9-2020
169

Energy and Technology Review

MASTER

DEC. 1975

Prepared for U. S. Energy Research & Development
Administration under Contract No. W-7405-Eng-48

NATIONAL
CCR COMPUTER
CENTER

LAWRENCE
LIVERMORE
LABORATORY

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

NOTICE

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Printed in the United States of America
Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$____; Microfiche \$2.25

*Pages	NITS Selling Price
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.50
501-1900	\$13.60

Energy and Technology Review

ABOUT THE COVER

On October 7, 1975, a fully dedicated CDC 7600 computer at the National CTR Computer Center, Livermore, went online to CTR researchers, offering large-scale computational support and advanced computer technology for solving the problems of fusion research. Features of the new central computer (shown here) include 64 000 words of small semiconductor memory, 500 000 words of large-core memory, and disk storage. The center's computing power will 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 article begins on p. 1).

Scientific Editor: Ronald B. Carr
General Editors: Charles S. McCaleb
Judyth K. Prono

BRIEFS

ii

ADVANCED ENERGY SYSTEMS

National CTR Computer Center

1

The National CTR Computer Center, Livermore, is now operational, providing large-scale computational support to the CTR community.

SCIENCE AND TECHNOLOGY

High-Field Superconducting Magnets for Fusion Research

8

Work is well under way to develop the multifilamentary superconductors of niobium-titanium and niobium-tin needed for future CTR experiments.

Digital Image Processing: A Flexible Diagnostic Tool

15

We have developed complex mathematical techniques for enhancing and restoring digital images and, ultimately, for extracting quantitative data from these images.

NOTES AND REFERENCES

21

CUMULATIVE INDEX

22

University of California

Livermore, California 94550

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

249

Briefs

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

LLL TO ASSESS WIND POWER POTENTIAL

The Laboratory is investigating the feasibility of developing wind power as an alternate energy resource. For ERDA's Division of Solar Research, we have begun a 27-month analytical and computer-modeling survey of airflow patterns over Oahu, Hawaii, to establish techniques for evaluating potential wind-power sites both on the island and nationwide. Wind-current data collected by LLL and the University of Hawaii, which is collaborating in the study under State support, will be telemetered via satellite to LLL computers for processing. The project's goal is to develop accurate computer models for determining optimum sites for wind-power research, verify these models with field conditions on Oahu, and make them available for use throughout the energy research community.

During the first 15 months, we will concentrate on developing methodology and building up a data collection system for wind measurements. We are exploring the use of lasers to measure average wind velocity across long distances. Turbulence in the air breaks up the laser beam into a mottled, nonuniform

scintillation pattern. A detector then measures the drift velocity of the scintillation pattern and from it computes average air movement across the laser beam. Initial tests, in which we shined a laser beam from Koko Head to a detector about 10 km distant at Diamond Head, have been completed and appear successful. We will be setting up other field stations that include both lasers and conventional cup anemometers. These stations will provide data to complement those available from existing wind-monitoring facilities, shown on the map. Solid circles are stations for point speed and direction measurements. The two open circles denote stations that already include lasers; the solid square marks the laser detector.

The project's final year will be devoted to collecting data and refining computer models. The basis of our computer modeling work will be the two- and three-dimensional codes developed and used at the Laboratory for analyzing and predicting the movement of atmospheric pollutants. These codes can analyze wind movements over a wide range of grid scales, resolving areas ranging from less than 100 m to several kilometres on a side (see last August's *Energy and Technology Review*, pp. 9 and 12). Exact knowledge of wind movement will be critical in locating a wind power plant. Because power is proportional to the cube of wind speed, even a small change in wind speed alters its power dramatically. Sites only a few hundred metres apart could have significantly different average wind speeds because of funneling effects due to topography.

Oahu is an attractive site for wind-power research for several reasons. One is the existence of strong (5- to 10-m/s) tradewinds that blow reliably nine months of the year. The island's hills, mountains, and valleys channel these tradewinds into strong, local currents that may be suitable for wind power. Second, the lack of local fuel resources and the cost of transporting fuel from the mainland make alternate, indigenous energy sources all the more desirable. Third, the greatest population concentration is in Honolulu, a relatively short transmission distance from the potential wind power sources. Analyses indicate that as much as 50% of Honolulu's energy needs might be met with wind-generated electricity.

