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25-FOOT CRYOGENIC BUBBLE CHAMBER PROPOSAL*

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PREFACE TO THE SECOND PRINTING

Early in 1968, the Brookhaven Bubble Chamber Group, jointly with the National Accelerator Laboratory, developed criteria for a large-volume cryogenic bubble chamber for use at the 200-Bev accelerator. The physics aspects, preliminary design, and cost estimate were presented in a proposal for a 25-foot, 100-cubic-meter volume chamber. About 100 copies of this proposal were printed and distributed for consideration at the NAL-Aspen Summer Study of 1968.

The Atomic Energy Commission has recently approved funds for additional preliminary design and cost analysis of this chamber. Since a broader distribution is now appropriate, a second printing has been made in this smaller, more convenient size.

It is planned to prepare a more detailed report by October 1969 of the design and cost of the proposed chamber. Thus, no attempt has been made to rewrite the text of the original proposal other than the incorporation of minor corrections.

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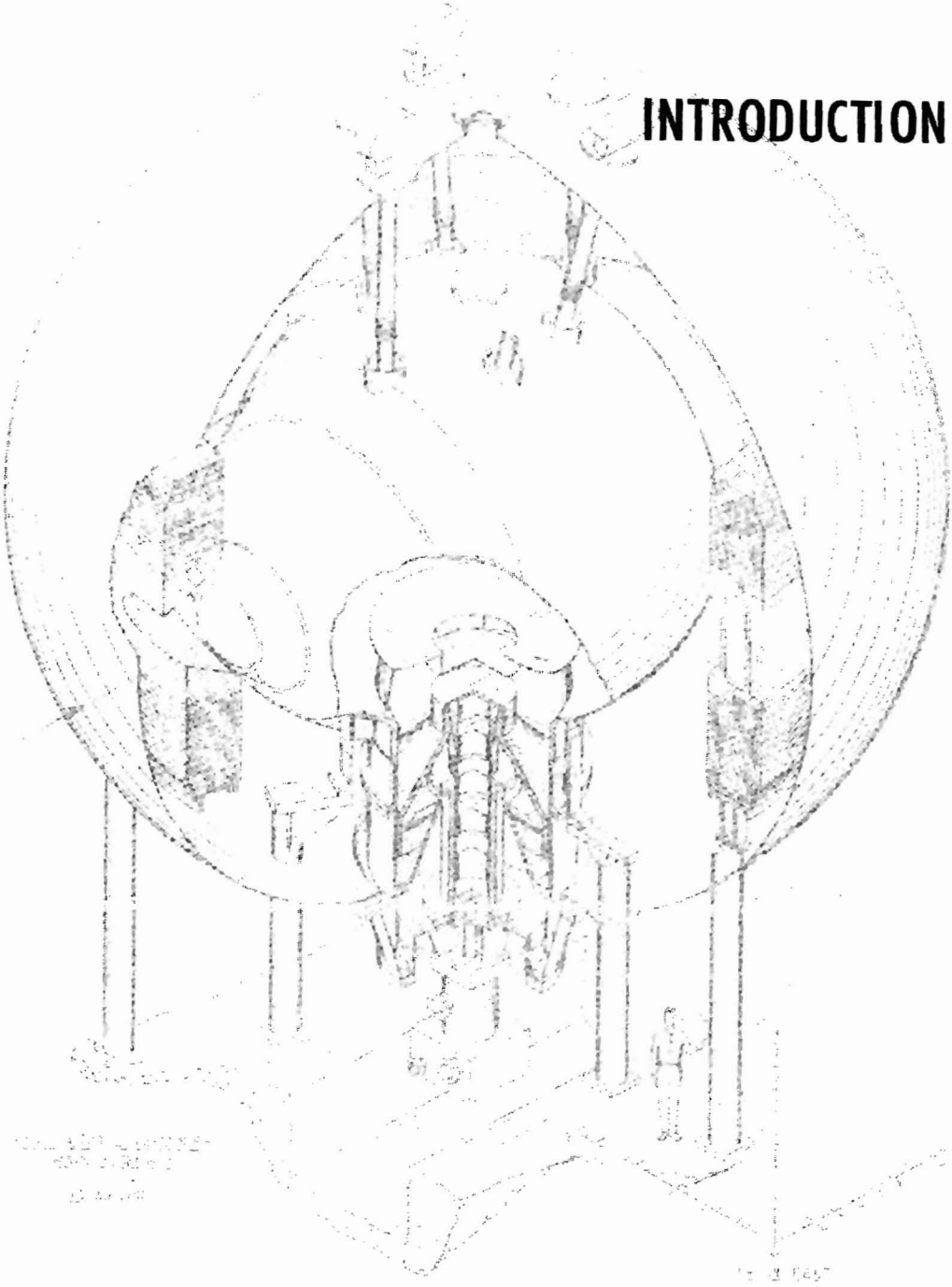
INTRODUCTION



1. INTRODUCTION

I. Summary

This is a preliminary proposal for the construction of a 25-foot cryogenic bubble chamber for performing experiments at the 200 BeV accelerator at the National Accelerator Laboratory at Batavia, Illinois. The chamber will be a major research device suitable for a multiplicity of experiments in particle physics over a period of many years. Implementation of this project will enable a strong high energy physics research program to be carried out using the bubble chamber detection method while serving many university research groups in a very efficient way. The 200 BeV accelerator will be a principal center in high energy physics research beginning in 1973 when it will make available the highest proton beam energy in the world and, since the accelerator also has the capability of an energy increase to 450 BeV, this center will stay in the forefront for many years and will require the best particle detectors for utilization. The 25-foot chamber proposed is an attempt to optimize the design for efficient use at the new accelerator. The experiments performed with this chamber can be expected to answer many of the most interesting questions challenging high energy physicists today and in the future.

The 25-foot chamber is to be designed in detail by BNL personnel and manufactured by outside fabricators. The concept is such as to make this chamber a most versatile particle detector. It includes flexibility in the selection of from three to five non-distorting cameras where the stereoscopic views used can be matched to the requirements for a particular experiment. The possibility of operating the chamber with hydrogen-neon in addition to pure hydrogen or deuterium is of prime importance, and this possibility is included in the design. Studies of using inner track-sensitive targets filled with hydrogen or deuterium are under way, and this possibility will be included during detail design.

The design is to be based on Brookhaven's experience in bubble chamber construction which includes the recent completion of a large-bubble-chamber research and development program which will have verified most of the new design features. To complete the research and development program, efforts will be initiated on hollow superconductors and 140° optics. Some changes may be adopted in the course of further theoretical, experimental, and engineering work.

This preliminary report includes the detailed physics justification for the project and a conceptual design of the bubble chamber. A detailed cost estimate is given for construction of the facility. A total cost of the project, including escalation and contingency allowances, is approximately $13.6 million. For neutron interaction studies, an alternative plan is suggested for supplying deuterium gas for filling the chamber. Requirements for funds for operation of the chamber after the construction is completed are also outlined. Wherever possible, the design has been optimized to reduce costs. The present design is believed to be a fully workable solution. The time schedule for the construction of the facility has been developed assuming project funding in the FY-1970 budget. This schedule shows the start of physical construction in the fourth quarter of FY-1970 and chamber completion, ready for experiments after initial test operation, on July 1, 1973. This design proposal was prepared for consideration by the NAL Aspen Summer Study of 1968. A final proposal, taking into consideration the recommendations of that study, was submitted to the AEC in the fall of 1968. This proposal includes approximately $4 million for deuterium gas.

II. History

The bubble chamber, invented in 1952 by D. A. Glaser, consists of a pressure vessel containing a liquid which is suitable for use as a target material and as a detector for particle tracks. The vessel must allow for photography of the interior volume. A momentary increase in the volume of the liquid, usually accomplished by an expansion piston, reduces the pressure of the liquid and, under proper conditions, causes formation of bubbles along the tracks of any charged particle. The chamber liquid is initially in a subcooled state and becomes superheated by the temporary pressure reduction which causes the liquid to be at a pressure lower than its vapor pressure at the existing temperature. During the time of minimum pressure, particles are admitted from the accelerator to the chamber, and the bubble tracks are formed and photographed for later scanning for nuclear events of interest. A strong magnetic field produces measurable curvatures in tracks even for very energetic charged particles. These curvatures are used to determine the momenta of the particles. It is important to study not only the properties of particles but also their production

process. This is best accomplished by using interactions with single protons in liquid hydrogen or with neutrons in liquid deuterium. Therefore cryogenic techniques are required and the chamber must be very well insulated and refrigerated.

Accelerator development since the time of the discovery of the bubble chamber has provided increasingly powerful beams of particles for use in particle physics research. There has been a steady increase in the energy of the beams available, and increases in available beam intensity have resulted in improved methods for separating pure beams of rare particles. To provide more efficient detection and more accurate measurement of particles under study, new cryogenic bubble chambers have been constructed and old ones refined or significantly improved. By 1963, several 2-meter-long chambers, with volumes up to about 1000 liters, had been constructed and brought into operation, and neutrino experimentation using accelerators had been proved to be feasible by using multi-ton spark chamber arrays. Analysis of the early neutrino experiments shows that further progress in this very important field of physics requires studies of neutrino interactions in hydrogen and deuterium. Since even the largest 2-meter-size chamber contained only 0.067 tons of hydrogen, it became obvious that cryogenic bubble chambers with volumes more than a factor of 10 larger would be required. In feasibility studies, particular attention was given to ideas which would allow construction at a lower cost than had previously been possible. Three innovations were developed at BNL. These were: (1) wide-angle photography, fisheye windows; (2) large superconducting magnet coils; (3) fiberglass-reinforced plastic expansion system components and hydraulic expansion control. With the incorporation of these ideas, it was possible for BNL to propose in June 1964 the construction of a 14-foot-diameter hydrogen bubble chamber for use at the AGS. Argonne National Laboratory in June 1964 proposed a 12-foot-diameter chamber with a visible volume of 24,000 liters which could contain over three tons of deuterium. The construction cost of the 12-foot chamber was estimated to be $14 million with a construction period of four to five years. This latter project received funding and is scheduled for completion in 1969. Since the 14-foot-chamber design

departed in several respects from conventional bubble chamber design, it was decided to conduct tests of these new features in order to minimize the possibility of delays in the project or cost overruns when funded. Early in 1966 the three major tests, i.e. the hydraulically controlled plastic expansion system, the optics system, and the superconducting magnet system, were combined into a 7-foot test facility which could produce bubble chamber pictures. This facility was implemented, and by May 1968 all components for the superconducting magnet were in place and a test was completed. A test of the complete chamber, under actual working conditions, is scheduled for March 1969.

In 1965, along with the design studies carried out at LRL for the 200 BeV accelerator, consideration was given to the need for hydrogen bubble chambers at the 200 BeV accelerator. Judgment of program requirements must necessarily be based on present interest and in particular on scientific questions now raised but not solved. The consensus was that present research in strong interaction physics would continue by gradually proceeding to higher energy. The utility of the bubble chamber for these experiments is well recognized since most particles with masses greater than ~100 MeV have first been detected with visual devices, and with few exceptions their static properties or quantum numbers, such as spin, isotopic spin, etc., have been measured with the use of hydrogen bubble chambers. This technique has also been particularly amenable to studies of decay properties. These facts, as well as the recognition of the need for investigations of weak interactions at high momentum transfer by using neutrino interactions with protons and neutrons, led the LRL group to consider a 6-meter-diameter hydrogen bubble chamber of 100 cubic meters total volume for use with the 200-BeV accelerator. In a 1966 summer study, a group affirmed the 100-cubic-meter volume but concluded that an aspect ratio (length:diameter) of 3:1 would better fit the physics need at the 200-BeV machine.

Reappraisal of the BNL 14-foot cryogenic bubble chamber project was brought about by final failure to obtain the inclusion of this project in the FY-1969 budget. This review seemed appropriate since the

proposal for the 200 BeV accelerator to be built at Batavia, Illinois, was submitted to Congress for authorization in fiscal year 1969 with a proposed 5-year schedule. Severely restricted funds for the next few years could mean that only one large cryogenic bubble chamber project will be approved in the near future. Therefore, it seems proper that first priority should be given to a chamber optimized for use at the 200-BeV accelerator. Ideas leading to further design improvements and simplifications resulting in cost reductions are of great importance and should be constantly explored. The efforts of Brookhaven's Bubble Chamber Group have been devoted recently to updating the design concepts for the 14-foot cryogenic bubble chamber along these lines. Design and cost estimates were made for a set of large cryogenic bubble chambers with superconducting air-core magnets, and the result of this scaling study has been reported.[1] An agreement was made with the National Accelerator Laboratory for BNL to take the design responsibility for a large cryogenic bubble chamber to be used at NAL, and the justification and preliminary chamber design are the subjects of this proposal.

III. Justification and Description of Chamber

The contribution to physics research of any accelerator depends on its intrinsic capabilities and on the flexibility of its research equipment, including the particle detectors that are directly responsible for data production. Since its invention, the bubble chamber has proved to be a very versatile device and has provided an effective method of obtaining data for many experiments. The 25-foot chamber proposed here will be used as a detection instrument at the new accelerator to provide a means for studying neutrino interactions with simple nuclei, a field inaccessible by other means. Before the 25-foot chamber operates, experiments with neutrinos at energies up to about 3 BeV will have been carried out at the AGS and CERN and at the USSR 76-BeV Serpukhov Accelerator. The large volume and length of the 25-foot chamber will allow the continuation at Batavia of this very interesting and potentially important kind of research to higher energies, where it should be possible to determine whether the weak processes can

be characterized by very small conventional coupling constants and to answer other important questions concerning the existence of an intermediate boson, the degree of satisfaction of the weak interaction by the proposed current algebra schemes, and whether the vector and axial vector form factors for the elastic processes are the same or different. As previous bubble chambers have in the past been used for studying the detailed properties of strong-interaction resonances, the 25-foot chamber can be expected to be a major source of information for the extension of these studies to higher masses and higher energy. In the 25-foot chamber, (1) there will be more secondary interactions in the longer available path lengths, (2) the increased track lengths of the secondary tracks will yield a better determination of momenta, (3) the large volume will allow more secondaries to stop in the chamber. Combined, these attributes make possible the resolution of higher mass resonances and the detailing of other strong interactions at high energies. Unbiased detection of particles in any direction and throughout the bubble chamber volume is of great importance when searching for new processes. The real strength of the new chamber will be in its ability to have in the one instrument many different aids in sorting out the details in nuclear processes. In the same chamber we may see the basic interaction in hydrogen, make accurate momentum measurements, trap many secondaries, detect neutrons and gamma rays, make visible the decay of charged and neutral particles, and measure bubble density (for velocity determination) and rate of momentum loss. All of these aids in the identification of particle masses make this a most versatile and useful detector. Furthermore, by using a hydrogen-neon mixture filling of the chamber or by placing a hydrogen-filled track-sensitive target in the neon-filled chamber, new gains can be expected in the ability of the chamber to detect gamma rays so that processes involving neutral secondaries can be explored in detail. The 25-foot bubble chamber will be a very essential part of the exploitation of the opportunities created by the new accelerator facility. Full and well-rounded utilization of this facility requires the 25-foot bubble chamber.

In summary, the 200-BeV accelerator will open up new energy regions which will require equipment such as the 25-foot bubble chamber with its large useful volume of over 70,000 liters for experimentation. Thus extraordinarily important results can be expected in weak-interaction experiments, i.e. neutrino and antineutrino interactions with protons and neutrons. Vital contributions to the more extensive program of understanding strong interactions can also be expected and, because of the unbiased detection of interactions of particles with protons and neutrons, this technique is ideal for exploration. Utilization of the accelerator by supplying bubble chamber photographs to numerous university users' groups is a most effective way to advance education and research in high energy physics.

This proposal covers a 25-foot-long cryogenic bubble chamber for use with liquid hydrogen, deuterium, and neon-hydrogen mixtures. It is described in detail in the following sections of Chapter 3: I-Chamber Body and Vacuum Tank, II-Expansion System, III-Refrigeration, IV-Optics, V-Magnet, VI-Vacuum, VII-Instrumentation, and VIII-Site, Enclosures, and Facilities. Section I covers the two principal vessels of the assembly, the chamber body and the vacuum tank. The chamber body has been chosen to be a 25-foot long vessel composed of three spherical sections with a thin-walled spherical beam window at one end. The total volume of expandable liquid is 105,000 liters with 72,000 liters visible to three cameras simultaneously at acceptable demagnification on an economical film size. The vacuum tank provides for thermal insulation of the chamber and the superconducting magnet. It also serves as a containment vessel in the case of an accidental spill or pressure buildup. Section II covers the expansion system for expansion of the chamber which is accomplished by a 90-inch-diameter nonconducting fiberglass-reinforced plastic piston. This piston, located at the bottom of the chamber, is driven by a fast response hydraulic actuator capable of expanding the chamber with a 0.083-sec expansion cycle. Section III covers the hydrogen refrigeration system required to fill and cool the chamber and provide temperature control during operation. The helium refrigeration system required for operation of the superconducting magnet at about 4.5°K is also described. Section IV covers the optical system used to photograph the bubbles

produced along paths of charged particles passing through the chamber liquid. The optical design influences strongly the shape of the chamber. By using 140° field angle lenses, a very large fraction of the chamber volume can be photographed. In order to retain the 70mm film width which is widely used in existing data-processing equipment and in order to retain reasonable demagnification, this fraction has been reduced to the presented value of 70 percent. The design gives data which can be scanned and measured by conventional equipment and in which track correlation between the views can be made by inspection. Section V covers the proposed air-core superconducting split-pair magnet designed to generate an average magnetic field intensity of 40 kG over the bubble chamber volume. The design proposes the use of hollow stabilized superconductor cooled by an internal flow of helium. Section VI covers the high-vacuum pumping system. This provides for insulating the chamber and superconducting coil. Adequate redundancy is provided to prevent loss of vacuum. Section VII covers the instrumentation and control system needed for operating the bubble chamber with ease and efficiency as well as with maximum safety. Section VIII covers the site, enclosures, and facilities which would be classified as conventional construction. This proposal minimizes the physical plant items through the use of relocatable weatherproof structures. This scheme also facilitates such adjustments in equipment position as may be occasioned by the experimental program.

A section on data processing procedures and requirements for using the 25-foot bubble chamber photographs has been included under the chapter concerning High Energy Physics. It is concluded that photographs produced are expected to be readily understood by human scanners and that they can also be easily handled by existing measuring equipment (whether automatic or manual).

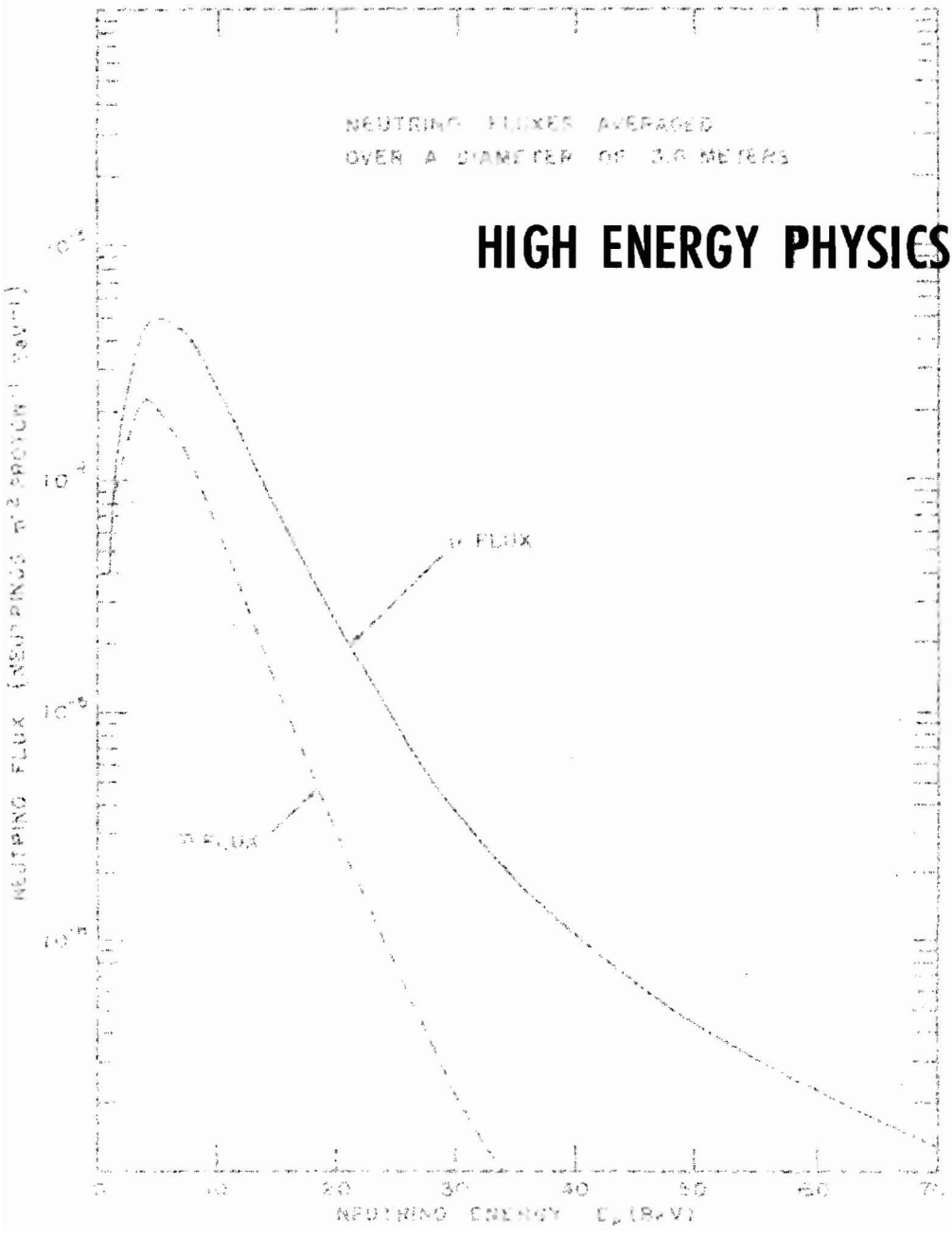
Chapter 4 gives the considerations that have gone into making the present chamber design as safe as is reasonably possible. Hydrogen and oxygen gas mixtures have wide flammable limits. The proposed chamber would contain about 105,000 liters of liquid hydrogen, and hydrogen gas will also be used in compressor room equipment. Every

precaution is taken to prevent hydrogen gas from escaping into the rooms in order to eliminate the primary hazard. Maximum safety is best assured by utilizing sound design practices and eliminating possible ignition sources. In addition, explosive gas detection equipment, coupled with automatic hydrogen emergency ventilation, is necessary to minimize hazards. Further details to assure adequate safety are also described. In addition, efforts will continue to examine and review the design with a view toward improving the safety.

References

1. Scaling Studies of Large Cryogenic Bubble Chambers. BNL Bubble Chamber Group, April 1, 1968. BNL #12336

HIGH ENERGY PHYSICS I



2. HIGH ENERGY PHYSICS

I. Weak Interaction Experiments

A. NEUTRINO PHYSICS WITH THE 25-FOOT CHAMBER

a) Introduction

The neutrino (ν) has recently been shown to be a useful tool in the study of weak interactions.[1] Knowledge of the weak interactions to date is derived mainly from β, μ and hyperon decays, and μ-meson absorption experiments. Since these reactions involve momentum transfers up to only 100 MeV/c, they encompass only a small domain of the very large energy region to be explored. In this limited area, the Fermi theory, which is a phenomenological theory, has been quite successful in dealing with the experimental observations. However, from unitary considerations alone this theory is certain to break down at higher energies, certainly for center-of-mass neutrino energies of 300 BeV and possibly at laboratory energies $\leq$ 200 BeV. The previous limitations on the performance of experiments on ν collisions were the lack of ν beams and sufficiently large detectors. These have been partially eliminated by the advent of the Brookhaven AGS, CERN PS, and large spark chamber detectors. At present, one neutrino event could be observed in a 40-ton spark chamber in every 50 pulses of the AGS. Unfortunately, such events occur in heavy nuclei and the physics is difficult to unravel due to the influence of secondary nuclear interactions inside the heavy nuclei. What is needed is a large hydrogen and deuterium detector. In fact, the most effective apparatus for studying ν interactions is a large cryogenic bubble chamber. By 1973, when the 200-BeV accelerator will be ready and ν experiments can be performed, it is reasonable to estimate that there will have been a year of ν experiments at each of the following high energy detectors: BNL's 7-foot test facility, Argonne's 12-foot chamber, CERN's 3.7- and 4.5-meter chambers, and Serpukhov's 4-meter chamber. A large 25-foot cryogenic bubble chamber is necessary to exploit properly the higher energy ν flux available at Batavia. Such a chamber will provide ν event rates (see below) of ~1 event per picture. It will also give a much higher efficiency for detection of neutrals (see section III-C on detection of neutrals) and

identification of particles (e.g. e, μ, π, K, p, etc.) by much greater visible path lengths. All of these advantages will be necessary to start a new generation of neutrino and antineutrino experiments.

b) Calculation of Event Rates

In the past several years many reports have been written on neutrino facilities at 200- to 300-BeV accelerators.[2] Two types of neutrino beams have come from these studies, the wide-band system (WBS) and the narrow band system (NBS). The wide-band system, which is currently used at existing accelerators, consists of the extracted proton beam (EPB), a target, a focusing element (i.e., horn, plasma lens, Palmer fingers, etc.), a drift space and a shield of sufficient length to stop muons of a momentum equal to the EPB. The narrow-band system consists of EPB, target, bending magnets, many quadrupoles, more bending magnets, and a shield. The advantages of the NBS are that it provides a simultaneous muon beam and requires a shorter shield length. The energy spectrum of the neutrinos is quite narrow but, as pointed out by Perkins,[3] it is not sufficient to provide another constraint in kinematic fitting. Its disadvantage is that the flux is down by an order of magnitude from the WBS. For this reason event rates have been calculated using a wide-band beam with a long shield.

