3000 m or more) or operate at the coldest temperatures (e.g., - 600C). Also, existing drills and those under construction cannot penetrate sub-ice material effectively. It is probable that all requirements cannot be met in a single drill system.

# ICE CORE ANALYSIS TECHNIQUES

The principal geochemical constituents providing proxy climate information include isotopic composition of the ice ( $^{18}0/^{16}\,0$ and $^{2}H/^{1}H$), microparticles (insoluble dust) and soluble impurities (sulfates and other ionic components), heavy metals (Pb, Hg) and enclosed gases (isotopic composition of 02, concentrations of C02, methane, and others), and the isotopic composition of trace elements ($^{14}C$, $^{13}C$, $^{10}Be$, $^{26}Al$, $^{36}Cl$). These constituents also provide means for age dating the ice through identification of annual layering in ice isotopes and impurities, distinct stratigraphic features caused by events dated external to the ice, and the isotopic composition of combinations of trace elements, which change by radioactive decay (Hamn and others, 1978; Herron, 1982a; Oeschger, 1982). Physical and structural measurements on ice cores, including ice texture, rheology, and electrical properties are also important. These are crucial for understanding the flow of the ice sheet and are also related to the geochemistry (Koerner and Fisher, 1979; Herron and others, 1981; Herron and Langway, 1982; Shoji and Langway, 1985). It is particularly important that ice deformation studies be carried out on samples from the crucial region close to the base of the ice.

Capabilities for measuring most of these ice core properties exist in the United States. The major activities are microparticle analysis (Ohio State University), ice chemistry, and mechanical and physical property analysis (SUNY, Buffalo), and oxygen isotope analysis (University of Washington). A listing of U.S. institutions with active or strongly interested researchers is given in Appendix C. The principal missing technique in the United States is dry gas extraction needed for measurement of concentrations of trace gases such as $C0_2$,

Efficiency and capacity are of major importance. A large number of measurements, exceeding the output of the combined laboratories, may be required for certain parameters. The University of Washington has a capacity of 7000 samples per year for oxygen isotopes. Capacities for hydrogen isotopes are much more limited. The microparticle facility at Ohio State University could measure approximately 15,000 samples per year under full-time active operation. SUNY, Buffalo can do multiple ion analysis at about 8000 samples per year. For comparison, the number of samples needing measurement for a thorough examination of a single deep core is in the range 10,000 to 100,000.

Accelerator mass spectrometry (AMS) must play an important role in future ice core research. It is essential for measurement of isotopic composition of the minute amount of trace elements, which are at the forefront of current techniques in ice dating. Measurements can be made at 5 U.S. universities (Appendix Q. However, the sample throughput is far below what is required, because four of these facilities only perform part-time AMS research.

Laboratory facilities for ice core analysis are more highly developed in Europe. A major organizational difference is that the research efforts are concentrated into a few research institutes, the foremost ones being in Copenhagen, Bern, and Grenoble. The capabilities of these institutes involve all levels of ice core research including drill development, field work including coring and sample preparation, as well as diverse laboratory measurements on the ice, and imaginative interpretation of the results. This coordinated concentration of effort and the positive feedback between capable and committed personnel has resulted in very productive ice core research programs, and the principal innovative techniques in the last decade.

With the exceptions of total gas content and $CO_2$ concentration (including $^{13}C$ and $^{14}C$ isotopes), these European labs do not have a broader spectrum of in-lab measurements than that which is available in the United States. However, the Europeans have been able to achieve a high sample analysis rate (including the new AMS techniques) and sharper focus on interpretations. They have been particularly successful in the development of in-field measurements on cores such as solid conductivity (Hammer, 1980) and bulk particulate concentrations (Hammer, 1977). These are important for optimizing field sampling by providing a tentative time scale and quickly isolating the most interesting sections of core. The United States is behind in this area, although there are some notable successes in field analysis of ion chemistry and mechanical properties (Shoji and Langway, 1985; Herron and Langway, 1985).

## ICE CORE STORAGE

The principal ice core repository in the United States is the Ice Core Storage Facility and Information Exchange of the Department of Geological Sciences at SUNY, Buffalo. Information on this ice core repository is contained in Appendix D. This facility is supported by DPP. The Buffalo ice core storage facility is responsible for the storage, cataloging, and redistribution of ice cores obtained under NSF projects in Greenland, Antarctica, and other regions. Eighty percent of the ice cores in this facility are stored in a commercial freezer facility in the Buffalo area with the remainder stored in SUNY, Buffalo facilities. The NSF/DPP contract under which the facility operates specifies the use and distribution of the ice cores. The Buffalo ice core storage facility is an independent unit that is formally separate from the glaciological research programs at SUNY, Buffalo, although there is an overlap of personnel.

Small amounts of core are stored temporarily at other U.S. laboratories where ice core measurements are made.

## LOGISTICS

Ice core drilling in the polar regions requires a strong logistical base for transporting field personnel and supplies, scientific and drilling equipment, fuel and fluid for filling core holes, and the ice core. For deep drilling, the major weights are hole fluid transport to the site and ice core transport from the site.

Major deep drilling operations have relied almost entirely on the logistical base provided by the United States and organized through DPP directly in its Polar Operations Section or indirectly under contract to PICO. One exception is the successful coring at Vostok by Soviet research teams. In this case important measurements on Vostok ice in European labs were made 'possible, in part, by transportation of personnel to the Vostok site by U.S. aircraft.

Shallow and intermediate coring does not require so much transport capacity. Some programs of this scale have been conducted with little reliance on U.S. logistics, as for example by the Australians in Wilkes Land. Additional programs independent of U.S. logistics are probable in the future.

The general perception at both the national and international levels is that major ice core programs in the future can only be carried out with a major logistical contribution from the United States similar to that provided in the past.

## 4.

## Elements of an Ice Coring Program in the United States

### OUTLINE OF REQUIREMENTS

The essential ingredients for a successful ice coring program, together with an assessment of their respective current strengths in the United States, include the following:

- Equipment for obtaining high-quality ice cores from suitable locations, regardless of depth (currently weak for depths exceeding 300 m).
- Capability for logging (moderately strong) and selective on-site analyses of ice cores (weak).
- Capability for laboratory analysis of a broad range of ice core properties (moderately strong).
- Transportation, storage, and distribution of ice cores (moderately strong).
- Personnel with scientific and technical knowledge and motivation who are committed and willing to participate in the field and guide the research to successful completion (inadequate numbers).
- Logistic structure for deploying hardware and personnel to the best drill sites (strong).
- Organizational structure that promotes accessory geophysical and other studies needed for site selection and interpretation of core stratigraphy (strong); coordination of scientific and technological development requirements (weak); international cooperation, which optimizes scientific output (strong); and extensive utilization of the results of ice core studies in associated fields (strong).

The importance and interdependence of these requirements are discussed below; specific steps to strengthen certain areas are recommended.

