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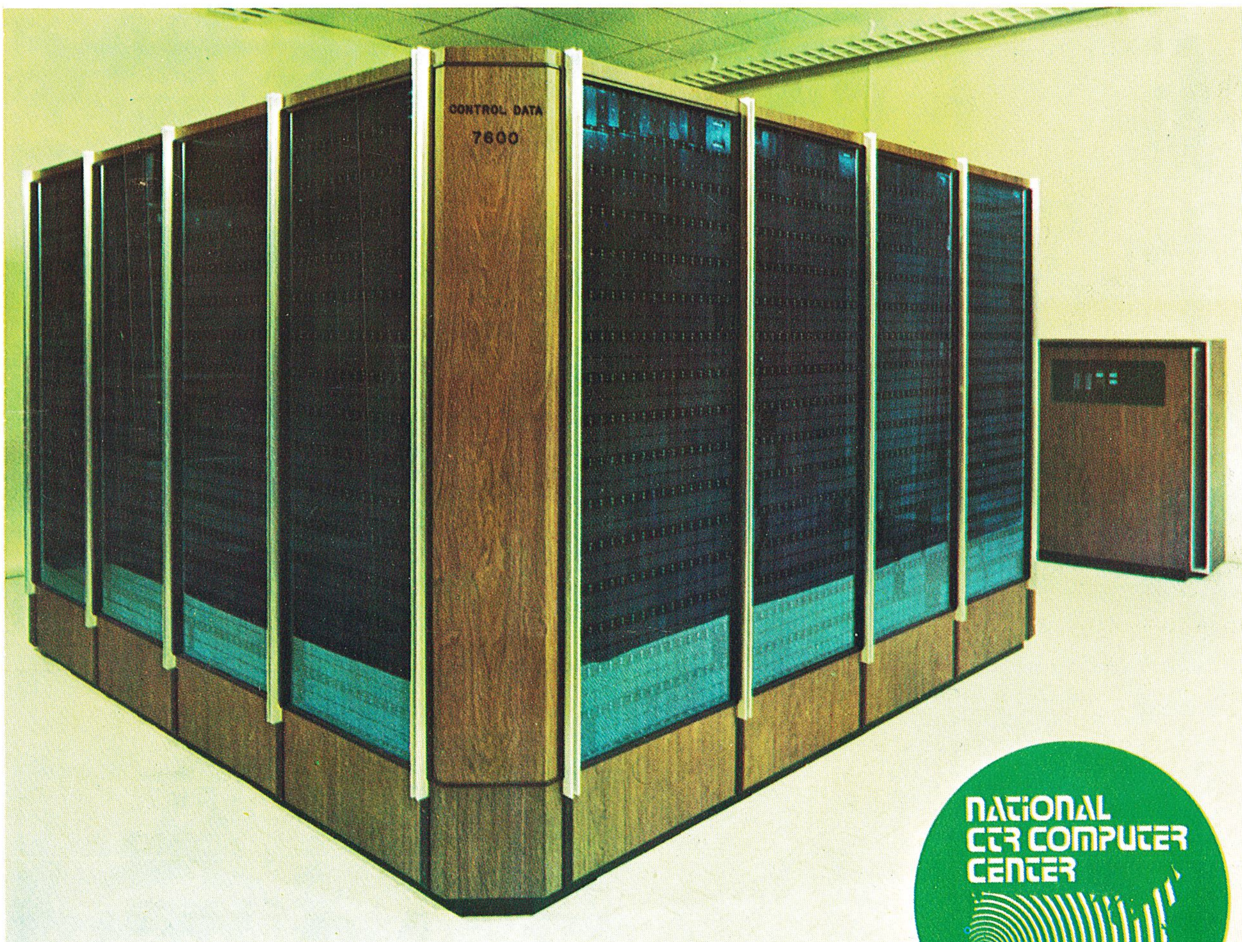

NATIONAL
CTR COMPUTER
CENTER

LAWRENCE
LIVERMORE
LABORATORY

ADVANCED ENERGY SYSTEMS

NATIONAL CTR COMPUTER CENTER

The central computer (a CDC 7600) went online last October at the National CTR Computer Center, Livermore, inaugurating large-scale computational support to the CTR community. The first high-speed (50 000-bit/s) transmission lines become operational in January 1976 to four major CTR research sites, marking the start of a national wideband communications network. Access to the national center is also being expanded for offnet users: scientists at universities with ERDA-sponsored CTR research projects.