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 became 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 offsite 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 study³ 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)

Contact John Killeen (Ext. 3278) for further information on this article.

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 10 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 FRDA-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 offsite 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 m², will cost approximately \$5 million. In FY 1979, another 3700 m² 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 study³ 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 non-linear 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 schemes²:

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 LLNL, whereas both GUIDON and EPT (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, i.e., 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, DCCTR 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 emergent 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

SCIENCE AND TECHNOLOGY

HIGH-FIELD SUPERCONDUCTING MAGNETS FOR FUSION RESEARCH

Work is in progress at LLL to develop superconducting magnets for upcoming CTR experiments as well as for future fusion reactors. Our effort is proceeding on two fronts. First, we are developing multifilamentary niobium-tin superconductors capable of generating the high magnetic fields (up to 12 T) for future CTR research facilities such as FERF. Second, for more immediate machines such as the proposed MX experiment, we are developing conductor and coil designs and fabrication techniques; this work centers on niobium-titanium superconductors. Both program areas entail considerable cooperative effort with industry.

In all CTR magnetic confinement methods, plasma density is limited by the plasma pressure that can be supported by the available magnetic field. The ratio of plasma pressure to magnetic field pressure, β , depends on the specific field topology but is proportional to the square of the confining magnetic field, B . Fusion power density varies as β^2 ; thus, it also varies as B^4 . This B^4 dependence — rapid increase in fusion power with increasing field strength — is a strong incentive for operating fusion experiments and reactors at high magnetic fields and, hence, for developing higher-field superconductors. Another equally strong incentive is that superconductors, once operating, need only a relatively small energy expenditure for keeping them cold — to perpetuate their current and, thus, their magnetic fields. For power reactors, the prospective economic advantages of both incentives are compelling.

Two superconducting magnet systems for plasma containment experiments have already been designed and built by LLL: Baseball II, completed in 1969 and still operating, and the Superconducting Levitron, operational from 1971 to 1973. Both systems used Nb-Ti conductors; the Levitron also used Nb₃Sn tape. Until recently, the brittleness of Nb₃Sn has limited its use for conductors to a thin surface layer on niobium or steel tapes.

For reasons of electrical and mechanical stability, such tape conductors are unsuited for larger CTR magnets. Large circulating currents are induced in wide

superconducting strips when a magnetic field normal to the plane of the tape tries to penetrate, producing large flux jumps. A greater difficulty lies in ensuring the integrity of large coils when thin, wide, brittle strip conductors are used, especially if the tape must be bent on edge. However, if the superconducting material is in the form of very fine filaments embedded in a metal matrix and interwoven or twisted to allow field penetration, flux jumps can be avoided, and there is more flexibility in conductor configuration. Also, the superconducting properties of these fine-filament conductors are expected to be less degraded by strain (brittleness) than those of tape conductors. These advantages are all realized in the Nb-Ti composite conductors now available commercially. Since mid-1974, we have been working closely with industry to develop similar multifilamentary Nb₃Sn conductors. Other A-15 compounds are also being investigated, but Nb₃Sn is at present the most advanced. Manufacturing problems and strain effects are expected to be similar for all A-15 compounds.

Niobium-Tin Conductor Development

Preliminary design specifications for LLL's mirror fusion engineering research facility (FERF) indicate that the superconductor in the confining magnets will have to operate in fields of 12 T. Because of the large size (10-m diam) and stored energy (~2000 MJ) of the system, high-current conductors (~10 kA) are required to limit the voltage under fault conditions to an acceptable value. Stabilizing elements, structural members, and the insulation network will result in an overall current density of 2000 to 3000 A/cm². Nb₃Sn is a prime candidate material for such magnets.

Most of the multifilamentary Nb₃Sn conductor specimens tested to date have been supplied by AIRCO, Inc., Montvale, New Jersey. Their fabrication technique involves drawing down a high-tin bronze billet in which niobium rods have been inserted and then heat-treating the composite to form Nb₃Sn on the outer surfaces of the rods. Nineteen niobium rods are first embedded in a bronze matrix that is extruded and drawn several times to a hexagonal cross section (~6 mm). This composite rod is then cut into short lengths, 187 of which are packed into a tantalum-lined can of oxygen-free, high-conductivity (OFHC) copper.

