**THE
APPLICATION OF COMPUTERS
TO CONTROLLED
THERMONUCLEAR RESEARCH**

**A REPORT TO
THE USAEC DIVISION OF CONTROLLED
THERMONUCLEAR RESEARCH**

JULY 1973

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The Application of Computers to Controlled Thermonuclear Research

A Report to the USAEC Division
of
Controlled Thermonuclear Research

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PREFACE

The Division of Controlled Thermonuclear Research of the Atomic Energy Commission has the responsibility for the development of fusion power using magnetic confinement methods to create, contain, and burn thermonuclear plasmas. The activities supported by the Division of Controlled Thermonuclear Research are grouped into three programs. These are: Magnetic Confinement Systems, Development and Technology, and Research. The Research Program supports a broad spectrum of experimental and theoretical studies that are essential to the realization of the short and long term goals of the Controlled Thermonuclear Research Program. To assist in the advanced planning needed to meet the schedules developed by the Magnetic Confinement Systems Program it has been necessary to conduct a number of studies on different facets of the Research Program activities. These studies have involved DCTR staff and engineers and physicists from national laboratories, universities, and other government agencies.

The first study was initiated shortly after the establishment of the Research Program in the fall of 1972. As its title, "Review of the Research Program of the Division of Controlled Thermonuclear Research" (WASH-1271) indicates, the report based on this study was a review of the entire Research Program. The report contains a description of all the activities on a contract by contract basis for the present (1973) and recent past and an analysis of the required research studies within the six activity categories (Plasma Production and Heating; Plasma Measurements and Instrumentation; Computer Applications to CTR; Exploratory Concepts in CTR; Plasma Properties: Equilibrium, Stability and Transport; and Atomic, Molecular and Nuclear Physics in CTR) that make up the Research Program. It also contains specific recommendations regarding the future course of the Research Program so that it will provide the CTR Program with the data needed to design, construct, and operate large plasma confinement experiments and fusion reactors. This first report indicated specific areas in which detailed studies were needed. These included a study of computer applications to CTR, which is the subject of this report, a study on the uses of intense relativistic electron beams in CTR, the uses of long wavelengths lasers to heat magnetically confined plasmas, and the application of symbolic computation methods to CTR.

This report "Application of Computers to CTR" surveys the need for large computers in analyzing the properties of magnetically confined plasmas and simulating the characteristics of fusion reactors. The major conclusion of the report is that to meet the program schedule developed by Magnetic Confinement Systems, it would be necessary to immediately scale up the CTR computerized effort to a level of two Class IV computers by FY 1975. Based on this report, and in an attempt to best meet this need, it was decided to establish the National CTR Computer Center at the Lawrence Livermore Laboratory.

This Center, which is planned to be operational in the Spring of 1975, will be connected to all major CTR laboratories and other contractors by means of a wide-band communications network. The increased computing power made available by the Center will accelerate the development of the theoretical models and associated large-scale computer codes needed to predict the behavior of plasma confinement systems and the operating characteristics of fusion power reactors.

My special thanks go to the authors of this report for the way in which they responded on short notice when I asked them to conduct a thorough study of the CTR computer problem, to develop viable options for the solution of the problem, and to prepare a report based on their studies. I also thank Dr. Bennett Miller of the AEC who did an outstanding job as chairman of the committee and as the editor of the report which the committee developed.

I sincerely appreciate the advice and encouragement that Dr. Robert L. Hirsch, Director, Division of Controlled Thermonuclear Research; Dr. Stephen O. Dean, Assistant Director for Confinement Systems; and Dr. Robert W. Bussard, former Assistant Director for Development & Technology; gave me during the course of this study and the follow-on activities that lead up to the establishment of the National CTR Computer Center.

A. W. Trivelpiece
Assistant Director
for Research
Division of Controlled
Thermonuclear Research

Other reports in this series are:

Review of the Research Program of the Division of Controlled Thermonuclear Research (WASH-1271) 1973.

Application of High Current Relativistic Electron Beam in CTR (WASH-1286) 1974.

I. FOREWORD

Dr. Alvin W. Trivelpiece, Assistant Director for Research in the Division of Controlled Thermonuclear Research commissioned an Ad Hoc Panel on the Application of Computers to Controlled Thermonuclear Research in May 1973 to provide him with a technical assessment on the size and scope of the computing facilities and associated level-of-effort needed to meet the goals of the CTR program.

The impetus for making this assessment came from several sources nearly simultaneously. First, the Office of Research conducted a survey of computer facilities available to CTR and the level at which they were being used. The survey indicated that a number of problems of importance to CTR were not being given adequate attention as a result of insufficient access to large scale digital computers. This was followed by a review * of the Research Program that tentatively concluded, among other things, that a rapid growth of the use of computers in CTR is needed in order to meet the present CTR program goal. And, finally, the Standing Committee at its April 1973 meeting recommended that "... the size and scope of the computational activity in CTR should be independently reviewed as soon as possible."

As a result of the above, the *Ad Hoc* Panel on the Application of Computers to Controlled Thermonuclear Research was created on May 18, 1973 and asked

- (a) to survey and summarize the existing level-of-effort in the application of computers to CTR.
- (b) to identify important CTR physics and engineering questions that are or may be soluble by the use of computers, and to evaluate the benefits that would accrue to the CTR program if such solutions were obtained, and
- (c) to survey, summarize and evaluate the status of present and anticipated computer technology for the purpose of accurately forecasting the type, size, scope, and composition of a facility

* "Review of the Research Program of the Division of Controlled Thermonuclear Research." United States Atomic Energy Commission, prepared for the CTR Standing Committee Meeting held at the Massachusetts Institute of Technology on April 26-27, 1973.

that would realize the benefits identified in (b) above, and the lead time necessary for assembling it.

The wide range of the questions posed to the panel dictated that its composition be as diverse as the issues it was asked to address. Therefore, besides AEC Headquarters personnel, the panel had three different groups of participants—plasma physicists, plasma engineers, and computer scientists—who were organized along functional lines into three sub-panels, as shown on page 3.

The Sub-panel on Computational Physics and Engineering Aspects of CTR devoted its attention primarily to objectives (a) and (b); the Sub-panel on Computer Technology concentrated on (c). The Overview Sub-panel worked with the other two panels, and with the Chairman, to help coordinate and integrate information as it was developed. Each Sub-panel Chairman assumed responsibility for organizing information generated by his sub-panel and transmitting it to the Overview Sub-panel and to the Chairman.

The Physics and Engineering Sub-panel was further divided into three Working Groups on Physics, Engineering, and Simulation. The first and second groups addressed the question of what physics and engineering problems will arise that may require computer solution independent of how the computer is used to solve them. The third group considered the question of the techniques used to solve the problems identified by the other two.

The panel and its sub-panels met for six days during the month of June 1973. All recommendations presented in this document were developed in plenary session and represent the unanimous opinion of the panel. I would like to extend my sincere thanks to the panel members for their unstinting cooperation throughout this project. The direct and dedicated attitude with which they approached the problems that were posed to them and their appreciation of the art of productive group interaction was the epitome of effective committee action.

Bennett Miller, *Chairman*

II. SUMMARY OF RECOMMENDATIONS

The *Ad Hoc* Panel on the Application of Computers to Controlled Thermonuclear Research has reviewed the present utilization of large scale digital computing by the Controlled Thermonuclear Research Program and has evaluated the program's future requirements for significantly increased effort in that activity. The recommendations below are based on the panel's unanimous belief that an increased use of advanced computer techniques and technology will play a vital role in the realization of fusion power.

While the panel had been charged to identify both the long-term and short-term needs of the CTR program, the immediate demands for increased computing in CTR are so acute that the panel has emphasized near-term needs, i.e., through FY 1976, and has recommended an appropriate way to meet them.

Recommendations:

A. Near-term Requirements:

1. To meet the minimum, near-term computational needs of the Controlled Thermonuclear Research program, the level of computing activity must be increased immediately to the equivalent of at least one-half of a Class 4 computer * in FY 1974. This scale-up should be followed by the addition of another equivalent in FY 1975, and again by one and one-half equivalents in FY 1976. To meet the computational demand identified in this report, the Controlled Thermonuclear Research Program should have available for use on a priority basis the equivalent of at least three Class 4 systems full time by FY 1976. Failure to follow this recommendation will result in a serious delay in developing the problem solving capa-

* Class 4 will be used generically to denote any one of the following computers or their equivalents: Control Data Corporation (CDC), Model 7600; International Business Machines (IBM), Systems 360 Model 195 (360/195); Texas Instrument Corporation (TI), Model ASC (1 pipe). Class 5 will be used to denote Control Data Corporation, Model STAR (CDR STAR); Texas Instrument Corporation, Model AS (4 pipe), or their equivalents. Class 6 will be used to denote the generation of machines beyond Class 5, such as CDC 8600 or its equivalents.

bility needed by the CTR program as it moves into the design, construction, and operation of large fusion feasibility experiments.