Computational studies at the national computer center are presently keyed to the research needs and developmental schedules of the three principal CTR confinement schemes: tokamaks, high-β machines, and magnetic-mirror machines. Expanded uses will include prompt data reduction for confinement experiments and engineering studies for experimental and demonstration fusion power reactors (the first experimental reactor is scheduled for 1985).

As described in last month's *Energy and Technology Review*,[1] the goal of the U.S. magnetic confinement fusion program is to develop electrical power reactors based on the nuclear fusion process. Advantages include inherent operational safety and an effectively infinite supply of deuterium fuel from the world's oceans. The program's long-range objective – projected for the late 1990's – is a demonstration reactor producing 500 MW(e) or more of electrical power. Two intermediate experimental reactors of smaller scale are planned for about 1985 and 1989-90, respectively. The federal government, through ERDA's Division of Controlled Thermonuclear Research (DCTR), expects to bear most of the research and development costs, with industries and the electrical utilities providing the major portion of plant costs beyond the demonstration phase.

Orderly development of fusion power has required the evolution of a comprehensive developmental plan, mostly during this decade. DCTR is now pursuing, concurrently, three main confinement schemes: low-density closed systems (principally tokamaks), high-β systems (principally the theta pinch), and open systems (magnetic mirrors). Each faces crucial developmental work. The near-term funding is 60% tokamaks, 20% high-β devices, and 20% mirrors.[2]

DCTR has assigned most of the developmental work on tokamak devices to the Princeton Plasma Physics Laboratory (PPPL) and to Oak Ridge National Laboratory (ORNL). General Atomic Company, San Diego, California, is studying noncircular tokamak geometries. Los Alamos Scientific Laboratory (LASL) is developing high-β pinch devices and LLL, mirror machines. United Aircraft Research Laboratories, East Hartford, Connecticut, is investigating one aspect of mirror systems. About 75% of the present program is being conducted at the four national laboratories, the balance going to General Atomic, United Aircraft, and several universities.

Development of the comprehensive plan has also required detailed analyses of the basic research and engineering needs for the confinement systems and, ultimately, for the experimental and demonstration reactors. These analyses, in turn, have permitted detailed projections of the needs for large-scale computational support, without which the research and engineering studies cannot proceed. A 1973 *ad hoc* study for the Atomic Energy Commission categorized these needs by general type (seven categories) and estimated the time and equipment requirements for each, predicting a rapid expansion in demand that would quickly outstrip computer availability. This study[3] urged the AEC to enlarge its CTR computer capabilities both locally – at individual CTR research sites – and through creation of a national CTR computer center. Other options were considered, such as two regional centers; however, the single-center plan seemed most viable.

In 1974, the AEC adopted this plan. LLL was selected as the site for the national CTR Computer Center (CTRCC). Requests for quotation went out in June 1974, and the AEC subsequently approved capital purchases including immediate acquisition of a CDC 7600 central computer and supporting equipment for the national center, equipment for the individual CTR research sites, and high-speed transmission lines. Meanwhile, about October 1974, the national center went online to CTR users via voice-grade telephone lines, using a CDC 6600 computer and a remote job entry terminal (RJET)

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designed and built for Princeton. The thrust of the early work was both programmatic and organizational, i.e. software and protocol development. Last October, the CDC 7600 became operational, replacing the CDC 6600. Other equipment is being phased in as ready.