The beam consists of a 633-meter decay path followed by a 167 meter iron shield[4] before the chamber, resulting in a total distance of 800 meters from target to detector. The magnetic finger focusing device can be set to focus either positive or negative particles giving primarily ν's or $\bar{\nu}$'s, respectively. The fluxes for the two cases may be calculated given the fluxes of π mesons and K mesons from the target. For the purpose of this proposal, these fluxes are taken to be those predicted using the Cocconi[5] formula modified[6] in the small-angle region. With this modification the formula fits all present experimental data at 30 BeV within 30 percent.

The expected ν fluxes at NAL, with these assumptions, are shown in Fig. 1. The $\bar{\nu}$ flux is less than the ν flux by roughly a factor of 2 because of the smaller production of π^- compared with π^+.

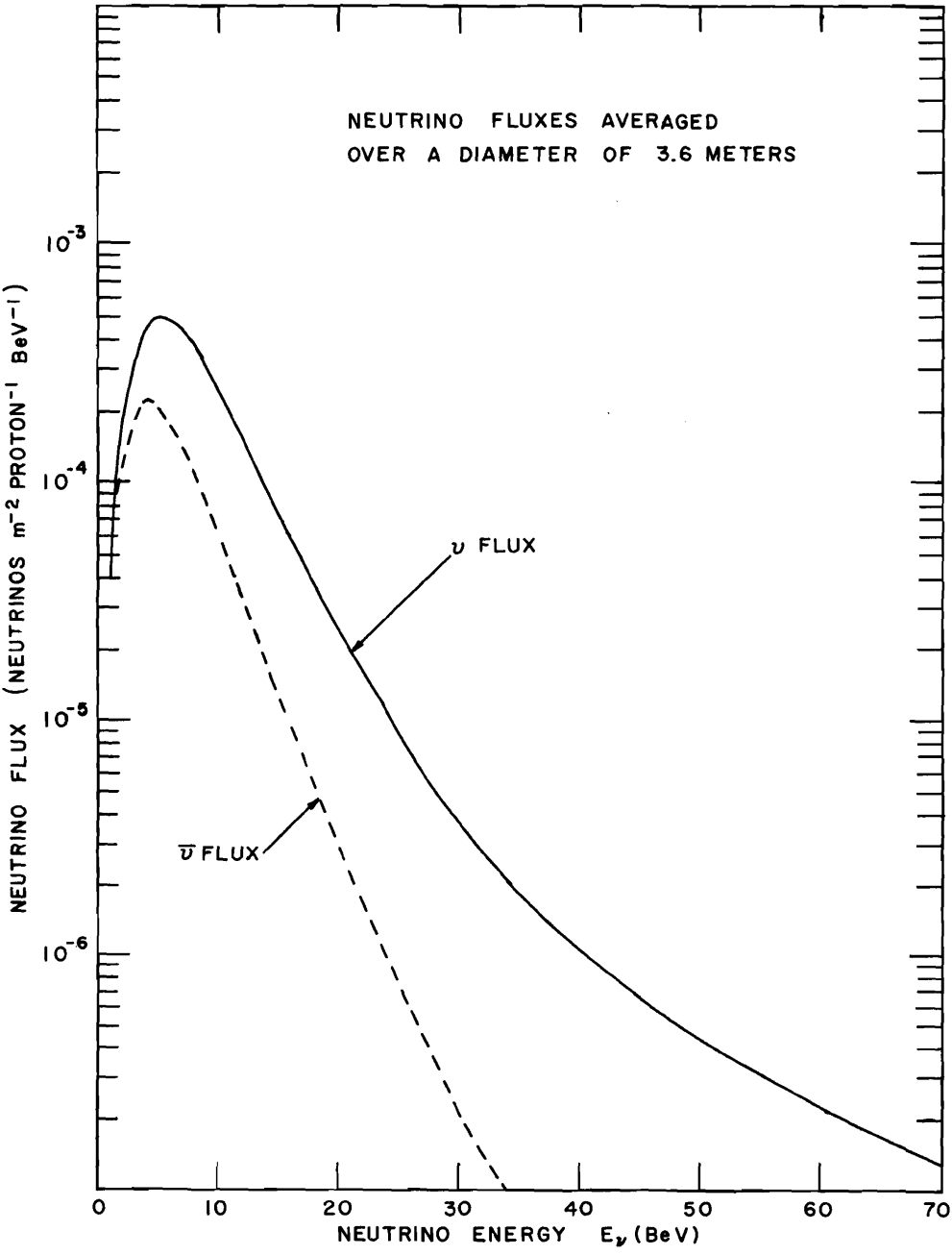

NEUTRINO FLUXES AVERAGED
OVER A DIAMETER OF 3.6 METERS
10^{-3}
10^{-4}
10^{-5}
10^{-6}
NEUTRINO FLUX (NEUTRINOS m^{-2} PROTON^{-1} BeV^{-1})
ν FLUX
$\bar{\nu}$ FLUX
0
10
20
30
40
50
60
70
NEUTRINO ENERGY E_ν (BeV)

FIG. 1

The faster decrease at higher energies is in turn due to the much smaller K^- to K^+ production ratio.

The total volume of the proposed chamber is 105,000 liters of which 72,000 liters are viewed in their entirety by three cameras. The anticipated flux for the 200-BeV accelerator is 5×10^{13} protons per pulse with a repetition rate of one pulse per three seconds. The liquids that can be used in the chamber are hydrogen, deuterium, and neon with densities of 0.06 gm/cm^3, 0.12 gm/cm^3, and 1.0 gm/cm^3, respectively. Since the region of neutrino energies above 2 BeV is as yet unexplored and since, further, the theory is inadequate to predict detailed cross sections for all the reactions of interest, we have calculated the yield for a ν cross section of 10^{-38} cm^2. This is a reasonable value since the elastic neutrino cross sections approach this value at lower energies. Using the flux figure shown in Fig. 1 and the above assumption, the yield is calculated to be one neutrino (ν) event and 1/2 antineutrino ($\bar{\nu}$) event per picture in deuterium with 40 percent of the contribution occurring in the region 5-10 BeV, 20 percent below, and 40 percent above this range. In discussing event rates, it is convenient to separate the reactions into various categories.

Basically there are four classes of ν and $\bar{\nu}$ induced reactions on nucleons, namely νp, νn, $\bar{\nu} p$ and $\bar{\nu} n$. To be more specific, one can further classify final states into three general categories:

i) "Elastic" Events

These have two-body final states, a nucleon and a lepton, e.g.

$$\bar{\nu} + p \rightarrow \mu^+ + n$$
$$\nu + n \rightarrow \mu^- + p$$

ii) "Inelastic" Events

In this channel we consider three- or more-body final states, not involving hyperons, where the main contribution comes from pion production, e.g.

$$\bar{\nu} + n \rightarrow \mu^+ + n + \pi^-$$
$$\bar{\nu} + p \rightarrow \mu^+ + p + \pi^-$$

$$\nu + p \rightarrow \mu^- + p + \pi^+$$
$$\nu + n \rightarrow \mu^- + p + \pi^o$$

iii) Hyperon Production

For example,

$$\bar{\nu} + n \rightarrow \mu^+ + \Sigma^-$$
$$\bar{\nu} + p \rightarrow \mu^+ + \Sigma^o$$
$$\bar{\nu} + p \rightarrow \mu^+ + \Lambda^o$$
$$\bar{\nu} + n \rightarrow \mu^+ + \Lambda + \pi^-$$
$$\bar{\nu} + p \rightarrow \mu^+ + \Lambda + \pi^o$$
$$\nu + p \rightarrow \mu^- + K^+ + p$$
$$\nu + n \rightarrow \mu^- + K^+ + n$$

Due to the large volume of the 25-foot chamber, a program of probing the weak interaction structure of the nucleon as well as testing the symmetry rules seems clearly feasible. In what follows we have enumerated several types of experiments which can be performed and which will attack some of the more puzzling questions in this field. The list is far from complete; its purpose is mainly illustrative. However, one of the most exciting aspects of the high energy neutrino program is the profusion of new ideas, experiments, and theories that emerge year after year and which can be most directly tested using the neutrino as a probe.

c) Physics

i) Form Factors for "Elastic Processes"

This involves a detailed study of reactions listed in this section, part b(i). In electron scattering experiments, for example, the interaction is due to the exchange of a vector particle, a study of which gave the first clue to the possible existence of the subsequently discovered ρ and ω resonances. This information is usually expressed in terms of a vector form factor. In the case of the weak interactions, both vector and axial vector form factors are involved in the interaction. The essential questions are whether in this latter instance the two form factors (axial vector and vector) are the same or different, and further whether the vector form factors in the case of electron and neutrino scattering are also the same or different.

ii) Point Structure of Lepton Current

In present theories of weak interactions involving μ^- capture, β decay, etc., the interaction is represented by an effective Lagrangian involving currents of the strongly and weakly interacting particles. In particular, it would be interesting to know to what extent the lepton current acts only at a single space-time point. This assumption introduces strong restrictions on the forms of inelastic cross sections for both neutrino and antineutrino reactions of the type written down in this section, part b(ii). It has been pointed out by Lee and Yang[7] that, by measuring such cross sections at various neutrino energies but similar momentum transfers, the validity of such an assumption can be checked with approximately 1,000 events.

As mentioned in the Introduction, the concept of a point interaction is certain to break down at center-of-mass neutrino energies of 300 BeV and possibly at much lower energies. A systematic measurement of the $\bar{\nu}n$ and νn total cross sections will give a positive indication where a nonlocality concept has to be introduced into the weak interaction such as the weakly interacting boson conjectured by Lee and Yang. Present experimental searches have only set a lower limit of 2 BeV for the mass of the W. With the NAL machine, one can search for this boson effectively up to a mass of 5 BeV.

iii) Symmetry Rules

The neutrino reactions serve to determine restrictions on the form of the currents used to describe the action of the strongly interacting particles. In particular, the following rules can be investigated by exposure of the 25-foot chamber to ν and $\bar{\nu}$ beams. (In the ensuing discussion, ΔQ, ΔS, and ΔI refer to increments of the charge, strangeness, and isotopic spin, respectively, of the strongly interacting particles.)

(1) $\Delta Q/\Delta S = -1$ Currents

To date, this question has been pursued by studying the decays $\Sigma^+ \rightarrow n + \ell^+ + \nu$ (where ℓ is a lepton). By studying inverse processes, namely

$$\nu + n \rightarrow \Sigma^+ + \ell^-$$
$$\nu + n \rightarrow \Lambda^o + \pi^+ + \ell^-$$

the sensitivity can be increased due to increased statistics (i.e., a one-million-picture exposure would yield $\sim$ 10,000 such events) and a completely new kinematic region can be investigated, namely momentum transfers in the BeV/c range compared with less than 100 MeV/c.

(2) $\Delta I = 1/2$ Rule

This rule applies to the strangeness changing current. It predicts

$$\frac{\sigma(\bar{\nu} + n \rightarrow \ell^+ + \Sigma^-)}{\sigma(\bar{\nu} + p \rightarrow \ell^+ + \Sigma^o)} = 2/1$$

and

$$\frac{\sigma(\bar{\nu} + n \rightarrow \Lambda^o + \pi^- + \ell^+)}{\sigma(\bar{\nu} + p \rightarrow \Lambda^o + \pi^o + \ell^+)} = 2/1$$

and once again can be verified to an accuracy of a few percent in a deuterium exposure to a beam of antineutrinos.

(3) $\Delta I = 1$ Rule

The cross sections for reactions

$$\nu + n \rightarrow \mu^- + n + \pi^+$$
$$\nu + n \rightarrow \mu^- + p + \pi^o$$
$$\nu + p \rightarrow \mu^- + p + \pi^+$$

should obey the following inequality relationship for the cross sections σ:

$$\sqrt{\sigma(\nu n \rightarrow \mu^- n \pi^+)} + \sqrt{2\sigma(\nu n \rightarrow \mu^- p \pi^o)} \geq \sqrt{\sigma(\nu p \rightarrow \mu^- p \pi^+)}$$

(4) $\Delta S < 2$

Up to now, the only test of a violation of this rule has been the unsuccessful search for the Ξ hyperon decaying into a nucleon and two leptons. The existence of $\Delta S = 2$ and 3 currents can be tested from the inverse reactions

$$\bar{\nu} + n \rightarrow \Xi^- + \ell^+$$
$$\bar{\nu} + n \rightarrow \Omega^- + \ell^+$$

iv) Cabibbo Theory

Successful demonstrations of the Cabibbo theory[8] in hyperon weak decays can be checked further in relating the cross sections involving strangeness changing and strangeness nonchanging reactions induced by $\bar{\nu}$. Some predictions based on the Cabibbo theory can be written as follows:

Reactions	Relative Intensity	
$\bar{\nu}n \to N^*_{3/2}(1238)^- \mu^+$	100	also by $\Delta I = 1$
$\bar{\nu}p \to N^*_{3/2}(1238)^o \mu^+$	33	
$\bar{\nu}n \to Y^*_1 (1385)^- \mu^+$	2.5	also by $\Delta I = 1/2$
$\bar{\nu}p \to Y^*_1 (1385)^o \mu^+$	1.25	
$\bar{\nu}p \to n\mu^+$	100	
$\bar{\nu}n \to \Sigma^-\mu^+$	2.5	also by $\Delta I = 1/2$
$\bar{\nu}p \to \Sigma^o\mu^+$	1.25	
$\bar{\nu}p \to \Lambda\mu^+$	4	

v) Test of the Conserved Vector Current (CVC) and Partially Conserved Axial Vector Current (PCAC) Hypothesis in High Energy Neutrino Reactions

It has been pointed out by S. L. Adler[9] that inelastic high energy neutrino reactions are particularly well suited to test possible current conservation theories. In the reaction

$$\nu + \alpha \to \ell + \beta$$

α is a nucleon or nucleus, ℓ is a lepton, and β is a system of strongly interacting particles, and (1) the invariant mass of β is greater than the mass of α, (2) the lepton momentum is parallel to that of the incident neutrino, and (3) the mass of the lepton can be neglected. Then the squared matrix element for the above reaction is proportional to the divergences of the vector and axial vector currents. This powerful theorem gives rise to tests of CVC and PCAC.

(1) Test of CVC

As a result of the Adler theorem, it is clear that, if the vector current is conserved, then all parity-violating effects must vanish for the subsample of events satisfying the criteria previously enumerated. This can be verified by observing a spin-momentum correlation ($\vec{\sigma} \cdot \vec{p}$) or a vector triple product term ($\vec{q}_1 \cdot (\vec{q}_2 \times \vec{q}_3)$) where $\vec{q}_1$, $\vec{q}_2$, $\vec{q}_3$ are the momenta of three different particles in the final states. The observation of the former effect does not appear practical even in a chamber as large as the one proposed. More promising is the possibility of observing non-zero triple vector products between momenta in four-body final states. If such a parity violating product were observed when the lepton has a large angle but were reduced to zero at small angles, this would be direct evidence for CVC.

(2) Test of PCAC

There are at present two successful predictions of the PCAC hypothesis, namely the Goldberger-Treiman relations for charged pion decay,[10] and a consistency relating the pion-nucleon scattering amplitude and the pion-nucleon coupling constant.[11] If one assumes CVC, then the Adler theorem supplies further tests in high energy neutrino reactions. In particular for the reactions

$$\pi^+ + \alpha \rightarrow \beta$$

$$\nu + \alpha \rightarrow \mu^- + \beta$$

with the given restrictions under which the Adler theorem is valid, PCAC predicts that the distribution in energy, angle, and charge of particles in the final-state β will be identical for the two processes at the same invariant mass of β.

vi) Test of Current Commutation Relations

The recent success of the Adler-Weisberger[12] sum rule relating the axial vector coupling constant renormalization in β decay in terms of off-mass-shell pion-proton total cross section has given greater credence to the use of current commutation relations in deriving further relationships. Adler and Gilman[13] have recently

used the same technique to relate total neutrino and antineutrino cross sections to the Fermi coupling constant, G, and the Cabibbo angle, θ_c, namely

$$\lim_{E_\nu \to \infty} \left\{ \frac{d\sigma_T}{d(q^2)} (\bar{\nu} + p \to \beta(S=0)) - \frac{d\sigma_T}{d(q^2)} (\nu + p \to \beta(S=0)) \right\} = \frac{G^2 \cos^2 \theta_c}{\pi}$$

Adler further investigated the manner in which the above limit is reached and, noting that $\sigma(\bar{\nu}\, p) = \sigma(\nu\, n)$ for $q^2 = 0$, deduced

$$\left. \frac{d\sigma_T}{d(q^2)} (\nu + n \to \beta(S=0)) - \frac{d\sigma_T}{d(q^2)} (\nu + p \to \beta(S=0)) \right|_{q^2 = 0}$$

$$= \frac{G^2 \cos^2 \theta_c}{2\pi} (1 + F_1 (E))$$

where $F_1(E)$ is a monotonically increasing function which reached 90 percent of its asymptotic value of unity for energies $E > 2$ BeV. This relation is expected to be valid to approximately 5 percent in this higher energy region. It has been estimated that about 2 percent of all events would have lepton momentum transfer less than one pion mass, and about 80 percent of all events would have neutrino energies above 5 BeV. Therefore this prediction of the current commutation relation can be tested in quite a meaningful manner with the 25-foot chamber at Batavia.

II. Strong Interaction Experiments

A. INTRODUCTION

Studies of strong interactions in the 25-foot bubble chamber are discussed below in four sections: 1) Search for new short-lived particles, 2) Hyperon interactions, 3) High energy interactions, and 4) Summary.

B. SEARCH FOR NEW SHORT-LIVED PARTICLES

Bubble chambers are uniquely and ideally suited for searching for and identifying new short-lived particles in the lifetime region $\sim 10^{-10}$ sec. The 200-BeV accelerator opens up a new range of possibilities for the production and subsequent discovery of such particles, whether predicted or not. In the past, the strange particles were discovered in cosmic-ray interactions in cloud chambers and nuclear emulsions through general experimentation, whereas the Ξ^0 and Ω^- were searched for and found because of prior theoretical predictions about their existence. Surely the future will hold exciting discoveries of new particles at this accelerator. Decay lengths of a millimeter to a meter, a range ideally suited to bubble chambers, correspond to lifetimes in the range 10^{-13} to 10^{-10} sec. This is the lifetime range of many currently known particles. The large volume high-field cryogenic chamber proposed here will allow the isolation and unique identification of even a single example of such new particles, such as was done in the past for the Ξ^0 and Ω^-. This one aspect of high energy interactions will itself be important enough to warrant the construction of such a chamber.

C. HYPERON INTERACTIONS

With currently known experimental techniques, the only way to make detailed studies of hyperon interactions is to measure the secondary interactions of hyperons produced in a bubble chamber. This type of study will be most profitable for high hyperon momenta since the long decay lengths allow a useful total hyperon path length to be accumulated. For example, at 25 BeV/c, the mean decay length of a Λ is 1.8m, of a Σ^- 1.0m, and of a Ξ^0 2.3m. A large chamber is essential for

such experiments since for each event the hyperon must be produced, interact, decay, and still leave enough path length in the chamber for measurement of the decay products. A typical length for each step is a meter or more, thus requiring a very long chamber in order to observe with high probability each link in the sequence.

Some hyperon reactions which may be studied with good statistics are $\Lambda + p$, and $\Sigma^{\pm} + p$ elastic and inelastic scattering. Diffraction scattering has been of great theoretical interest for the past several years. Also, there are many inelastic channels, and it is difficult to predict which will be dominant. Reactions like $\Lambda + p \rightarrow \Sigma^{+} + n$ are particularly interesting in order to complete the determination of the two-body scattering matrix among members of the nucleon octet.

A good source of high momentum hyperons consists of high energy proton collisions. With several incident tracks per pulse, there will be a useful hyperon interaction in a reasonable fiducial volume in every fifty or so pictures. In exposures of a few hundred thousand pictures, several thousand events can be obtained— numbers comparable to those usually analyzed in present-day bubble chamber experiments with the long-lived particles.

D. HIGH ENERGY INTERACTIONS

The problem of kinematic analysis of events at high energies in large bubble chambers has been examined by several authors.[14] They show that a complete kinematic analysis is possible for the events created by beam particles of accurately known momentum where all the secondaries are charged particles with transverse momenta of the order of their rest masses or less and with measured lengths of the order of one meter. If there is even one missing neutral, there will very often exist ambiguities among several mass hypotheses which are consistent with the measurements. If there are two missing particles, the missing mass has a continuum of possible values. Thus, in order to analyze high energy interactions fully, all the secondaries must be detected.

The majority of high energy interactions produce one or more π^{o}'s

or γ rays. In order to analyze these events, it is necessary to detect the γ rays. Some will convert in hydrogen, but for higher detection efficiencies the use of neon or a set of plates is necessary as discussed elsewhere in this report.

The increased accuracy of momentum measurements in the large chamber and 40-kilogauss magnetic field will greatly reduce the ambiguities due to wrong mass assignments. Particles originating near the center of the chamber cannot escape through the sides if they have a momentum less than 1500 MeV/c and are not nearly parallel with the field, since they make complete turns inside the chamber. Many secondaries will be trapped, yielding unambiguous mass determinations for these particles. Many more neutral particles will decay or interact in the large chamber, and secondary interactions of these neutrals as well as charged particles will help in their identification. The longer track lengths will give increased information on bubble density for slower particles, and fast particle tracks can sometimes be identified by their energetic δ rays. In addition, some tracks, especially electrons, will be identified by their rate of energy loss. The trapping of protons to 1500 MeV/c has a special application to high-resolution missing-mass (MM) experiments. For momentum transfers as large as 1 $(\mathrm{BeV/c})^2$, the proton will stop and be accurately measured. Therefore studies can be made of $\pi^{\pm}p$, $K^{\pm}p$, $p\bar{p}$, $pp \rightarrow p + MM^{\pm}$ with a mass resolution for the recoiling mesonic or baryonic state of a few $(\mathrm{MeV/c})^2$. The interest and importance of such experiments in the study of the masses, widths, and decay modes of such states have recently been demonstrated in bubble chambers in studies of the "splitting" of the A_2, i.e. resolving the A_2 meson into two states, as was first observed by counter techniques.

Most strong-interaction experiments at the 200 BeV accelerator will probably be done in the 10- to 100-BeV region, where separated beams of $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$ appear feasible. However, some experimental studies will certainly be made, especially with π^- and p beams, to the highest available machine energies.

E. SUMMARY

Exciting discoveries of new short-lived particles will be made. Single examples of such particles will be identifiable due to the characteristics of the bubble chamber. Bubble chambers have been the major source of information for studying the detailed properties of resonances and will be used for the extension of these studies to higher masses and higher energies. The unbiased detection of particles, as provided by bubble chambers, is of great importance when searching for new processes, and the real strength of a large chamber lies in its ability to have in one instrument many different aids in sorting out the details in nuclear processes. In the same chamber we may see the basic interaction in hydrogen, make accurate momentum measurements, observe many secondary interactions, trap many secondaries, detect neutrons and gamma rays, make visible the decay of charged and neutral particles, and measure bubble density and rate of momentum loss. All of these aids in the identification of particle masses make this a most versatile and useful detector. Furthermore, by using hydrogen-neon mixtures, or by placing a hydrogen or deuterium target in hydrogen-neon mixture chambers, or by using sets of plates, new gains can be expected in the ability of a large chamber to detect gamma rays so that processes involving neutral secondaries can be explored in detail. A large-volume bubble chamber will be a very essential part of the exploitation of the opportunities created by the new accelerator facility. Full and well-rounded utilization of this facility requires a large bubble chamber.

III. Other Considerations Concerning the Use of Large Bubble Chambers at the 200-BeV Accelerator

Most high energy physicists are confident that by 1973 advances in physics and proper utilization of the 200-BeV accelerator will require a large cryogenic bubble chamber as is proposed in this document. This chamber will open important new fields of study, e.g. neutrino and hyperon interactions, and will allow the extension of present studies of resonances and production mechanisms to the higher energies made available by the accelerator. Some considerations and requirements which determine the parameters for the chamber are given in the following sections.