## ICE CORING CAPABILITIES

The most immediate way the United States can strengthen its ice coring capabilities is to modify existing intermediate ice corers or build new ones to operate in fluid-filled holes. This appears to be the best practical means for achieving good core quality in the intermediate depth range and will extend the usable depth of light weight intermediate coring capability. This approach can proceed without major changes in existing winches, cables, and other surface support, although the use of hole fluid entails additional logistics. It is also the next logical step in the development of a deep drill.

Development of a deep drill in the United States would bring, scientific benefits in much greater proportion than its incremental cost, when scaled by present expenditures in the polar regions. Without a deep drill, the United States will continue to play a secondary role in the study of pre-Holocene ice. The cost of drill development, although substantial, is small compared to the total logistical effort of fielding a deep drilling operation. In this regard, a deep core drill may be regarded as a "logistics vehicle" for access to the interior of the ice sheet similar to transportation vehicles moving on or over the surface of the ice sheet. The cost of the drill should be considered in comparison with these other vehicles. The development of a deep drill would represent a step toward a long range U.S. commitment to ice coring. This would promote a commitment by U.S. laboratories to ice core research and would augment the U.S. scientific contribution to the international effort required in a major coring program.

Drill construction should be based on the most current technology and a thorough assessment of past and present coring experiences in the United States and other countries. Capability should include penetration to the deepest ice in Antarctica. The design should also attempt to incorporate a capability to penetrate moderately dirty ice near the bed at least as well as the current Danish drill, but preferably as well as the drill used at Camp Century (see Appendix B). If it is technically possible, without undue burden of cost to achieve a capability for penetrating sub-glacial material (both consolidated and unconsolidated and frozen and unfrozen), this should be implemented--as long as it does not compromise the drill's overall efficiency and utility for core collection in the ice column. Samples and probes to study the basal zone are needed to study important unresolved questions in ice dynamics.

In view of the scientific and technical coordination required to achieve a balance between scientific requirements and technological limitations, it is important that these drill developments are carried out by a group or groups closely tied to research laboratories and optimally, although not necessarily, to core storage.

## ICE ANALYSIS TECHNIQUES

It is important to update existing U.S. lab facilities to increase the efficiency of ice sample analysis. This should include oxygen isotope analysis, microparticles, and especially accelerator mass spectrometer measurements. The United States should continue to develop capabilities for measurements of gases including chemical and isotopic composition, such as oxygen isotopes of the trapped air (Bender and others, 1979) and climatically active trace gases (Kahlil and Rasmussen, 1983a, b). Ion and trace chemistry, radioactive isotope chemistry and dating, and studies of physical and mechanical properties are also important to promote. There may be other opportunities to exploit.

Dry gas extraction techniques must be developed in the United States. This is essential for study of trace gas concentrations in the prehistoric atmosphere. Recently there has been great focus on the concentration and isotope composition of $C0_2$ in ice core gases. The major contributions have been made by groups in Bern and Grenoble, who have developed methods for the dry extraction of gases from ice (Berner and others, 1980; Delmas and others, 1980; Neftel and others, 1982; Raynaud and Barnola, 1985; Neftel and others, 1985b). While the trends of $C0_2$ concentration with time from ice age to present measured by the two labs are in agreement, there is a disagreement about the preindustrial level. This points to the difficulty of measuring the minute amounts of $C0_2$ trapped in the ice and relating this to the former atmosphere composition. There is a need for additional examination of these problems (see Appendix D). Furthermore, dry gas extraction may open up research frontiers in the study of other climatically important trace gases such as nitrogen oxides and fluorocarbons. It is also important to increase the emphasis upon on-site core handling and measurement techniques and participation in the field work by lab personnel. Initial logging of visible stratigraphy, profiling of solid surface and liquid melt conductivity, and core splitting and packing are essential steps in core recovery. The researchers working in the field effort will naturally have the best access to the core. At the Dye 3 site it has been demonstrated that experimental data on various chemical, physical and mechanical parameters of core ice can be readily obtained in field laboratories (Langway and others, 1985). Development of techniques that allow the most essential information to be gathered on-site without transport of solid core away from the site could promote a major revolution in coring programs because of the consequent reduction in logistics.

## SUPPORTING MEASUREMENTS AND MODELING

A deep core drilling, project must be supported by ancillary measurements and analysis. Foremost among, these supports are those needed for selection of a site with a maximum potential and a minimum of complexities to confound interpretation. It is essential to conduct radar sounding to establish surface, bed, and internal layer geometry; motion measurements to establish flow patterns; and mass balance measurements. These must be at a spatial density much higher than is typical of reconnaissance surveys. The data should be fed into mass and heat flow models to determine what complexities might exist in the subsurface flow and to verify that large amounts of the oldest ice near the bed have not been melted off the bottom. Data from pits, shallow and intermediate depth cores should be gathered from an array of locations around a proposed deep) drill site to establish regional stratigraphic continuity and gradients in relation to current climate.

These necessities have long been recognized and criteria for assessing the suitability of a core site have been carefully considered in detail (Dansgaard and others, 1973; Langway and others, 1985). However, up to now core sites have been chosen primarily by logistical considerations, rather than by optimal scientific judgments. This is to be expected in the difficult circumstances of the polar environment. Some important questions cannot be answered at any existing stations. it is now time to exploit the scientifically optimal sites and design the logistics to make this possible. Because of the immense logistical problems and consequent expense, an orderly, measured schedule should be designed to maximize the information required for final site selection.

Once the large investment has been made to obtain a core, it is important to make as many useful measurements in the borehole as possible. Borehole logging measurements including vertical straining, hole tilting, ice temperature and acoustic and electrical properties all provide important information about the physical state of the ice necessary for understanding the ice sheet dynamics and for remotely sensing its interior and base. These data contribute to the interpretation of the stratigraphy measured in the core, and help identify changes caused by ice deformation. The U.S. capability in these areas is already fairly strong. It needs to be maintained by continued development of advanced techniques.

Ice flow modeling to establish the distribution of finite strain, origin position, and age along the core length is essential. Ice flow and temperature modeling directed specifically at ice core analysis is not highly developed anywhere, but there are productive efforts in a number of countries including the United States. This is an area the United States can easily advance.

## ICE CORE STORAGE

The handling and storage of ice cores is another key element requiring coordination. The physical condition of a core is subject to change with time as a result of stress relaxation upon removal from the depth of the ice sheet, diffusion process when the temperature is near the melting point, and thermo-elastic stressing from temperature cycling of the aggregate of anisotropic ice crystals. These may also have chemical consequences especially if there is microcracking, which provides pathways for escape of sample gases and introduction of contaminants. Strategies for minimizing these effects must be kept in mind.