Computer Center Concept

Figure 1 shows the present status and future plans for the data communications network that links the remote sites with the national center. The first priority – to be realized this January – is activation of the leased 50 000-bit/s transmission lines to four major CTR sites: Princeton, Oak Ridge, LASL, and General Atomic. Plans eventually call for extending service to other laboratories and universities across the nation that are involved in ERDA-supported CTR research projects. At present there are 20 such support centers anticipated, some to be connected directly to the national center and others through an intermediate site such as Oak Ridge (see Fig. 1). Plans also provide for high-speed interconnecting transmission links among the major research sites: from General Atomic to LASL, from LASL to Oak Ridge, and from Oak Ridge to Princeton. These will provide users at least two independent pathways for transmitting data and priority messages.

The concept is to provide different levels of local computer capability at the various remote locations according to research priorities and anticipated computational demand. At the national center, available to the entire community, is the high-speed CDC 7600 central computer with 64 000 words of small semiconductor memory, 500 000 words of large-core memory, and disk storage. Additional equipment at the national center includes a PDP-11/50 central communications control processor, a PDP-11/50 network control station, and a CDC 6400

THE ROLE OF COMPUTERS IN CTR RESEARCH

High-speed digital computers have been used in CTR research since the early 1950's: the advent of the present program in magnetic confinement. Initially, computers were used for such tasks as calculating the ionization and heating of plasmas (extremely hot ionized gases) in stellarators, for designing magnets, for analyzing experimental data, and for evaluating the complex mathematical expressions that were beginning to appear in developing theory. Without detailed knowledge of the equations governing plasma behavior and the approximations used to derive these equations, there was little confidence that large-scale computer simulations could faithfully reproduce or predict plasma behavior in confinement configurations.

During these early years, research concentrated mainly on the problems of confining and heating plasma. By the late 1960's, solutions to these problems had progressed such that the maximum theoretical plasma confinement had been calculated in several different magnetic-field configurations. To achieve this milestone, it was necessary to develop to a sophisticated state not only the basic science of plasma physics but also a variety of supporting technologies. Faster computers with much larger memories were now available. Also available – from the Atomic Energy Commission's classified weapons programs – were computational methods for problems involving, for instance, multidimensional fluid-dynamics effects similar to those in plasmas. For the first time it became reasonable to consider simulation as a means of studying plasma behavior.

This basic departure triggered a twentyfold expansion in computer demand for CTR research during the period 1966-1973. Another tenfold jump is expected shortly, and other dramatic increases are forecast for the ensuing decades. Plasma theory (simulation) has now matured such that it can be used effectively to predict plasma behavior. For example, the adiabatic toroidal compressor (ATC) experiment at Princeton, which demonstrated a new method of controlling and heating toroidally confined plasmas, was conceived and designed on the basis of magnetohydrodynamic plasma theory. Simulations have provided an explanation of confinement scaling in high-density mirror confinement systems, a new direction for noncircular tokamak studies, and an explanation of recent experimental results in a theta-pinch confinement system.

In the future, as the fusion program moves on to large, complex experimental systems with burning plasmas, computational studies will provide critical input for guiding system design, predicting system performance, and discovering and solving unanticipated problems. Large-scale computers are expected to play a particularly cost-effective role in these activities. They will be used to simulate the characteristics of plasma confinement experiments and fusion power reactors. Eventually they can be expected to model whole systems before actual construction.