A. SIZE AND MAGNETIC FIELD

One of the most compelling reasons for the large volume of this chamber is to have an adequate neutrino interaction rate, because many different neutrino and antineutrino experiments using hydrogen, deuterium and neon chamber fillings can be carried out. The interaction rate should be sufficient so that only part of the accelerator intensity or running time is needed to perform these experiments since it is important that other experiments can run simultaneously or in short succession. The chamber volume arrived at in studies of neutrino facilities for 200- to 300-BeV proton accelerators has been ~100,000 liters. The volume of the proposed chamber is 105,000 liters of which 72,000 liters are viewed simultaneously by three cameras, providing photographs on 70mm film with a demagnification of 75 in the beam plane. It is possible to view a greater fraction (82,000 liters) of the total volume if a greater demagnification (170) is used; however, this extreme demagnification is highly undesirable. For a given chamber volume, the efficiency of a chamber for neutrino detection increases with its aspect ratio (length divided by average width or height, assuming width and height are approximately equal). Take the example of an aspect ratio of 3:1; then about 40 percent more neutrino-produced events can be expected than for an aspect ratio of 1:1. This is an important advantage of larger aspect ratios or oblong chambers over other possible chamber geometries.

To consider chamber length it is important, for simple events, to think of the chamber as divided into three regions: 1) beam definition (~1 foot), 2) interaction region (6 to 15 feet, depending on cross section and beam intensity), and 3) measuring region (6 to 20 feet, depending on momentum). Note that for high energy it will be a great advantage to have beams with a well-defined momentum and angle. For example, a 50-BeV/c beam with momentum (p) definition $\Delta p/p = \pm 1/4$ percent and angle (θ) definition $\Delta\theta = \pm 0.5$ mrad results in an uncertainty in momentum perpendicular to the beam direction of $\Delta p = \pm 125$ MeV/c and parallel to the beam direction of $\Delta p_{\parallel} = \pm 125$ MeV/c from the unknown beam parameters alone. As mentioned in the report on kinematic fitting by Plano,[14] 4-constraint fits can be made for a $\Delta p_{\perp} \leqslant 40$ MeV/c and $\Delta p_{\parallel} \leqslant 400$ MeV/c. This requires for a 100-BeV particle at least 16 feet of track length. Therefore, a simple 100-BeV event will very often occur in the proposed 25-foot chamber so that a 4-constraint fit analysis will determine the exact details of the interaction. More complicated events involving secondary interactions such as decays or second or third collisions will consume enough available path length that unambiguous fits will be rarer at 100 BeV than for the simple event, but unambiguous fits will still be very frequent at lower energies, say 50 BeV. Of course, in many cases production of secondaries will result in degradation of the energy thus requiring shorter measuring lengths, but this means that sufficient chamber width and height have to be available to accommodate the associated larger deflections.

Required chamber width and height, to a great degree, decrease with beam energy but increase with complexity of events. Especially if electron pair production by γ-ray conversion is to be observed directly in the liquid, width and height must be large. The very promising possibility of developing track-sensitive target chambers immersed in neon-hydrogen mixtures, however, will make the latter requirement unnecessary. Chamber width has to be sufficient to accommodate track azimuthal angles and curvatures and a spaced-out beam. Chamber height has to be sufficient to accommodate track dip angles and in addition has to provide for the extra track length needed for sufficiently accurate curvature measurements even with reduced magnetic field components. In practice, chamber height must be limited for optical and

economic reasons. Aspect ratios between 2:1 and 3:1 have been considered adequate for bubble chamber experimentation at the 200-BeV accelerator.

Once an aspect ratio has been fixed, the cost of a bubble chamber increases approximately with the square of its linear dimensions. Thus, a 35-foot chamber may cost about twice as much as a 25-foot chamber. The cost of filling the chamber, however, increases with its volume or would almost be tripled for a 35-foot chamber. For instance, the proposed 25-foot chamber is to cost approximately $13.6 million, and to fill it with liquid deuterium would cost about $4 million, a total of approximately $18 million. A 35-foot chamber would cost $18 million, deuterium filling $11 million, for a total of $29 million. Certainly a larger chamber (disregarding eventual optical limitations) would frequently accommodate still more energetic or complex events but economic considerations, especially under present circumstances, seem to dictate acceptance of a chamber size that is not larger than is considered to be completely useful.

Other considerations which enter into the choice of the chamber shape are:

a) The advisability of photographing a very large fraction of chamber volume with each individual camera, which avoids camera systems requiring more than three cameras. The 18-foot central sphere of the tri-spherical design locates the 140° lenses sufficiently high for this purpose.

b) The need to minimize optical distances in the liquid that are used for photography. This is accomplished best in oblong chamber designs. The 7-foot test facility will give data on optical turbulence while simulating the 25-foot chamber optical distances.

c) The availability of sufficient space to add plates, track-sensitive target chambers or counters for special purposes, such as detection of neutrals.

d) Provision for a simple but, in an oblong chamber, effective expansion system that does not detract from the working volume. Again, the 18-foot central sphere makes this possible.

A magnetic field of 40 kG has been chosen for economical reasons. To go beyond 40 kG requires niobium-tin instead of niobium-titanium superconductors, increasing the cost of the magnet considerably. Although

the chamber has an oblong shape the coils are circular, though of minimum diameter, for the following reason. A relatively economical design for oblong magnet coils (racetrack shaped) has been found, but this design remains economical only for the larger aspect ratios which would require more than three cameras for photography. For the chamber shape and optics presented in this proposal, circular magnet coils are less costly and in addition result in greater field uniformity in the chamber. The space between coils and chamber can be made useful for many purposes mentioned below. The large gap between the circular magnet coils gives easy access to the central part of the chamber and to magnet components, permits utilization of a large thin beam window actually located between the coils, and produces a field with very good uniformity.

The design of the chamber is such as to facilitate moving it. This could become necessary for many reasons, for example, orientation of the chamber for various beam entries or actually moving the chamber to a new location if the accelerator energy should be increased from 200 to 450 BeV.

B. VERSATILITY

The 25-foot chamber will be a very versatile particle target and detection instrument. Access to the thin chamber walls will permit many innovations. For example, additional beam entry windows can be placed at almost any point on the chamber as well as spark chambers or counters, according to the demands of the experiment. Easy access to the interior of the chamber will allow installation of plate arrays or track-sensitive hydrogen or deuterium targets. The design of the 25-foot chamber includes multipulse operation. It will be able to pulse at least once every 150 msec during one accelerator cycle. In a report by J.R. Sanford,[15] as an example of desirable operation, a triple pulse mode is proposed where one beam burst occurs at the beginning of a 1/2 sec flat-top, followed by one in the middle and, finally, one at the end of the slow beam spill.

The above examples of specific advantages of the proposed 25-foot chamber design must be added to the general advantages of cryogenic bubble chambers. These chambers provide enormous versatility. They operate with the simplest target nuclei, namely protons, deuterons, or

admixtures of nuclei of neon which enhance the probability for detection of neutral particles. A magnetic field is present everywhere in the chamber, providing momentum measurements in addition to well resolved coordinate measurements on tracks which are formed. Biases are kept to a minimum because no particular selection of event geometry is necessary; a chamber has "4π-geometry." One chamber covers a very large range of beam energies and particles and an almost inexhaustible multitude of experiments which can be proposed and analyzed by a very large number of research groups located anywhere in the United States. This versatility of a large cryogenic bubble chamber complements almost perfectly experimentation with electronic detectors usually requiring a special arrangement for each particular experiment but providing much better time resolution, allowing experiments that require very high statistics or time-of-flight measurements.

C. DETECTION OF NEUTRALS

At 30 BeV only 10 percent of the events do not have missing neutrals. Interactions with one missing neutral particle are difficult to separate from events with more than one. Interactions with more than one missing neutral cannot be analyzed. At higher energies, the situation will become more difficult since the particle multiplicity increases and more neutrals will be produced. Thus, with the high energy that will be available at the 200 BeV accelerator, the detection of neutrals in a bubble chamber will be a necessity for many experiments. For some experiments the detection efficiency in pure hydrogen will be sufficient (see Table Ia, page 31), but other experiments will require higher efficiencies. Three methods are discussed below which can provide for detection of neutrals.

a) The addition of metal plates into a large bubble chamber has been considered in detail in another BNL report.[16] The conclusion is that an array (~15) of thin (0.2 radiation lengths) metal plates could be arranged to cover a large solid angle. Such an arrangement would give a detection efficiency of 80 percent for forward γ rays. The detection efficiency for a forward K_L^o or neutron would be 50 percent but low energy neutrons would be missed since they are produced at large angles. Even so, this technique would suffice for many experiments.

b) Another possibility for detecting neutrals is to use a mixture of hydrogen and neon in the chamber.[17] This method gives 4π solid angle and a detection efficiency that can be varied continuously between pure hydrogen (see Table Ia) and pure neon (99 percent). The limitations of this method are the separation of events on hydrogen from those on neon and the larger multiple scattering error on charged tracks. However for a typical high energy experiment, a 7 atomic percent admixture of neon would give 50 percent of the interactions on hydrogen with a background of "fake" hydrogen events less than 4 percent.[16] The multiple scattering error on momenta would be one percent, which is typical of present day hydrogen chambers. The detection efficiency for neutrals would be about the same as those listed in Table Ib.

c) A new technique that is being developed at CERN and DESY[18] appears to be very promising. It consists of placing inside the bubble chamber a small chamber filled with hydrogen or deuterium and filling the rest of the chamber with a hydrogen-neon mixture. It seems feasible to make both regions sensitive simultaneously. The inner chamber can be constructed by placing Mylar or similar material over a light frame. This technique gives interactions and measurement of charged secondaries in pure hydrogen plus the detection and measurement of neutral particle interactions or decays in the surrounding hydrogen-neon. Table Ib gives detection efficiencies for an inner chamber $0.5 \times 0.75 \times 5.5 m^3$ surrounded by a 30 percent neon—70 percent (atomic) hydrogen mixture.

Any one of the above techniques is sufficiently versatile that many experiments could be performed with the same setup.

Table I. Detection Efficiency of Neutrals

a) HYDROGEN

Particle	Detection	Efficiency	Potential Length
Gamma	Compton, pair production	10-40 %	1.5 - 6.5m
Neutron >150 MeV/c	Secondary interaction with at least 1cm proton	20-50 %	1.5 - 6.5m
K_L^o	Secondary interaction with at least 1cm proton	10-40 %	1.5 - 6.5m

b) HYDROGEN TARGET SURROUNDED BY HYDROGEN-NEON

(e.g. 30% atomic neon, radiation length 70cm; interaction length 250cm)

Particle	Detection	Efficiency	Potential Length
Gamma	Compton, pair production	75-90 %	1.25 - 2.1m
Neutron >150 MeV/c	Secondary interaction with at least 1cm proton	40-60 %	1.25 - 2.1m
K_L^o	Secondary interaction with at least 1cm proton	40-60 %	1.25 - 2.1m

D. USERS

It is expected that 3/4 of the research time of this new facility will be for outside users' groups. Already 33 bubble chamber users' groups have formed and are actively pursuing experimentation in high energy physics. These groups plus new groups from institutions which are developing into new centers of excellence can be expected to propose bubble chamber runs for data which will extend their research into the higher energy region opened up by the 200-BeV accelerator. One of the great values of a large-volume cryogenic bubble chamber lies in the

fact that it greatly enhances the scope and effectiveness of education and research performed by the bubble chamber's user groups. Indeed many of today's high energy researchers received their training in bubble chamber users' groups while their peers who left high energy physics to work in other fields benefited greatly from the breadth and depth of their educational experience. It is estimated that as much as one half of the high energy physics research program at the accelerator will use the bubble chamber technique in a wide variety of investigations. It is, therefore, extremely desirable that the 25-foot chamber be available for supplying the needs of the user groups soon after startup of the accelerator. Beam facilities should include both a ν beam and a high energy separated beam to insure sufficient scope to the program. Of course, first priority has always to be given to maintaining sufficient flexibility to accommodate new ideas for experiments which will advance our understanding of particles and fields.

IV. Data Processing

A. INTRODUCTION

The 25-foot chamber design is unusually well adapted to meet the needs of data processing. The utilization of relatively low distortion lenses of field angle 140° together with the effectively ellipsoidal shape of the chamber permit photographic recording by only three cameras and allow a camera placement to give almost conventional stereoviews of the liquid. In view of the continuing effort to improve the economics and effectiveness of data processing, the possibility of nearly standard technique for recording events on film is a very desirable attribute of the chamber. The photographs produced are expected to be understood readily by human scanners and will probably be as easily dealt with by existing measuring equipment (whether automatic or manual) as can possibly be arranged for a chamber which is to provide the indispensable attributes of extended interaction length and large visible volume.

B. TRACK DATA RECORDING

Photographic film remains the best storage medium for bubble chamber stereoscopic images. It provides the desirable stable interface between the bubble chamber complex and the data analysis system. For the 25-foot chamber, 70mm film will be used to minimize the costs for film and for data analysis hardware. The film format is designed for optimal effectiveness of the data processing. The three nondistorting lenses have been arranged with their optic axes perpendicular to the long axis of the chamber. Non-interacting beam tracks will produce effectively parallel track images on the photographs. The sign of charge of most tracks is determined by their sign of curvature. Present visual methods for matching tracks from view to view and for determining the possible neutral particle connections will apply.

Some characteristic features of the larger chambers are expected to present new data-processing problems. The somewhat unknown optical properties of thick layers of superheated liquid occasion most of these

problems. The choice of conventional data recording will enable the analysis effort to be focused on the fundamental problems.

C. ANL 12-FOOT CHAMBER AND BNL 7-FOOT TEST FACILITY DATA-PROCESSING EXPERIENCE

Within one year and two years, respectively, pictures from the Brookhaven 7-foot test facility and the Argonne 12-foot chamber will have been analyzed. Data-processing developments for these pictures will provide valuable full-scale experience for 25-foot-chamber film processing. These three large chambers each will have about the same depth of liquid. Each is designed for use of 70mm film and Scotchlite bright field illumination. The ranges of film-to-chamber magnifications are similar.

A major design difference in the chambers under construction is the Argonne choice of 60 percent distortion lenses and the Brookhaven choice of 1 percent distortion lenses. The Argonne lenses will map approximately equal volumes of the chamber onto equal areas of the film. However, the lower distortion lenses should produce photographs that are easier to analyze. A significant difference between the 25-foot chamber and the Brookhaven 7-foot test facility is in the field angle of the lenses (140° vs. 90°).

Only two changes may be required to extend the present Brookhaven data processing system capability to 7-foot-chamber film: (1) The geometry program must be modified to reconstruct events recorded by cameras with non-parallel optic axes; a subsidiary problem here is the development of methods for determination of optical constants. (2) The scan table magnification must be increased, probably from ten to twenty.

An important question, perhaps the main question about all large chambers from the point of view of data extraction, is the contrast which can be achieved for bubble images on film, especially for tracks distant from the cameras. Fortunately, the 7-foot test facility and the Argonne chamber will show what contrast can be achieved. The good picture contrast obtained using the Brookhaven 31-inch Scotchlite-illuminated chamber is encouraging in this regard.

D. DATA EXTRACTION

Several methods for extracting track data from the film and preparing it for input to a geometry program are available. Good facilities for manual scanning must still be provided, and the possibility of convenient image-plane digitizing at the scan table probably should be preserved. Existing automatic measurement systems will be applicable to the 25-foot-chamber film if contrast problems are not too severe. Computers will probably continue to expand their role in data extraction; the film from the proposed chamber should be well suited to any of the improvements currently being considered.

a) Manual Scan

The 25-foot-chamber photographs are designed to be readily understood by human scanners working with modified versions of existing scanning projectors. Although the eye can resolve one minute of arc, visual scanning of existing bubble images occurs at two to three minutes of arc (20 to 30 micron film images, scan table magnification of ten, and 30cm distance). A magnification increase from the present ten to the value of twenty should be adequate for the 10 micron film images expected from the large chamber if higher quality lenses are used at the scan table to achieve the needed resolution. The 25-foot-chamber images projected at 20:1 magnification would be one third full scale at the beam plane. The full chamber image projects up to 4.5 feet wide by 7.5 feet long on the table.

It is felt that the scanner can have sufficient lateral mobility for close inspection of detail at any point across the width of the image. (The Nuclear Interactions Group at Brookhaven uses scan tables for 80-inch-chamber film with the scanner seated at the side. Satisfactory scanning performance is achieved for a projected chamber length about six feet "wide.") Many existing scan tables for the LRL 72-inch chamber and the BNL 80-inch chamber have platen motions along the beam direction. This feature would be adopted for the large chamber to enable the entire 7.5-foot-long image to be moved towards the scanner for close inspection. For optimal use of the film width, sprocket holes would be run along only one edge and at a reduced

density. Present film transport designs could be used with some modification.

b) Image-plane Digitizers at the Scan Table - Measuring Projectors

The scanning-projector operator will be able to move the 7.5-foot-long 25-foot chamber image along the beam direction for closer inspection and digitization. Several inexpensive ways to digitize the displaced image are available.

To achieve the current space-point precision from image-plane digitizers, the scan table precision must be doubled. At least for the "rough" digitizers which are part of flying spot digitizer systems, such an improvement is feasible and inexpensive. Existing manual measuring projectors will be able to extract data from the 25-foot-chamber film. Film measurement accuracies of about one micron will be desirable. Track followers can probably be improved to yield this accuracy.

c) Automatic Measurement

The application of the present automatic measurement systems (FSD, Spiral Reader, POLLY, PEPR) to 25-foot-chamber film provides the benefits of a greater number of measured events and automatic bubble density measurement. Secondary particles of momentum up to ~2 BeV/c will frequently be trapped in the large chamber and this phenomenon offers some interesting experimental possibilities. The particle trapped will in general be identifiable either by its behavior on stopping or by its rate of energy loss. In special cases it may prove possible to measure cross sections for certain types of interaction by the secondary particle as a function of its energy. For such experiments, the measuring system should handle a number of spiral turns.

d) Automatic Scan Plus Measurement

The responsibility for measuring is being transferred from people to computers. This transfer may in the future be possible for scanning also. Designs for new and faster digitizers are available. These machines could extract track coordinates fast enough to digitize several million pictures per year. As with present digitizers, the

very short (stub) tracks are likely to be poorly digitized. Coordinate-organizing programs for computer scanning are beginning to work well enough to encourage the study of computer-assisted scanning: a manual recovery of incompletely recognized events and the "sub-digitizer" tracks would be provided. A computer of the class of the CDC 7600, with extended core storage, would begin to compete favorably with unassisted manual scanning costs and performance. Since the 25-foot-chamber photographs are designed for standard visual understanding, the computer-assisted scanner would not find the fixup of events unduly strange and complicated. Automatic extraction (scan plus measurement) might make feasible some experiments presently impossible because of unavoidable random visual scanning biases.

D. LATE STAGE DATA PROCESSING

Processing of the extracted track data with digital computers has become more standard in recent years. The development of faster scientific processors and the use of FORTRAN language to move up to them has encouraged more thorough analysis of each event without added cost.

a) Geometrical Reconstruction

Geometrical reconstruction of events for the large chamber will be simpler than for the 7-foot test facility because the camera axes will be more nearly parallel. Since synthetic tracks have already been adequately reconstructed for the 7-foot case, there should be no basic difficulty in geometry.

Random distortions introduced by photographing through a thick layer of liquid hydrogen may require the measurement and geometry processing of fiducial marks near each of the tracks. Some of the automatic measurement systems are able to measure many fiducial marks routinely, so this problem can be studied and any systematic behavior included in the geometry program distortion correction routines; the number of fiducial marks to be measured for each event might then be reduced.

The use of track matching in geometry programs is increasing. As an example, this capability of the Brookhaven geometry program is

able to do a significantly better job than a measuring-projector operator for the case of four-prong events from 29-BeV/c protons incident on the 80-inch hydrogen chamber. Track-matching by computer program will certainly be important for exposures at NAL energies.

b) Kinematic Fitting

Conventional kinematic fitting will have more limited application in event identification at NAL energies because the fraction of events with more than one unseen neutral particle will approach unity. However, the technique currently under development of a central target-chamber containing pure hydrogen or deuterium, surrounded by a neon-hydrogen mixture for detection of neutrals, is expected to provide an effective extension of event-identification capability. The size and shape of the 25-foot chamber make it well suited to the new technique. In addition, the trapping of charged particles by the magnetic field, mentioned earlier, will aid in event identification.

Recent advances in kinematic analysis programs at Brookhaven have shown that automatic "event type" routines save a considerable amount of computer time (especially if bubble density measurements are available to block unwanted fits) and still allow the desired physics control. Also, "clusters" of vertices which may be related by neutral linkages are reduced to separate "events" by this program. These features will certainly be desirable at NAL energies. Automatic event identification, especially with bubble density measurements, is important for high statistics experiments where the number of events precludes their individual examination by the physicist.

F. SUMMARY

The relatively conventional camera arrangement and film format provided by the 25-foot-chamber design should make possible effective and economical solutions to the problem of data processing. The pictures should be readily understood by scanning personnel. Minimal modifications should be required for existing hardware and program systems whether the data extraction is automatic or manual. The photographs should also be well suited for data extraction by new

techniques currently under development and being considered for development.

The principal unknowns in the design which affect data processing are: (1) the contrast obtainable for distant tracks, and (2) the distortions which may result from photography through thick layers of liquid. On both questions, the BNL 7-foot test facility and the Argonne 12-foot chamber will provide full-scale tests.

The 25-foot-chamber geometry is well suited to the use of an inner target-chamber of hydrogen or deuterium and a surrounding volume of neon-hydrogen mixtures; such hybrid chambers are expected to become increasingly important for event identification especially at NAL energies.

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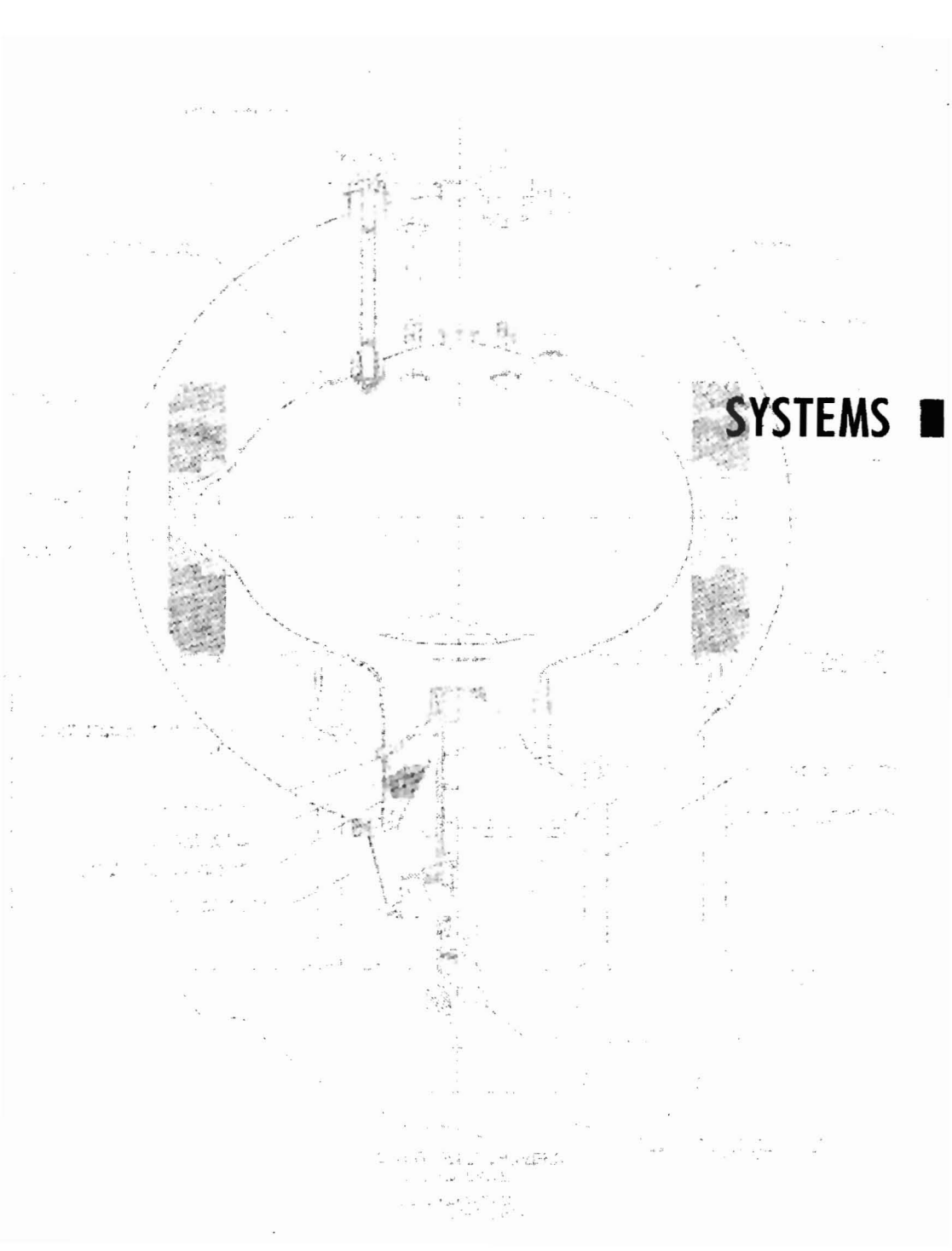


SYSTEMS

3. SYSTEMS

I. Chamber Body and Vacuum Tank

A. INTRODUCTION

This section covers the two principal vessels of the assembly, the chamber body and the vacuum tank.