2. The optimum implementation of recommendation A1 requires an immediate and significant build-up of the existing computational programs at the present controlled thermonuclear research sites, followed by the acquisition of a Class 4 computer system dedicated to controlled thermonuclear research. This computer must be connected with high capacity communication links to all other components of the program in a way that allows satisfactory user access to the central facility, or facilities.
3. As advanced computer technology evolves and as the Controlled Thermonuclear Research Program expands to feasibility experiment levels, the acquisition in 1976-1977 of Class 5 or Class 6 computer systems at some facility or facilities appears consistent with forecast computational needs.

In anticipation of the future availability to CTR of Class 5 machines, immediate provision must be made to begin problem definition and exploration to take advantage of that eventuality.

B. Long-Term Requirements:

1. The panel believes that the basic arguments leading to the conclusion that increased computational activity in the near-term will have significant impact on the CTR program apply to the long term as well; and, therefore, the panel recommends that the level of effort continue to increase beyond FY 1976.
2. Because CTR will continue to benefit from improved methods arising out of research in the mathematical and computer sciences, it is recommended that the AEC's research program in the Mathematical and Computer Sciences intensify its efforts to (a) explore new mathematical methods, particularly for the effective solution of partial differential equations appropriate to CTR, and (b) improve the general effectiveness of computers for CTR problem solving by exploring new methods for utilizing computer networks, graphical displays, programming languages, and related aspects of computer science.

III. INTRODUCTION

Since 1966 the Controlled Thermonuclear Research Program has increased its use of large scale, digital computers by twenty-fold; and, it is estimated that that usage will increase by a factor of ten more by 1976. This rapid expansion is the result of two factors, the natural growth that accompanies any expanding program and the type of problems that computers are called on to solve in CTR. The former cannot explain a projected 200-fold increase in computer usage in a decade. The latter can, for analysis of the nonlinear properties of the plasma state and solution of the equations that model the operating characteristics of large fusion systems, are among the most challenging and difficult research problems yet encountered. Only computers, with their unique ability to process and manipulate immense amounts of interdependent data, can handle the simultaneous interplay of the host of factors that influence the confinement of a thermonuclear plasma in an experimental device. Thus, computers will play an increasingly vital role in the CTR program as it progresses to a demonstration of fusion feasibility.

In this report, a brief history of the AEC's use of computers to solve its problem's is presented (Section IV). This is followed by a summary of computing in CTR (Section V), and a projection of CTR's future need for a significantly increased level of computing effort (Section VI). Three options to meet the forecast demand are presented in Section VII. Based on an analysis of those options, the report concludes in Section VIII with recommendations for the appropriate level of computational effort in CTR through FY 1980.

IV. COMPUTING IN THE AEC

Digital computers came into being at approximately the same time as the Atomic Energy Commission. Foresighted leadership within the agency encouraged the program divisions to take advantage of the new tool. Since then, large scale digital computation has played an important role in most of the major projects undertaken by the AEC.

AEC computers were first put to use in the highly classified nuclear weapons program. They were used to solve mathematical problems involving multi-dimensional fluid dynamic effects, which required great computational power. Nuclear reactor designers and high energy physicists were also quick to appreciate the potential of computers for solving problems which involved manipulating complex, interactive systems. Problems in neutron diffusion, similar to those used in the weapons program, and perhaps even more demanding of computer capability, were posed and solved by the reactor designers; while the high energy physicists used, and are still using, computers to process voluminous quantities of data from bubble and spark chambers. The quantity of this data is such that unless the most powerful computers are utilized it would be impossible to survey the totality of data generated.

Many of the known techniques of computational physics used today were generated by AEC computer users. For example, major contributions have been made in the solution of multi-dimensional hydrodynamics problems, neutral transport including the use of Monte Carlo techniques, and molecular dynamics, to name a few.

Moreover, the AEC has used its problem solving needs to effectively pioneer computer hardware and software development throughout the past 30 years. Aided by such outstanding consultants as John von Neumann, many of the pre-commercial computers of the late 1940's and very early 1950's were built at AEC laboratories or with AEC funding inspired by needs that were not met commercially. Some of the computers constructed in those early days were AVIDAC for Argonne, ORACLE for Oak Ridge, MANIAC I for Los Alamos, and ILLIAC I for the University of Illinois.

The first commercially developed large scale computer was Univac I. Of the first half dozen built (1952), AEC purchased two of them, primarily for its nuclear weapons development. In quick succession, AEC acquired the best scientific computers constructed by the major

computer manufacturers of the day. In the early 1950's, the AEC led the world in installed computer power. It still does. At the present time, the AEC has 60 large computers each costing more than \$1,000,000 and a total of 954 computers that represent the equivalent of 88,000 Univac I's, see Figures 1 and 2.

The Univac LARC and IBM Stretch were among the first of the major computer systems inspired directly by the AEC. With these systems, which stretched the state-of-the-art in the late 50's, problems were solved that could not have been tackled otherwise. These systems provided an improvement in power of a factor of 10 over what was previously available. The AEC also funded the first of the high performance Control Data Corporation 6000/7000 series of machines in the 60's. And, in the late 60's, the AEC funded the first of the so-called "pipe-

FIG. 1

FIG. 2

line” or “streaming” computers, the CDC STAR. This is one of the Class 5 computers aimed at maximizing performance on vector operations.

While the needs of the AEC are such that the power to be obtained from Class 5 computers will be needed to solve many of the more sophisticated problems being formulated today, the solution of CTR’s immediate and most pressing problems can be accomplished with Class 4 equipment, as is detailed in Section VI. Class 6 computers may be necessary for problems involving fusion systems of the prototype or demonstration reactor generation.

V. SUMMARY OF COMPUTING IN CTR

From the 1950's forward, the CTR program has made use of available high speed, digital computers. In the early days, they were used to calculate the ionization and heating of plasmas in Stellarators, to design magnets, to analyze experimental data, and to evaluate the complex mathematical expressions which appeared in the then developing theory. However, they only began to be used extensively in the period 1966-1968. Prior to that time, the fundamental physics of the plasma state was still being developed. Without detailed knowledge of the equations governing plasma behavior and the approximations used to derive those equations, there was little confidence that large scale computer simulations could faithfully reproduce or predict plasma phenomena in confinement configurations. Any simulation is only as good as the models upon which it is based, and the plasma models that are used today did not exist in the early 1960's. In addition, the capabilities of the computers of the early 1960's were unable to meet the requirements of the models that then existed, unsatisfactory as they were.

Plasmas are very complex physical systems. Their properties are much more difficult to analyze than those of ordinary fluids. The long range nature of the electrostatic forces between the individual charged particles of a plasma give rise to collective phenomena of a sort not encountered in other type of simulation; such as those used for weather or for weapons simulations. In the latter two, the fluids are basically single species and the equation of state is known, if only in tabular form. In plasmas, on the other hand, multi-species effects play an important role and the existence of electric and magnetic fields, either self-generated or externally imposed, ensure a marked anisotropy that leads to complex motions that are difficult to predict and very sensitive to small parametric changes.

Toward the end of the 1960's as the speed and memory size of computers advanced by approximately three orders of magnitude and as plasma models improved to the point where it became reasonable to consider simulation as a means of studying plasma behavior, computers began to make significant contributions to the field. For example, large programs were set up at NRL and Los Alamos to provide essential information on the effects of high altitude nuclear explosions, particularly effects involving plasma phenomena. Computer calculations formed

the core of those programs because of the limited amount of information which existed from actual tests or which could be obtained from laboratory experiments. And, more recently, computers have played a major role in the rapid development of the laser fusion program. The possibility of laser fusion via implosion was first demonstrated by applying fluid dynamic codes, developed for the nuclear weapons programs, to the problem of heating a small pellet of thermonuclear fuel with a laser.

The expansion of the CTR program's computational effort was initiated in 1966 to take advantage of the increased problem solving capability of the then current generation of computers. As shown in Figure 3, the program's usage of computers soared from 500 equivalent CDC 6600 hours in 1966 to almost 9000 in 1972.

The figure shows that throughout the entire period almost 90 percent of the effort was laboratory-based and that well over 50 percent of the effort was devoted to large scale code development for studies and investigations of advanced computational techniques.

It is interesting to note that in 1973 the level remained almost unchanged over 1972, reflecting the relatively tight funding of the previous years and the urgent need of the large experimental programs for increased support. Unfortunately, this leveling off occurred at a time when the prior years' investment in building-up the program's capability for large scale computing was just beginning to pay off. During the past two years, there have been a significant number of major achievements in the application of computers to CTR. They are described elsewhere in this section (see page 18). Continued productivity of that quality cannot be maintained at the present level of effort. In fact, the simulation effort, which is the core of the computational programs and which depends more heavily on the availability of large blocks of dedicated time than any other area (Purpose 1, Figure 3 (b)), has been held to a constant level since 1971.