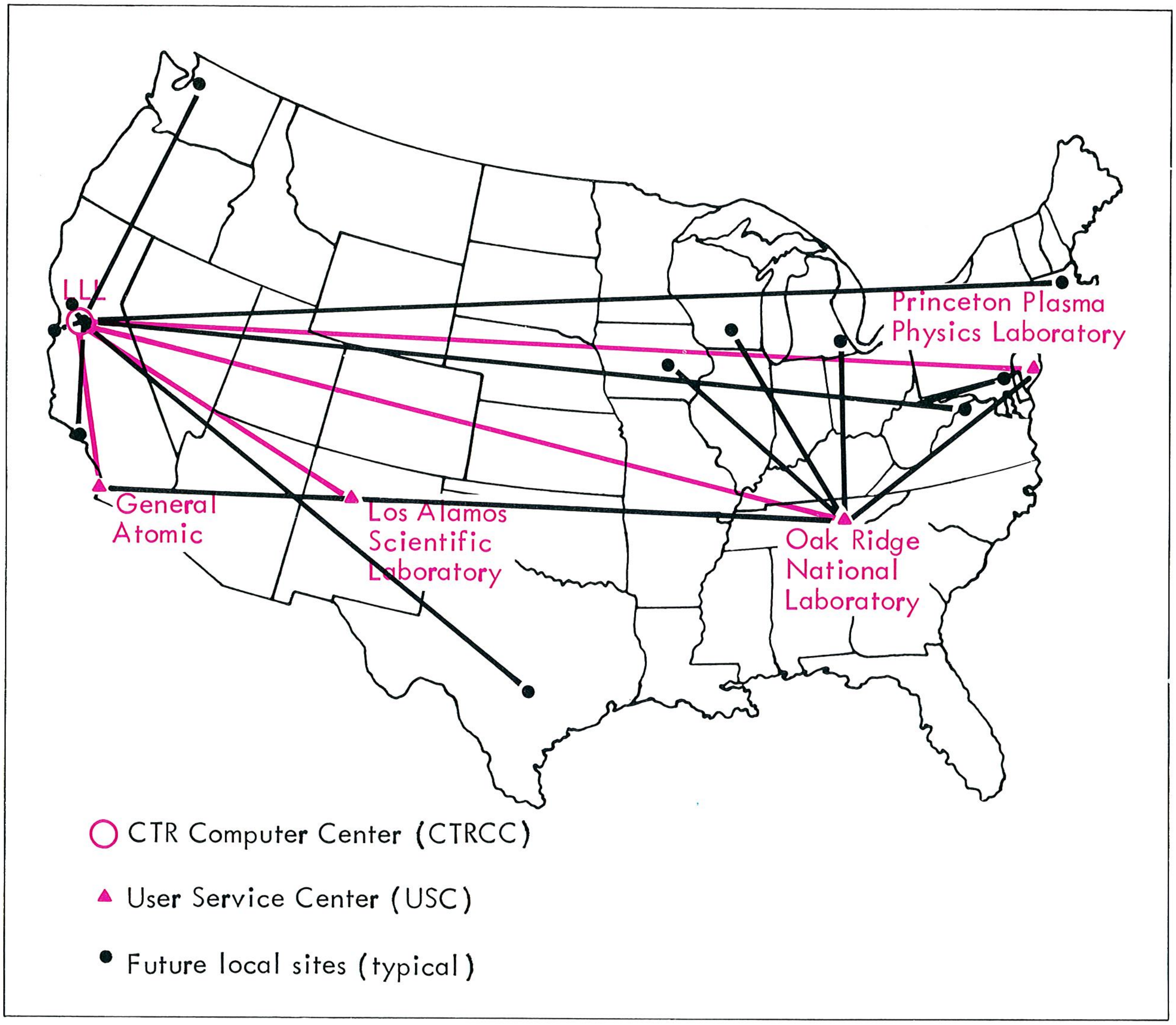

Fig. 1. National CTR Computer Center now serves five major CTR research sites including LLL (red) plus several secondary centers: universities and other laboratories with ERDA-sponsored CTR research projects. A national wideband communications network is being implemented incrementally, with the first high-speed transmission lines (red) to become operational this January. Other high-speed transmission lines (black) will be completed later to universities and among the major sites. Shown here are typical support centers and interconnections; the map is not complete.

file management computer that stores files and maintains indices for information retrieval. Short-term storage is accomplished on rotating disk units with instantaneous access. Long-term file storage, now handled on conventional magnetic tape, will be switched over, in 1976, to a mass storage device whose capacity is about 500 billion bits.