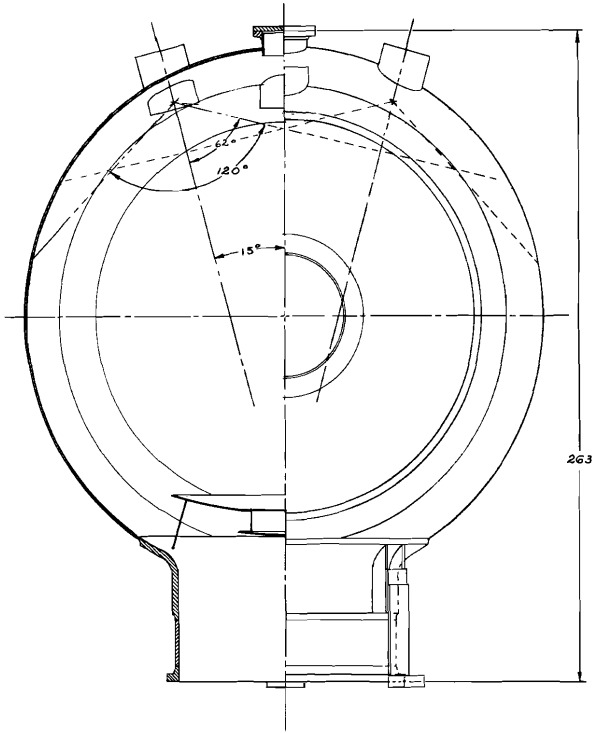
In order to satisfy the requirements for physics experiments, provide efficient use of the wide-angle lenses and adequate space for the expansion system, the chamber body has been chosen to be a 25-foot-long vessel composed of three spherical sections with a thin-walled spherical beam window at one end. Identical windows can be added at other locations if required. The principal dimensions of the chamber body and the field of view covered by the optics are shown in Fig. 2. The total volume of expandable liquid in the chamber is 105,000 liters with 72,000 liters visible to three cameras simultaneously.

The vacuum tank provides the necessary vacuum insulation for the chamber and the superconducting magnet. It also serves as a containment vessel in the case of an accidental spill or pressure buildup within the system. The vacuum tank also provides a mounting base for the internal assemblies and has feed-throughs for instrumentation, controls, and cryogenic fluid lines.

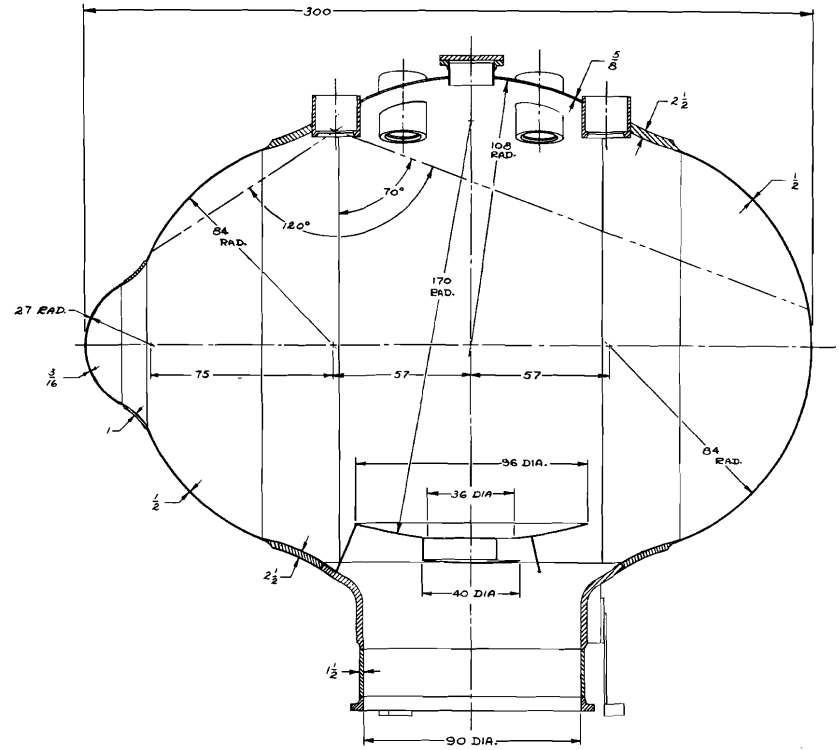
B. DESCRIPTION

a) Chamber

The chamber is a cryogenic pressure vessel designed for an internal working pressure of 200 psi based on room temperature mechanical properties; thus the increase in strength at low temperature increases the margin of safety of the design. The basic shell thicknesses are determined from the requirements of the ASME Unfired Pressure Vessel Code. Reinforcements not covered by the code are determined by a detailed discontinuity analysis of the sections involved.



25 FT. BUBBLE CHAMBER
CHAMBER ASSEMBLY
FRONT ELEVATION



25 FT. BUBBLE CHAMBER
CHAMBER ASSEMBLY
SIDE ELEVATION

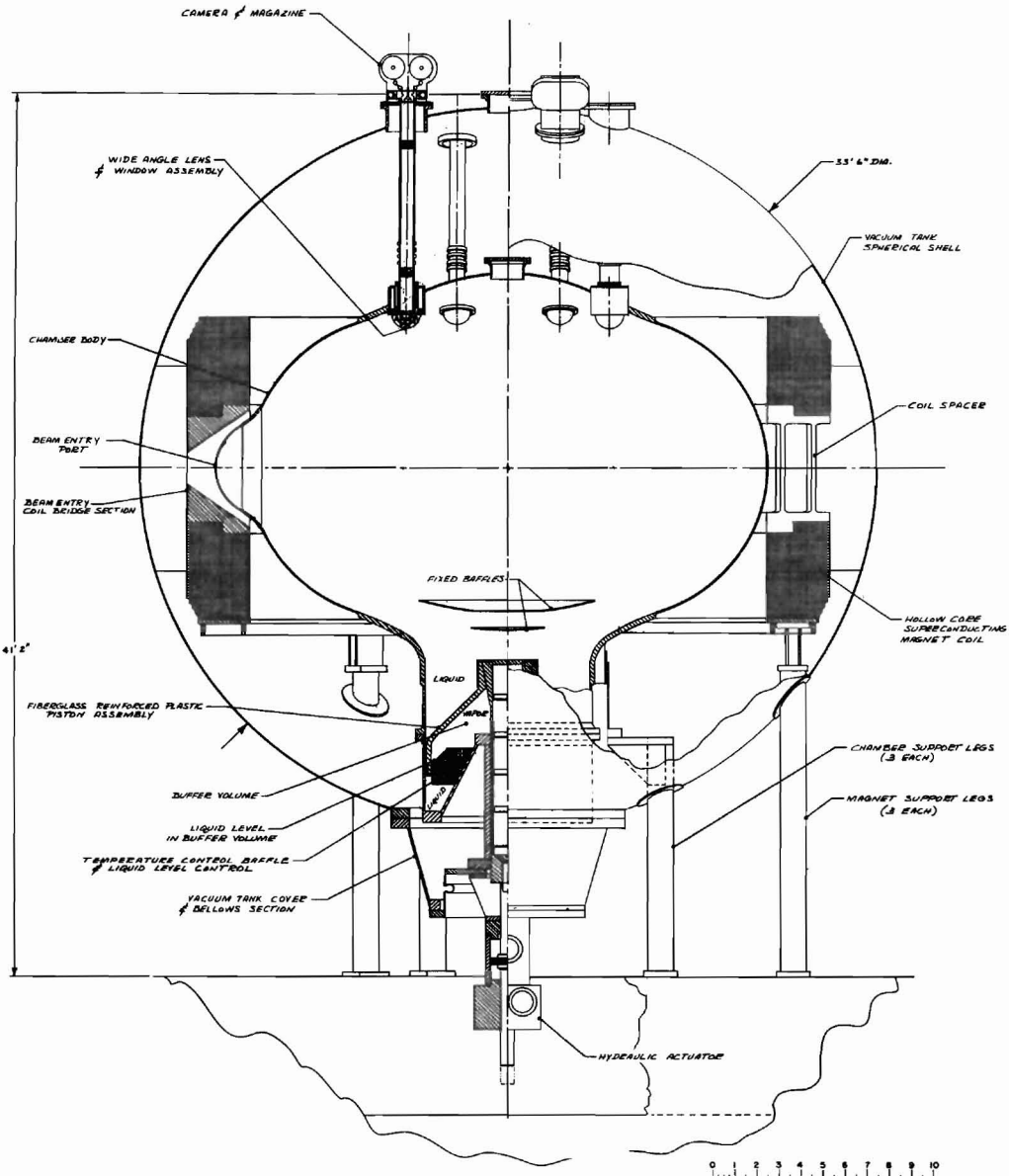
FIG. 2

The vessel is constructed of Type 316L stainless steel. This material has excellent low temperature mechanical properties, good resistance to martensite transformations, and can be readily fabricated by welding with filler metal of the same composition. Fabrication welds are subject to 100 percent radiographic inspection according to the ASME Unfired Pressure Vessel Code. In order to reduce the cost of the vessel, it is planned to eliminate large diameter flanges in the design. Fabrication is in three pieces consisting of the two 14-foot-diameter spherical sections for each end and the 18-foot-diameter spherical center section with the expansion cylinder attached. These pieces are small enough to be shipped to the assembly site and then welded together.

b) Vacuum Tank

The vacuum tank consists of an upper spherical shell with a lower support section and closure as shown in the main assembly drawings and assembly isometric, Figs. 3, 4 and 5. The basic shell thickness is determined by the external pressure requirement for an evacuated vessel plus any magnetic forces superimposed on the vessel. Such a shell adequately serves as a protective pressure vessel since the internal pressure requirement of 200 psi without exceeding two thirds of the ultimate strength is more than satisfied when the design is based on the external pressure requirements. The choice of the material for the vacuum tank is determined by the ability to withstand exposure to cryogenic fluids without becoming embrittled and by economy of construction. At present two possible materials are under consideration, 9 percent nickel-steel and 5083 aluminum, both of which appear to fulfill the functional requirements with low construction cost. The final choice depends on a more detailed engineering and cost analysis. The present cost estimate is based on the assumption of using 9 percent nickel-steel for the shell. A non-magnetic material is required for the support structure; thus stainless steel, austenitic manganese steel, or aluminum may be used. The present cost estimate is based on a stainless steel support structure similar to that used for the 7-foot test facility.

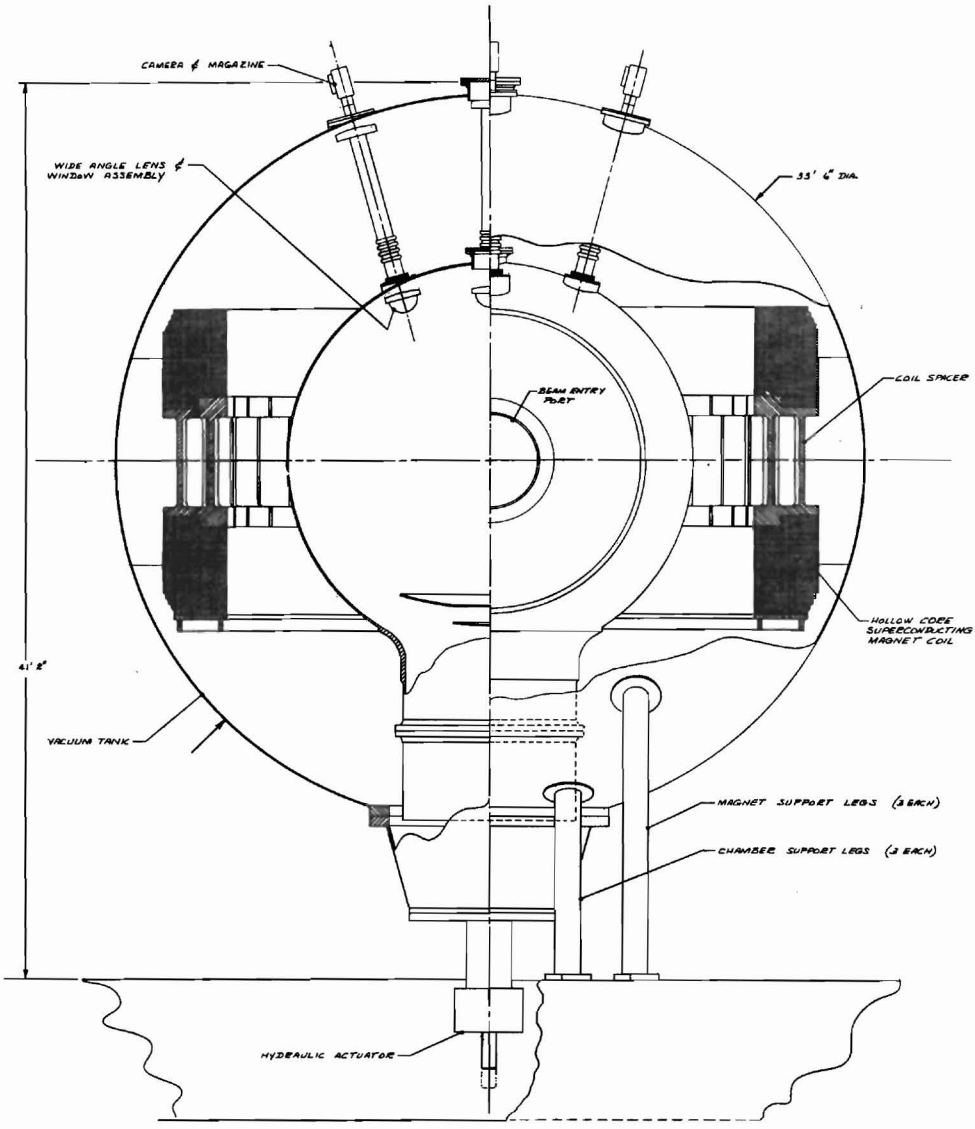
Because of the size of the vacuum tank, it will be necessary to field-fabricate the vessel at the assembly site. It is proposed that



25 ft BUBBLE CHAMBER
MAIN ASSEMBLY

SIDE ELEVATION
SECTIONED VIEW

FIG. 3



25 FT. BUBBLE CHAMBER
MAIN ASSEMBLY

FRONT ELEVATION
SECTIONED VIEW

FIG. 4

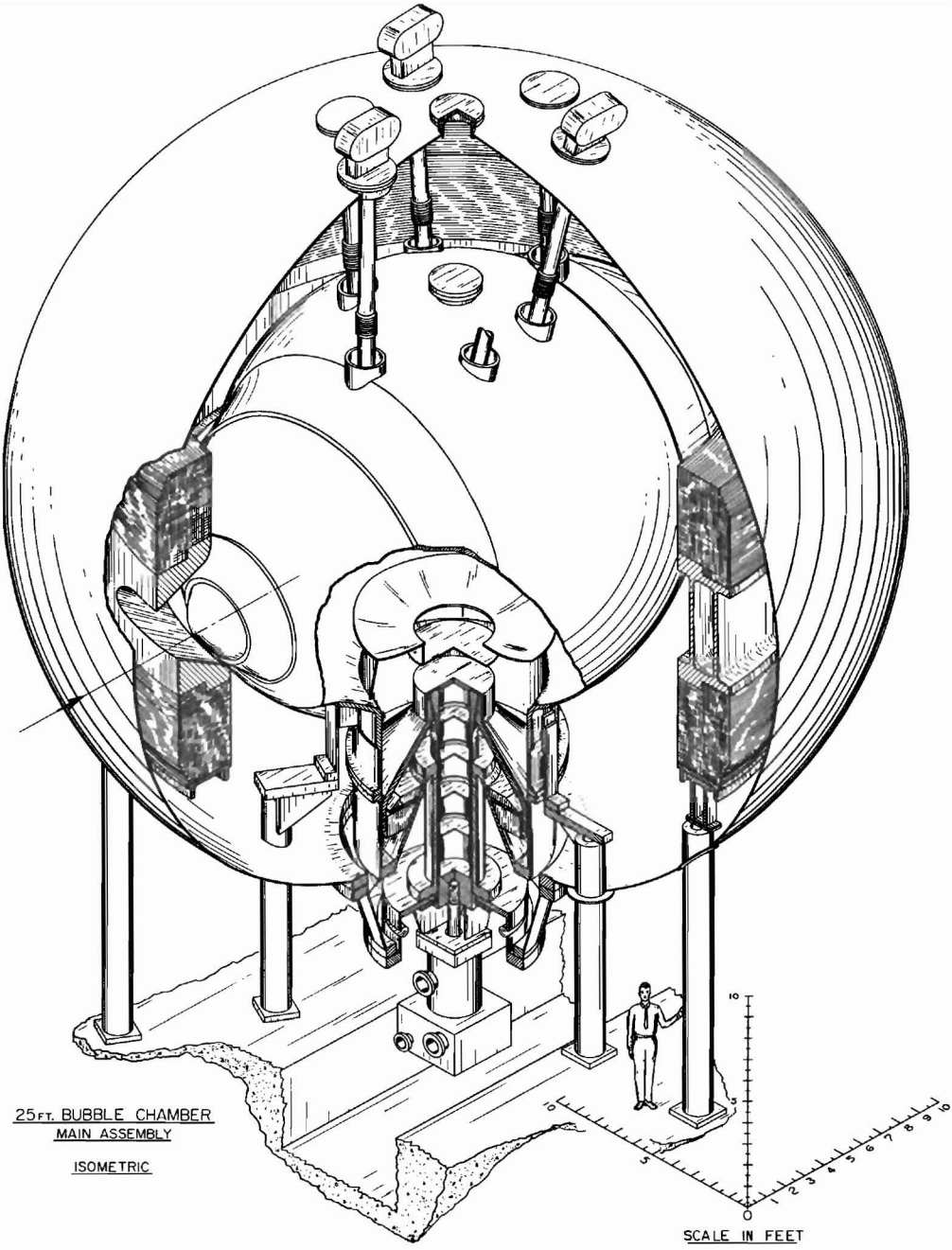

25 FT. BUBBLE CHAMBER
MAIN ASSEMBLY
ISOMETRIC
SCALE IN FEET
0
5
10
1 2 3 4 5 6 7 8 9 10

FIG. 5

the shell be constructed in two halves, the upper hemisphere and lower support section. After the internal components have been installed, final assembly will involve welding the equatorial seam. Should it become necessary to remove and reinstall a large internal component, the equatorial seam could be cut and rewelded.

II. Expansion System

A. INTRODUCTION

Expansion of the 25-foot cryogenic bubble chamber is accomplished by a 90-inch-diameter, nonconducting fiberglass-reinforced plastic piston in contact with the chamber liquid. The piston is located at the bottom of the chamber and is connected to a high-response hydraulic actuator as shown in Figs. 3, 4 and 5 (pages 46, 47, 48). This expansion system is virtually the same as the Title I design for the previously proposed BNL 14-foot Cryogenic Bubble Chamber Project and is more fully discussed in the Title I Report, BNL 10700.

B. DESCRIPTION

For the 25-foot chamber, the piston diameter has been increased to 90 inches from 84 inches for the 14-foot chamber. A series of fixed spherical baffles are used to direct the liquid in and out of the expansion system and to provide for mounting Scotchlite for illumination.

A considerable amount of research and development work on the large chamber expansion system was employed in the construction of the 7-foot test facility which uses an approximately half-scale version of the proposed design. A description of the 7-foot test facility expansion system is given in BNL 11810, 14-foot Cryogenic Bubble Chamber Research and Development Program, The 7-foot Test Facility. Fig. 6 shows the 42-inch-diameter fiberglass-reinforced plastic piston for the 7-foot test facility. In this view the piston is being pre-assembled into the cylinder section of the 7-foot chamber. These components are approximately half-scale versions of those proposed for the 25-foot

FIG.6

chamber. The high-response hydraulic actuator for the 7-foot system is shown in Fig. 7. This unit contains a 10-inch-diameter hydraulic cylinder and a built-in 5-inch-diameter high-response spool valve. The piston rod is supported at both ends by externally pressurized hydrostatic bearings. The unit is scaled up in size to an 18-inch bore with a 12-inch-diameter spool valve for use in the 25-foot bubble chamber. Table II lists the expansion system parameters for both the 25-foot chamber and the 7-foot test facility.

Table II. Chamber and Expansion System Parameters

	25-foot Chamber	7-foot Test Facility
CHAMBER		
Total chamber volume	105,000 liters	9,400 liters
Piston diameter	90 inches	42 inches
Piston area	6,362 sq in	1,385 sq in
Stroke for 1% expansion ratio	10 inches	4.2 inches
Normal chamber spring constant	62,660 lbs/inch	32,500 lbs/inch
Dynamic Mass		
FRP piston	2,840 lbs	635 lbs
Hydraulics	1,400 lbs	350 lbs
Expansion cycle time		
Normal	0.083 sec	0.055 sec
With 50% greater spring constant	0.068 sec	0.045 sec
Maximum normal piston velocity at 1% expansion ratio	31.5 ft/sec	24.2 ft/sec
Maximum normal piston acceleration at 1% expansion ratio	74 g	71 g
HYDRAULIC ACTUATOR		
Bore	18 inches	10 inches
Stroke	24 inches	10 inches
Rod diameter	8 inches	5 inches
Displacement/stroke	8.83 gal	1.07 gal

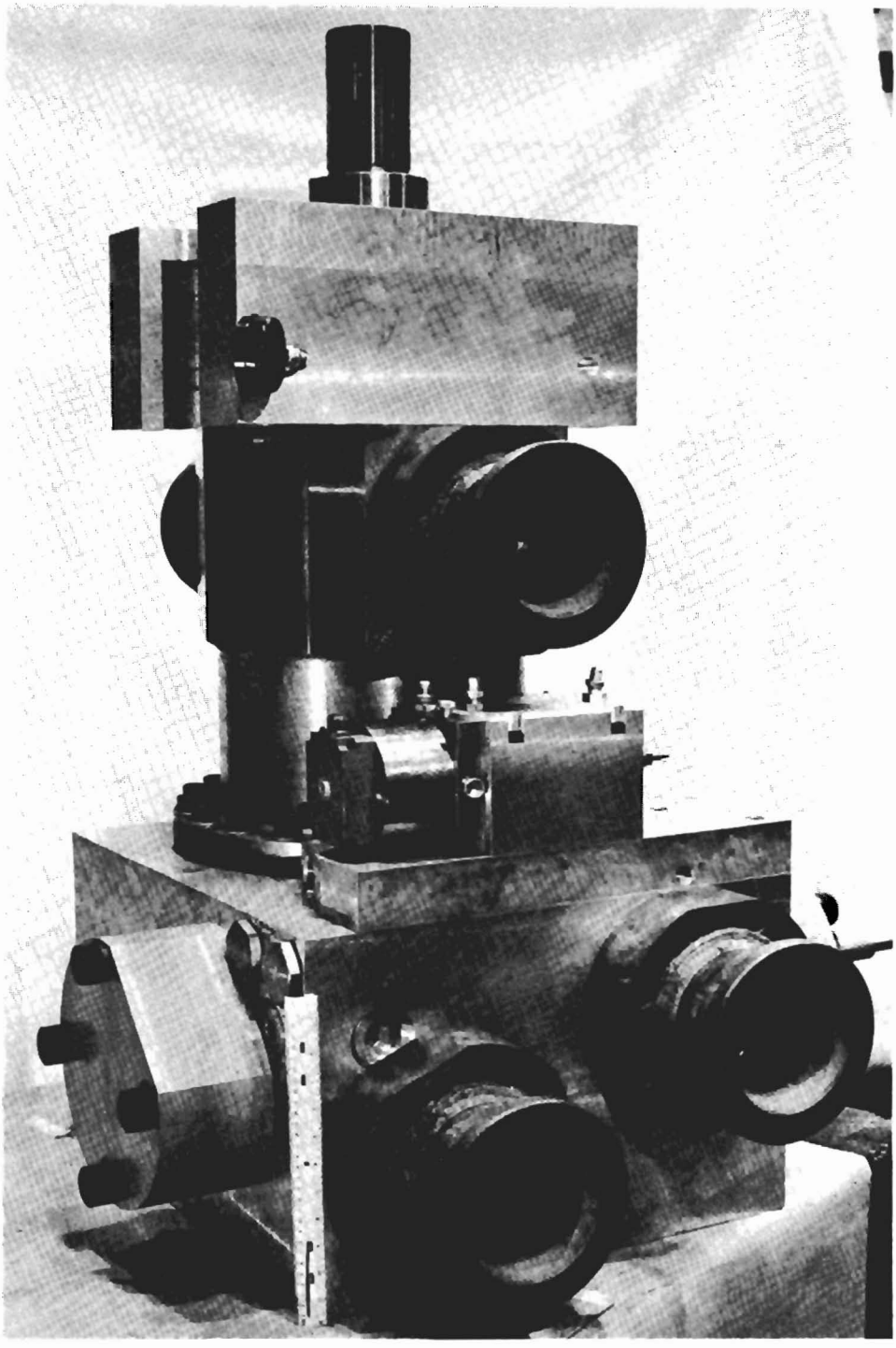


FIG. 7

	25-foot Chamber	7-foot Test Facility
Piston area	196 sq in	58.9 sq in
Pressure rating	3000 psi	3000 psi
Bearings	-Externally pressurized (both ends) -	
Third stage spool valve		
Type	- 3-way closed center -	
Diameter	12 inches	5 inches
Flow rating, pressure drop	27000 gpm at 200 psi	4400 gpm at 200 psi
Traverse time	0.017 sec	0.011 sec
HYDRAULIC SYSTEM		
Power supply		
Fluid	- Phosphate ester "Cellulube 150" -	
Maximum pressure	1500 psi	3000 psi
Maximum delivery	550 gpm	100 gpm
Power requirement	660 hp	250 hp
Filtration	10 micron	10 micron
Reservoir capacity	600 gal	250 gal
Auxiliary power supply	40 gpm at 3000 psi	Not required
ACCUMULATORS		
Expansion accumulator (2500 psi)	8 ea., 20 gal	4 ea., 5 gal
Recompression accumulator (2500 psi)	4 ea., 20 gal	2 ea., 5 gal
Buffer accumulator	4 ea., 20 gal	2 ea., 5 gal

III. Refrigeration

A. INTRODUCTION

Refrigeration is required to cool and fill the chamber and to provide temperature control during operations. Since liquid hydrogen boils at ~20°K, all of the equipment is termed "cryogenic" and must

satisfy the special criteria for operation at very low temperatures. A separate helium refrigeration system is required for operation of the superconducting magnet with an operating temperature of ~4.5°K. The chamber's hydrogen system is normally used at ~25°K and the capacity of the refrigerator is outlined in Table III, page 56. It also liquefies the gas that is used as the chamber working fluid. Refrigeration requirements for the helium refrigerator are shown in Table IV, page 57. Its capacity is based on using a supercritical stream of helium circulating through the hollow-core superconductor to remove the estimated heat inputs. In addition, a liquid nitrogen supply system is provided for precooling equipment and supplements the refrigerant in the hydrogen and helium systems.