In some circumstances multiyear on site storage of parts of ice core should be considered. Successful onsite storage would require special procedures to minimize loss of core quality and to maintain accessibility in spite of burial by accumulating snow. From a logistical point of view, onsite storage might be advantageous by allowing an opportune time stepped transport of the massive weight of the ice cores. It would also provide a repository of ice that could be later retrieved without a new coring effort, for example to take advantage of new more advanced measurement opportunities. There is now much valuable ice core stored at Vostok, which is providing a resource for Soviet scientists working in collaboration with the French.

## SCIENTIFIC INTERFACES AND PLANNING

There are important needs for scientific interfaces between ice core researchers and others focusing on paleoclimate data. These interfaces are needed not only for optimum scientific utilization of ice core data, but also to promote development of the most forward looking measurement and interpretation techniques and perspective in scientific planning. For example, a global strategy of ice core drilling, like the strategy involved in deep ocean floor drilling, is required for any large scale ice core program in order to obtain the maximum scientific results. Unlike the situation for ocean floor drillers, the locations of sites available to ice drillers is not almost unlimited. Only a small number of nonpolar ice caps, the relatively small Greenland ice sheet and the much larger Antarctic ice sheet, are available. But even for these ice masses there arc, depending upon the most immediate outstanding scientific questions, very bad choices and very good choices for site locations. These decisions necessarily involve the glaciological community, for example, to assess site suitability in terms of ice dynamics, preservation of stratigraphy, or other factors. However, at any given time the decision about whether to core in Greenland, Antarctica, or nonpolar regions as the next step must be based on a perception on how the results will be integrated into the outstanding problems in climate reconstruction and dynamics.

## MANAGEMENT GUIDELINES

Past U.S. scientific research on ice cores from polar ice sheets has been carried out by individual scientists at different universities and government laboratories. Because of the diverse skills needed for obtaining the maximum information from ice cores, it is realistic to expect that the most qualified researchers on ice cores will always be spread out among a number of institutions. However, a dynamic, integrated scientific interpretation of ice core data is promoted by a close synergistic working relationship between scientists from various disciplines. Strong cooperation between the research scientists, the engineers who develop ice core drilling equipment, and the operators of this equipment is also important. The recent success of Danish and Swiss scientists is in part based on such a closely knit working relationship between people performing these three roles. In these groups some individuals play two or three roles. The fact that some of the U.S. efforts in ice coring have lagged behind those in other countries may in part arise from the splintered approach in the United States.

It is recommended that the future management of the U.S. ice core program be structured so that positive coupling factors are built-in to insure closer interaction between the different investigators as well as between scientists and engineers who have responsibility for drilling operations and drill equipment development.

This may be achieved in two stages.
(1) The first stage is of approximately one- to two- year duration. The operating mode will not be substantially different from the one used at present. A scientific plan (developed from National Research Council committee reports, NSF sponsored workshops, and the like) serves as the basis for invitations for proposals from individual university and government investigators. The best proposals are selected in the customary method by the granting agencies. If necessary, a second call for proposals is then made to ensure, if possible, that important research problems are not neglected.

During this initial stage it is expected that researchers who intend to participate in the ice coring field will develop close working relationships with colleagues at sister institutions. These relationships will be necessary in the second stage.

(2) In the second stage the granting agencies will request multi-institutional proposals. The second stage will start within the second or third year and will continue for the next decade. Although individual proposals will continue, a substantial fraction of the potential research funds will be earmarked for large multi-investigator proposals from a number of institutions. The primary research that will be carried out on ice cores will develop from these proposals. Science committees, both national and international, however, will continue to identify the most important scientific problems and to develop scientific plans for attacking them.

It is anticipated that in the second stage:

- Some institutions will increase their strength in polar ice core research.

- These institutions will become the leaders in developing polar ice core multi-institutional programs. At these stronger institutions, it is hoped that it will become easier for "new blood" to enter the field. The establishment of a capable personnel pool is one of the major requirements of the program. The "leader" institutions might logically develop at those places willing to take on ice core drilling development and the setting up of ice core repositories.

- Senior researchers involved with the analysis of ice cores (at all institutions) will be at field sites during periods when ice cores are first collected and initially examined before being transported to core repositories. This ensures that timely decisions by experienced scientific workers can be made about unexpected opportunities (or to minimize the impacts of setbacks).

Modern computer-based communication systems and a carefully considered data management program can aid greatly in producing a close interaction between researchers at distant locations. This should be exploited to the fullest in order to minimize the problems associated with the geographic spread of institutions in the United

States. This has already been used with substantial benefit for international communication between Bern, Copenhagen, and Buffalo in GISP I.

### INTERNATIONAL COOPERATION

Research institutes outside of the United States have played a major and often dominant role in ice core research in the last decade or more. A strengthening of the U.S. ice coring program will be promoted by continued and increased close interaction with these groups through international cooperation. This may proceed along currently established lines, but with some modification. First, there must be a better mechanism to represent the interests of U.S. scientists. In the past this has been done by the DDP program manager, but such dependence upon a single individual is unwise. Second, while the U.S. must expect to remain the principal provider of heavy logistics in international field efforts, future U.S. funding of the science effort should more strongly emphasize development of scientific capabilities within the United States.

It would be unfortunate if the present, somewhat inadequate, pace at which ice core data are generated by all of the world's scientists were to be significantly slowed because of reduced U.S.-international cooperation and funding. The international community in polar ice coring work has a splendid record for scientific and technical cooperation and funding. The collaborative involvement of SUNY, Buffalo with European labs in every aspect of GISP I is a good example. A strengthened U.S. ice coring program should continue in this tradition. Major ice coring efforts can only be mounted successfully with a multinational effort.

## 5.

## Recommendations for an Ice Coring and Analysis Program (ICAP)

### SCOPE OF THE SCIENTIFIC PROGRAM

1. <u>The U.S. should make a commitment to support a balanced and carefully planned program of ice coring and core analysis over a period of at least 10 years.</u> This length of time will be needed, first, to develop an appropriate management structure, scientific plan, engineering capability, and manpower pool; and second, to mount field and laboratory efforts adequate to realize the major scientific opportunities now in sight.

2. <u>Drilling for this program should penetrate high-latitude ice sheets in both polar hemispheres as well as selected low-latitude ice masses</u>. Such a broad geographic coverage is needed to define how climate has changed over the past several hundred thousand years, and to provide a basis for understanding the physical and biological processes that accompanied those changes.

3. The program should obtain records of ice properties and climatic parameters from an appropriate distribution of shallow, intermediate, and deep ice cores. Because different climatic processes operate on different time scales, records of different lengths are needed to understand and predict the course of climate and human impact on it.

4. Within each depth category, the drilling phase of the program should be carefully planned to obtain, archive, and distribute a sufficient number of cores to address the outstanding scientific questions. Because the processes by which ice accumulates are complex, the first question to be asked of each core record is the degree of stratigraphic continuity. This question can only be answered by obtaining and studying more than one core from each study area. Once an observed change is shown to result from climatic processes rather than noise in stratigraphic processes, the second question to be defined is the geographic scale of the phenomenon. Our ability to answer this question will depend primarily on the number and spacing of drilling sites within each depth category.