Major Achievements: A Chronology

The use of computers to solve physics problems of importance to CTR is generally referred to as computer or plasma simulation. This term includes several distinct activities. They can be grouped into two categories: 1) fluid simulation and 2) particle simulation. In fluid simulation, the differential equations that describe the plasma state are solved by computers for appropriate plasma confinement configurations. These fluid codes vary in complexity, but their relative simplicity makes it possible now to simulate some features of large-scale plasma confinement experiments. It will be possible in the future to extend this work to include most of the important features of such experiments.

FIGURE 3

PURPOSE

- 1: *Plasma Simulation or Modeling*, e.g. code development for large, integrated systems studies, including advanced algorithm development and investigations of advanced computational techniques; PIC and CIC studies; etc.
- 2: *Extensions of Analysis*, e.g. direct p.d.e. solving; function evaluation; parametric studies of analytic formulations; automatic algebraic expansion algorithms, etc.
- 3: *Experimental Design*, e.g. magnetic coil design, electron and ion optics studies; ray tracing; stress analysis, design related activities such as PERT programs; etc.
- 4: *Other*

In particle simulations, the attempt is made to follow on the computer the motions of a large number of charged particles under the influence of their self-consistent electric and magnetic interactions. In this sense, particle models most nearly approximate a plasma. However, they suffer from the fact that they must use time steps measured in terms of the plasma frequency and space scales measured in Debye lengths. Also the computer can follow the motion of relatively few particles compared to the number contained in any real system, i.e., 10^6 compared to say 10^{18} . Even so, this is a powerful method and yields important data on plasma properties. It is possible to extend computer effectiveness in such calculations through the use of techniques such as finite-size particles, quiet starts, and periodic smoothing. For some time to come, codes based on single particle models will be limited in their ability to handle large systems and long times.

These single particle codes are very useful and have provided a number of important results over the past few years. They have led the way in examining nonlinear and turbulent behavior of plasmas, and have provided the vital microscopic information on transport coefficients needed in the macroscopic fluid codes. Thus the two techniques are inextricably tied to one another.

Date	Achievement
1958-1962	—Basic plasma processes such as Landau damping, Debye shielding, the two-stream instability, collisionless and collisional shock structures, etc., were verified by computer simulation in one-dimension. The inherent power of computer modeling for CTR was first recognized.
1966-1968	—Fluid calculations, based on particle-in-cell (PIC) codes, provided graphic and accurate simulations of the behavior of the dense plasma focus. This was a transition period during which the numerical techniques appropriate for large scale CTR simulation were developed. At the same time, the size, speed, and capacity of computers were being increased. These two effects combined to produce the dramatic upsurge in CTR usage in the years 1968-1971 (see Figure 3).
1968-1969	—Idealized infinite geometry models provided the first detailed look at microturbulence resulting from high frequency ion cyclotron mirror instabilities. Many direct ties to and extensions of analytical calculations resulted. Nonlinear saturation mechanisms were described in detail. Esoteric nonlinear phenomena ("explosive" instabilities) were discovered to be unimportant under normal conditions. Calculations using the Hain-Roberts fluid code, which dated

back to the early 1960's, showed that the diffusion of plasma across the magnetic field in θ pinches was described by the classical collisional model. This was perhaps the first theoretical indication that Bohm diffusion, which scientists had worried might dominate all plasma behavior, did not dominate the behavior of at least the high beta theta pinch systems. Almost simultaneously, experimental evidence was presented showing classical diffusion in a low-beta toroidal system as well. Together the above results launched a wave of optimism in the controlled thermonuclear research community that subsequent experiments have shown was fully warranted.

1970-1971—Finite geometry models of ion cyclotron mirror instabilities examined several effects expected to play a significant role in actual devices: finite length effects on flute modes, effect of nonlinear end loss electron current, long containment time characteristics of particles oscillating in flute like electric fields (superadiabaticity).

1971-1972—Fluid codes have given reasonably good fits to tokamak discharge data over a modest range of parameters. Such calculations have shown that the observed plasma transport is much faster than the best theoretical prediction (neoclassical theory), though they agree fairly well with what is known as the pseudoclassical formula. Since one such computer calculation typically costs only a small fraction of one pulse on a tokamak device but gives an instantaneous picture of all pertinent machine and plasma parameters, such codes are being used extensively to predict the detailed behavior of large experiments.

Free boundary simulations of MHD equilibria and stability applicable to both low and high-beta closed systems have been carried out successfully. Such computations have been used to guide the Scyllac program and to help interpret the compressive phase of the ATC experiment.

Particle simulations have shown that parametric instabilities associated with the propagation of intense waves through a plasma lead to turbulence and through turbulence to plasma heating. Such anomalous heating involves nonlinear effects that are difficult to attack analytically.

Recent particle studies of plasma diffusion across a magnetic field have shown that so-called anomalous diffusion can be present in thermal plasmas. These simulations have shown features quite similar to the behavior observed in octopoles and stellarators.

In addition, these computer simulations have had a pro-

nounced effect on the laser fusion program. Fluid codes successfully verified the intuitive idea that implosions of laser irradiated pellets were not only possible, but could produce significant amounts of thermonuclear energy. Particle codes later showed (1972–1973) that energetic electrons produced during irradiation of such pellets would play an important role in determining the final imploded state.

1972–1973—Single particle models verified the applicability of quasi-linear theory to a number of weak turbulence situations. They showed that this theory gives reasonably good answers for a number of cases where one would not expect the theory to apply. Since one of the experimental approaches to fusion depends in a major way on the turbulence predicted by quasi-linear theory, these recent simulations add confidence to the viability of that approach.

A varied set of relativistic electromagnetic codes were used to examine Astron E-layer formation and stability. These codes were continually and intimately involved with the most successful modeling of a CTR device to date.

SUMMARY

The application of computers to CTR is a vital activity in the controlled fusion research program. During the past two years alone, significant advances in controlled thermonuclear research have been made using large scale, digital computers. Continued advances will require a significant expansion of the use of computers in CTR, as described in the next section.

VI. PROJECTION OF CTR COMPUTING NEEDS

The immediate needs of CTR for a significantly expanded computational program can be separated into seven categories, the first five of which represent the bulk of the computing that would be done. All are important, but the first five are crucial to the present effort.

1. Multi-Dimensional, Dynamic Fluid Code Development for *IN SITU* Plasma Simulations.

Representative examples of work in this area include 2 and 3-d fluid models capable of simulating the dynamic behavior and time evolution of plasmas in various confinement devices. The codes would contain phenomenological transport coefficients determined from experiments, particle codes or theory.

Impact on CTR:

The successful development of three dimensional fluid codes of the sort described above may well be the most important contribution that theory will make to the near term goal of the CTR program. Such codes should predict in detail what will happen to the plasma in present and next generation systems. In addition, they will permit the rapid determination of the validity of existing theories. For example, the neoclassical theory of toroidal geometry is reasonably well developed, but agreement with experiments is not complete. Analysis and quick numerical calculations give approximate checks. However, the reliability of this theory for future predictions can only be tested if the transport codes based on them can include such parameters as observed levels of impurities, neutral gas, charge exchange, ionization, etc. and still predict observed current density and temperature profiles. Calculations using 1-d phenomenological transport codes are a start in this direction, but certainly only scratch the surface of what is required.

2. Multi-Dimensional, Equilibrium and Stability Code Development for *IN SITU* Plasma Simulations.

Here fluid codes would be developed to extend theoretical calculations on plasma equilibria and stability to real geometries with

realistic density, current and temperature profiles. The development of codes to test stability using the energy principle are a step in this direction. However, it is not clear that such simple MHD fluid models are sufficient, and considerable effort should be devoted to developing more realistic models and to determine their pertinence by comparison with experimental results and with results from particle codes.

Impact on CTR:

In contrast to codes developed under (1) above, which tell what will happen to the plasma in a specific situation, the codes developed in this area will tell whether there are better end-states to the plasma's evolution. Insofar as the transport codes give optimistic predictions that are borne out by experiment, the work in this area would be devoted to optimizing designs and thus would be of lower priority in the near-term. To the extent that the transport codes predict problems, this area would require essential information on how to proceed. It would then become the highest priority area. In any event, it is an area of computational activity that must be expanded.

3. Dynamic Guiding Center Code Development

This area includes the development and application of more complete computer plasma models such as the Chu-Goldberger-Low (CGL) model, mixed fluid-particle models, etc.

Impact on CTR:

Codes developed in this category will provide the basic understanding of microscopic processes occurring in fluid-like situations. As such, they implement (1) and (2)-type codes. The particle nature of these codes demands large blocks of computing time. It is hoped that extensive code development of this type will not be required. However, if fluid codes should prove inadequate, these codes will be essential, and therefore, activity in this area cannot be neglected.