B. DESCRIPTION

a) Nitrogen System

The liquid nitrogen supply system consists of a 20000 gallon liquid nitrogen storage vessel and a distribution system. The liquid nitrogen is channeled through vacuum-jacketed transfer lines to the hydrogen and helium refrigerators and other components requiring liquid nitrogen temperature cooling. In the refrigerators, both the latent heat of vaporization and the heat capacity of the nitrogen gas are used to precool either the hydrogen or helium gas streams. In some cases, where the liquid nitrogen is used to cool a radiation shield or to reduce conduction losses, only the latent heat of vaporization is used. The peak consumption of liquid nitrogen will occur during the cooldown of the chamber and magnet structure when the nitrogen will be used to cool the hydrogen and helium gas streams which are circulated through the chamber and magnet during the cooling process.

b) Hydrogen Refrigerator

The hydrogen refrigeration system requires the use of carefully engineered equipment, piping, and controls to operate properly for several months at a time. The hydrogen is first compressed to an elevated pressure (~30 to 60 atms) after which it passes through successive heat exchangers until it is ≤ 35°K when it is expanded to some lower pressure (1 to 8 atms) resulting in a lower temperature where

a portion of the flow becomes liquid. During the passage through the heat exchangers, some of the heat of the gas is removed by boiling liquid nitrogen and by the nitrogen gas generated. A fraction of the high-pressure flow is diverted through a work-producing expansion device such as a reciprocating engine or a turbine. In producing work, the gas is cooled and is then returned to the compressor through exchangers where it removes heat from the incoming high-pressure gas stream. At the cold end of the refrigerator, the unliquefied portion of the incoming gas stream is also returned to the compressors by passing through all of the heat exchangers where heat is removed from the incoming stream. The liquid formed is diverted either into storage or through cooling passages in the chamber body. The heat generated in the chamber is removed by vaporizing the liquid flowing in the cooling passages. The cold gas thus generated is also returned through the heat exchanger system. The amount of fluid flowing in any cooling passage or temperature control loop is controlled so that all of the liquid entering is vaporized and also that the temperature of the gas leaving an individual loop is not significantly higher than the temperature of the liquid entering. Only the latent heat of vaporization is used to control the temperature of the chamber.

The hydrogen system also has the capability of producing the liquid used in the chamber proper. Depending on experimental requirements, this might be hydrogen, deuterium, neon, neon-hydrogen mixtures, or neon-deuterium mixtures. This liquid is produced by condensation in the 30,000-gallon storage vessel. The low-temperature hydrogen gas from the refrigerator flows through a condensing coil in the top of the storage vessel. At the same time, the gas to be liquefied is introduced, under pressure, into the volume of the precooled vessel. The gas condenses on the coil and is collected in the vessel. When the chamber has been cooled to the operating temperature, $\sim 25^{\circ}K$ for hydrogen, the liquid in the storage vessel is then transferred into the chamber. In an emergency or when it is necessary to empty the chamber, the liquid is transferred back to the storage vessel where it is either stored as liquid or vaporized and stored as high-pressure gas.

c) Helium Refrigerator

The helium refrigerator operates on the same principle as the hydrogen system except that it will have an additional stage of precooling and will operate at lower pressures. Usual practice for helium refrigerators is to provide either liquid hydrogen precooling or an additional expansion engine or turbine and to operate at pressures ≤ 30 atms. The liquid produced is placed in a 5,000-gallon storage vessel containing a heat exchanger covered by the liquid. A flow of compressed helium ($\sim$30 atms) is passed through the heat exchanger where it reaches a temperature near 4.3°K. This flow is then directed through the hollow magnet conductor where it accepts heat from the magnet and maintains the conductor at its operating temperature. The gas flow evaporates liquid helium for cooling in the storage vessel. This stream of supercritical helium (helium above its critical pressure but below its critical temperature) is circulated by a pump operating near helium temperature. However, based on future tests, a system of heat exchangers and a compressor may be used to circulate the supercritical fluid.

Table III. Hydrogen Temperature Refrigeration Parameters

REFRIGERATION REQUIREMENTS	
Chamber static losses	500 watts
Chamber pulsing load (0.15 joules/liter of volume/pulse/sec)	15,750 watts
Transfer line losses	1,500 watts
Hydrogen storage dewar (30,000 gal) and connection losses	250 watts
Helium refrigerator precooling	2,000 watts
Total requirements	20,000 watts
OPERATIONAL PARAMETERS	
Total hydrogen flow = 2,750 scfm = 3.95 x 10^5 gm/hour	
Compressor horsepower required	800 hp
Liquid nitrogen precooling required per hour	160 liters
Liquid hydrogen produced when operated as a liquefier per hour	1,350 liters

Time to cool chamber to hydrogen temperature	~48 hours
Time to fill chamber	~72 hours

Table IV . Helium Temperature Refrigeration Parameters

REFRIGERATION REQUIREMENTS	
Supply and return transfer line losses	150 watts
Vacuum tank connections and piping losses	125 watts
Radiation losses to magnet structure	55 watts
Magnet structure support losses	65 watts
Conductor joint losses (I^2R)	150 watts
Current lead losses (30 liters/hour of liquid, equivalent to 125-watt refrigerator capacity)	125 watts
Helium storage dewar (5,000 gallon)	30 watts
Refrigeration necessary for I^2R losses during current sharing mode operation	1,300 watts
Total requirements	2,000 watts
OPERATIONAL PARAMETERS	
Helium flow in basic refrigeration = 2,000 scfm = 5.6×10^5 gm/hr.	
Helium flow in supercritical stream (based on a temperature increase of 0.33°K)	$\leq 9 \times 10^6$ gm/hr
Compressor horsepower required	800 hp
Liquid nitrogen precooling required per hour	75 liters
Hydrogen temperature precooling required	2,000 watts
Liquid helium produced when operated as a liquefier per hour	~500 liters
Time to cool magnet to helium temperature	~48 hours
Time to fill liquid helium dewar	~48 hours

IV. Optics

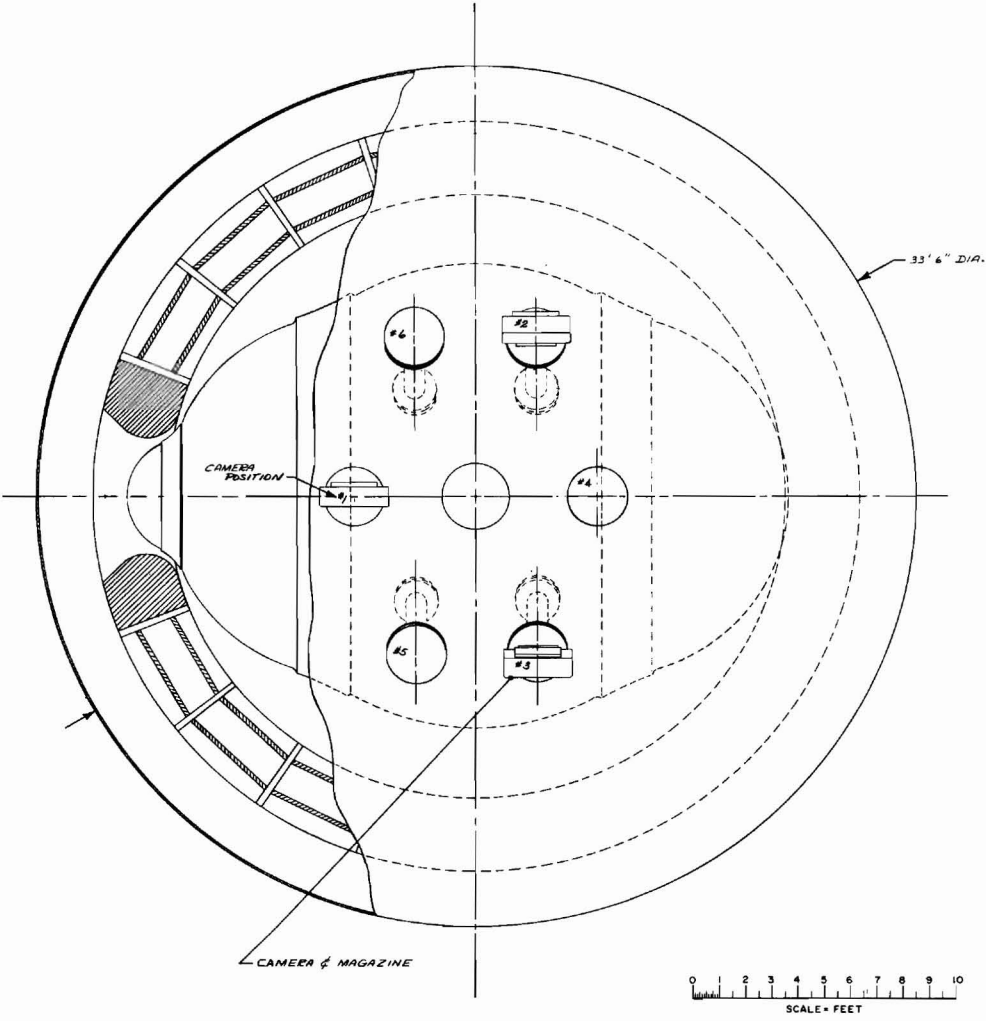
A. INTRODUCTION

The shape of the proposed chamber provides an advantage for the optics system over a cylindrical chamber of similar volume in that the lens near-points are moved farther from the beam plane and a larger fraction of the total volume becomes visible.

The use of lenses of 140° field allows photography of a very large fraction of the chamber volume with a single lens. This means that a conventional array of three cameras can be used efficiently. It is not necessary to provide large numbers of cameras to cover a reasonable fraction of the total volume as is the case with higher aspect ratio cylindrical chambers employing 110° lenses, such as "Mirabelle" and "Gargamelle," both being constructed at Saclay in France. The latter chambers will require completely new analysis systems capable of handling eight views and probably involving on-line computer correlation of track elements seen in different views since the overlap between views is not large. This implies some rough digitizing for all scanning operations, which would be costly in machines and manpower. That 140° lenses of high resolution and small random distortion can be constructed has been demonstrated by Tropel, Inc., in producing them for the 12-foot chamber at Argonne National Laboratory. These lenses have a large, smooth, radial distortion. Similar lenses of greater physical length as proposed here can be made with much smaller distortions.

The proposed system, with small distortions, 70mm film, only three views, all optic axes in planes perpendicular to the chamber axis (beam direction), and reasonably small stereo-angles ($\leq 60^{\circ}$ in beam plane), will yield data which can be scanned and measured by conventional equipment and in which track correlations between views can be made by inspection.

Six camera ports are provided for flexibility in accommodating different beam entries and various possible plate arrays. They are located at equal distances around a circle of diameter 9.2 feet, as shown in Fig. 8, the plan view. Except for the case where plates are installed, only three of these ports (numbers 1, 2, and 3 on the



25 FT. BUBBLE CHAMBER
MAIN ASSEMBLY

PLAN VIEW
PARTIAL SECTION

FIG. 8

corners of an equilateral triangle) are used for cameras; one is used for the visual inspection periscope and the remaining two are blanked off.

Because the optic axes are in planes perpendicular to the chamber axis, parallel tracks in the beam direction will be imaged in all views as parallel lines. The optic axes of the two downstream (or upstream) cameras are inclined 15° from the vertical, in order to increase the volume seen by them, as shown in Fig. 2, page 44.

Experience will soon be gained in scanning and event reconstruction using views with non-parallel axes in the 7-foot test facility at BNL and the 12-foot bubble chamber at ANL. Final decisions regarding the system proposed here can be based partly on this experience.

Since, in the bright-field Scotchlite illumination system, the light sources are toroidal flash tubes mounted concentrically with the lenses, the illuminating light passes through the same windows through which photography takes place. Dirt on the windows will scatter this light directly into the camera lens, reducing bubble contrast. The cameras are therefore placed at the top of the chamber primarily to minimize the rate of dirt accumulation on the windows.

B. DESCRIPTION

a) Resolution

In order to use 70mm film with lenses of 140° field angle, it is necessary to choose a short focal length also consistent with resolving bubbles in the back of the chamber. If it is assumed that bubbles can be grown to about 1mm in diameter, then demagnification of 150 will give 7μ images on film. This is just acceptable for Microfile-type film which has a resolution of 5μ. A lens of focal length 27mm will give this demagnification at the bottom of the chamber. The demagnification in the beam plane is then 75.

At these demagnifications, bubbles in this chamber can be considered point sources, and their images on film are diffraction patterns. The central bright disc of this diffraction pattern is called the "Airy disc" and its radius is given by:

$$R = 1.22\ \lambda \left(\frac{g}{\alpha}\right)$$

where λ is the effective wavelength of the light used, q is the image distance, and α is the diameter of the lens aperture. For a bubble in the plane of best focus in object space, the phase difference between axial and peripheral rays falling on the film from the lens aperature is 0. Let the maximum intensity of the Airy disc under these conditions be I_o. For a plane sufficiently out of focus to make the phase difference $\pi/2$ (Rayleigh limit), the maximum intensity is 0.8 I_o. The variation of light distribution in the diffraction pattern with variation in phase difference (variation in distance from plane of best focus) is shown in Fig. 9. At twice the Rayleigh limit (phase difference π), the Airy disc still contains almost half as much light flux as it does for the plane of best focus. This can be taken as a practical limit for photography.

This chamber requires a range of focus from about 100cm to 400cm, which can be achieved with a lens aperture of 2.5mm. This gives a diameter for the Airy disc of ~15μ. Taking the full width at half height of the distributions shown in Fig. 9 as the effective Airy disc width, this becomes ~7μ, which corresponds to a bubble of diameter ~0.5mm in the beam plane and ~1mm at the bottom of the chamber.

b) Film Format and Visible Volume

The lens chosen yields a full field circular image of diameter 148mm. If the film is sprocketed on one side only and aligned with the chamber axis, the clear image width is 65mm. This geometry cuts off 46 percent of the image area at the sides, but this corresponds to a loss of only about 10 percent of the chamber volume. The total volume in the chamber exclusive of that hidden by the expansion system baffle is 100,000 liters. The cameras proposed see volumes as shown in Table V.

Table V. Visible Volume

Camera(s)	Volume Imaged on Film (liters)
1	74,000
2 or 3	77,000
1 and (2 or 3)	73,000
2 and 3	76,000
1 and 2 and 3	72,000

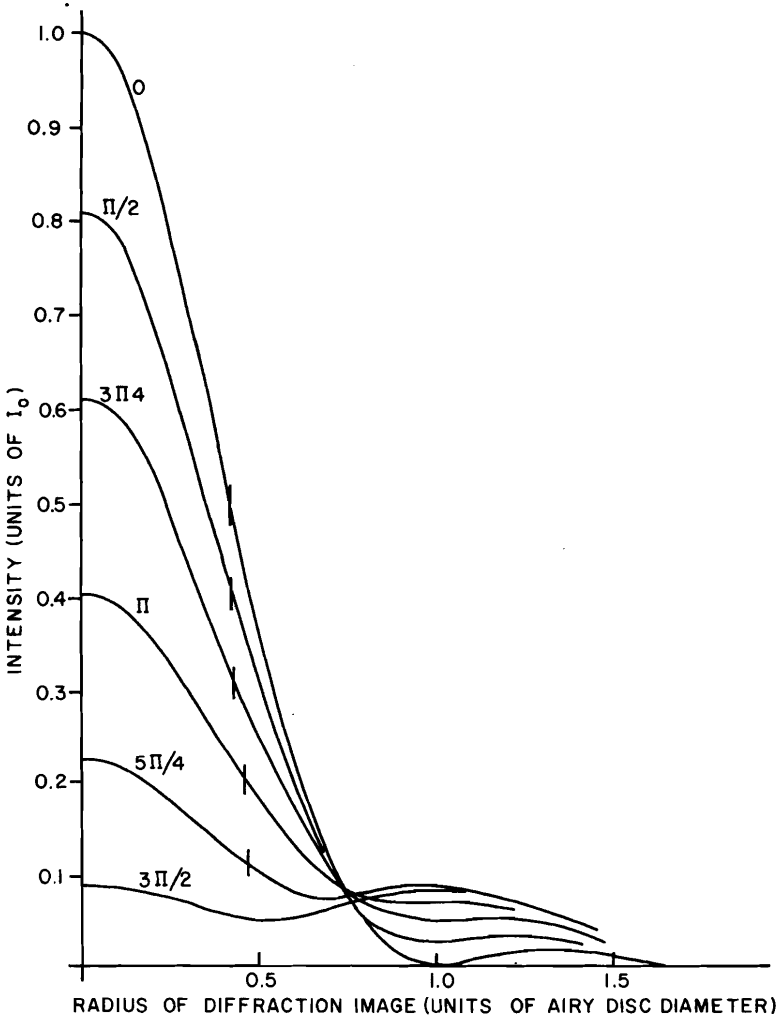

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
INTENSITY (UNITS OF I_0)
0
Π/2
3Π4
Π
5Π/4
3Π/2
0.5
1.0
1.5
RADIUS OF DIFFRACTION IMAGE (UNITS OF AIRY DISC DIAMETER)

FIG. 9

Fig. 10 shows a computer-generated stereotriad with a beam of K^- at 50 BeV/c, using the format and camera orientation described in Table V. The fourth view is the projection of the chamber contents on a plane perpendicular to the magnetic field. Two of the five beam tracks interact. The interaction farthest downstream is:

$$K^- + p \rightarrow \Sigma^- + \pi^- + \pi^+ + \pi^+ + \pi^0$$
$$\hookrightarrow \pi^- + n$$

The remaining event shows:

$$K^- + p \rightarrow n + K_1^0 + \pi^+ + \pi^-$$
$$\hookrightarrow \pi^+ + \pi^-$$

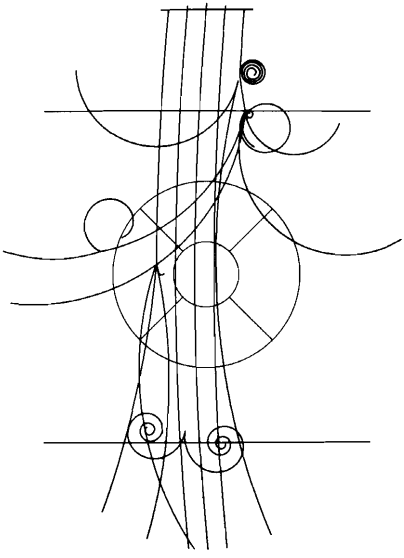
where the π^- from the primary interacts as follows:

$$\pi^- + p \rightarrow p + \pi^+ + \pi^- + \pi^- + \pi^0$$
$$\hookrightarrow \gamma + \gamma$$
$$\hookrightarrow e^+ + e^-$$
$$\hookrightarrow \text{elastic scatter}$$

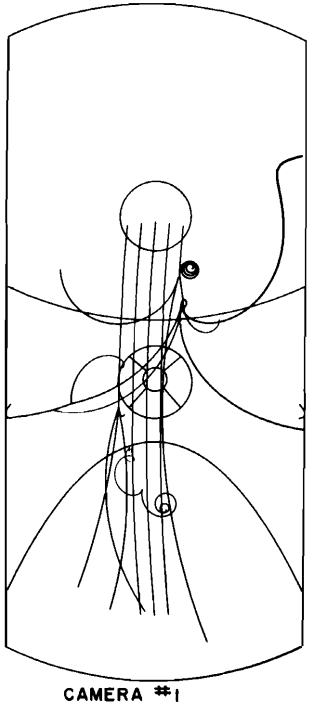
c) Windows and Lenses

Lenses for this chamber are 27mm focal length with a full field angle of 140°. They are near-telecentric, meaning that all rays strike the film at nearly 90° regardless of their angle with the optic axis in object space. This eliminates random distortions due to film-plane deviation from flatness, which would otherwise be severe for a lens of such wide field angle. They also have low distortion, probably a few percent at most. Their design uses as a departure point the design of the 110° field angle lenses for Gargamelle, the large heavy-liquid chamber now under construction in France. This lens involves a transport section which displaces the image axially 6 feet from the entrance pupil. In the chamber proposed here this distance is lengthened to 9 feet, but this should present no problems.