5. The United States should maintain a state-of-the-art technology and continue to improve it to drill shallow. intermediate, and deep ice cores, while continuing to contribute its expertise to an international effort. Because the scale of the drilling program required to accomplish ICAP goals is large, and the expense of the operations substantial, no nation can reasonably be expected to accomplish these goals by itself. A cooperative, international program is clearly required to accomplish ICAP. The United States should play its proper role in this international effort, not only with an appropriate contribution to logistics, but also with scientific apparatus that ensures direct access by U.S. scientists to core material.

## RECOMMENDATIONS FOR IMPLEMENTATION

1. The National Science Foundation (NSF), through its Division of Polar Programs (DPP), should be the lead agency in funding, the new ice coring and analysis program (ICAP) and should manage the program on behalf of the scientific community.

2. The responsibility for providing NSF with scientific and technical planning and advice in its role as manager of ICAP should be vested in a new U.S. national action group, the Ice Core Working Grout) (ICWG). By drawing on the knowledge and experience of members of the international community of scientists and engineers, it is envisioned that ICWG would provide the driving force for a vigorous U.S. activity in ice coring and analysis.

To some extent, the model for the management structure recommended here was taken from the highly successful Deep Sea Drilling Program, and its successor programs International Program for Ocean Drilling (IPOD) and Ocean Drilling Program (ODP). In that endeavor, the crucial element of scientific leadership was provided by the scientific advisory structure known as Joint Oceanographic Institutions Deep Earth Sampling (JOIDES), and particularly by the Planning Committee of JOIDES, which was the scientific prime mover of the entire enterprise. The experience of the Deep Sea Drilling

Program was, in essence, that it is unreasonable to expect the level of scientific leadership required for a complex program to come from any one academic institution or any single NSF program staff. We believe that this is true in the area of ice core drilling and analysis as well, and strongly recommend that a U.S. national body known as ICWG be created. The initiative for setting up this body should be taken by the scientific community, in consultation with the PRB Committee on Glaciology and the DPP.

Several options are available for the funding and structure of ICWG, including setting it up as a separate corporation, like the University Corporation for Atmospheric Research (UCAR), which has corporate responsibility for the National Center for Atmospheric Research (NCAR), or like the Joint Oceanographic Institutions (JOI), with operational as well as advisory functions. We favor a simpler structure in which a group of committed investigators, representing at least five U.S. institutions that have personnel with scientific or technical command of relevant disciplines, put forward a proposal for funding an ICWG through DPP. The responsibility for ICAP's scientific planning and management would therefore be vested in active principal investigators (PIs) from U.S. institutions. Responsibility for leadership would be vested in a PI at a lead institution, which by plan of ICWG could rotate. Similarly institutional membership in ICWG may shift as the program evolves, as was the case with JOIDES.

The ICWG's operations must include a carefully defined set of tasks, which include the following:

- Scientific coring plans and provide oversight for each of the three broad geographical regions (Arctic, Antarctic, and mid-latitudes) and a global strategy,
- Plan for drilling technology development,
- Recommendations for an appropriate balance between capabilities in shallow, intermediate, and deep drilling,
- Plan for development and validation of geochemical and geophysical ice analysis techniques,
- Representation of U.S. scientific interest in international planning, specifically by participation in the international advisory body proposed in recommendation 5 below, and
- Interface of ice core research with other disciplines.

To accomplish these and other tasks that may arise, ICWG may find it desirable to establish panels having membership drawn from the international scientific and engineering communities.

3. <u>NSF should sequester funds for the support of U.S. ice core research.</u> It is suggested that NSF take on a lead agency role in the funding of the polar ice program and be the coordinator of funding from other interested government agencies, to whom ice core information will be of great interest. For example, the information about past atmospheric carbon dioxide content and processes in the carbon - cycle are of interest to the Department of Energy, and the problem of future sea level changes produced by future

size changes of ice sheets will be of interest to both the U.S. Army Corps of Engineers and the Environmental Protection Agency.

4. Funding must be managed to ensure long-term continuity of the program so that a capable personnel base will be developed and maintained.

5. As the United States develops its own expanded program of ice coring, and analysis, it should coordinate its effort with that of other nations through a formally constituted advisory body that draws on the experience of the international community of working scientists. The cooperative nature of the international effort envisioned for this program can, fortunately, be viewed as a natural extension of the cooperative international effort that characterized, previous programs of high-latitude ice coring.

## 6.
## Action Plan

YEAR I

1. Establish the Ice Core Working Group (ICWG) with members from at least five U.S. institutions.

2. Establish within ICWG the lines of responsibility for carrying out its specific tasks.

3. Establish funding in NSF/DPP for a new program of ice core drilling and analysis (ICAP), and coordination by NSF/DPP for funding by other government agencies and other NSF divisions.

4. Complete regional coring plans (Arctic, Antarctic, and low-latitude) within the context of a well-defined global strategy. The principal element of these plans should be a sequence in priority order of proposed locations for future coring that encompasses the goals of extending both geographical and time scale coverage.

5. Develop plans by ICWG for drilling technology and ice analysis techniques. The plan for drilling technology should take into account how best to bring together engineering and scientific activities.

6. Investigate by ICWG mechanisms for fostering international cooperation in ice core drilling and foreign advisory input into the U.S. program.

7. Call for proposals to implement the recommended plans.

8. Interface by ICWG with other climate disciplines.

### YEAR 2

1. Scientific programs are started with existing drill technology.

2. Drill development for future scientific program started.

### YEAR 3 AND SUBSEQUENT YEARS

1. Yearly review by ICWG of ongoing science research and drill technology development.

2. Yearly update by ICWG of the science and engineering plan and initiation, if needed, of new science plans and new engineering drill technology plans.

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# Appendix A

## CRREL ACTIVITY IN DEEP DRILLING

Based on statement by Donald Garfield
given to the Polar Research Board's
ad hoc Panel on Polar Ice Coring

## HISTORICAL SUMMARY

CRREL's involvement in deep ice core drilling began in the 1950s when SIPRE, one of CRREL's parent organizations, initiated efforts to obtain deep ice cores for scientific analyses.

The first projects were undertaken using modified conventional mobile oil drilling rigs. Four cored holes were completed using this method. The first two were at Site 2, Greenland during 1956 and 1957, when cores were obtained to depths of 305 m and 411 m, respectively.

A second similarly modified rig was shipped to Antarctica in 1956 for use on the IGY program. Two sets of cores were obtained--the first at Byrd Station to a depth of 308 m in 1957-58, and the second at Little America V to a depth of 257 m in 1958-59. Drilling at Little America V was the first major ice coring operating to be conducted in a fluid-filled hole.