4. Vlasov Solvers

The Vlasov equation is one of the fundamental equations of plasma physics. Extensive efforts should be made to use existing particle codes, and extensions thereof, to determine the importance of collective and turbulent transport of plasma energy, momentum and current.

Impact on CTR:

The results of such calculations will provide input information to fluid models on such crucial parameters as transport coefficients, etc. They will also provide data for testing fluid models and valuable information on non-linear plasma processes, including intense wave heating, loss cone instabilities in mirrors, and others.

5. Fokker-Planck Solvers

The development of multi-dimensional, multi-species codes that include spatially varying magnetic fields and ambipolar potentials will be pursued.

Impact on CTR:

Accurate solutions to the Fokker-Planck equation in realistic geometries will yield vital information on the stability, losses, and Q values of mirror confinement systems that cannot be obtained in any way short of committing resources to additional large experimental programs. In addition, such studies will allow detailed investigation of the effect on confinement of reacting plasmas and of neutral injection.

6. CTR Engineering Reactor Design, Control, Safety, Radiation Studies, etc.

This broad area of activity encompasses all the engineering and technology aspects of CTR that can effectively use large scale digital computers. For example, models and codes would be developed to study the operation of divertors, the neutronics of blankets, the operation of direct energy converters, the dynamics of reacting plasmas including reaction products, the interaction of hot plasma with solid surfaces and with cold neutral gas surrounding a hot plasma, to name just a few.

Impact on CTR:

The construction of a feasibility experiment and all subsequent generations of fusion systems will depend heavily on these kinds of calculations.

7. Other Theoretical Research

Some effort must be devoted to stimulating new exploratory concepts for fusion. These calculations might use codes developed in other areas and could be carried out in university programs.

Provision must be made to develop new computing techniques. Individual groups will do their own to some extent, but the pressure to get answers to pressing problems will not allow them to explore techniques which might in the long run have a large impact. Much of this effort might go on in universities, but again the major laboratories cannot afford to neglect such activities.

The Mathematical and Computer Sciences Program of the Division of Physical Research can play an important supporting role. Recommendation B2 (Section II) is directed toward identifying certain specific contributions which that program can make to the longer range theoretical efforts of the CTR program.

Impact on CTR:

Improved theoretical methods will extend the range of applicability of *ad hoc* numerical experiments and provide a more secure base for the CTR program as it moves into the prototype and demonstration phases of its development.

With the categories that need attention identified, the appropriate level of effort for each category must now be established. For computational studies of the sort considered here, the most accurate measure (and the one most often used) is hours of computing time from which dollar levels are easily obtained.

The computer usage per month required in each of the categories is summarized in Table 1. Using 500 hours per month as full utilization, the monthly figures are converted in the last line to a yearly equivalent.

The conservative nature of the estimates for FY 1974 can be seen from the following representative example based on a Class 4 type computer capable of executing approximately 2×10^7 machine instructions per second. Consider a three-dimensional, magnetostatic particle simulation with 10^{s1} particles requiring 300 operations per particle time step. The total number of operations is then $300(10^6)$, and if the computer does $2(10^7)$ operations per second, it will take 15 seconds to do one time step. The total number of time steps that can be run in one day will be about 5600.

TABLE 1
Computer Usage in CTR by Category
(in equivalent Class 4¹ hours per month)

Fiscal Year	73 ¹ (actual)	74	75 (estimated)	76
Category				
1 -----	20	65	100	300
2 -----	10	25	200	400
3 -----	30	75	150	300
4 -----	40	100	200	300
5 -----	10	25	75	100
6 -----	10	30	75	100
7 -----	5	10	25	50
Monthly Totals -----	125	330	825	1550
Equivalent Class 4 ¹ per year ----	.25	.65	1.7	3.1

¹ Class 4 = CDC 7600; IBM 360/195; TI ASC (1 pipe)

² Individual category levels are estimated since the category breakdown used here is more detailed than that used in the past. The total, however, is exact.

For a large run which could give important results, one might have to run 100,000 time steps or almost 18 days. Admittedly, this is a brute force method of computing which the use of drift equations or other techniques might shorten by an order of magnitude or more. Nevertheless, the magnitude of computing involved in CTR-type problems is

apparent. The above problem alone would use 430 hours of Class 4 computing time. For FY 1974, the panel estimates that 330 hours/month would cover the program's needs in all categories since most runs would be done on smaller systems and would take much less time. It is, however, important to recognize that computations of almost the above length have been successfully undertaken in weather simulation, in weapons development and in the simulation of weapons effects.

From Table 1 the panel concludes that in order for the CTR program to meet its minimum immediate needs it will require the equivalent in hours of .65 of a Class 4 computer in FY 1974, 1.7 in FY 1975, and 3.1 in FY 1976. Roughly 70-90 percent of that effort will be devoted to solving large problems, i.e., problems requiring many multiple hour runs on a single problem.

Since the projections throughout the remainder of this report will be keyed to the above figures, it is important to understand what they imply. First, all options considered must provide the required level of effort in terms of Class 4 equivalent hours.

Second, any option that uses a class of computers other than Class 4 must be normalized to the Class 4 level and the results reflected in the operating and capital costs. For example, if an option proposes the use of CDC 6600-type computers which are only $\frac{1}{4}$ as powerful as Class 4 equipment, then in FY 1974 the program would require 2.6, 6600's to meet its needs ($4 \times .65$), and the purchase of one to two such units would have to be reflected in the cost of that option. Alternately, if Class 5 equipment, which is estimated to be three times faster than Class 4 equipment, were specified only 20 percent ($.65/3$) of a Class 5 system would be needed in FY 1974.

This latter fact leads naturally to the question of what class of computers should be specified in any recommendation. Based on the above, CTR will need only a little more computing power in FY 1976 than could be provided by a Class 5 computer. Assuming that the lease or purchase of capital equipment is indicated (as opposed to spreading the effort around), isn't a Class 5 computer then the obvious choice to meet CTR needs? With some qualifications, the panel answered this question in the negative. The reasoning follows.

- (1) The CTR program is a mission-oriented program with a demonstrable need for a reliable problem solving capability now. Class 4 systems have been in operation for several years and reliably perform the bulk of all general purpose, large scale scientific computations. They are the workhorses of the industry and will continue to be for the next few years at the very least. They are immediately available and can be put into reliable operation from scratch on a three to six month time scale.
- (2) As yet, no Class 5 system has been delivered or operated anywhere.

- (3) Even if a Class 5 system were available tomorrow, it would take a minimum of a year to make such a system operate reliably.
- (4) The increased computing power of a Class 5 computer, which comes both from increased speed and larger memory, will be realized only if optimum use is made of its vector processing property. Those problems that can be formulated to take advantage of this very powerful feature will benefit by the predicted factor of three or more in computing power. However, those problems that cannot be better run on a Class 4 system. Since it is not clear at this time how efficiently the major CTR problems can be programmed for vector processing, Class 4 equipment seems preferable to Class 5.
- (5) While the memory of the typical Class 5 system may be twice that of present Class 4 equipment, expansion of memory on a Class 4 system can be accomplished relatively easily.
- (6) Moreover, even if CTR problems could be formulated for efficient processing by a vector-type machine, programming can be expected to be difficult since the organization of the Class 5 computer is quite different from its predecessors.
- (7) Any option that addresses CTR needs and includes a central, dedicated computer for processing the 70-90 percent of the jobs that will require large blocks of computer time, must assure that long-distance, remote operation can be accommodated efficiently, reliably, and cheaply, else the benefit of the central computer is almost no benefit at all. Long-distance, remote operation can be routinely accomplished with Class 4 equipment. Inasmuch as a complete Class 5 computer has not yet been operated, one can only speculate on whether it can accommodate remote operation easily. Indeed, there is every reason to believe it will, but only time will tell.

In summary, when CTR's immediate need for increased computing power is coupled to the ready availability of Class 4 equipment, the familiarity of CTR users community with that equipment, and its adaptability to long-distance, remote computing, the panel concluded that CTR should proceed on the assumption that if a dedicated computer or computers is desirable then it ought to be of the Class 4 generation. However, in view of the anticipated availability of the very powerful Class 5 generation of computers, they also felt that CTR ought to prepare for eventual Class 5 operation by funding an exploratory effort in FY 1974 aimed at reprogramming large CTR test problems for vector processing and testing those programs on the AEC's STAR and the TI-ASC (4 pipe) machine when they go into operation.

In the next section, three possible ways of providing CTR's projected computational needs are discussed and costed out. The panel focused its attention only on the years 1974-1976 because the needs in 1974-1976 are identifiable and acute, and because analyzing the period beyond 1976 in the same detail as that provided for the prior period would have required an evaluation of more variations than time permitted.