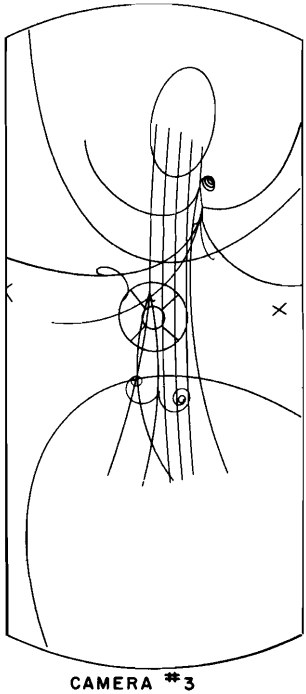
Each lens views the chamber through a set of three spherical "fisheye" windows, fixed to three concentric invar rings by an epoxy technique similar to that used for the 7-foot test facility heat shield and vacuum tank windows. The mechanical mount supporting the window is then in contact with the chamber hydrogen and seals it



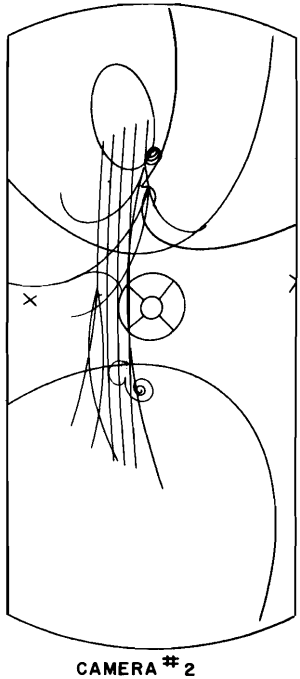
PLANE PROJECTION



CAMERA #1



CAMERA #3



CAMERA #2

FIG. 10

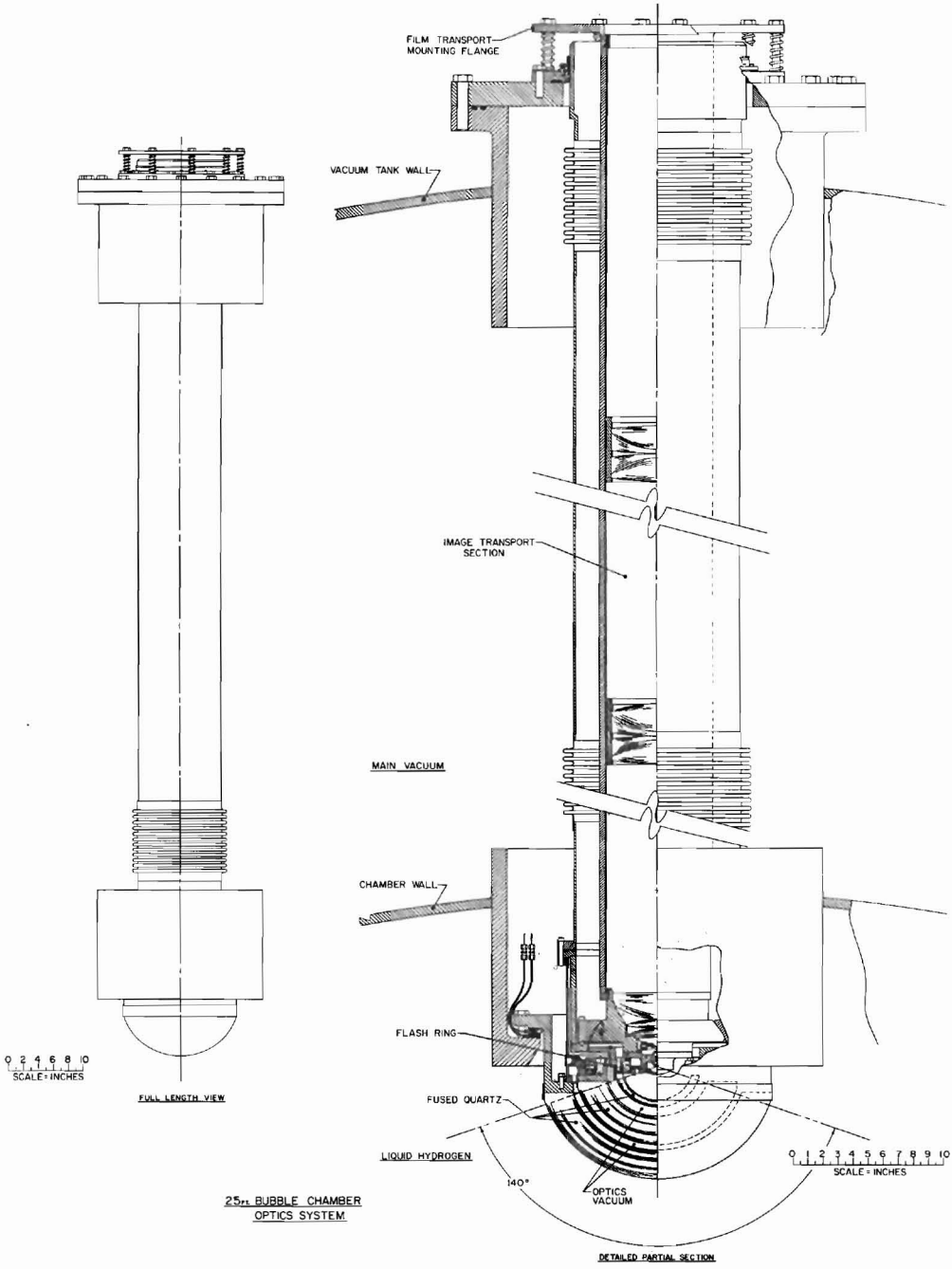
from the insulating vacuum. Next is the heat shield window to reduce radiation falling on the chamber window, and next to the lens is the vacuum tank window which seals the insulating vacuum from the air. They are made of fused quartz to minimize the chance of breakage in the event of large temperature gradients caused by either loss of insulating vacuum or intentional rapid cooling or warming of the chamber. The windows are coated, as are all the lens surfaces, for maximum transmission in the 500-600mμ range. The system is shown in Fig. 11.

d) Illumination

The illumination system is very similar to that used in the 7-foot test facility. Scotchlite, Type SPR-1042, with selected small beads, is glued directly to the interior of the chamber walls and the expansion system baffle. A toroidal xenon flashtube is mounted close around the front element of each lens and provided with power supplies sufficient to deliver 320 joules per flash. This is four times the energy which is required, but less than 10 percent of the ultimate limit for these tubes, and should give lifetimes greater than 10^6 flashes. Hydrogen chambers now operating successfully with bright field systems similar to this one include the BNL 30-inch and 31-inch chambers and the SLAC 40-inch chamber. For single or double pulsing per accelerator cycle of one second, the flashtube heat is removed by recirculated nitrogen gas. For higher multipulsing, a water-cooling jacket, which can be constructed as part of the tube, would probably be necessary.

e) Cameras

Film transports have been developed at BNL, and are being constructed for use with the 7-foot test facility and the 80-inch chamber, which are capable of advancing one frame length in 25-30 milliseconds. This is accomplished by driving the film into a sinusoidally-shaped "transfer pocket" by means of a jet of air. A similar system is used on this chamber in order to make it possible to take more than one photograph per accelerator pulse. Pneumatic valves and motors are used in the design to make operation in the fringing magnetic field feasible. Since the lens has a long image transport section to bring the image



25μ BUBBLE CHAMBER OPTICS SYSTEM

FIG. 11

outside the vacuum tank, no long film transport section is necessary to bring the film near the chamber. This makes the film transport very compact with all parts including the platen easily and quickly accessible for cleaning or repair.

Data box information is written on the film by photo-emitting semiconductor matrices installed directly in the transports. This is also similar to the system developed for the 7-foot test facility.

V. Magnet

A. INTRODUCTION

The utility of a large cryogenic bubble chamber as an instrument of research at a high energy accelerator depends significantly on the intensity of the magnetic field in which the bubble chamber operates. A magnetic field needs to be provided with sufficient intensity to insure that measurements of the momenta of charged particles may be made with precision. Another important criterion for the magnitude of the field is the magnetic trapping of particles over an appreciable range of momentum.

Until recently, bubble chambers were usually equipped with conventional magnets with water-cooled copper coils and an iron flux-return path. For these magnets, both capital costs and operating costs increase steeply for field intensities above the saturation flux density of iron. In the past few years, developments in superconductor technology have made feasible the construction and safe, reliable operation of superconducting magnets which can economically generate magnetic fields of increased intensity over large volumes. Two such superconducting magnets, using stabilized superconductors cooled by liquid helium contained in a magnet dewar, have been completed for bubble chambers, and several other large superconducting magnets are being designed.

The magnet proposed for the 25-foot cryogenic bubble chamber is an air-core superconducting split-pair magnet designed to generate an average magnetic field intensity of 40 kG over the bubble chamber volume. The superconducting air-core design, in addition to giving

large savings in magnet costs and power for operation, makes more accessible the component parts of the bubble chamber assembly.

To eliminate the need for a magnet helium dewar and to achieve a magnet coil configuration that is compact and mechanically strong, the 25-foot chamber magnet conductor is designed as a hollow stabilized superconductor cooled by an internal flow of helium.

B. DESCRIPTION

a) Magnet Conductor

Very good thermal and electrical contact between the superconductors and the normal conductor material is produced by embedding and metallurgically bonding superconducting filaments in normal conductors such as copper. Enough normal conductor and sufficient cooling are provided so that during transient instabilities, such as flux jumps, the full magnet current can be carried by the normal conductor without the temperature at the superconductor rising above that at which it makes the transition from the superconducting to the resistive state. The amount of normal conductor and cooling must also be sufficient to prevent the magnet suddenly becoming completely resistive if the critical current is exceeded in the magnetic field at the superconductors.

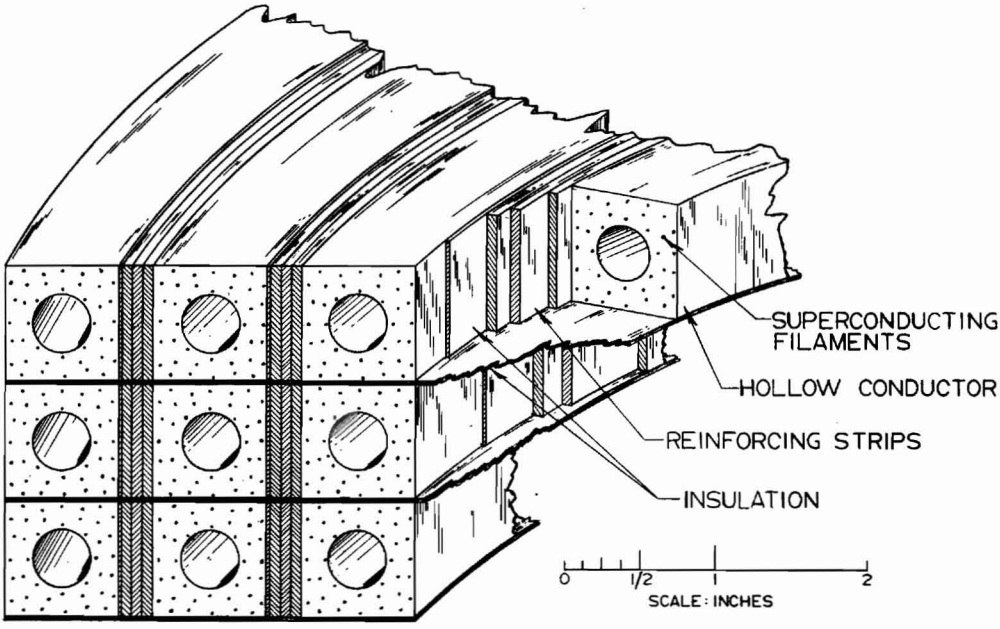
Hollow stabilized superconductors have recently been fabricated which consist of a number of superconducting filaments embedded in the wall of a copper tube of square or rectangular cross section. These conductors may be cooled by an internal flow of helium which is maintained at a temperature of $4.5^{\circ}K$ and at pressures above its critical pressure of 2.23 atm. The rate of heat transfer from the conductor to the helium depends on the heat transfer coefficient and on the surface area of the conductor in contact with the helium. By maintaining the pressure of the helium fluid above 2.23 atm, the formation of two phases within the conductor is prevented and the heat transfer coefficient is enhanced. The one-phase positive fluid flow through the conductor also insures that cooling is continuously brought to all parts of the magnet conductor. The total volume of helium in contact with the conductor is less than that required to cool the magnet by pool boiling.

Thus liquid and gas storage requirements are minimized with the hollow superconductor design.

The normal conductor material in which the superconducting filaments are bonded not only stabilizes the superconductors but also aids in supporting the electromagnetic forces to which the magnet is subjected. The amount of normal conductor to be bonded to the superconductor for stabilization for a given magnet current depends on the rate of heat transfer from the conductor to the helium coolant and on the resistivity of the normal conductor. The resistivity of the normal conductor is a function of its purity, of the stress in the conductor, and of the magnetic field intensity at the conductor.

An evaluation of data from tests performed on aluminum and copper indicates that, for magnets of intermediate field intensities where the magnet windings are subjected to large forces and the magnetoresistivity of the windings is not an overriding consideration, the use of copper as the normal conductor material permits a design for substantially higher stress levels with a consequent reduction in the volume of the conductor and stiffener material required.

The 25-foot bubble chamber magnet is designed for 3×10^7 ampere-turns to generate a central field of 38 kG with an average magnetic field intensity of 40 kG over the chamber volume. At this value of average field, the maximum field at the magnet windings will be 65 kG and the magnet coil will be subjected to total radial pressures of the order of 2800 psi. To aid in supporting the stresses in the magnet windings, to limit deformation of the conductor material, and to reduce the amount of normal conductor required, a reinforcing or stiffener strip of a high-strength material such as stainless steel is wound in the magnet coil windings with the hollow conductor. A thin strip of fiberglass epoxy or Mylar tape is also wound in the magnet coil between the surfaces of the hollow conductor strip and the stiffener strip to provide turn-to-turn electrical insulation. A schematic of the proposed magnet coil configuration is shown in Fig. 12. A hollow copper-multifilament superconductor composite of the type shown in the schematic, 0.75 inches square with an 0.375-inch-diameter hole, may be designed to carry 8500 amps in a magnetic field of 65 kG. Enough copper of resistivity ratio $\rho_{300^oK}/\rho_{4.2^oK} = 200$ may be



MAGNET COIL COMPONENTS

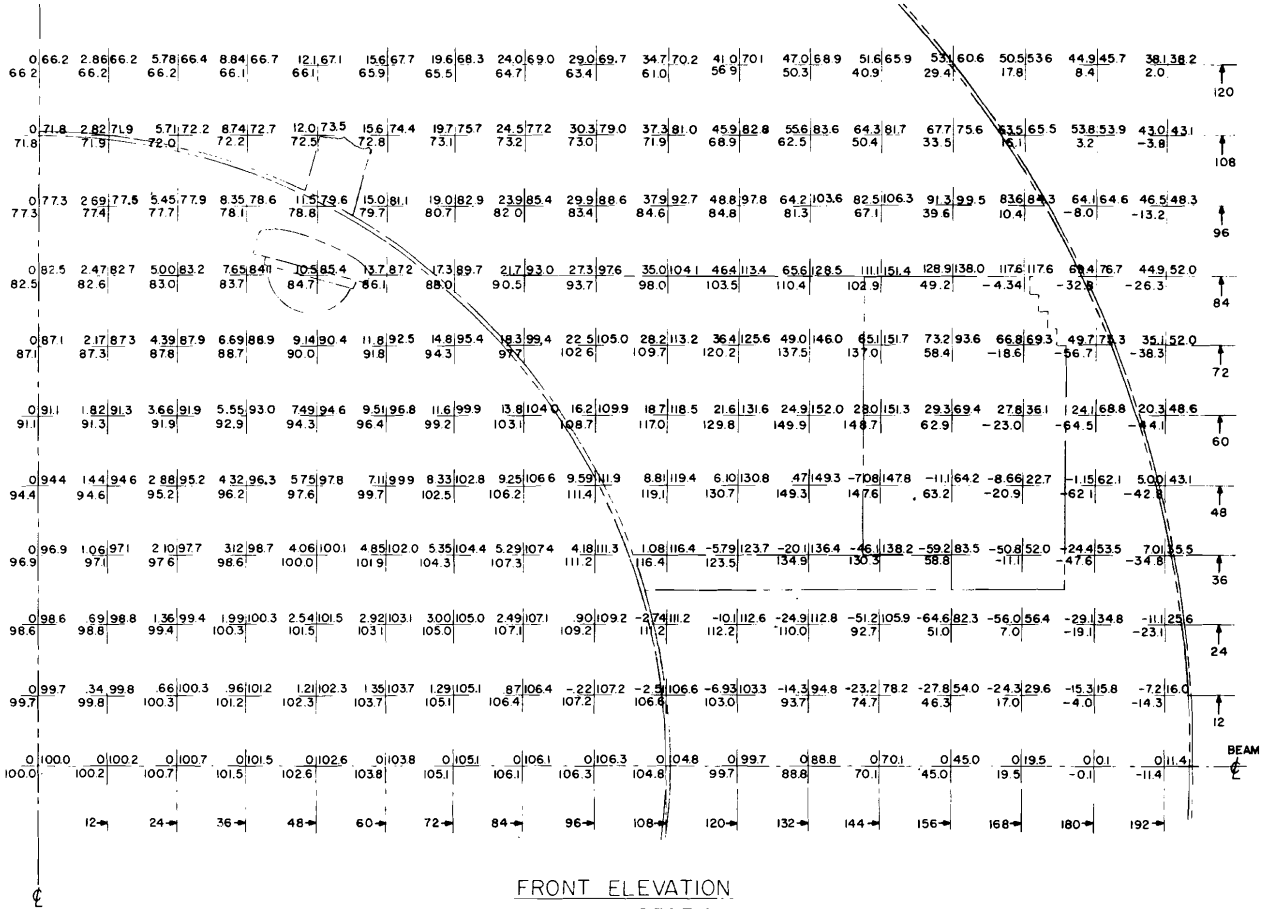
FIG. 12

incorporated in the conductor so that even with an assumed heat transfer coefficient of 0.3 $W/cm^2\ {}^oK$, which is no better than that achieved with helium pool boiling, the entire current of 8500 amps may transfer to and be carried by the copper without the temperature of the conductor increasing by more than 1^oK. Sufficient reinforcement is also wound in with the conductor to limit the stress in the copper to 15,000 psi.

b) Magnet Assembly

The 25-foot bubble chamber magnet is a split pair of coils, each half-coil consisting of a number of single-layer pancakes as shown in Fig. 4, page 47. The pancakes are insulated from each other by thin sheets of fiberglass epoxy. Each pancake is made self-supporting against radial forces by clamping the external free end of the conductor at the periphery of the coil. The pancakes are connected electrically in series with stabilized superconducting connectors soldered and clamped at the inner and outer diameters of the magnet coils. The pancakes are connected in parallel to the helium supply manifold at the inner diameter of the magnet and to the helium return manifold at the outer diameter of the magnet coil.

The single-layer pancakes are stacked vertically for each of the two magnet half-coils. Each magnet half-coil is 4 feet 6 inches high and has an inner diameter of 23 feet 6 inches and an outer diameter of 29 feet 2 inches. The two half-coil assemblies are separated by 5 feet to allow for particle beam entry to the bubble chamber. This large coil separation permits the winding of magnet coils of a smaller diameter, reduces the axial forces on the coils, and improves the uniformity of the magnetic field over the bubble chamber volume. It also permits the large curved beam window section of the bubble chamber to extend 2 feet into the gap between the coils for easy entry of particle beams with a large range of momentum. The magnetic field intensity transverse to the beam axis has an average value of ~22 kG in the volume in the beam window between the coils. An elevation view of the magnetic field intensity plot is shown in Figs. 13a and 13b. With a total of 3×10^7 ampere-turns in the magnet and an average field over the chamber volume of 40 kG, the two half-coil assemblies are

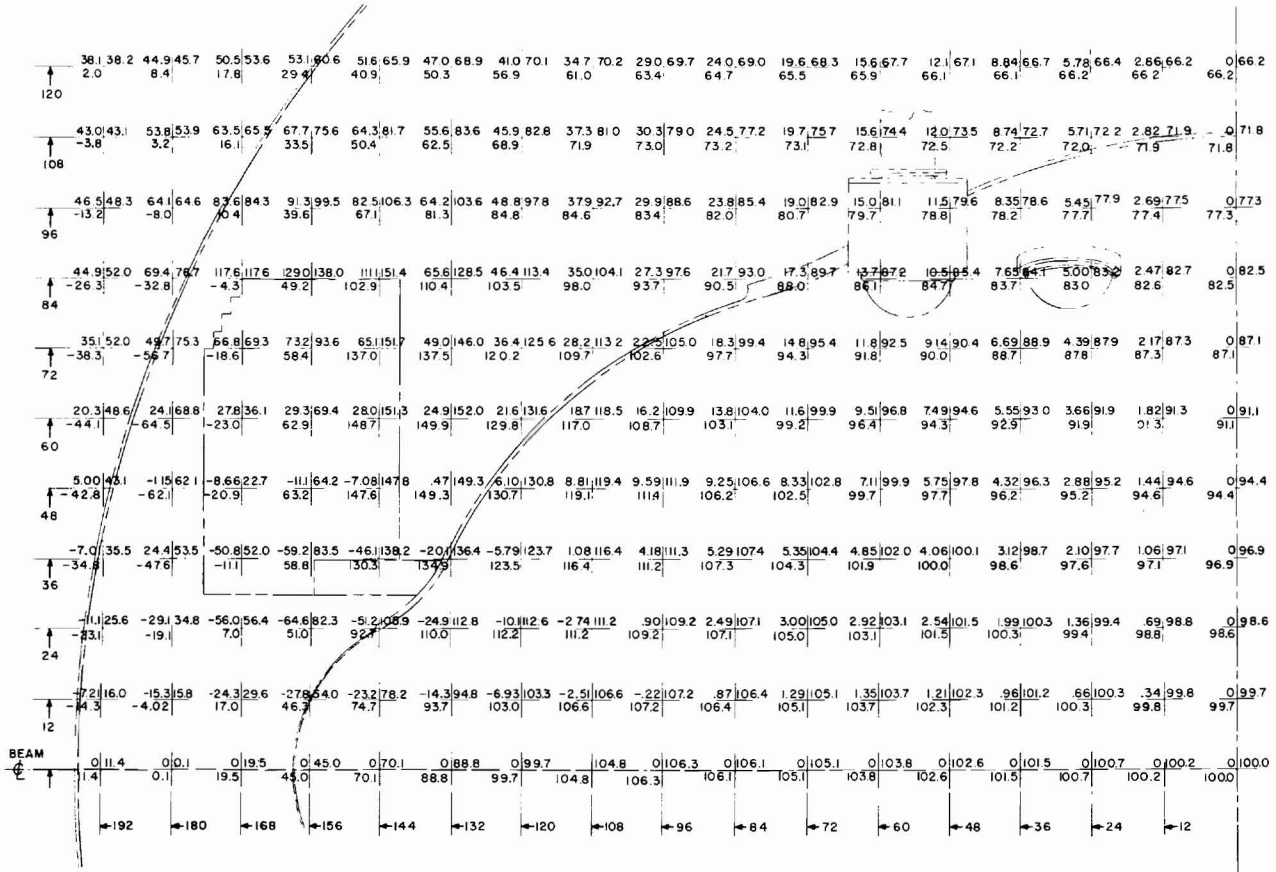


FRONT ELEVATION
QUARTER SECTION

RADIAL FIELD STRENGTH | TOTAL FIELD STRENGTH
VERTICAL FIELD STRENGTH |

FIG. 13a

FIELD STRENGTHS EXPRESSED IN PERCENT OF FIELD STRENGTH AT INTERSECTION OF VERTICAL ℄ AND BEAM ℄.



SIDE ELEVATION
QUARTER SECTION

RADIAL FIELD STRENGTH | TOTAL FIELD STRENGTH
VERTICAL FIELD STRENGTH

FIG. 13 b

FIELD STRENGTHS EXPRESSED IN PERCENT OF FIELD STRENGTH AT INTERSECTION OF VERTICAL ℄ AND BEAM ℄

attracted to one another with a force of the order of 30,000 tons. This force between the coils is supported by a coil spacer which is reinforced around the chamber beam window so that a large aperture is available in the spacer for beam entry.

The pancakes of each magnet half-coil assembly are tied together by vertical rods at the inside and outside diameters of the magnet which are threaded into or bolted to stainless steel washers at the top and bottom of each half-coil. These rods serve to align the coils. The bottom washer of the top coil and the top washer of the bottom coil are bolted to the coil spacer, while the bottom washer of the bottom coil is bolted to the three support legs. These legs support the magnet and bridge assembly in the vacuum tank and are designed to carry the total weight of approximately 400 tons. Thermal insulating pads are placed between the coil-halves and the coil bridge and between the bottom coil and the support legs to minimize the heat leak from these structures to the coil. The magnet is thermally insulated from the bubble chamber and the vacuum tank by multilayer insulation.

c) Current Supply

The stabilized superconducting magnet is connected to an external current supply. An SCR regulated, rectifier-type power supply is used with special output circuit breakers. Shunt diodes are provided at the supply terminals which automatically discharge the magnetic field energy safely and slowly in the event of a power failure. Provision will also be made to open the output line automatically to discharge the magnetic field energy rapidly through an external resistor. The magnet current leads are of the conventional copper type between the current supply and the bubble chamber vacuum tank. Helium-cooled leads will be used between the vacuum tank and the magnet. Electric current feedthroughs in the vacuum tank are of copper electrically insulated with a fiberglass epoxy. The magnet current leads will be designed to accommodate the differential contractions which result from the temperature differences in the system. The magnet current will be measured by a conventional shunt at the current supply. Voltage drops along the current leads are monitored at various

points to insure that heat leaks are minimized. The voltage across each pancake, across each joint in the magnet, across the magnet at the magnet superconducting terminals, and at the current supply are continuously monitored. The temperature at various points in the coil assembly will be measured by thermocouples and with carbon resistors.

Three nuclear magnetic resonance probes will be placed at 120° intervals outside the magnet at points where the magnetic field gradient is zero. These resonance probes will be used to provide field symmetry information and to monitor the magnetic field.

VI. Vacuum

A. INTRODUCTION

This section covers the high-vacuum pumping systems, the multilayer superinsulation, and the emergency vent system for the hydrogen. The main vacuum pumping system is used to pump out residual gases and minor leaks into the vacuum chamber that surrounds the bubble chamber and the superconducting coil. Effectiveness of the multiple-layer insulation in minimizing radiation losses requires pressures of $< 10^{-4}$ mm Hg. The dual-module main vacuum pumping system consisting of oil diffusion pumps and mechanical forepumps achieves the desired vacuum at minimum cost and adequate redundancy against loss of vacuum. A separate oil-less pumping system is used for the window vacuum. A large emergency vent line is attached to the vacuum chamber to protect it from overpressure and to enable the chamber contents to be dumped in case of emergency. A hydrogen disposal system is provided at the end of the vent line.

B. DESCRIPTION

a) Vacuum Pumping System

Since cost studies have shown that use of an oil-less type of high-vacuum system, employing large turbomolecular pumps, is uneconomical for this application, the high-vacuum pumping system consists of forepumps, two stages of blower-type pumps, oil diffusion

pumps, and baffles as defined in Table VI. In order to insure a clean vacuum for the window areas, a smaller separate oil-less high-vacuum system will be provided only around the windows. This clean pumping system, which needs relatively low pumping speeds, consists of ion pumps backed up by sorption-type forepumps. Two mechanical turbo-molecular pumps will be used to back up the ion pumps. Such a system is capable of achieving pressures of 10^{-7}mm without the use of any mechanical pumps.

b) Vacuum Instrumentation

The type of instrumentation to be used on the vacuum pumping system has been used successfully on the BNL 80-inch bubble chamber. Remote instrumentation, calibrated in terms of the main vacuum at the chamber, will be used in order to avoid magnetic field interferences.

c) Insulation

The superconducting magnet and the cryogenic bubble chamber are shielded from radiant heat gains by many layers of multiple-layer insulation. This type of insulation was used successfully on the BNL 80-inch chamber where the need for hydrogen- and nitrogen-cooled shields formerly used for such applications was eliminated. The helium-cooled magnet, which operates at a lower temperature and is in closer proximity to the warm vacuum chamber wall than the inner hydrogen chamber, requires more layers of insulation. Thus the magnet is completely surrounded by 400 layers of insulation which are protected by Mylar covers. The type of insulation for this application has been chosen for maximum effectiveness at minimum cost and minimum space requirements. The space requirement is an important consideration since sufficient space between the inner components and the outer tank must be provided to accommodate the required amount of insulation. As this space is increased, the size, and therefore the cost, of the vacuum chamber increases.

c) Emergency Vent Line

An 18-inch-diameter emergency vent line, 1000 feet long, is connected to the vacuum chamber. A check valve, set to open when the pressure in the vacuum chamber exceeds a few psi, separates the vent

line from the vacuum chamber. At the end of the 1000-foot run a vertical stack is provided which is equipped with a flare assembly for safely disposing of the chamber contents in case of emergency. The primary method of emptying the chamber contents is by means of the two "cold" valves located at the bottom of the cryogenic chamber and connected to a 30,000-gallon dewar through a vacuum jacketed line. The piping system also permits the chamber contents to be dumped directly into the 18-inch vent line should there be failure of the dewar or associated equipment. This flare assembly is equipped with a molecular seal which protects against aspiration or downdrafts of air at the end of the stack. Flare stacks with similar or larger hydrogen flows have been used by several installations in the United States. The emergency dump line is sized to dispose of the chamber contents safely without exceeding the design pressure of the vacuum chamber or associated piping. The 105,000-liter chamber contents can be vented and burned through the 18-inch line and flare in a period of five and one half minutes.