Because of the extensive trip time involved in making and breaking drill pipe joints to recover each core, conventional oil field coring techniques were abandoned in favor of cable-suspended thermal coring methods. The thermal concept evolved over several years and ultimately resulted in coring to a depth of 535 m in 1964 at Camp Century, Greenland.

Thermal coring proved to be quite slow, especially in fluid-filled holes, so this concept was abandoned in favor of electromechanical coring methods. The first electromechanical ice coring drill (Electrodrill [The Electrodrill was invented by Mr. Armi Arutunoff, Reda Pump Co., Barlesville, Oklahoma.}) was a modified non conventional oil well tool, which was cable-suspended, with a submersible electrical motor and drive system. Ethylene glycol was used to dissolve the ice cuttings. It was the first drill to successfully penetrate a major ice sheet, reaching a depth of 1390 m at Camp Century, Greenland, in July 1966. To assist in the further development of this drill, a drill test facility was constructed at CRREL. This facility is a 200-foot deep, three-foot diameter water-filled hole capable of being frozen from top to bottom with ice temperatures down to -200 C.

The modified Electrodrill was shipped to Antarctica in 1966 to be used in coring a hole at Byrd Station. This hole was successfully completed to a depth of 2164 m in January 1968. Unfortunately, the drill was lost during the following 1968-69 season while attempting to clear the bottom portion of the hole to subsequently recover cores of sub-ice material. The drill became stuck in a heavy slush caused by water at the bottom of the ice sheet.

For the next several years, CRREL concentrated on developing electromechanical coring drills for obtaining shallow (100 m) and intermediate (500 m) depth ice cores. In 1978, CRREL initiated an effort to fabricate a drill similar to the original Electrodrill system for use on the GISP deep drilling program. This effort was terminated after a few months because there was some doubt that the GISP schedule could be met due to long delivery times for some major drill components. There was also considerable reluctance to continue when price quotations on some major components substantially exceeded original estimates. A decision was made to sponsor the Danish drill development effort, which was already in progress, with CRREL providing advice and assistance. Assistance was provided in writing major component specifications, testing the drill in the drill test facility, drilling and casing the upper portion of the DYE 3 hole, and monitoring progress during drilling. CRREL's involvement in deep ice core drilling ended in 1981 when the Danes successfully completed coring to a depth of 2037 m at DYE 3, Greenland.

## FUTURE DEVELOPMENT CHALLENGES

Several new design criteria must be met in order to accommodate future deep ice coring needs. Future drills should be capable of drilling almost twice the depth of previous deep holes. New drill systems must be able to operate over a wide temperature span--in ice as cold as -600 C. The new systems should also be able to core frozen sub-ice materials. Just these three requirements greatly restrict available design options, and indeed, perhaps one single drill system cannot satisfy all requirements.

<u>Hydrostatic pressure</u> Non freezing and relatively inexpensive hole fluids must be used to maintain hydrostatic equilibrium in the hole to prevent closure. The greater hydrostatic pressures associated with deeper holes make attainment of leak-free dynamic seals much more difficult than on previous drills. Electromechanical components, such as motors and gear trains, can be operated in a fluid and pressure compensated with their external environment, but many standard electronic components operate reliably only in air at normal atmospheric pressures and temperatures.

<u>Ice cutting disposal</u> Methods for collecting and disposing of ice cuttings depend upon the type of hole fluid selected and the temperature profile in the drill hole. Three obvious options are to (1) separate the cuttings from the hole fluid and remove them from the hole, (2) dissolve the cuttings and remove the solution from the hole, or (3) dissolve the cuttings and leave the solution in the hole.

<u>Drilling torque reaction</u> Torsional restraint of the drill continues to be a problem, and may be critical when drilling through warm ice into sub-ice material. The Electrodrill relied heavily upon the torsional rigidity of the suspension cable for its reaction. The Danish drill also had some reported problems with torque restraint, even though this drill produced relatively low torque and was equipped with specially designed anti-torque springs.

Cutter design Current cutter designs may have to be modified for coring in extremely cold ice. Certainly new cutters will be required for coring in sub-ice materials. Methods for retaining sub-ice samples will have to accommodate the following three possibilities:

(1) frozen consolidated material,
(2) unfrozen consolidated material, and
(3) unfrozen unconsolidated material.

These are a few of the technical challenges facing the designer. Solutions to various problems are likely to involve trade-offs, so the final product may not completely meet all requirements.

## ESTIMATED DEVELOPMENT COSTS

Based upon development cost estimates obtained during initial stages of CRREL's 1978 drill development project, it has been estimated that approximately $2 million would be required to develop and fabricate a new drill system.

## ESTIMATED DEVELOPMENT TIME

CRREL has recently conducted some research into the drilling problems cited above, but a substantial amount of additional work is required. We estimate that 36 months total would be required to design, fabricate, and lab test a complete drill system that could be fielded with confidence.

## RECOMMENDATIONS

Based upon past experience, four recommendations should contribute to a successful development program:

(1) Separate the drill development schedule from the science plan until tests indicate that the drill will be fully operational.
(2) Conduct laboratory tests whenever possible to reduce expensive field testing.
(3) Construct an insulated, refrigerated building over the CRREL deep ice well to permit year-round testing.
(4) Involve key field operational personnel during the latter stages of drill development.
(5) CCREL experience and facilities should be considered as a resource to assist in implementing a new U.S. initiative in deep ice drilling.

# Appendix B

## ICE CORE DRILLING

Prepared by
Karl C. Kuivinen and Bruce R. Koci
Polar Ice Coring Office
University of Nebraska -Lincoln

Donald E. Garfield
Cold Regions Research and Engineering Laboratory

## INTRODUCTION

The purpose of this report is to assess existing capabilities in ice core drilling from a national and international perspective, and to provide a realistic assessment of the technological problems and available resources that may be involved in future (5-year) shallow, intermediate, and deep drilling operations.

Advancements in ice core drilling technology and results of operational experience with various drill systems are published in reports of the 1974 Symposium on Ice-Core Drilling (Splettstoesser, 1976) and the 1982 Second International Workshop/Symposium on Ice Drilling Technology (Holdsworth and others, 1984).

## DRILL TECHNOLOGY

The primary application of ice drilling technology has always been the acquisition of cores for glaciological, hydrological, and climatological research. Secondary applications have been the provision of access holes through glaciers or ice shelves and the acquisition of take and sea ice cores. The wide variety of drilling equipment and techniques used to meet these applications can be classified based on four functions: the means of penetration (thermal or mechanical), the removal of the cuttings or meltwater formed during penetration, control of hole closure or opening due to plastic flow of the ice, and coring or non-coring applications (Hansen, 1984; Mellor and Sellman, 1976). The temperature of the ice (temperate or cold) is an additional constraint on the equipment and techniques that can be used.