VII. OPTIONS

The panel seriously considered the following three options for fulfilling the CTR program's computational needs through FY 1976:

- (1) Build-up the present effort at all the existing CTR research centers (laboratory sites and offsite contractors), including provisions for each site to acquire extensive capital equipment to meet its own specific needs.
- (2) Build-up the present effort at all the existing research centers and add two dedicated Class 4 computers at one site. This option reduces the individual capital equipment requirements at all the centers and provides a central facility for large scale, dedicated computing that would be linked to all the research centers by high-speed communication lines. At least two Class 4 computers would be needed inasmuch as the computing needs in FY 1976 are predicted to require more than three.
- (3) Build-up the present effort at all the existing research centers and add two dedicated Class 4 computers, one at each of two separate sites. This option, like (2), reduces the individual capital equipment requirements at all the centers and provides the necessary large scale, dedicated computing. In addition, by siting one computer on the west coast and one on the east, possible long-distance communications problems would be reduced.

In each of Option (2) and (3), the build-up at the existing research center is reduced over that projected in (1).

Each of the options will be discussed below in detail. The elements in each option and the operating and equipment costs for each will be developed. Since Option (1) is the foundation upon which the other two are based, it will be developed in more detail.

Discussion of the advantages and disadvantages of each option will be deferred to Section VIII, Analysis, Conclusions and Recommendations.

OPTION (1): Build-Up

On the premise that each component of the CTR computational program build-up its own effort to meet its own needs on the time scale that it wants them met, the following detailed expansions were developed.

Princeton Plasma Physics Laboratory

A build-up of the present Princeton effort would proceed along the following lines. The highest priority for FY 1974 is the development of large fluid codes for Tokamak studies (Category 1) and the running of Vlasov solvers (Category 4) for determining the transport coefficients to use in those fluid codes.

To carry forward this program the laboratory would acquire the third shift on Princeton's IBM 360/91. This amounts to 2000 hours of 91 time, or 0.16U, where the unit U stands for one year's usage, or about 6000 hours, on a Class 4 computer system. The cost of the machine time is \$700K and the personnel costs \$480K. To make efficient use of this time will require the addition of three computer physicists and two non-scientific staff members above the FY 1973 manpower levels.

In FY 1975, it is expected that emphasis will shift to extensive running of the large scale fluid codes that were developed in the previous year. This would require AEC's purchase of an IBM 370/168 to be installed at the Princeton Computer Center. This machine would serve as a front-end to the 91; however, it would also serve as a separate operating computer. The total use by CTR of the 91 and the 168 would equal 0.40U. The costs of the 168, of additional graphics equipment and of a building to house the expected computer expansion in FY 1976 is estimated to be \$8100K. The total operating expenses for FY 1975 would be \$2200K. An additional five computer physicists and three non-scientific personnel would be required.

In FY 1976, major emphasis would be given to running fluid codes in conjunction with initial operation of the Princeton Large Torus (PLT), which is scheduled to become operational during that year. Extensive use of those codes are expected to measurably enhance the prospects of early success in PLT. It is estimated that computing capacity of 0.90U will be required for rapid parametric studies of PLT operation. To provide that capacity, Princeton would rent an additional IBM 370/168 which would be coupled to the 91 and the existing 168. The operating and personnel costs for FY 1976 would be \$2800K and the addition of seven scientific and three non-scientific personnel would be required. As envisioned, this arrangement would allow for easy expansion of computer capacity in FY 1977 if required. For example, the rented 168 could be dropped and a larger machine bought, say an IBM 360/195. The already purchased 168 would then serve as a front-end to control the job flow through the new machine. With such a system, remote terminals at other sites and universities would be possible. It is possible that a 360/195 could be installed instead of the first 370/168 and retained for a longer period of time. In this case, costs would be somewhat higher.

Lawrence Livermore Laboratory

All areas of the LLL mirror research program utilize extensive and complex computing. In FY 1974, expansion is planned in three major areas of mirror research already underway.

There is an immediate need for extensive computation with existing Fokker Planck codes (Category 5) to examine plasma build up with the new neutral beams in 2X-II and Baseball. Additional effort is required in extending Fokker Planck codes to include special dependence and to study build up using target plasmas. The present effort in this area is one and one-half computational physicists. Three and one-half are required plus one and one-half support personnel. Computer usage totaling .08U is anticipated.

The development of realistic three dimensional codes for equilibrium studies (Category 1 and 3) has already started with one computational physicist and one support person. The problem requires at least two more computational physicists and three support persons and computer usage totaling .06U per year.

A major computational effort is needed to develop and use large particle type simulation codes for stability studies (Category 4). In addition, the solution of three dimensional eigen value problems arising from linear stability analysis is required (Category 2). The present effort of one and one-half computational physicists must be expanded to two and one-half plus three support persons. Computer usage of 0.04U will be required.

Other areas that need additional effort include magnetic design, direct conversion studies, and fusion engineering (all Category 6). In these areas, the present effort is only one and one-half computational physicists. For a minimal effort, two and one-half computational physicists are needed with two support persons and computer usage of 0.02U. The total required for FY 1974 will be 11 computational physicists, 9 support persons and computer usage of 0.20U.

FY 1975 will require a build-up of personnel in all of the areas listed to a total of 15 computational physicists and 15 support persons and a doubling of computer usage to a total of 0.40U. This increased computer usage will be caused by production running of codes developed in the previous year and further development of the other areas. In addition, the level of computer usage would be optimized by a capital investment in the LLL computer complex of approximately \$3,000,000, which would eventually lead to a full Class 4 capability for the laboratory.

In FY 1976, large scale computation leading to the design of scientific feasibility experiments is anticipated. This will require staff totaling 20 computational physicists and 20 support persons and another doubling of yearly computer usage to a total of 0.60U.

Los Alamos Scientific Laboratory

In FY 1974, a build-up of the present LASL computing program would emphasize the following three areas:

- 1) Continuation of the present program aimed at improving existing two-dimensional, dynamic MHD simulation of high-beta systems (Category 1) and extending them to three dimensions. This effort would require one SMY and approximately 0.04U of computer usage per year.
- 2) The present program on high-beta MHD stability (Category 2) that primarily supports the Scyllac effort would double its computer usage to 0.04U per year. No increase of scientific staff would be needed.
- 3) Full-scale dynamic particle simulations (Category 3) would increase from the present FY 1973 usage level of 4 hours per month to 20 hours per month, or to a yearly level of .04U. No increase in scientific manpower would be required.

Reactor modeling and engineering design studies (Category 6) would need an additional SMY and increased computer usage to a level of about 10 hours per month.

Programming assistance for the entire program would increase by six people. The total anticipated effort for FY 1974 is 0.14U, costing \$900,000 in operating funds.

In FY 1975, extensive running of the Category 1 and Category 3 codes developed during FY 1974 would constitute the bulk of the Los Alamos program. This would involve a major increase in computer usage in those areas to 0.10 and 0.14U per year respectively, and the addition of 2 SMY's in the dynamic MHD simulation area and 1 SMY in the particle simulation activity. These two programs will play dominant roles in determining the development of the high-beta toroidal confinement program. Expansion of computer usage to the level indicated will require capital investment in the LASL computer complex of approximately \$2,500,000. This would cover anticipated usage through FY 1976 as well.

Modest increases in the Category 6 studies requiring one and one-half additional scientific man years would be accommodated under this plan. No increase in the Category 2 program is envisaged.

Total effort in FY 1975 is estimated at a 0.30U, costing \$1400K in operating funds.

Continued expansion of the Category 1 and Category 3 programs is anticipated through FY 1976 as the high-beta toroidal program prepares to initiate scientific feasibility experiments. Fully 80 percent of the computing effort will be devoted to continued code development and extensive running of these codes. Requirements are estimated to be 0.20U per year for the 3-d MHD fluid simulations and 0.30U per year for the

particle simulations. A decrease in the high-beta stability studies (Category 2) is projected as increased confidence is gained in the fluid and particle simulations.

The remainder of the effort would be devoted to increased engineering design and reactor modeling studies. The total FY 1976 effort is projected to require 0.60U, costing \$2300K in operating funds.

Oak Ridge National Laboratory

Build-up of the ORNL computing effort would be concentrated in the following areas:

- 1) Fluid Simulation of Tokamak Discharges on the Diffusive Thermal Conduction Time Scale (Category 1).

This mature effort, underway for three years, has given strong support to interpretation of the ORMAK experiments and led to major improvement in the level of understanding of the detailed behavior of the plasma discharge. The effort is now and will continue to be a major factor in the design of feasibility experiments. The level of realism now in the work is high, but needs considerable increase in order to treat toroidal effects, to treat the dynamics of neutrals and impurities, and to permit realistic treatment of the radiation problems anticipated for reactors. This effort will require an estimated 0.01U in FY 1974, 0.03U, and 0.05U in FY 1975 and FY 1976.