Contact Donald N. Cornish (Ext. 4663) for further information on this article.

(The copper is required for protection and stability.) Additional bronze filler strips ensure tight packing. The resulting billet is also extruded and drawn to a hexagonal cross section. This second extrusion product, consisting of 3553 filaments in a bronze matrix, becomes the basic building block for all conductors. It, too, is sectioned and packed into an OFHC copper can, with copper strips separating the superconducting sections and ensuring a tight fit. This billet is then extruded, drawn, twisted, and rolled to the final conductor dimensions.

Following these metal working steps, the conductor is heat-treated at 650°C for up to 120 h. During this time, tin diffuses from the bronze to the surface of the niobium filaments, where it reacts to form a layer of Nb₃Sn. The tantalum liner prevents the tin from diffusing into the pure copper, where even very small quantities would seriously degrade its low-temperature conductivity. Figure 5 is a scanning electron micrograph of a Nb₃Sn conductor. DCTR considers the fabrication of these conductors to be a major technical advance.

Short-Sample Tests. Critical current (i.e., that at which the superconductor becomes resistive) was measured on short lengths of conductor containing 67 507, 259 369, and 664 411 Nb₃Sn filaments.⁵ A superconducting, split-pair solenoid supplied the magnetic fields (6 to 13 T), and a special noise-free 10-kA regulator provided the sample current. We measured field values with calibrated magnetoresistance

probes built into the magnet and with a Hall probe mounted near the conductor specimen. Specimens were inserted into the field through a radial access port. Our measurements were taken by first setting the magnetic field at the desired value and then slowly increasing the current through the specimen.

These critical-current measurements indicated that the superconducting properties of the samples are satisfactory and that, in the range investigated (1 to 10 kA), the critical current is in fact proportional to the number of filaments. Figure 6, for example, shows the critical current of the largest conductor, nominally rated at 10 kA at 12 T. Figure 7 shows test data for a 1-kA conductor (67 507 filaments), 3.5-kA conductor (259 369 filaments), and 10-kA conductor (664 411 filaments), all normalized to the 12-T critical current. The field dependence of the critical current in Fig. 7 is clearly independent of conductor size. Thus, there appears to be no intrinsic problem in scaling up conductor size to that ultimately needed for the FERF magnets.

Coil Tests. We have also tested a relatively large (27.5-cm-bore) coil wound from 67 507-filament superconductor supplied by AIRCO. The coil had a 32.8-cm outer diameter, a winding length of 13.3 cm, and conductor length of 300 m. We fabricated the winding mandrel from 6061-T6 aluminum alloy, perforating more than 30% of its surface area to allow helium ventilation. For insulation, 50% of the conductor surface area was spirally wrapped with

SUPERCONDUCTING MAGNETS: RESEARCH AND DEVELOPMENT

One important aspect of CTR research now under way is the development of large superconducting magnets for confining plasmas in toroidal and mirror confinement geometries. The incentives are both practical and economic. Tokamak reactor studies project the need for D-shaped niobium-titanium superconducting magnets with inside dimensions of 15 X 20 m which, when arranged in toroidal geometry, will produce a central field of about 4 T. Projections for mirror devices indicate a Yin-Yang magnet configuration enclosing a volume nominally equivalent to a sphere 8 to 10 m in diameter. The anticipated vacuum central field is about 5 T, and the field in the mirror region is about 10 T. Niobium-tin is needed for this application because it remains superconducting at the higher field strengths required for mirror devices. Magnet fabrication is more complex for mirror devices than for toroidal devices because of the complicated Yin-Yang geometry.

Oak Ridge National Laboratory is conducting the niobium-titanium magnet development program for toroidal tokamaks, under auspices of ERDA's Division of Controlled Thermonuclear Research. LLL is pursuing the development of niobium-tin superconducting magnets. As described in the accompanying article, we recently realized a breakthrough in the development — by AIRCO, Inc. — of niobium-tin conductors containing up to 664 411 filaments. Test results are encouraging. These or other similar conductors will be needed for fabricating a subsize magnet for our mirror fusion energy research facility (FERF) before building a full-size magnet around 1980. LLL is also exploring niobium-titanium superconductors suitable for MX, a plasma physics experiment being considered as an intermediate step between 2XIB and FERF. The MX magnet is expected to use niobium-titanium, but the geometry will be Yin-Yang.