Ice core drills and techniques may be further classified by depth. For this purpose the depth interval 0-50 m is designated as shallow or manual core drilling, the interval 0-300 m (dry hole) as intermediate, and beyond 300 m and requiring a liquid-loaded hole as deep drilling.

Shallow and intermediate coring capabilities exist today in several countries including Australia, Canada, Denmark, France, Japan, Soviet Union, Switzerland, United States and the Federal Republic of Germany (Table 1). Of these countries, the United States probably has the largest drill inventory, and virtually all of these drills are fabricated, maintained, and operated by the Polar Ice Coring Office (PICO) at the University of Nebraska-Lincoln (UN-L) under contract to the National Science Foundation's Division of Polar Programs (NSF-DPP) (Table 2).

Ice core drilling in the United States has focused in recent years on dry hole drilling to shallow and intermediate depths. In the U.S. inventory there are three kinds of drills used to obtain cores to various depths depending on ice temperature and strain history.

First, the manually-operated coring auger is capable of drilling to 50-m depth, which allows scientists to obtain core for preliminary evaluation without calling for a full-scale drilling operation. The SIPRE coring auger and the PICO lightweight auger (Koci, 1984) are also currently in use.

Second, the electromechanical drill employs the principles of the hand auger but extends the capability to the 300 m range where core quality generally deteriorates because of stresses within the ice. The drill is raised and lowered by means of an electromechanical cable, which also transmits power to drive the drill. In the U.S. inventory, the PICO 4-inch drill and 200-m winch provide the intermediate-depth drilling capability. In principle, this type of drill has unlimited capability if adapted to drill in a fluid-loaded hole.

Third, thermal core drilling has been done successfully in ice over the temperature range of 00 to -550C to depths of over 2000 m in a fluid-filled hole and to 990 m in an open hole. The current PICO thermal drill was designed for use in ice warmer than -100C.

TABLE 1. Current International Ice Core Drilling Capabilities

| | Drill Type | | | |
|---|---|---|---|---|
| Country | Electro-mechanical | Electro-thermal | Max. Depth (m) | Diameter (mm) |
| Australia | | X | 385 | 118 |
| Canada | X | | 270 | 98 |
| Denmark | X | | 2038 | 102 |
| | X | | 200 | 75 |
| France | X | | ? | 115 |
| Japan | X | | 143 | 105 |
| | | X | 148 | 105 |
| Soviet Union | X | | 2000+ | 110 |
| Switzerland | X | | 300 | 75? |
| West Germany | X | | 100 | 75 |

TABLE 2 Current U.S. Ice Drill Capabilities of Equipment Maintained by PIC( for the National Science Foundation

A. Downhole Component

| Drill Title | Qty. | Type | Depth Capability (m) | Core Diameter (cm) |
|---|---|---|---|---|
| PICO Lightweight Auger | | | | |
| 20-m System A | 2 | Manual Coring Auger | 50 | 7.6 |
| 50-m System B | 5 | | | 10.0 |
| | | | | 15.0 |
| NSF-Swiss Drill | 1 | Electromechanical | 115 | 7.6 |
| PICO 4-Inch Drill | 6 | Electromechanical | 353 | 10.0<br>500[1] |
| PICO Thermal Drill | 1 | Electrothermal | 312<br>4000[2] | 8.7 |
| PICO Hot Water Drill | 1 | Hot H20 | 220 | 30.0 Hole<br>500[2] |
| Temperature Logger | 1 | Logging Instrument | Dry Hole 300 | Any Size Borehole |
| Borehole Instrumentation Package | 1 | Logging Instrument | No Limit | 20.0 Maximum Borehole Diameter |

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1 Depth capability is dependent on ice temperature and strain history: usual limit is core quality or hole closure.

2 Untested to specified depth

B. Winches

| Winch Title | Qty. | Drills Applicable to Winch | Depth Capability (m) |
|---|---|---|---|
| PICO 100-m Winch | 1 | NSF-Swiss Drill<br>PICO 4-Inch Drill | 200 |
| NSF-Swiss 100-m Winch | 2 | NSF-Swiss Drill | 100 |
| PICO 200-m Winch | 7 | PICO 4-Inch Drill<br>NSF-Swiss Drill<br>PICO Thermal Drill | 300 |
| PICO 500-m Winch | 1 | PICO Hot Water Drill | 500 |

The PICO thermal drill was used to collect cores to bedrock (168 m and 154 m) on the tropical Quelccaya Ice Cap, Peru, in 1982 (Koci, 1983). Any of these U.S. shallow and intermediate drills currently in the PICO inventory can be used in remote areas of the world and are capable of being backpacked, if required.

In the development and use of deep ice core drill technology, the United States was the undisputed leader in the mid-1960s with the success of the Electrodrill in obtaining a deep core to 1390 m through ice and into sub-ice material at Camp Century (Ueda and Garfield, 1968) and to 2164 m at Byrd Station (Ueda and Garfield, 1969). After the loss of the Electrodrill in 1968-69, there was no decision made to replace the drill.

A unique wireline core-drilling system was designed and constructed at CRREL to drill ice core and access holes for the Ross Ice Shelf Project (Hansen, 1976; Rand, 1977). The wireline system, utilizing components and techniques from the diamond core drilling and rotary drilling industries, provides the capabilities of directional drilling and sampling sub-ice material. Test of the wireline system conducted in Greenland during 1975 and on the Ross Ice Shelf during 1976-77 and 1977-78 demonstrated the effectiveness of lightweight composite drill pipe and both air and fluid circulation systems to remove cuttings.

Today, deep drills exist or are under development in Australia, Denmark, France, and the Soviet Union. The Danish deep drill (Gundestrup and others, 1984), which penetrated to a depth of 2037 m at Dye 3, has proven its ability to drill deep in ice; however, it appears that cutter design, motor torque, and drill torque restraint are not adequate for drilling in sub-ice material. There is also some question as to whether the electronics component will continue to function in deeper and colder ice. Further development and testing would be required to determine its capabilities. The Australian deep drill, currently under development is fashioned after the Danish drill.

The French electromechanical drill is still being developed. Their major problem with this drill has been excessive power consumption in the fluid-circulation/ chip-collection system. It is doubtful that the French will have the ability to recover deep sub-ice cores in the near future. Their present and future deep coring efforts concentrate mainly on thermal techniques. The French thermal drill which was used to collect core to 905 m at Dome C, Antarctica, in 1977-78 was used in an open hole. They are now modifying this to penetrate to 4000 m.

The Soviet Union has also concentrated mainly on developing deep thermal coring devices. Their thermal drills operating at Vostok Station, Antarctica, are approaching the deep ice coring record set by the United States in 1968 at Byrd Station.

The Electrodrill is the only deep drill capable of coring, and which did core, into sub-ice material. The Soviets are reportedly developing an electromechanical drill that may eventually have this capability.