Adequate treatment of fast injected neutral particles requires an extension of Tokamaks of the Marx-Killeen code (already in use at ORNL) and the coupling of this to the transport code. Computer usage is estimated at 0.01U in FY 1974.

In addition, initial investigations of non-circular cross section systems will be expanded. This work couples existing one dimensional transport codes to the two dimensional equilibrium code to give transport analysis in natural magnetic coordinates. Further development will be done in FY 1974, leading to production codes projected for usage at the level 0.15U and 0.25U for FY 1975 and FY 1976.

- 2) MHD Simulation of Tokamak Discharges on the Macroinstability Time Scale (Category 2).

The effort in this area will emphasize the extension of an existing 2-d code, which treats MHD kink and interchange instabilities using toroidally correct equilibria, to include non-circular cross section discharges and plasma resistivity.

Production runs of this code will require 1-5 hours on the ORNL 360/195 and a full scale study program can be expected to use about 0.05U in FY 1974, leading into full scale production runs in FY 1975, FY 1976 at levels of 0.2-0.3U.

The existing linear 1-d version of the code will permit study of effects of neutrals and impurities. In FY 1974 a nonlinear version will be developed and converted to 2-d. This will allow simulation of a full Tokamak discharge on a fast time scale. Typical production runs will require approximately 1 hour on the 195, and experimental modeling in FY 1974 will use about 0.02U in FY 1974 and FY 1975.

3) Studies of Plasma Confinement in Realistic Geometries.

This work is in the conceptual stages and is difficult to predict, except that without devotion of approximately 2 man years effort in FY 1974 with a doubling for FY 1975–FY1976, this very important area will not have been adequately explored.

Codes are already in hand for investigating Tokamak equilibrium flux surfaces (when they exist) in the presence of magnetic deviations. The preliminary codes could well use 0.01U in FY 1974, and be replaced by more complete production versions in FY 1975–FY 1976 requiring usage estimated at 0.1–0.2U.

In order to provide the large increase in computer usage projected, a considerable increase in the capability of the Oak Ridge Computer Center would be required. This can be provided by increasing the throughput capability of the existing IBM 360/195 at a cost in FY 1975 of \$4,000,000 which provides 3 megabytes additional memory and adequate graphics (movie) capability. In the meantime, an upgrade of the remote job entry capabilities in the Thermonuclear Division would require \$100,000 in FY 1974. For the FY 1974–1976 period, manpower estimates are 8, 15 and 25 SMY and an equal number of support programmer man years.

Universities and Off-Site Research Centers

A build-up of the off-site program would involve expansion of the current level-of-effort at each of the present sites and an expansion of the number of sites as well. In 1973, the off-site effort totaled 0.03U and costed \$370K which was roughly 12 percent of the total program effort and 20 percent of the total cost. It was concentrated at eight universities, five of which were solely engaged in computer studies. The other three maintained strong computer applications programs as part of a larger CTR effort. During 1974, this effort would be expanded by about $\frac{1}{3}$ to 0.04U at a total cost of \$990K. Five additional SMY's would be added. Problem areas would range from advanced symbolic computation to algorithm development and data management for 3-d simulations. Equipment totaling \$210K would be required to up-grade the NYU Computing Center to handle increased CTR activities there.

By 1976, it is anticipated that the off-site program would grow to 0.12U and \$1400K per year. The effort would be devoted to supporting

the major laboratory programs, which by that time would be carrying over 95 percent of the computing load, and to providing the trained manpower that will be required to meet the forecast demand.

In this connection, it is important to note that the most critical problem in mounting a large computer effort is not hardware or software, but people—in particular, those special people with simultaneous background in plasma physics and computer science, or plasma engineering and computer science. At present, only one-half dozen or so are being trained yearly. Since 80 additional people will be needed by 1976 (see Table 2), only 18 of which will be trained at the present rate, the output over the next three years must almost quadruple. Much of this need will be filled by people already trained in other areas of physics, engineering and computer science who choose to join the CTR effort. But, nonetheless, not all of it will; and, therefore, serious attention must be given to increased university support for training computational plasma physicists and engineers. This will be even more important in the years following 1976.

Table 2 summarizes the elements of Option (1). Total dollar levels for each site were calculated according to a formula that charged computing time at the dollars per hour rate indicated. Hours were determined by the Class 4 equivalent effort, assuming that 6000 hours = one Class 4 equivalent. Manpower costs at the rate of \$40,000 per total man year were added to get final totals.

OPTION (2): Build-Up, Plus Two Dedicated Class 4 Computers at One Site.

For purposes of cost out this option, it will be assumed that one computer is dedicated in FY 1975 and the second in FY 1976, though optimum implementation would probably call for simultaneous purchase and installation.

Operating Costs Associated with the In-House Laboratory Efforts

Since the program does not acquire any dedicated facilities in FY 1974 and since a build-up of the effort is needed to meet FY 1974 demands under any of the options considered, the FY 1974 operating levels for Option (1) apply equally well to this option and to Option (3).

TABLE 2
SUMMARY OF OPTION 1
Operating & Equipment Costs

Site	Items	Fiscal Years			
		73	74	75	76
Princeton Plasma Physics Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.07	.16/700	.40/450	.90/300
	Operating Funds (in thousands of dollars)	550	1200	2200	2800
	Equipment Funds (in thousands of dollars)	0	0	8100	0
	Scientific Man Years	5	8	13	20
	Total Man Years	7	12	20	30
Los Alamos Scientific Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.03	.14/400	.30/300	.60/300
	Operating Funds (in thousands of dollars)	250	900	1450	2300
	Equipment Funds (in thousands of dollars)	0	0	2500	0
	Scientific Man Years	6	8	12	18
	Total Man Years	8	14	22	30
Lawrence Livermore Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.10	.20/350	.40/175	.70/175
	Operating Funds (in thousands of dollars)	360	1200	1600	2400
	Equipment Funds (in thousands of dollars)	0	0	3000	0
	Scientific Man Years	6	11	15	20
	Total Man Years	8	20	30	40
Oak Ridge National Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.02	.10/385	.50/385	.80/225
	Operating Funds (in thousands of dollars)	135	800	2200	2500
	Equipment Funds (in thousands of dollars)	20	100	4000	0
	Scientific Man Years	4	8	15	25
	Total Man Years	6	16	30	40
Universities & Off-site Centers	Equivalent Class 4 Effort/est. \$/hr. computing time	.03	.04/400	.07/350	.12/300
	Operating Funds (in thousands of dollars)	370	990	1220	1400
	Equipment Funds (in thousands of dollars)	0	210	0	0
	Scientific Man Years	11	16	20	24
	Total Man Years	11	16	20	24
TOTALS	Equivalent Class 4 Effort/est. \$/hr. computing time	.25	.65	1.67	3.12
	Operating Funds (in thousands of dollars)	1665	5090	8670	11400
	Equipment Funds (in thousands of dollars)	20	310	17600	0
	Scientific Man Years	32	51	75	107
	Total Man Years	40	78	122	164

In FY 1975, a dedicated computer is acquired that will provide one Class 4 equivalent of the 1.67 required. The remaining .67 of the effort would be provided internally at the individual sites. Operating figures for the laboratory and off-site program for FY 1975 can now be estimated quite accurately. For example, referring to Table 2, LASL requires .14 of a Class 4 equivalent in 1974 and .30 of a Class 4 equivalent in 1975. Since under the present option the total computing that remains to be done in-house after one computer is dedicated in FY 1975 is virtually identical to the FY 1974 level (.67 vs. .65), it is clear that LASL under this option would do exactly the same amount of computing in-house in FY 1975 as it had done in FY 1974, i.e., 0.14U. The in-house operating costs for LASL are then calculated using the FY 1975 costs for computer time and for the total number of man years. In this way, operating costs for FY 1975 are developed for Option (2). They are shown in Table 3. It should be noted in Table 3 that per hour costs of internal computing for Princeton are at the FY 1974 rate and not the FY 1975 rate of Option (1). Under Option (1), hourly charges dropped because of the acquisition of equipment at the laboratory. For the multi-disciplinary laboratories, hourly charges for Option (2) in any year are the same as for Option (1) since the rate is determined by the overall laboratory usage, rather than just CTR's usage.