At the next level are user service centers (USC's): PDP-10 computer systems with direct high-speed access to the national center through PDP-11/40 remote communications control processors. The general arrangement is shown in Fig. 2. Five USC's are now operational (Princeton, Oak Ridge, LASL, General Atomic, and a USC for the CTRCC). Another will soon go online: a hard-wired USC at LLL for the mirror confinement program. PDP-10's were chosen for this application partly for their ease of upgrading by the addition of field-installable memory and disk units. (Their memories have already been upgraded to 192 000 words.) Local capabilities include text editing, compilations, and programs that do not require the speed and capacity of the CDC 7600.

Figure 3 illustrates the intended uses of the USC's and the national center. Smaller problems are handled locally. Large-scale problems go to the national center and are returned to the USC for final processing, e.g.

display and printout. The advantages of this arrangement include local availability, cost-effective equipment utilization, and an interactive computing network among the various user service centers.

For the offsite users (those without USC's), the ultimate intent – depending on research priorities, anticipated demand, and the availability of capital funds – is to provide either mini-USC's or RJET's. The RJET comprises a card reader, printer, and the equipment needed for multiple-terminal access to the national center. The mini-USC provides all the above plus a 64 000-word memory. Meanwhile, we will maintain access to the national center, for these users, via the voice-grade telephone lines. Demand is already such as to warrant expanding the present 16-line dial-up capability to 32 lines. A second, similar dial-up capability might be added in the East, accessing the national center through a local USC.