## TECHNOLOGICAL CHALLENGES

Recent technological development and core drilling successes in the U.S. program of shallow and intermediate coring have led to the call for quality ice core from greater depths in both temperate and cold ice in polar, mid- and low-latitude regions. The next logical step in U.S. drill development would be to enhance core quality and to extend the depth capability beyond the 200 m range. Both of these goals can be accomplished by adapting existing intermediate-depth coring drills to work in a fluid-loaded hole. The ultimate long-range goal would be the development of a deep drill capable of operating in ice at -550C to 4000 m depth with added capability of coring into sub-ice material.

Many of the technological challenges associated with development of a U.S. deep drill are already being addressed. Materials that will work in ice at -550 have been tested at the South Pole with favorable results. Several alloys are available that meet the hardness and toughness requirements for cutters and core catchers.

Cutter-geometry is being defined, which will allow the generation of coarse chips that can be easily pumped and filtered within the drill. Techniques for pumping and filtering slurries are being investigated. Laboratory tests of these components using a modified PICO 4-inch drill will be useful in determining the final configuration of a deep drill.

Investigators involved in analysis of the physical and chemical properties of ice have as a primary concern the collection of good quality, unfractured core. Fluid contamination of the core surface is not a major concern for most investigators except for those working on trace metals and for all others in instances where the core is severely fractured. Increasing the core diameter from the current 10 cm to 15 cm will provide more robust core and larger samples, while making the design task easier.

A parallel program emphasizing lightweight drill components and alternate energy sources is also justified. The value of collecting core from high attitude remote locations on a worldwide basis was demonstrated in 1983 with the collection and analysis of two ice cores to bedrock on the Quelccaya Ice Cap, Peru. A PICO 200 m winch, thermal drill, and 2-kW solar array were used to collect the cores. Additional lightening measures are in order, but the downhole and winch components of the drill remain intact. Significantly lighter and less expensive solar panels will be available in the near future.

Additionally, hot water drills and instrumentation for gaining access to the glacier bottom are currently available with a practical depth limit of 1000 m based solely on system size. This system could be designed to take core at intervals if necessary.

## A STEPPED PROGRAM FOR DRILL DEVELOPMENT

We recommend an integrated approach to ice core drilling and drill development in the United States The equipment and techniques for reliably drilling shallow and intermediate depth cores already exists in the U.S. inventory. These drills should continue to be used while efforts are being made to meet the larger objectives of deep core drilling. Many opportunities exist in the worldwide glaciology program in the polar regions, tropics, and temperate glaciers of North America and Eurasia that could take full advantage of the existing capabilities while awaiting the development of a deep drill.

The first phase in the development of a U.S. deep drill system would be to expand the capability of the existing intermediate drill to enable it to work in a flu-id-loaded hole to depths in the 1000 m range. This could be accomplished by using existing surface components (winch, cable, generator), and modifying and instrumenting the downhole components or the PICO intermediate drill. The capability should be sufficient to ensure the collection of core samples that predate the Wisconsin-Holocene boundary at the South Pole, the Little Ice Age at Siple Station and on the Antarctic Peninsula, and reach to 2000-3000 years B.P. in central Greenland.

The second phase would be to extend the depth capability to the 4000 m range, develop the capability of coring into sub-ice material, and improve the borehole logging instrumentation package.

Cooperation among core users and drilling engineers on a national and international basis is essential to ensure the successful and timely development of deep ice core drilling capability in the United States and the provision of core samples and other data that best benefit the scientific community.

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# Appendix C

Laboratory Analysis of Ice Cores
Listing of U.S. Institutions

Prepared for the ad hoc Panel by
Minzie Stuiver
University of Washington, Seattle

The institutes of those researchers that are known to the committee to be either active or strongly interested in ice core analysis are listed below, according to research emphasis.

Stable Isotopes
University of Washington
University of Rhode Island
Scripps Oceanographic Institution

Microparticles
Concentration and size distribution:
  Ohio State University
Elemental and chemical composition:
  New Mexico Institute of Mining and Technology
  Ohio State University
  University of Rhode Island

Ice Chemistry
Carnegie-Mellon University
Cold Regions Research and Engineering Laboratory
Lawrence Livermore Laboratory
State University of New York, Buffalo
University of New Hampshire

Gas Chemistry
California institute of Technology
Oregon Graduate School
Scripps Institution of Oceanography
Smithsonian Institution
University of Rhode Island

Trace Metals
California Institute of Technology
'U.S. Geological Survey
University of Chicago
University of Kansas

### Radioisotopes

Lawrence Livermore Laboratory
Scripps Institute of Oceanography
New York State Department of Health
University of Arizona*
University of Pennsylvania*
University of Rochester*
University of Washington*
(* AMS facilities)

### Physical Properties of Ice

California Institute of Technology
CRREL
PICO
State University of New York, Buffalo
University of Alaska
University of Colorado
University of Maine
University of Minnesota
University of Washington
University of Wisconsin

# Appendix D

## Status of Ice Core Storage Facility at SUNY, Buffalo

Abstracted from a report prepared
by Prof. C. Langway, Jr.

The facility is the responsible unit for processing, cataloging, and redistributing ice cores that are drilled in Antarctica, Greenland, and other polar and sub-polar regions. Samples remaining after preprogrammed studies are satisfied are redistributed to approved recipients, in accordance with the research objectives of the National science Foundation's (NSF) Division of Polar Programs (DPP) and their Core Sample Distribution Policy. Under this arrangement a commercial freezer facility stores most of the cores (80 percent), with some storage capacity used and located at the State University of New York (SUNY) at Buffalo, Department of Geological sciences (20 percent). A curator handles and arranges for redistribution and shipment of the ice cores.

The objective of maintaining the Central Ice Core Storage Facility is to centralize and to maintain an accurate inventory of the ice cores and other polar samples recovered in DPP's general ice core drilling operations in both the northern and southern hemispheres and to make the portion of these samples not originally preprogrammed available to NSF-approved recipients at worldwide locations for various investigations.

The facility operates under contract with DPP. The contract identifies the work to be performed and the costs required which are as follows:

- to provide technical advice (but not transport costs) to assist in the coordination of ice core shipments from the field to a U.S. port-of-entry;
- to provide technical advice (but not transport costs) to assist in safely transporting the frozen cargo from the port-of-entry to the storage facilities;
- to process, handle, catalog, and redistribute ice core samples on a national and international basis in accordance with the research objectives and policies of NSF/DPP;
- to upgrade procedures, equipment, and materials used for handling and transport of ice core samples;
- to arrange for and rent suitable commercial freezer space to store ice core samples;
- to update, organize, and distribute an information sheet maintained for each ice core or parts thereof remaining; and
- to maintain a graphical inventory of the ice cores that are available for redistribution under the general program.

The listing below is of curator activities for the period November 1983 through July 1984.