TABLE 3
SUMMARY OF OPTION 2
In-house Operating & Equipment Costs

Site	Items	Fiscal Years			
		73	74	75	76
Princeton Plasma Physics Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.07	.16/700	.16/700	.18/700
	Operating Funds (in thousands of dollars)	550	1200	1470	1960
	Equipment Funds (in thousands of dollars)	0	0	0	0
	Scientific Man Years	5	8	13	20
	Total Man Years	7	12	20	30
Los Alamos Scientific Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.03	.14/400	.14/300	.25/300
	Operating Funds (in thousands of dollars)	250	900	1130	1650
	Equipment Funds (in thousands of dollars)	0	0	0	0
	Scientific Man Years	6	8	12	18
	Total Man Years	8	14	12	30
Lawrence Livermore Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.10	.20/350	.20/175	.35/175
	Operating Funds (in thousands of dollars)	360	1200	1400	1965
	Equipment Funds (in thousands of dollars)	0	0	0	0
	Scientific Man Years	6	11	15	20
	Total Man Years	8	20	30	40
Oak Ridge National Laboratory	Equivalent Class 4 Effort/est. \$/hr. computing time	.02	.10/385	.10/385	.25/225
	Operating Funds (in thousands of dollars)	135	800	1430	2200
	Equipment Funds (in thousands of dollars)	20	100	0	0
	Scientific Man Years	4	8	15	25
	Total Man Years	6	16	30	40
Universities & Off-site Centers	Equivalent Class 4 Effort/est. \$/hr. computing time	.03	.04/400	.04/375	.09/300
	Operating Funds (in thousands of dollars)	370	900	970	1120
	Equipment Funds (in thousands of dollars)	0	210	0	0
	Scientific Man Years	11	16	22	24
	Total Man Years	11	16	22	24
TOTALS	Equivalent Class 4 Effort/est. \$/hr. computing time	.03	.65	.64	1.12
	Operating Funds (in thousands of dollars)	1665	5090	6400	8895
	Equipment Funds (in thousands of dollars)	20	310	0	0
	Scientific Man Years	32	51	77	107
	Total Man Years	40	78	124	164

In FY 1976, a second dedicated computer is acquired. Now two of the required 3.12U are provided by the dedicated computers and operating costs can be pro-rated for FY 1976 as they were for FY 1975 (see Table 3). Inasmuch as Princeton would almost saturate its in-house capability at the .16 equivalent that it would need in FY 1974, its in-house computer use does not increase as much as the other sites. It would rely more heavily on the dedicated computers for its computing.

Costs Associated with the Dedicated Computer

Table 4 and associated appendices summarize the estimated capital costs and operating costs for a stand-alone, Class 4 computer with four megabytes of memory, disc storage for 200 million 64 bit words, a large archival storage system, and assorted peripherals. For costing purposes, the computer is assumed at one of the major laboratories and is linked to the other laboratories and at least two off-site centers by leased 50,000 baud communications lines.

TABLE 4
A Single Dedicated Computer
(with 50,000 baud communications links
to all major computing sites)

<i>Capital Costs</i> (in millions of dollars)	<i>Dollars</i>
1) Central Computer—Class 4 (estimate)	9.0
2) On-site facilities	2.7
a) graphic facility	0.5
—movies	
—other graphic capability	
b) remote access facilities	0.2
—keyboard terminals	
—Remote job entry terminals (RJETs)	
—CHT terminals	
c) large (10 ¹¹ bit) archival storage device, e.g., an integrated system of 3330's or the IBM system Digital System.....	2.0
3) Off-site facilities	0.8
a) remote access facilities (see Note)	0.8
—10 R.J.E.T.	0.5
—remote keyboards	0.3
4) Plant Construction (see Appendix A, pg. 73)	1.9
Total: Capital Costs	14.4
<i>Operating Costs</i> (in millions of dollars per year)	
1) Computer Center (see Appendix B, pg. 74)	2.2
Total: Operating Costs per year	2.2

Note: Two RJET's would be required for each laboratory for a total of eight. The remaining two would be located at two of the major CTR university computing centers. There would also be upwards of 50 remote keyboard terminals distributed throughout the user community.

"On-site" in the context of the Table refers to the site of the dedicated computer. "Off-site" refers to those sites linked to the computer by the high-speed communications lines. It is postulated that to the extent possible the off-site and on-site facilities will be made equal so that those sites which do not have hands-on access to the computer suffer almost no penalty. The only major on-site facility that would not be available to off-site users would be high-resolution movies of extended length. Overnight availability of that facility could be provided by air freight and messenger service at nominal cost.

The capital cost for a single dedicated computer including construction is \$14,400,000 and operating costs are estimated at \$2,200,000 per year. The capital costs for acquisition and installation at a single site of a second computer would be \$10,000,000 since no new construction would be required, nor would there be need for a second archival store or a second on-site graphic facility. The annual operating costs of the single site with two computers would increase by about \$700,000 to \$2,900,000 per year to allow the appropriate doubling of support personnel below the Chief Administrative Officer level (see Appendix B, page 48).

A summary of the capital costs and operating costs of the options is shown in Table 5.

OPTION (3): Build-Up, Plus Two Dedicated Class 4 Computers, One at Each of Two Separate Sites.

As in Option (2), it will be assumed that one computer is dedicated in FY 1975 and the second in FY 1976, though again optimum implementation would probably call for simultaneous purchase and installation.

TABLE 5
Capital and Operating Costs for All Options
FY 1974-1976

Annual Operating Cost (in millions)	FY 1974	FY 1975	FY 1976
<i>Option 1</i>			
Lab and Off-site	\$5.1	\$8.7	\$11.4
Computer Center	—	—	—
Totals	5.1	8.7	11.4
<i>Option 2</i>			
Lab and Off-site	5.1	6.4	8.9
Computer Center	—	2.2	2.9
Totals	5.1	8.6	11.8
<i>Option 3</i>			
Lab and Off-site	5.1	6.4	8.9
Computer Center	—	2.2	3.3
Totals	\$5.1	\$8.6	\$12.2

Capital Cost (in millions)

Option 1	\$.3	\$17.6	\$ —	\$17.9
Option 2	\$.3	14.4	10.0	24.7
Option 3	\$.3	14.0	11.5	25.8

Operating Costs Associated with the In-House Laboratory Efforts

The in-house operating costs for this option are identical to those for Option (2), since as far as the user is concerned the computer is a "black box" that he simply dials-up and uses. All costs associated with leased lines, maintenance, etc., are covered under the center operating costs.

Costs Associated with the Dedicated Computers

Capital costs for the installation of the first computer in this option will be identical to those for the installation of the first computer in Option (2), except that only one-half the floor space for the computer would be needed. This reduces the construction costs to \$1,500,000.

Acquisition and installation of the second computer will cost \$11,500,000, which is \$1,500,000 more than installation of the second computer under Option (2) because construction would have to be duplicated.

Thus, the total capital cost for two dedicated computers under this option is \$25,500,000 compared to \$24,400,000 under Option (2).

Yearly operating costs for the first of the two computers would be \$2,200,000 as in Option (2). The second computer, since it would be at a totally different site, would need duplicate personnel at all levels costing \$900,000 additional, plus some duplicate maintenance and supplies estimated at \$200,000 per year. Thus, the operating costs for both computers would be \$3,300,000 yearly.

VIII. ANALYSIS, CONCLUSIONS AND RECOMMENDATIONS

The Controlled Thermonuclear Research Program needs a significant expansion of its level of effort in computational plasma physics and engineering. Since computers will play as vital a role for CTR as they have played for other major AEC scientific programs, the panel believes that that expansion must be initiated immediately.

Based on a detailed evaluation of the categories of research in which computers can contribute (see Section VI, page 19), it is the panel's conclusion that the minimum expansion consistent with overall CTR near term goals should take the following form:

- 1) In FY 1974, the program must provide a level of effort of at least the equivalent of one-half of a Class 4 computer.
- 2) In FY 1975, the program must provide a level of effort of at least the equivalent of 1.7 Class 4 computers.
- 3) In FY 1976, the program must provide a level of effort of least the equivalent of 3.1 Class 4 computers.
- 4) Roughly two-thirds of the above effort would be devoted to large-scale computations that are essential for accurately forecasting fusion system performance but are impossible to run at the present level of effort.

To provide an immediate problem solving capability for acute near-term needs and to take maximum advantage of the highly sophisticated computer technology that presently exists, the panel concludes that Class 4 equipment be used to meet the forecast demand of the next two to three years. While the projected cost/performance advantage of Class 5 computers is significant, the difficulties and uncertainties associated with using a system still in its developmental phase dictate that CTR not rely on such systems at this time. However, in anticipation of the future availability of Class 5 machines, CTR must make immediate provision to begin reprogramming large CTR test problems for vector type processing. As Class 5 machine time becomes available, these re-programmed codes could be run as test problems for comparison of Class 4 vs. Class 5 operation. Assuming that reliable and positive indications were obtained of increased cost/performance through use of Class 5 equipment, an orderly transition to the new generation of machines could be made.

In order to determine the resources needed to meet the level of effort identified above, the panel considered three options as discussed in Section

VII. Table 5 summarizes the capital and operating costs associated with all the options.

The annual operating costs for each do not differ by very much. This is not surprising for, in the final analysis, each of the options had to provide the same amount of computing time. For purposes of discussing the advantages and disadvantages of each option, the panel will take the position that operating costs for all three options are the same.