Table VI. Vacuum System Parameters

MAIN VACUUM SYSTEM	
Forepumps	
Total speed	120 cfm
Power required	8 kVA
Type	Oil-sealed, rotary mechanical, Single-stage with gas ballast
Blower-type pumps (low stage)	
Total displacement	700 cfm
Total pumping speed	600 cfm
Power required	6 kVA
Type	Two-stage, vane-type
Blower-type pumps (high stage)	
Total displacement	4600 cfm
Total pumping speed	4200 cfm
Power required	15 kVA
Type	Single-stage, vane-type

Oil diffusion pumps

Number required	4
Maximum pumping speed	17,500 liters/sec/pump
Total power required	45 kW

Baffles

Type	Chevron, water-cooled

System parameters

Volume of space to be pumped	~16,500 cu ft (465,000 liters)
Estimated overall pumping speed of system	30,000 liters/sec

WINDOW VACUUM SYSTEM

Sorption pumps

Type of fill	"Molecular sieve" adsorbent
Coolant	Liquid nitrogen
Reactivation	External heater

Ion pumps

Number required	2
Type	Titanium cathode ion pump
Pumping speed	2700 liters/sec/pump
Electrical characteristics	10 amps/230V

Turbomolecular pump

Number required	2
Type	Oil-less, multi-stage
Pumping speed	260 liters/sec
Electrical characteristics	9 amps/230V

System parameters

Volume of space to be pumped	75 liters (including piping and pump)
Estimated overall net pumping speed of system	200 liters/sec (with only ion pumps on line)

INSULATION

Type	NCR-2 (patented)
Material	Aluminized Mylar, 0.00025" thick/layer
Total weight	2500 pounds
Density	100 layers/inch
Helium magnet	400 layers (4 inches)
Between chamber and magnet dewar	100 layers (1 inch)
Between chamber and outer tank	300 layers (3 inches)

VENT LINE	
Size	18 inches
Wall thickness	3/16-inch
Length	1000 feet
Material	Type 304 welded stainless steel
Venting time	5 1/2 minutes
Flare	
Seal	Molecular-type
Disposal rate	42.5 pounds/sec

VII. Instrumentation

A. INTRODUCTION

The purpose of the instrumentation and control system is to provide a reliable means of remotely operating the bubble chamber complex with ease and efficiency. The system enables the operator to monitor and control the various components to achieve best performance. In order to keep operating costs as low as is consistent with safe operation while maintaining an efficient operating schedule and providing the experimenter with the maximum number of useful pictures, a coordinated system approach, designed around a central control room, is required. This section describes the control room, instruments, equipment and interconnections needed for the 25-foot cryogenic bubble chamber.

B. DESCRIPTION

a) Control Room

As the central operating point for the complex, the control room houses the controls for all subsystems. Interconnections are made by means of a generalized sub-floor cross connection system of low-level and coaxial cables and pneumatic tubing. Each subsystem rack grouping is connected to a central rack that serves to route incoming and outgoing signals through a disconnect panel in the wall of the control room.

In this way, each subsystem can be independently completed and combined for test or operation as required at a later time. The advantage of portability, important for the 25-foot chamber, is also inherent in this system. This modular technique was developed and tested on the BNL 80-inch chamber and is being applied to the operation and control of the 7-foot chamber.

b) Accelerator Interface

The expansion cycle (expand, illuminate, film advance) of the bubble chamber must be synchronized with the entry of beam into the chamber. A master clock referenced to accelerator injection time serves as a common time base. This, coupled to a sliding predetermined timer, assures the sensitivity of the chamber at beam-spill time. For chamber standby periods, a repetition rate reducer is used. This allows the chamber to expand at a reduced rate sufficient to maintain equilibrium conditions. In an effort to increase the fraction of useful pictures, it has been found useful to apply limits on the maximum and minimum number of particles per picture and their type for illumination. This technique, perfected at the BNL 80-inch chamber, saves film and decreases scanning time.

c) Communications and Monitoring

The chamber facility is linked by public address, direct telephone and intercom systems as well as portable hand-held receiver/transmitters. A few direct telephone lines keep the chamber operator in contact with the accelerator main control room, the target desk, and the beam area. Direct monitoring of the chamber area and compressor rooms is made possible by a closed-circuit television system. All camera outputs are video switched to a master monitor located in the control console. Fixed location monitors, as required, are centrally located in control/indicator racks in full view of the control console. Automatic monitoring of chamber systems is accomplished with an updated version of the alarm/annunciator system currently in use at the BNL 80-inch chamber and the 7-foot test facility. Each alarm has the immediate response (interlock) option that allows predetermined solutions to be effected automatically. Continuously operated, fast

response, hydrogen gas detectors directly operate emergency ventilating fans and air intake louvers. The time and alarm data are automatically recorded by the alarm/annunciator system.

e) Instrument Air System

Instrument air is required for the operation of the cameras and the pneumatic controls. A dual system is provided consisting of non-lubricated air compressors, aftercoolers, dryers, and filters which feed a single receiver. The plumbing is arranged so that either compressor side may be shut down for maintenance. Each side is capable of separately providing pneumatic control air and is backed up by a nitrogen bottle manifold with automatic cut-in to maintain chamber control in case of a power failure.

f) Test and Calibration

The test and calibration equipment required is that of a secondary standards calibration laboratory.[1]

g) Magnetic Effects Testing Program

A testing program is planned to continue the study of the effect of magnetic fields on the type of controls and equipment in the bubble chamber complex. In addition, the experience gained from the operation of similar equipment in the stray field of the 7-foot test facility will add to this program.

VIII. Site, Enclosures, and Facilities

A. INTRODUCTION

When designs are developed for the physical plant required for large-volume cryogenic bubble chambers, following conventional procedures used for 2-meter-sized chambers projects a very large cost.[1,2] Also, there is a need for better ability to relocate the bubble chamber and its associated equipment. This proposal minimizes the physical plant. At the same time, the plan facilitates possible relocation and reduces cost by the use of weatherproof, relocatable buildings or structures, each suited to house a particular piece of equipment. Other features emphasized include simplicity, expandability, access to

equipment, portable crane service on a shared basis, and the use of minimal volume shelters, low heating, lighting, and air-conditioning capacities.

B. DESCRIPTION

a) Site and Equipment Location

The site plan, Fig. 14, shows the arrangement of the bubble chamber and its associated equipment. A flat bituminous paved area of about 1-3/4 acres with a drainage ditch on two sides contains the bubble chamber and all ancillary equipment and facilities necessary for its operation and maintenance. It is located some distance from the accelerator at a point where the appropriate beams can be provided. The bubble chamber is positioned on the site so as to provide maximum flexibility in the use of the beam. The site is surrounded by a 6-foot-high chain link fence. It is assumed that a connecting road for accommodating cryogenic tankers and other service traffic and a parking area for the employees are part of the accelerator road system. It is also assumed that connections from the accelerator utilities, including emergency power, are brought to the bubble chamber site where the interface connections are made. Occasionally an 80-ton boom-type portable crane will be required.

The vacuum chamber (see Section I of this chapter) serves as an outdoor housing for the bubble chamber. It is supported by a foundation at the bottom of a shallow pit. The pit is needed for assembly and removal of the expansion mechanism. The remainder of the equipment within the site consists of components of the subsystems that are required for operation of the bubble chamber. Minimum clearances around the bubble chamber are determined by the access requirements for maintenance purposes and by the magnitude of the stray magnetic field. Maximum distances between some of the components and the bubble chamber are determined by the energy losses or efficiency incurred. For instance, the magnet charging supply, vacuum pumps, and refrigerators must be mounted as close to the chamber as possible in order to minimize such losses. A darkroom is also required near the chamber for changing film and producing test strips during operation, but it can be moved out

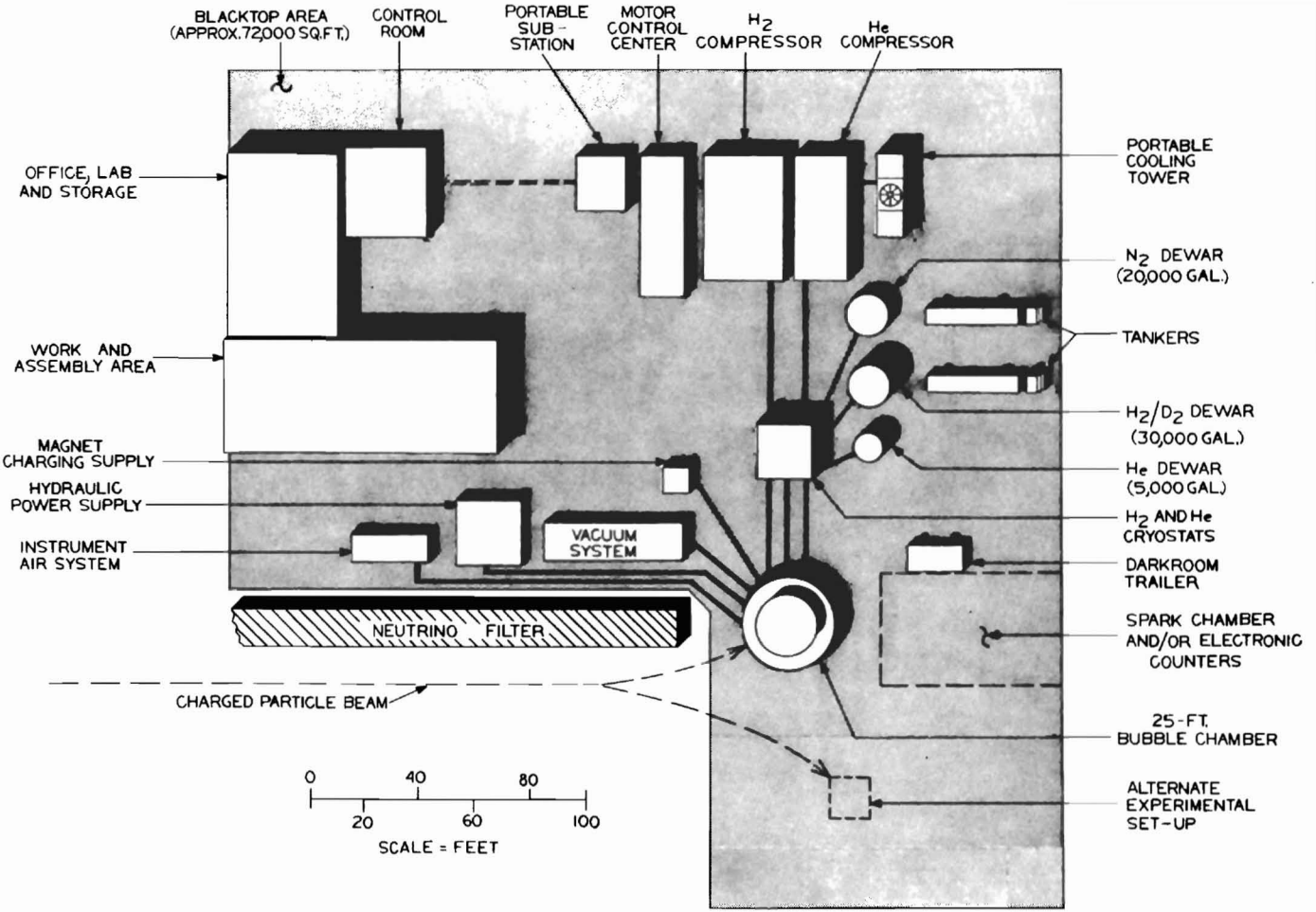

BLACKTOP AREA (APPROX. 72,000 SQ.FT.)
CONTROL ROOM
PORTABLE SUB-STATION
MOTOR CONTROL CENTER
H_2 COMPRESSOR
He COMPRESSOR
OFFICE, LAB AND STORAGE
WORK AND ASSEMBLY AREA
MAGNET CHARGING SUPPLY
HYDRAULIC POWER SUPPLY
INSTRUMENT AIR SYSTEM
VACUUM SYSTEM
NEUTRINO FILTER
CHARGED PARTICLE BEAM
PORTABLE COOLING TOWER
N_2 DEWAR (20,000 GAL.)
TANKERS
H_2/D_2 DEWAR (30,000 GAL.)
He DEWAR (5,000 GAL.)
H_2 AND He CRYOSTATS
DARKROOM TRAILER
SPARK CHAMBER AND/OR ELECTRONIC COUNTERS
25-FT. BUBBLE CHAMBER
ALTERNATE EXPERIMENTAL SET-UP
0
20
40
60
80
100
SCALE = FEET

FIG. 14

of the way during servicing. Three storage dewars for cryogenic fluids are located near the refrigerators to minimize transfer losses.

The distances between the remainder of the components and the bubble chamber are not as critical as those already mentioned. The arrangement is planned for above-ground interconnections using trays, cables, and pipes and for good access to the individual components.

b) Enclosures

The enclosures are of three types:

(1) A high-bay building with a two-story wing.

(2) Individual shelters for the control room, cameras, expansion system, vacuum system, hydraulic power supply, hydrogen and helium compressors and cryostats, and the instrument air system.

(3) Shelters that are part of the weatherproof portable equipment such as the substation, cooling tower, motor control center, and magnet charging supply.

All buildings and enclosures that are not an integral part of the weatherproof portable equipment are also relocatable and utilize Butler-type construction now in use at BNL and other national laboratories. This consists of a steel, aluminum, or treated wood structural frame with an outside covering of aluminum. Insulation is provided by blankets hung between the structural members or by rigid sheets combined with the outside aluminum covering in the form of a sandwich. No interior covering or finish is required. The equipment pad serves as the foundation in most cases. A minimum of disassembly is required for relocation. The smaller enclosures can be lifted intact from the equipment. All of the enclosures are of minimum size for operations, with removable panels or sections as required for maintenance of the equipment. Electric heat, light, ventilation, and air-conditioning are provided as required. The enclosure requirements are shown in Table VII.

c) Facilities

The facilities include all utilities for use within the site and a maintenance facility for the bubble chamber complex. All interfaces with the accelerator systems will be at or near the site.

Table VII. Enclosure Requirements

Enclosure	Type	Total Area (Sq.Ft.)	Room Height (Feet)	Lighting (KVA)	Heating (KVA)	Ventila-tion (KVA)	Air Condi-tioning (KVA)	Total	Remarks
Maintenance Facility									
High Bay	Butler	4000	30	24.0	240.0	3.6	-	267.6	(1)
Two Story	Butler	5000	10	15.0	100.0	-	30.0	145.0	
Control room	Butler	1000	12	3.0	30.0	-	20.0	53.0	(2)
Camera (chamber top)	Butler	400	9	1.1	10.0	-	2.0	13.1	(3)
Expansion (chamber bottom)	Butler	400	9	1.1	10.0	-	2.0	13.1	(3)
Vacuum system	Butler	700	10	2.1	14.0	0.6	-	16.7	
Hydraulic power supply	Butler	600	10	1.8	12.0	0.5	-	14.3	
Hydrogen compressor	Butler	1400	15	4.2	28.0	11.0	-	43.2	(4)
Helium compressor	Butler	900	15	2.7	18.0	0.8	-	21.5	
Refrigerator Cryostat	Butler	400	25	1.2	12.0	6.0	2.0	21.2	(4)
Instrument air system	Butler	300	12	0.9	6.0	0.3	-	7.2	
Dark room	Trailer	200	10	0.6	4.0	-	1.5	6.1	
Motor control center	Integral	800	12	2.4	16.0	0.6	-	19.0	(5)
Magnet current supply	Integral	100	10	-	-	-	-	-	(5)
Substation	Integral	360	12	-	-	-	-	-	(5)
Cooling tower	Integral	300	20	-	-	-	-	-	(5)
TOTALS		16860		60.1	500.0	23.4	57.5	641.0	

Remarks:

(1) 30-foot clearance under crane hook
(2) Air conditioning includes both temperature and humidity control
(3) Air conditioning located remotely due to large stray magnetic field at enclosure
(4) Class I, Group B, Division 2 area. Emergency ventilation provides for 1 minute air change
(5) Dimensions are for the enclosure containing the equipment plus the personnel space where required

i) Utilities and Interfaces

The electrical system consists of a 3.0-MVA, 13.8kV/480V 3-phase weatherproof portable secondary substation complete with switchgear and above-ground distribution system to the motor control center and then to all electrical loads within the site. The 13.8kV 3-phase feeder connection to this transformer represents the electrical interface with the accelerator electrical system. The portable motor control center is of weatherproof construction and contains a heated and lighted shelter for personnel involved in operations or maintenance. The electrical power requirements are shown in Table VIII. The closed-circuit cooling system for the compressors, hydraulic power supply, air conditioners, etc., consists of a 2-MW cooling tower and associated 300-gpm pumping system with a makeup connection to the domestic water system. The domestic water, sanitary sewer, storm drainage, telephone, and fire alarm systems are all distributed within the site for connection to the accelerator systems at the interface location.

ii) Maintenance Facility

A works and assembly area is housed in a high bay of about 4000 square feet with 20-ton bridge crane coverage of the entire floor area. The remainder of the building with a total floor area of 5000 square feet on two stories provides offices, light assembly rooms, electronic laboratories, and storage space. Movable partitions are used wherever possible. Ample access for fork lifts and trucks is provided.

References

1. 14-foot Cryogenic Bubble Chamber Project Title I Report. December 1, 1966, BNL 10700.

2. Proposal for the Construction of a 12-foot Hydrogen Bubble Chamber, June 10, 1964. Argonne National Laboratory.

Table VIII. Electrical Requirements

Item	Size (hp)	Type	Use	Load (KVA)
Motor	400	Synchronous	H_2 refrigerator	280
"	400	"	H_2 refrigerator	280
"	400	"	He refrigerator	280
"	400	"	He refrigerator	280
"	660	"	Expansion system	462
"	100	Induction	Expansion auxiliary	100
"	100	"	Instrument air	60
"	100	"	Instrument air	60
"	20	"	Process vacuum	20
"	10	"	Camera vacuum	10
Motors	Various	"	Main vacuum pumps	80
"	"	"	Auxiary vacuum pumps	20
"	"	"	Cooling tower	30
"	"	"	Building crane	25
Charging supply			Magnet	163
Oil diffusion pumps			Vacuum system	60
Dryers			Refrigerator	30
Dryers			Instrument air	5
Vacuum pump			Window	10
Control room			Instrumentation and controls	60
Buildings			Heat, light, ventilation, A/C	641
Lighting			Yard	15
TOTAL LOAD (KVA)				2971

SAFETY I

4. SAFETY CONSIDERATIONS

I. Introduction

Safety considerations are vital for all phases of cryogenic bubble chamber design, during the preliminary design phase when concepts are developed, during detailed design when such concepts are more clearly defined, and during construction when quality of workmanship and adherence to specifications are verified and tested. An operational safety analysis is made for all components of the facility as soon as the designs are sufficiently advanced to allow for such an analysis. This includes various failure modes and their consequences. Such studies minimize hazards to personnel and equipment in case of a malfunction.

II. Safety Organization

A. GENERAL

Safety aspects are studied and considered in detail by physicists and engineers who are responsible for the design. These groups have been associated with the BNL 20-inch, 30-inch, 31-inch and 80-inch chambers, as well as the 7-foot test facility. Besides the experience of designing and constructing these chambers, many years of operating experience is available. Individual knowledge has been improved by advisory services to other organizations which include equipment design reviews and work towards establishing national guidelines for improving safety in the high energy physics research program.

B. REVIEW BY OUTSIDE COMMITTEES

The policy has been to have cryogenic chamber designs reviewed at various stages by groups of people not directly associated with the project. Such reviews have been undertaken by 1) Brookhaven Safety personnel, such as the BNL Safety Office, the Cryogenic Safety Committee, and the Special Hazards Engineer; 2) In the case of the 14-foot cryogenic bubble chamber Title I design, an outside review committee was organized which consisted of internationally recognized experts in the field. This group independently reviewed the proposed design and operational procedures and prepared a report listing its findings with recommendations for further study.[1]

C. GROUP SAFETY COMMITTEE

The Brookhaven Bubble Chamber Group has an internal safety committee comprised of physicists and engineers within the group. This committee works closely with the designers during all phases of design and construction. The aim is to promote safety by early identification of possible hazards with immediate recommendations for design changes.

D. ADHERENCE TO ACCEPTED CODES

Where applicable, components of this facility comply with the accepted codes, including the following:

National Fire Protection Association

American Society of Mechanical Engineers

Instrument Society of America

Compressed Gas Association

American Standards Association

American Society for Testing Materials

National Electrical Code

Safety Guidelines for High Energy Accelerator Facilities

Accepted industrial practice is followed and enforced pertaining to workmanship, testing, and quality.

E. EMERGENCY AND OPERATIONAL PROCEDURES

Emergency and operational procedures are written in detail when the designs are complete. These include actions to be taken to fit the type and degree of emergency ranging from corrective actions of limited scope to complete halt of operations and evacuation of personnel.

III. Buildings and Facilities

A. INTEGRITY OF THE BUILDINGS

The design criteria for the buildings are based on weather conditions for the locality. In order to prevent building overpressures, walls and roofs are designed to relieve at low pressure. This affords protection to the structural framework and the equipment. Panels are of low mass to minimize hazards of possible projectiles.

B. ISOLATION OF COMPONENTS

Areas which contain flammable cryogens and gases are separated from normally occupied spaces. Isolation of components is widely

recognized as a major safety requirement provided to prevent interactions between hazardous modules. Location of cryogenic storage vessels is consistent with accepted code requirements. Isolation of the control room insures the availability of a safe area during emergency conditions. Instrumentation readout and process control are remoted to this area so that the operator can identify the hazard and take corrective action immediately. The control room serves as the central communications center allowing audio as well as television contacts with personnel and equipment throughout the facility.

C. CLASSIFICATION OF AREAS IN ACCORDANCE WITH NATIONAL ELECTRICAL CODE

All areas where flammable gases or volatile liquids are present are classified as Class I, Group B, Division 2. Division 2 applies to this type of installation because the hazardous fluids are normally confined within closed systems or containers and released only in case of a component failure. All electrical equipment in these areas is consistent with this classification. A grounding system is provided and lightning protection is also connected to this system.

D. PROVISION FOR EGRESS

In all facilities, emergency exits and doors are provided to allow for more than one means of exit to personnel should one route be blocked. Emergency exits are identified and provided with bar-type release.

E. ELIMINATING HAZARDOUS GAS MIXTURES

The rooms containing hazardous cryogens are equipped with sensors for detecting combustible gas mixtures. Automatic emergency ventilation systems are provided to remove gases released to the atmosphere as quickly as is possible.

F. EMERGENCY POWER

Emergency power is needed for power failure protection. Sufficient capacity maintains operation of vital components on a standby basis during power failures. These include lighting, communications, instrumentation and controls, emergency ventilation, instrument-air-compressors, compressors, vacuum pumps, and gas analysis equipment.

IV. Pressure Vessels

A. CRYOGENIC CHAMBER

The cryogenic chamber, described in detail in Chapter 3, I, is designed to the ASME Unfired Pressure Vessel Code for a working pressure of 200 psi. The materials used for its fabrication are subjected to chemical analysis to assure compliance with required standards. The type 316L stainless steel material used for its fabrication has proven stable at cryogenic temperatures against martensitic transformation, assuring that the required tensile strength, endurance strength, and ductility is maintained for this vessel which is subject to dynamic loading. The vessel is radiographed at welded joints and castings or forgings are fully radiographed. The vessel is tested at 1-1/2 times the design pressure at room temperature. An additional safety factor results from the increase of the material's strength at low temperature.

B. VACUUM TANK

The construction of the vacuum tank is described in Chapter 3, I. The primary function of this vessel is to provide a surrounding vacuum for the cryogenic inner vessel. However, to provide additional safety to the facility, this vessel is also designed as a pressure vessel for service as a safety container in case of failure of an internal component. All major welded joints are radiographed and the tank is subjected to vacuum and pressure tests. Camera ports are made of quartz to protect them against thermal shock failure.

C. CRYOGENIC STORAGE VESSELS AND GAS STORAGE TANKS

All dewars, vessels, storage tanks and their associated piping are designed, built, inspected and tested in accordance with applicable codes. ASME certification for pressure vessels is obtained where applicable.