Ice core sample redistribution during this period is as follows:

| Date | Institution | Location | Core Sample Study |
|---|---|---|---|
| 11/30/83-<br>3/05/84 | University of Rochester (Elmore) | C.C. 1963-66 Greenland | $^{36}$Cl,$^{10}$Be |
| 11/08/83-<br>01/03/84 | Oregon Graduate Center (Rasmussen) | C.C. 1961 Greenland | $CH_4$, $N_20$ |
| 11/08/83-<br>01/03/84 | Oregon Graduate Center (Rasmussen) | Byrd 1968 Antarctica | CH4, N20 |
| 11/22/83<br>02/07/84 | SUNY, Albany (Chylek) | C.C. 1963-66 Greenland | Elemental Carbon |
| 09/05/83 (and in progress) | Nat'l Bureau of Standards (Currie) | Dye 2, 1977 Greenland | Composition of particles in surface snow samples |
| 12/26/83<br>01/04/84 | University of California (Craig) | C.C. 1963-66 Greenland | Krypton 81 dating |
| 12/26/83<br>01/04/84 | University of Calif. (Craig) | Dye 3, 1981 Greenland | “ “ |
| 12/26/83<br>01/04/84 | University of Calif. (Craig) | Byrd 1968 Antarctic | “ ” |
| 01/27/84<br>02/15/84 | University of Bern (Oeschgcr) | Byrd 1968 Antarctic | $C0_2$ concentration |
| 01/04/84<br>03/21/84 | University of Calgary (Giovinetto) | Crete 1974 Greenland | Acidity |
| 04/24/84<br>06/15/84 | University of Bern (Oeschger) | Byrd 1968 Antarctic | $CO_2$ Concentration and 13C |
| 04/24/84 (and in progress) | University of Bern (Oeschger) | Dye 3, 1981 Greenland | $H_2$ concentration |

|  |  |  |  |
|---|---|---|---|
| 04/25/84 (and in progress) | University of Chicago (Smith) | Milcent 1973 Greenland | XRF analysis of pollutants |
| 04/24/84 | Oregon State University (LaViolette) | C.C. 1963-66<br>Dye 3,1981 Greenland<br>Byrd 1968 Antarctica | Ir, Ni, concentration of 17 gases |
| 06/04/84 (and in progress) | New Mexico Institute of Mining and Tech. (Kyle) | Byrd 1968 Antarctica | Volcanic ash |

The current ice core archive contains 16 individual ice cores recovered from various geographical locations in Greenland and Antarctica. Detailed information is contained in the brochure "Ice Core Samples from Greenland and Antarctica," October, 1983.

A total of nearly 10,000 meters of cylindrical aluminum foil reinforced containers encase the ice cores, which vary in diameter from 3 to 5-1/4 inches and which were recovered by various drilling methods. Various portions of all cores have been studied by a number of investigators; consequently no core is currently continuous over the original depth interval drilled.

NSF/DPP has funded the Buffalo service facility under a peer-review contract arrangement sinec'1975/76. Funding has been adequate with full cost justification required and provided on an annual basis.

Experience has showed that closer coordination and fuller understanding of the core storage facility's purpose and objectives might be better accomplished if management control were in the DPP science section. As an example, coordination of cold storage space, needs, projections, transport problems, redistribution, etc., would be better met if these requirements were discussed within the science section and integrated with anticipated ice core acquisition plans resulting from field drilling activities. Recommendations and approvals for ice core requests for scientific studies should be based on considerations established by scientists familiar with the total impact of the study. The studies should be approved based on scientific merit and judgment, especially if considerable resources are involved in sample preparation and analyses. In some cases, tens or hundreds of meters of ice samples that require weeks or months of sample preparation are requested and approved; in other cases single samples are requested and approved which require only a few minutes of preparation. Whether a large or small sample request is involved, considerable care and preparation is required for each sample shipment, These simple facts are often neither obvious nor necessarily reflected upon in the original sample requests. We are pleased to report that since the beginning, every frozen shipment that has been prepared or handled by this facility arrived safely at its destination.

Since full science justification is required initially to obtain an ice core (a science plan) and a significant effort is subsequently involved to store, ship, and catalog the ice, an appropriate and rigorous scientific decision-making system should exist for the further use of core samples. The establishment of a committee that decides action on ice core sample requests might improve the overall situation.

Finally, for the future Antarctic ice coring program, it would be prudent to consider ice core storage and limited laboratory science facilities for the proposed McMurdo laboratory.

# Appendix E

## Motivation for $C0_2$ Research

Prepared by Dr. Stephen Schneider
National Center for Atmospheric Research

The United States currently has no capabilities to measure ice core C02 content. Analysis of the carbon dioxide content in ice cores has been successfully carried out at Bern and at Grenoble although there are problems of the interpretation of the results. The basic idea that the C02 content of trapped gases in ice cores reflect paleoatmospheric conditions is rather straightforward. However, the measuring techniques are difficult, and the interpretation of the measured data in terms of atmospheric C02 concentrations is complicated.

From a scientific point of view, the amount of carbon dioxide in the air through time is of critical importance to the unraveling of cause and effect between suspected climatic forcing mechanisms and observed or proxy climatic. records. Thus, it was with considerable relish that climate theorists greeted the news that trapped C02 in ice cores had been analyzed by several groups (Berner and others, 1980; Delmas and others, 1980) Indeed, from Berner and others' (1980) first publication, climate modelers (Thompson and Schneider, 1981) plotted hypothetical temperature time series over the past 20,000 years based on assumed C02 forcing alone. But further analysis of their work by the Swiss scientists caused them to discount their preliminary, the very high mid-Holocene value. They attribute the initial result to drilling fluid contamination. This case points out the need for close and continuous interaction between those responsible for the scientific objectives of ice drilling and those responsible for the technical or engineering issues. In this case, the engineering imperatives may require drilling fluids, but the scientific objectives cannot tolerate certain kinds of contamination.

To reconcile such potential conflicts, a scientific oversight body could be consulted to help the technical specialists meet their needs without unduly degrading the purpose of the venture in the first place, scientific inquiry. Perhaps such problems could be solved by advanced laboratory testing to determine which drilling fluids cause what kinds of contamination to the signals under study. From such testing, preferred fluids might be identifiable that would be adequate from both the perspective drillers and that of the scientists. Many such examples can be given--and many will arise--that argue for the need to have strong scientific goal-setting and ongoing oversight of the spectrum of ice coring activities.

Because ice core C02 research already takes place at two European laboratories, the question of duplication of effort is relevant. In support of a U.S. CO laboratory it should be noted that duplication is not an issue because of the following:

1) The nature of interpretation (modeling of the results warrants multiple efforts by different groups).

2) The difficulties tied to the measuring techniques can be better evaluated if additional laboratories would play a role.

3) A total lack of U.S. expertise in ice core $C0_2$ research will be detrimental to the large scale U.S. efforts in understanding climatic change.

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