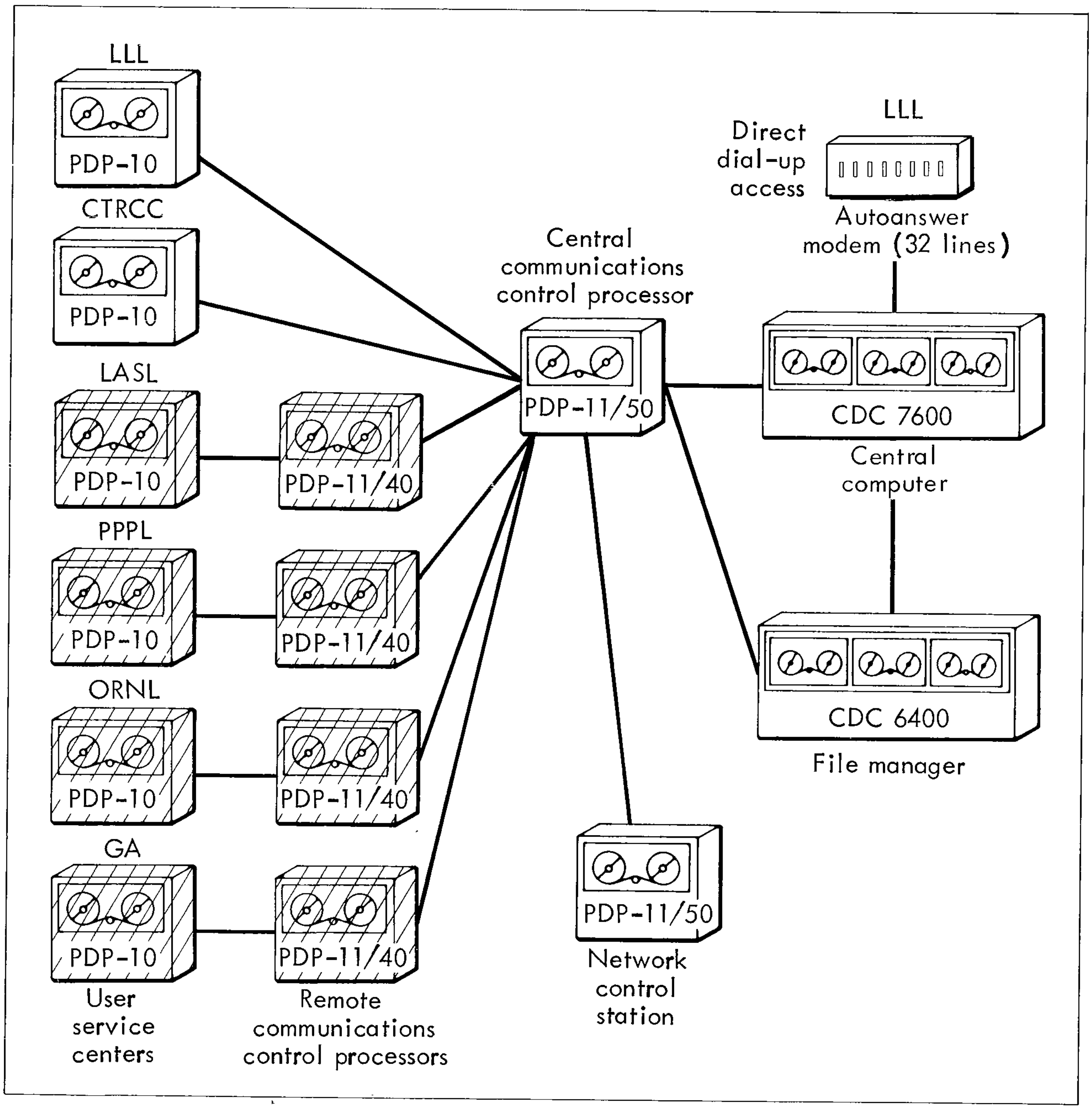

Fig. 2. General arrangement of equipment and connections between user service centers and the national center. A 32-line autoanswer modem (shown at upper right) provides offnet users with voice-grade, dial-up access to central computer facilities.

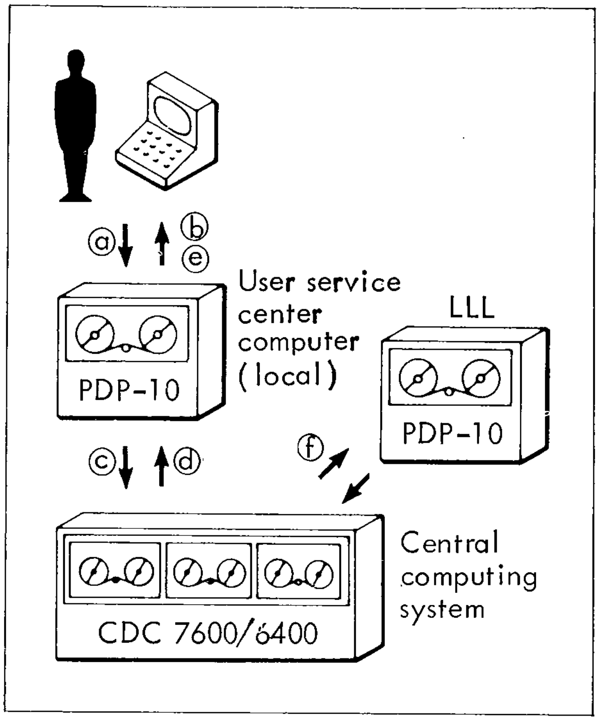

Fig. 3. Typical use of user service center (USC) and national facilities. (a) Researcher at a remote site gives problem to local USC computer. (b) Small problem is handled immediately by the local computer, which is timeshared by many users. (c) Large-scale problem is routed to the central computer. (d) Results are sent back to the USC and (e) returned to the researcher. (f) Another USC at the national center is used to control the central computer and to develop software for the system.

Funds have been budgeted in FY 1977 to construct a computer building at LLL to house the national center's equipment and personnel (see Fig. 4). This building will accommodate permanent staff members and some 25 to 30 visiting research scientists from participating CTR laboratories. The first increment of the structure, containing some 3700 m^2, will cost approximately $5 million. In FY 1979, another 3700 m^2 of space will be provided, at a cost of about $2 million, to accommodate the expected growth in computing machinery and personnel.