V. Vent and Dump Systems

Redundant emergency venting systems are provided for all process fluids. Gas venting and liquid dump valves are provided for all cryogenic fluids. Normal procedure is to transfer liquid to storage dewars, and only in the unexpected case that this system is inoperative is emergency dumping to atmosphere to be used. In the case of hydrogen a flare stack is provided for safe disposal. Any portion of the piping or vessels which may be valved off and therefore subjected to overpressure on warmup has automatic pressure relief.

VI. Refrigeration, Expansion, and Vacuum Systems

These systems are dynamic systems with complex piping, pressure vessels, heat exchangers, compression and expansion equipment, and control components. All piping and vessels are designed and tested in accordance with standard industrial practice and existing codes where applicable, and pressure relief protection is included.

Wherever possible, equipment is selected and designed so that loss of one component will not result in shutdown of the entire system. Sufficient backup equipment is available to enable operation to continue at a reduced level. This helps to improve safety since sufficient capacity for standby operation remains available in case one component should fail.

The process hydrogen gas is continuously analyzed by a gas analysis system. This system automatically samples the process gas at various strategic points and analyzes oxygen and other impurities. Should the level of contamination become excessive for safe or efficient operation, alarms provide immediate notification. In order to keep contaminants to a minimum, purification equipment is provided. The purifiers are of the dual type so that one side can be in use while the other system is undergoing reactivation.

High pumping capacity is provided for the vacuum pumping system for the vacuum chamber. Cryopumping of residual gases by cryogenic surfaces is not relied upon in order to avoid the hazard of solid oxygen accumulating on the cold surfaces. The entire magnet is surrounded by multiple-layer insulation encased in a Mylar bag to reduce cryopumping should a hydrogen leak occur inside the vacuum chamber. The multiple-layer insulation continues to provide insulation in case of vacuum failure so that the cryogenic liquid need not be dumped in case of momentary vacuum or power failure.

Phosphate ester-type hydraulic fluid is used in the hydraulic expansion system to reduce the fire hazard associated with the use of petroleum oil. This fluid will burn only at the source of ignition and will not propagate flame.

VII. Optics

The detailed design for the optical system is discussed in Chapter 3, IV. The use of smaller spherical windows here (rather than

large flat windows on previous chambers) makes it possible and practical to design windows with a larger safety factor than used in previous designs. An additional safety feature here is that the chamber window, the shield window, and the vacuum chamber window are all made of quartz to protect against thermal shocks. Thus, should both inner windows break in succession (an extremely remote possibility) the outer vacuum window would be protected. Likewise, should the vacuum chamber window break (assuming mechanical damage from the outside) the two inner cold windows would be protected. The entire optical assembly is surrounded either by vacuum or by inert gas which is circulated around the flashtubes to cool them.

VIII. Magnet

The coil windings of the superconducting magnet are fabricated from hollow, stabilized superconductor. These superconducting windings are stabilized by bonding normal conductor to the superconductor. The size of the normal conductor is such that if sudden momentary magnetic flux redistributions occur in sections of the magnet conductor, the normal conductor can carry the full magnet current for the duration of the flux redistribution without the temperature at the superconductor rising above the critical temperature of the superconductor. The heat capacity of the normal conductor with the internal helium coolant flow is sufficient to quench possible "hot" spots thus formed before they can propagate. This insures that the magnet coils do not suddenly go normal.

The stabilized superconducting windings will also be designed and instrumented to prevent the magnet coils from suddenly going normal if the current is increased beyond that value which the superconductor can carry in the magnetic field. If the current is increased beyond the current carrying capacity of the superconductor, the excess current will transfer to the normal conductor and a voltage will appear across the magnet. As soon as this voltage is detected, the current to the magnet will be reduced automatically through an external resistor or by reducing the applied voltage.

References

1. Brookhaven National Laboratory 14-foot Cryogenic Bubble Chamber Project Safety Review. April 1968. External Safety Committee.

COST ESTIMATES & SCHEDULE

5. COST ESTIMATES AND SCHEDULE

1. Cost Estimates

A. CONSTRUCTION

Cost estimates for large bubble chambers have been developed by the Brookhaven staff since May 1964. A detailed estimate was prepared as part of the Title I design of the 14-foot bubble chamber and presented in the Title I Report.[1] In that estimate, the cost of the technical components was estimated from quotations from vendors for equipment and fabrication. Such quotations made up about 90 percent of the cost estimate. The architect-engineering firm of Chas. T. Main, Inc., provided the estimate for the conventional facilities associated with the project as presented in their Title I design report[2] of November 1966. Since that time the Brookhaven staff has carried out additional cost studies of large bubble chambers[3] that have evolved into the present proposed design for the 25-foot chamber. This was done by means of an analysis of the costs of a series of spherical and oblong chambers using hollow core superconducting magnets with facilities of the presently proposed, relocatable type.

The 25-foot chamber cost estimate of approximately $13.6 million was obtained from an independent estimate of each of the seven subsystems that make up the chamber complex. The cost of the technical components of these systems was partly based on quoted costs of similar equipment for the 14-foot chamber, taking into account escalation since that time. In addition, the 7-foot test facility program has provided accurate cost and manpower information for a subscale system of many of the components for the 25-foot chamber. The estimate for the conventional facilities is based on the cost of similar structures now in use at BNL and NAL. The Butler-type buildings have been estimated with NAL costs, which are lower than BNL costs. Portable substations, motor control centers, and cooling towers were estimated from the 14-foot-chamber estimates of Chas. T. Main with escalation.

The cost estimate is presented in two parts, the construction cost summary in Table IXa, and the detailed cost breakdown in Table IXb.

Table IXa. Construction Cost Estimate

	(Amounts in Thousands of Dollars)		
1. Construction Costs			
A. Technical Components	6,768.0		
B. Conventional Facilities and Utilities	690.0		
C. Standard Equipment	556.0		
Subtotal		8,014.0	
2. Engineering, Design, Inspection, and Administration			
A. Technical Components (25%)	1,692.0		
B. Conventional Facilities (20.0%)	138.0		
Subtotal		1,830.0	
3. Contingencies and Escalation			
A. Technical Components and Manpower (25%)	2,115.0		
B. Conventional Facilities (15%)	124.0		
C. Standard Equipment (10%)	56.0		
D. Escalation (15%)	1,477.0		
Subtotal		3,772.0	
TOTAL PROJECT			$13,616.0

Table IXb. Detailed Construction Cost Estimate

	(Amounts in Thousands of Dollars)
CHAMBER	
Chamber body, 316L stainless steel with cylinder section, camera ports and support legs at $6.00/lb	424.0
Refrigeration loops and connections	30.0
Preparation for Scotchlite	10.0
Cryogenic seals for 90-inch-diameter flange	3.0
Fill, vent, dump valves	42.0

Instrumentation		32.0	
Spherical Baffles, 4800 lbs at $4.00/lb		19.0	
Total Chamber Construction			$560.0
EXPANSION SYSTEM			
90-inch-diameter fiberglass-reinforced plastic piston		169.0	
Piston rings and carrier		11.0	
Temperature control		20.0	
High-response hydraulic actuator with 18-inch-diameter cylinder and 12-inch diameter valve		112.0	
550 gpm, 1500 psi, hydraulic power supply		44.0	
40 gpm, 3000 psi, auxiliary power supply		14.0	
Accumulators and supports		50.0	
Power supply installation in building		20.0	
Valves, plumbing, control panels		75.0	
Accumulator charging system		5.0	
Instrumentation		50.0	
Total Expansion Construction			$570.0
REFRIGERATION			
Hydrogen Systems			
Basic hydrogen refrigerator 20 kW at $40.00/Watt	800.0		
Hydrogen/Deuterium chamber liquid storage; 30,000 gal at $3.90/gal	117.0		
Hydrogen special systems: fill and vent system, including purification, control and instrumentation	63.0	980.0	

Nitrogen Systems			
Liquid nitrogen storage for 5 days operation; 20,000 gal at $2.50/gal	50.0		
Liquid nitrogen distribution system	35.0	85.0	
Helium Systems			
Basic helium refrigerator	500.0		
Compressors and heat exchangers to provide super-critical helium at a maximum pressure of 30 atm and operating between 4.5 and 6.0°K	225.0		
5000-gal helium dewar with coils for cooling helium flow for magnet	75.0	800.0	
Total Refrigeration Construction			$1,865.0

OPTICS

Illumination			
Scotchlite (1000 sq ft of wall to cover; price is for 2000 sq ft at $6.50/sq ft	13.0		
Power supplies	6.0		
Capacitors	2.0		
Flash tubes	1.0		
Trigger circuits	4.0		
Light monitors	2.0	28.0	
Optical Glassware			
Hemispherical windows (6 sets of 3 each) Quartz at $18,000/set	108.0		
Lenses (3 telecentric, 35mm, 140°) not including design	60.0		
Transmission coating of windows, $2,500/set	15.0	183.0	

Mounting for Optics			
Window and Lens Mounts		60.0	
Periscope mount & miscellaneous		1.0	61.0
Cameras			
Film transports		30.0	
Transport drive electronics		16.0	
Film platens		3.0	
Data box heads		9.0	
Data box electronics		10.0	68.0
Total Optics Construction			$340.0
MAGNET			
Magnet Coil			
Material:			
Superconducting material 306,000 ft		855.0	
Copper (to be processed with superconductor) 306,000 ft		330.0	
Stainless steel stiffener strip, 306,000 ft		144.0	
Insulation, 306,000 ft		15.0	
Processing:			
Superconducting material copper, 306,000 ft		1,060.0	
Coil structure			
Coil support clamps	52.0		
Coil electrical clamps	12.0		
Insulating layer spacers	9.0		
Tie rods, etc.	4.0	77.0	
Winding Device		34.0	2,515.0
Support Structure, Plumbing & Assy Fixtures			
Coil bridge, 70,000 lbs		105.0	
Coil support structure		40.0	
Plumbing		30.0	175.0

Power Supply and Associated equipment		50.0	
Instrumentation		20.0	
Total Magnet Construction			$2,760.0

VACUUM TANK AND VACUUM SYSTEM

Vacuum Tank			
Spherical shell, 9% nickel-steel, field erected, 88,500 lbs at $1.50/lb	131.0		
Support structure consisting of six stainless steel legs and support pads, 50,000 lbs at $2.50/lb	125.0		
Bottom cover and flange, stainless steel, 8,400 lbs at $4.00/lb	34.0		
72" diameter omega bellows assembly in stainless steel	10.0		
Ports, plumbing connections, feedthroughs	35.0	335.0	
Main Vacuum Pumping System & Instrumentation		150.0	
Window Vacuum		40.0	
Auxiliary Vacuum System		30.0	
Insulation		125.0	
Emergency Vent Line		120.0	
Hydrogen Disposal System		60.0	
Total Vacuum Construction			$ 860.0

INSTRUMENTATION

Interconnecting cable and tubing		118.0	
Instrument Air System		18.0	
AGS Interface, timing, etc.		31.0	
Test and Calibration Equipment		31.0	

Monitor, Communications, and Control equipment		63.0	
Emergency Generator		44.0	
Total Instrumentation			$ 305.0

BUILDINGS AND FACILITIES

Improvements to Land			
Clearing and grading/erosion control; 1-3/4 acre	4.0		
Hardstands, 8000 sq yd	55.6		
Storm drainage, 800 ft	3.7		
Fencing, 1200 ft x 6 ft	2.7	66.0	
Buildings			
Works area, assembly area, laboratories and office bldg., 9,000 sq ft	272.0		
Hydrogen compressor bldg., 1350 sq ft by 15 ft high	37.0		
Helium compressor bldg., 900 sq ft by 15 ft high	25.0		
Cryostat bldg., 400 sq ft by 8-1/2 ft high	11.0	345.0	
Other Structures			
Chamber foundation, 500 cu yd	39.0		
Compressor bldg. foundation 200 sq yd	16.0		
Compressor foundation 300 cu yd	23.0		
Chamber optics shed, 400 sq ft by 8-1/2 ft high	11.5		
Chamber expansion wall, 400 sq ft by 8-1/2 ft high	11.5		
Control room, 1000 sq ft by 12 ft high	30.0		

Motor control room, 800 sq ft by 12 ft high	20.0		
Vacuum pump room, 700 sq ft by 10 ft high	14.0		
Instrument Air room, 300 sq ft by 12 ft high	6.0		
Hydraulic room, 600 sq ft by 10 ft high	12.0		
Dark room, 200 sq ft by 10 ft high	6.0	189.0	
Utilities			
Motor control center and interconnecting wiring	90.0		
Substation, 3000 kW	54.0		
Cooling tower	10.0	154.0	
Total Buildings & Facilities Construction			$ 754.0

For Schedule 44 type summary table IXa, page 96, $556,000 of standard catalogue equipment has been removed from the above detailed cost estimate for individual systems. Corrected systems totals are: Expansion $477,000, Refrigeration $1,673,000, Optics $319,000, Vacuum $718,000, Instrumentation $305,000, and Utilities $90,000.

B. GASES FOR FILLING THE CHAMBER

As has been mentioned, physics experimentation requires flexibility in the substances used to fill the chamber. Various possibilities exist. These include hydrogen, deuterium, neon, and mixtures of hydrogen and neon. Also, possibilities such as an inner track-sensitive target filled with deuterium used with an outer chamber filling of hydrogen and neon are thought to hold great promise for future experiments and, therefore, need to be included in the present considerations.

A plan has been developed for requesting the funds necessary for obtaining the gases that are needed for the chamber. First to be considered is hydrogen. In the case of BNL's 80-inch chamber, experimental operations began in September 1963, and over 3 million pictures were

taken with hydrogen fillings before May 1966 when deuterium was first used. Since then about 1.2 million pictures have been taken with deuterium out of a total of 3.2 million. On the other hand, to show the variation of program needs, the BNL 30-inch-chamber was first operated with deuterium in September 1962 and since that time 3.4 million pictures have been taken with deuterium out of a total of 6.2 million pictures. Our best estimate for the 25-foot chamber is that the first operation will be with hydrogen, and this will continue for about one year prior to first deuterium operation. (Initial operation with hydrogen for a check-out period is required before committing the much more expensive deuterium to a new bubble chamber system.) Also, about one half of the operation will be with hydrogen fillings. Using the latest cost for liquid hydrogen and allowing for a 10 percent contingency, $5,600 will purchase the liquid for one filling. This can easily be financed out of operating funds.

Next, the estimate should allow for about one half of the operation with deuterium beginning about one year after the first hydrogen runs. At current costs, ~$3.8 million is required for a deuterium filling including contingency. Two procedures have been followed in the past for obtaining requisite deuterium:

1) Heavy water was purchased from the AEC stock pile at Savannah River according to the following specification -

> "Heavy water, D_2O, for bubble chamber use, from Dana Plant stock, with an activity of 0.0003 microcuries per cm^3 or less due to tritium."

Operating funds were used for these procurements, and the heavy water was shipped to a commercial company for conversion and storage in high-pressure gas trailers. These trailers were then shipped to BNL and the gas has been used as needed. Soon ~$400,000 worth of deuterium gas will be at BNL for use with any of the four cryogenic bubble chambers.

2) At the time of the ANL 12-foot proposal, ~$1 million was included in the Schedule 44 Construction Project Data Sheets for ~60,000 pounds of heavy water for use in the 12-foot chamber. Our understanding is that an analogy was drawn to heavy-water reactors where deuterium necessary for operation had usually been carried as part of the construction project.

For greatest cost efficiency, we propose that the AEC Research Division set up a bubble chamber deuterium gas pool from which deuterium is assigned consistent with program needs. This proposal seems appropriate since a smaller total pool of deuterium would be required than if each chamber carried its own stock of deuterium and since all large bubble chambers would still be allowed to be scheduled with only slight inconvenience. As new large volume chambers are constructed, the pool would require some additional inventory but not necessarily proportional to new chamber volume. Makeup for losses would be operating expense. The size of the deuterium inventory in 1974 should be sufficient to operate simultaneously two out of the three large volume chambers which should exist at that time. This inventory could be made up as shown in Table X.

Table X. Deuterium Inventory

Deuterium on hand for BNL's 7-foot chamber	$ 400,000
Deuterium on hand for ANL's 12-foot chamber	1,000,000
FY-1972 line item for establishing pool	3,600,000
Total	$5,000,000

Net cost to the U.S. Government would be minimized under this plan, especially if new production of heavy water is not required since, in fact, the deuterium gas could be converted to heavy water and added back to the reserves in the event of an emergency requirement. Sharing of expensive materials when program efficiency is not adversely affected is particularly justified and, therefore, strongly suggests that this procedure should be followed. An alternate procedure would be to add $3.8 million to the 25-foot construction project increasing the project's total estimated cost from $12 million to $15.8 million.

Use of the 25-foot chamber with neon or neon-hydrogen mixtures, whether in the chamber proper or in a target-chamber configuration, is much more difficult to estimate than hydrogen and deuterium operation discussed above. The first neon-hydrogen run in the BNL 80-inch chamber was in March 1967 and these 360,000 pictures are still in analysis. The cost of neon was about $100 per liquid liter in 1965 and dropped to

$44 per liquid liter by 1967. Due to the great increase in use of liquid oxygen in the steel industry, high-tonnage air liquefaction plants are becoming more numerous and the basic cost of the processes is being substantially reduced. Our understanding is that neon separation loops can be added to these plants economically and that this should result in greatly reduced costs for neon in the future. Since the cost and the percentage usage are both in question, we propose that the neon filling estimates should be re-evaluated at a later time when more meaningful data will be available. It seems therefore wise not to include these possible future costs at the present time.

C. OPERATING COST ESTIMATE

The annual operating cost for the 25-foot chamber is based on the assumption of taking 3,000,000 pictures per year. The chamber is assumed to be scheduled for operation on a 7-day week, 24-hour-per-day basis. In addition, costs associated with the use of gases for filling the chamber and operating the refrigeration systems have been included. Other costs for capital equipment and improvements have been included that are consistent with BNL experience in operating bubble chamber facilities. A summary of these operating costs to be applied in fiscal year 1974 is shown in Table XI.

Table XI. Estimated Annual Budget in FY 1974

Operating Costs		(Thousands of Dollars)		
Wage Expense (47 full-time equivalents)		700.0		
Supplies		240.0		
Major procurements:				
Film and processing	500.0			
Power	170.0			
Gases (hydrogen, helium, nitrogen)	190.0	860.0		
Engineering and shop burden		150.0		
Total operating costs			1,950.0	
Other Costs				
Capital Equipment and Improvements			300.0	
Total Annual Budget				2,250.0

II. Schedule

The overall construction schedule is based on the event timetable shown in Table XII.

Table XII. Schedule

Event	Date
Submit proposal	June 1, 1968
Request Title I CP&D funds	July 1, 1968
Title I design	September 1968 to March 30, 1969
AEC to submit budget to BOB	October 1968
President delivers budget message	January 1969
Request Title II A/D funds	February 1969
Title I design review	April 1, 1969 to April 30, 1969
Title II design	May 1, 1969 to June 30, 1970

Project funds available	November 1969
Start placing orders	April 1, 1970
First material orders	April-May 1970
Fabrication of chamber	July 1970 to July 1, 1972
Prefitting	April 1972 to September 30, 1972
First 200 BeV proton acceleration	July 1972
Final assembly and tests	October 1, 1972 to June 30, 1973
First total chamber operation for tests	January 1, 1973
Chamber ready for experiments	July 1, 1973

A first-level breakdown of the project has been made and scheduled. The corresponding obligations and costs for each fiscal year of the project is given in Table XIII.

Table XIII. Obligation and Cost Schedule

Fiscal Year	Obligations	Costs
1969	$ 300,000	$ 300,000
1970	2,000,000	500,000
1971	7,300,000	1,300,000
1972	2,700,000	8,000,000
1973	1,316,000	2,900,000
1974		616,000
	$13,616,000	$13,616,000

The actual construction schedule is shown in Fig. 15. This includes the design, fabrication, and installation of the seven chamber systems and the facilities. Research and development programs on the optics assemblies and hollow core stabilized superconductors are also shown. It is anticipated that the project will be administered using a PERT/Cost technique in order to minimize the possibility of overrun in project cost and/or duration.

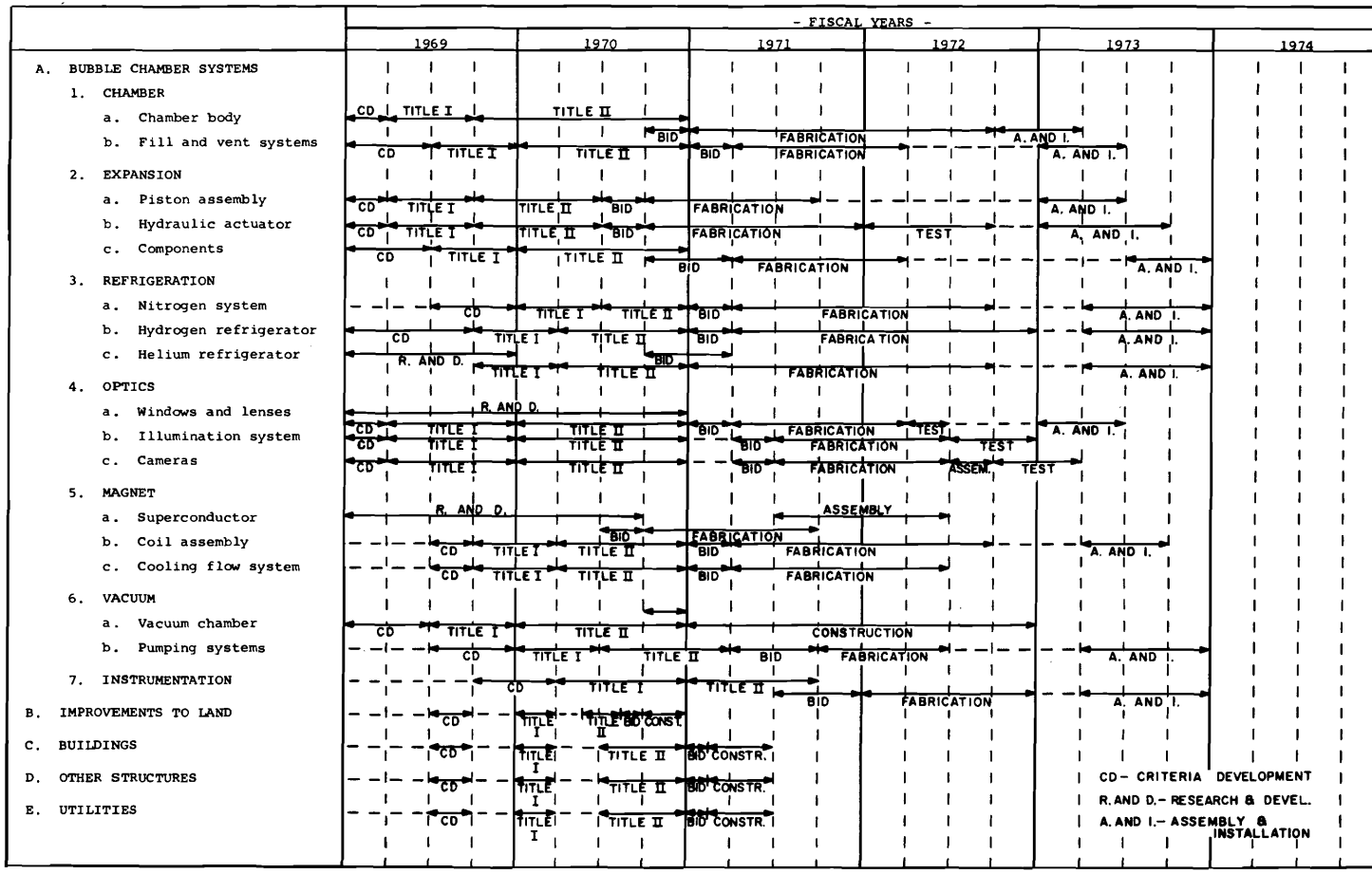

- FISCAL YEARS -
1969
1970
1971
1972
1973
1974
A. BUBBLE CHAMBER SYSTEMS
1. CHAMBER
a. Chamber body
b. Fill and vent systems
2. EXPANSION
a. Piston assembly
b. Hydraulic actuator
c. Components
3. REFRIGERATION
a. Nitrogen system
b. Hydrogen refrigerator
c. Helium refrigerator
4. OPTICS
a. Windows and lenses
b. Illumination system
c. Cameras
5. MAGNET
a. Superconductor
b. Coil assembly
c. Cooling flow system
6. VACUUM
a. Vacuum chamber
b. Pumping systems
7. INSTRUMENTATION
B. IMPROVEMENTS TO LAND
C. BUILDINGS
D. OTHER STRUCTURES
E. UTILITIES
CD
TITLE I
TITLE II
BID
FABRICATION
A. AND I.
TEST
R. AND D.
ASSEMBLY
ASSEM.
CONSTRUCTION
CONST.
CONSTR.
CD - CRITERIA DEVELOPMENT
R. AND D. - RESEARCH & DEVEL.
A. AND I. - ASSEMBLY & INSTALLATION

FIG. 15

References

1. 14-foot Cryogenic Bubble Chamber Project Title I Report. December 1, 1966, BNL 10700

2. 14-foot Cryogenic Bubble Chamber Project, Title I Report. Chas. T. Main, Inc. November 28, 1966

3. Scaling Studies of Large Cryogenic Bubble Chambers. BNL Bubble Chamber Group. April 1, 1968, BNL 12336