In capital equipment there is a significant difference between Option (1) and the other two. Two factors are responsible for this. First, Options (2) and (3) both include construction totaling a minimum of \$1,500,000. In this regard, it must be remembered that construction was only included in Table 5 on an "if necessary" basis. If dedicated computers were recommended, there is a real possibility that space could be found at some pre-existing computer center. This would reduce the need for construction to an installation charge probably equal to that required under Option (1) for installation of the equipment purchased under that option.

Second, the equipment purchased under Option (1) at each site would not only be compatible with the equipment existing at the site, and therefore installation costs would be minimized, but, in addition, the capital purchase could be done on a fractional basis. For example, LASL needs roughly 30 percent of a Class 4 system in FY 1975 (Table 2). They could "purchase" 30 percent of a Class 4 computer because other users at the laboratory would "purchase" the remainder. A single purchaser [the dedicated center, considered in Option (2) and (3)] cannot "purchase" a fraction of a machine. It must buy machines in units, or not at all. The opportunity to purchase fractional units results in a significant saving.

Option (1) has a number of other advantages. A variety of computers would be used. Each type provides special capabilities that might find use in other segments of the CTR program. However, it is also true that such information is often not used due to system incompatibilities.

Reliance on long distance remote job entry terminals and remote interactive access would be kept to an absolute minimum. There can be trouble with long distance communication links, though the experience of a number of laboratories, particularly NRL which uses long distance lines extensively, shows that the problem can be solved.

Rapid impact on the present generation of CTR experiments would be assured since each laboratory's build-up would be matched to its effort. Since in FY 1974 all options build-up equally, the impact on FY 1974 should be equally as great for Options (2) and (3), as for (1).

Insofar as existing sites already have an administrative infrastructure, administrative difficulties would be minimized.

The multi-disciplinary environment that exists at all the major laboratories would assure effective integration into CTR problems of pertinent

new techniques and results developed by other investigators. To the extent that each laboratory maintains its own in-house effort under the other options, they will share this advantage equally with Option (1). Option (1) has the decided disadvantages that without a dedicated computer for CTR, the CTR effort must compete with non-CTR situations at each site for available computing time; and the option does not allow as ready an expansion to projected 1980 needs as do Options (2) and (3).

In comparison, Options (2) and (3), because they involve dedicated CTR computers, ensure that non-CTR activities do not impede CTR progress. Large blocks of computer time would be available as needed to investigators, and the dedicated nature of the computers ensures that priorities are established according to CTR program needs and no others.

In addition, Option (1) does not encourage interlaboratory interaction, nor does it encourage broad university participation. Options (2) and (3) encourage both. With dedicated computers being used by personnel from all the laboratories, there is strong incentive for collaboration. With users sharing the same equipment, each user feels that a colleague elsewhere is more likely to understand his machine and systems problems better than if that individual were using another machine.

Broad university participation is encouraged since university investigators would have keyboards linked to the dedicated center located at their institutions, and some selected university centers would have remote job entry terminals for large scale computing. As a corollary, graduate students could obtain use of CTR programs and would have contact with the most advanced computing in the field. This would be a key element in building the necessary manpower base as rapidly as possible.

The main disadvantages with Options (2) and (3) are the possible long-distance communications problem, which, as was noted above, is not likely to be of any real significance. The administrative problems of running a new center(s) would be solved with time.

On balance, the panel felt that between Option (1), and Options (2) and (3) considered together, the latter would serve projected CTR needs better than the former. Interlaboratory collaboration and university participation is enhanced in Options (2) and (3) over (1); and Options (2) and (3) provide the large blocks of computer time that will be needed without competition from non-CTR activities. It is the panel's opinion that the capital equipment difference between Option (1), and Options (2) and (3), particularly if construction can be eliminated from Options (2) and (3), is not sufficient to alter our conclusion that CTR not adopt Option (1).

Between Options (2) and (3), the latter reduces reliance on long-distance lines and also provides significant flexibility for further expansion. For example, at a later date one computer might be dedicated to reactor design, the other to continued fusion physics studies. If one computer were on the west coast, it could serve the LLL and LASL efforts.

The second in the east could serve the PPPL and ORNL efforts. One possible problem with the arrangement would be unavoidable systems incompatibilities, especially if the east and west coast used different vendors. In addition, the overall systems organization and administration is more complex, since there are now two separate sites. The panel feels that such administrative problems could be solved.

Option (2) centralizes the dedicated portion of the computing effort, and to that extent probably optimizes it. On the other hand, separation of functions, if and when desirable, is not as easily accomplished as in Option (3). The capital costs of this option are almost \$1,100,000 less than that of Option (3), which is significant.

Between the three options, the panel felt that Option (2) was slightly more desirable than Option (3). Either Option (2) or (3) was more desirable than Option (1).

On the basis of the above evaluation, the recommendations of the panel can be summarized as follows:

A. Near-term Requirements:

1. To meet the minimum near-term computational needs of the Controlled Thermonuclear Research Program, the level of computing activity must be increased immediately to the equivalent of at least one-half of a Class 4 computer in FY 1974. This scale-up should be followed by the addition of another equivalent in FY 1975, and again by one and one-half equivalents in FY 1976. To meet the computational demand identified in this report, the Controlled Thermonuclear Research Program should have available for use on a priority basis the equivalent of at least three Class 4 systems full time by FY 1976. Failure to follow this recommendation will result in a serious delay in developing the problem solving capability needed by the CTR program as it moves into the design, construction, and operation of large fusion feasibility experiments.
2. The optimum implementation of recommendation A1 requires an immediate and significant build-up of the existing computational programs at the present controlled thermonuclear research sites, followed by the acquisition of a Class 4 computer system dedicated to controlled thermonuclear research. This computer must be connected with high capacity communication links to all other components of the program in a way that allows satisfactory user access to the central facility, or facilities.
3. As advanced computer technology evolves and as the Controlled Thermonuclear Research Program expands to feasibility experiment levels, the acquisition in 1976-1977 of Class 5 or Class 6 computer systems at some facility or facilities appears consistent with forecast computational needs.

In anticipation of the future availability to CTR of Class 5 machines, immediate provision must be made to begin problem definition and exploration to take advantage of that eventuality.

B. Long-Term Requirements:

1. The panel believes that the basic arguments leading to the conclusion that increased computational activity in the near-term will have significant impact on the CTR program apply to the long term as well; and therefore, the panel recommends that the level of effort continue to increase beyond FY 1976. It is expected that the CTR program will be using at least the equivalent of five Class 4 computers by 1980.
2. Because CTR will continue to benefit from improved methods arising out of research in the mathematical and computer sciences, it is recommended that the AEC's research program in the Mathematical and Computer Sciences intensify its efforts to (a) explore new mathematical methods, particularly for the effective solution of partial differential equations appropriate to CTR, and (b) improve the general effectiveness of computers for CTR problem solving by exploring new methods for utilizing computer networks, graphical displays, programming languages, and related aspects of computer science.

IX. APPENDICES

APPENDIX A

Plant Construction Estimate

Plant construction would be undertaken only if necessary and then with flexibility to expand facilities to accommodate additional computers.

Physical Plant Requirements

1. Computer Area	10,000 sq. ft.
2. Offices and Administration area	10,000 sq. ft.
3. Library	600 sq. ft.
4. Light Lab	1,500 sq. ft.
5. Mechanical Equipment Area	1,500 sq. ft.
6. Tape, Card, Disk Pack Storage	2,000 sq. ft.
7. Miscellaneous Areas, i.e., Restrooms, Storage, etc.	700 sq. ft.

Total typical floor space requirements	26,300 sq. ft.
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Assuming average costs of \$70 per square foot, the cost of providing the minimal space requirements represents an initial investment of approximately \$1,850,000. This would be amortized over a 40-year period as is present practice.

APPENDIX B

Computer Center Operating Costs

Personnel	No.	\$
Director	1	30,000
Associate Director	1	27,500
Chief Programmer	1	24,000
Chief Administrative Officer	1	18,500
Systems and applications programmers at an average salary of \$16,000 per year..	10	160,000
Engineering staff at \$16,000 per year ...	4	64,000
Clerical staff at \$6,000 per year	5	30,000
Documentarians at \$12,000 per year	5	60,000
Librarians at \$9,000 per year	2	18,000
Computer Operators at \$8,400 per year..	12	100,000
	<u>42</u>	<u>532,000</u>
Overhead @ 65 percent		347,000
TOTAL Personnel		879,000
Systems Maintenance		400,000
Expendable Supplies		100,000
Utilities		50,000
Travel		20,000
Leased 50,000 Baud Communications lines to four laboratories and two university centers		750,000
		<u>1,320,000</u>
TOTAL		<u>2,199,000</u>

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