Computational Studies

The overall goal of the CTR Computer Center is to provide large-scale computational support to hasten development of the theoretical models and associated computer codes needed to predict the behavior of plasma confinement systems and the operating characteristics of fusion power reactors. The 1973 study[3] grouped CTRCC objectives into seven categories, of which five were specific research objectives as follows:

- Multidimensional dynamic fluid code development for *in situ* plasma simulations: for example, two- and three-dimensional fluid models containing phenomenological transport coefficients determined from experiments, particle codes, or theory. This was seen as crucial to detailed predictions of plasma behavior in present and next-generation confinement experiments and also to determining the validity of current theories.

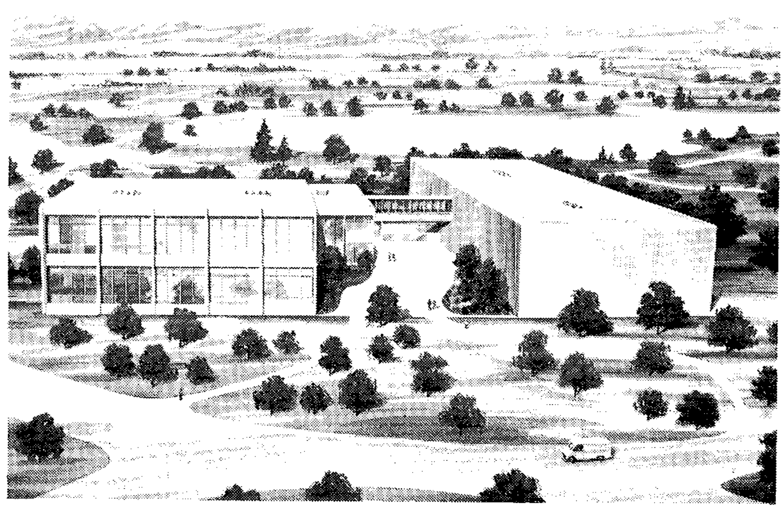

Fig. 4. Funds have been earmarked in FY 1977 for constructing a computer building at Livermore to house CTRCC equipment and personnel.

• Multidimensional equilibrium and stability code development for *in situ* plasma simulations, aimed at extending theoretical calculations on plasma equilibria and stability to real geometries with realistic density, current, and temperature profiles.

• Dynamic guiding-center code development, intended to provide basic descriptions of the underlying microscopic processes governing fluid (plasma) behavior.

• Intensive study of Vlasov solvers (for collective and turbulent transport of plasma energy, momentum, and current), intended to provide input data to fluid models on certain key parameters – e.g., transport coefficients – plus information on nonlinear plasma processes such as intense wave heating and loss-cone instability in magnetic mirror confinement systems.

• Multidimensional, multispecies code development to get accurate solutions to the Fokker-Planck equation in realistic geometries, aimed at providing vital information on the stability, losses, and overall efficiencies (Q values) of mirror systems that could not be obtained in any other way short of substantially enlarging the experimental programs. This development would also allow detailed investigation of the effect on confinement of reacting plasmas and of neutral injection.

The study panel specified the role of the national center in CTR reactor-design, control, safety, and radiation studies and also envisioned its use for other theoretical research, including the development of new computational techniques. This conceptual framework has persisted although further uses for the CTRCC are now planned and the research objectives have now been related to the major problem areas of the three main confinement schemes[2]:

Tokamaks: additional heating to raise the temperature to that required for a reactor; transport and scaling (increased size and power) problems; plasma shape optimization (circular vs noncircular geometry); impurity control and boundary-effects problems, chiefly cooling and the resulting instabilities.

Theta-pinch devices: toroidal equilibrium; shock and staged (shock plus adiabatic) heating to the required temperature for a theta-pinch reactor.

Mirror devices: confinement scaling (to longer confinement times); plasma heating by neutral injection, i.e., injection and trapping of an energetic beam of neutral atoms.

Computational studies are well under way at Princeton, Oak Ridge, and other locations. At the national center, we have focused on advanced computational capabilities and the development of new computer codes. For example, four codes have been developed specifically for Fokker-Planck particle calculations – HYBRID I, HYBRID II, ISOTIONS, and a *Z*-dependent version of HYBRID I, all for different purposes – plus a hybrid guiding-center particle and fluid code, GUIDON, that describes collisionless plasma behavior in axisymmetric toroidal geometries. (A hybrid code combines two or more basically different physical models and, hence, two or more basically different computational techniques.) A one-dimensional program has been written to study the formation of a plasma sheath and to compute the steady-state distribution functions for a self-consistent plasma potential. Transport and magnetohydrodynamic (MHD) stability codes are being developed. This is only part of a continuing effort aimed at eventually producing three-dimensional codes that fully describe plasma behavior in the various confinement geometries.

In some cases, such as for the two-dimensional multispecies Fokker-Planck code, the models have been generalized to treat more than one confinement geometry (in this case, both toroidal and open-ended configurations). Other codes are configuration-specific: for example, HYBRID I is for the mirror experiments at LLL, whereas both GUIDON and FPT (a coupled Fokker-Planck/transport code) are for the TCT (two-component torus) experiment at Princeton. Some general-purpose software has been developed, and the transfer of codes among the various laboratories has been eased. A good general description of the code work and computational objectives has been previously published.[4]

Generally speaking, we expect the overall CTR computational program to remain heavily committed, in the near term, to problems relating to plasma energy balance: that is, to plasma modeling, and to atomic and molecular processes. The development of improved models and equations for "burning" plasma – for deuterium-tritium mixtures undergoing fusion at rates that make the number, momentum, and energy balance in the plasma time-dependent – is a difficult theoretical problem that now must be confronted. Because line-radiation losses caused by high-*Z* impurities will undoubtedly pose problems in fusion reactors, the general area of atomic and molecular studies is of increasing importance. Such calculations are exceedingly complex, requiring large amounts of computer time.

Another continuing near-term emphasis will be refinement of the scaling laws for the various confinement schemes, to predict and explain instabilities and energy-loss mechanisms in each.

Prompt data reduction for support of experiments is an important thrust. The capability must be developed for storing, processing, and analyzing experimental data in a matter of minutes, to allow for changes in subsequent experiments. This will require significant computational support. Reactor-design, safety, and related studies will consume increasing amounts of computer time.

Also anticipated is a sizeable increase in confinement-related computational activities due to contributions from theoretical groups such as those at New York University, Science Applications, UCLA, and the Naval Research Laboratory. By then, these groups will be developing new techniques and codes applicable to the various confinement schemes, complementing the device-oriented efforts at the major CTR research sites.

Growth and Expansion

Based on the foregoing, DCTR anticipates a steady increase in demand and capabilities of the CTR Computer Center involving major expansions of equipment and function. The acquisition of new, larger central computers requires not only a substantial increase in ancillary equipment (such as file managers, storage devices, and network controllers) but also, as a prelude to specification writing, investigation into the compatibility of prospective next-generation machines with the existing system. This task is slated for FY 1977. Memory expansion at the national center and the user service centers is another priority project involving both hardware and software development.

Experimental results and expanding code capabilities – increasing accuracies of prediction – are opening pathways to new experiments not originally contemplated: for example, a proposed LLL experiment to create very dense plasmas by injecting convergent neutral beams in a spherical geometry. Directions are emerging for computer research, e.g. bit and character compression methods and the establishment of improved data-communication protocols (checks and balances among computers to ensure the accurate transmission and receipt of data). Also emerging are specialized equipment needs not originally envisioned, such as a new CTR standard interface channel – now being designed – that will allow researchers to interconnect almost any type of computer at remote stations.

As regards network development, the first task is to complete the remaining 50 000-bit/s transmission links. Eventually a space-satellite link may be established between LLL and the East, especially for very-high-bandwidth transmissions.

Key Words: CTRCC; plasma simulation; computer calculations; thermonuclear devices; magnetic fields; fusion research; tokamak; theta pinch; magnetic mirror.