6 × 0.08-mm Nomex tape. Strips of epoxy fiberglass 6 mm wide and 0.4 mm thick were placed axially along the winding length, about 6 mm apart, to provide layer-to-layer insulation and access channels for liquid helium. Mechanical reinforcement was provided by overwrapping the coil with 1850 turns of 0.8-mm-diam stainless steel with a tension of 200 N. The coil's inductance was 0.03 H.

The Nb₃Sn test coil was suspended inside a 35-cm-bore Nb-Ti solenoid capable of producing a background field of 5 T. With both coils energized, we obtained a peak field of 10 T. We monitored the coil's resistance during cooldown. The ratio of resistance at room temperature to that at liquid-helium temperature was approximately 100, indicating that

the tantalum diffusion barriers remained intact and prevented the tin from contaminating the copper.

Results from the most important aspect of the coil test — determining the conductor's ability to generate a high magnetic field — are given in Fig. 8, where coil performance is measured against the current-carrying capability of short specimens. For the first set of runs, we set the background field at 4 T and charged the coil at approximately 25 mV. The coil suddenly became resistive (i.e., quenched) at 1600 A; subsequent quenches occurred at 1750 and 1900 A. The conductor fields for these three quenches were 7.1, 7.4, and 7.7 T, respectively. On the fourth run, we reached 2500 A — corresponding to a conductor field of 8.8 T — without a quench. The background

Fig. 5. Scanning electron micrograph of an etched section of Nb₃Sn conductor made with the external bronze technique by AIRCO, Inc. The tantalum liner surrounds a bronze matrix in which 3553 niobium filaments are embedded. The tin in the bronze has reacted with the niobium to form a Nb₃Sn layer 1 to 2 μm thick. High-purity copper can be seen between adjacent tantalum liners.

Fig. 6. Quench current of a 10-kA Nb₃Sn conductor. The conductor more than equalled the design requirements of 10 kA at 12 T.

Fig. 7. Normalized quench currents of 1-, 3.5-, and 10-kA Nb₃Sn conductors, showing that the field dependence of critical current is independent of conductor size.

Fig. 8. Performance of a 27.5-cm-bore coil wound from Nb₃Sn superconductor with 67 507 filaments. After three premature quenches, the coil operated at short-sample current (the maximum current possible) in a field of 10 T.

field was then increased to 5 T and the coil energized until a quench occurred at 2550 A. This current corresponds to the short-sample limit and a field of 10 T at the conductor. These test results are encouraging for the potential feasibility of using multifilamentary Nb₃Sn to build large, high-field magnets.

MX Magnet Development

The second major area of our magnet development program is associated with the MX experiment. The confining field in MX will be generated by a pair of large Yin-Yang coils (Fig. 9) wound with Nb-Ti superconductor. The main field parameters — set by plasma conditions — are a central (vacuum) field of 2 T, a mirror field of 4 T, a maximum field at the conductor of 7.5 T, and a mirror separation of 3.4 m. The precise shape of the Yin-Yang magnets will depend on factors not yet established, such as magnetic-well depth and injector access, but the main magnet parameters have been set (see Table 1) and should not change significantly.

Although the superconducting properties of Nb-Ti are adequate for MX, some development of conductor fabrication techniques is needed. The conductor for such a large Yin-Yang magnet system must meet some stringent specifications. In particular, it must

- Generate a high field, which implies (a) low critical current density in the superconductor,

Table 1. Main magnet parameters for MX machine

Parameter	Value
Major radius	2.5 m
Minor radius	0.78 m
ΔZ (coil displacement)	0.78 m
Coil section	3.28×0.84 m
Total stored energy	500 MJ
Current density	3400 A/cm^2

Fig. 9. Basic Yin-Yang coil geometry (top) and tentative magnet support structure (bottom) for MX machine.

(b) large forces, and (c) high magnetoresistivity, thus increasing the surface required for cryostatic stability.

- Have high overall current density in the winding [in direct conflict with (a) above].

- Be cryostatically stable (i.e., operate for short periods with all current flowing in the stabilizing copper).

- Bend about two mutually perpendicular axes.

The large forces generated in the current-carrying conductors are a major problem. A field of 7.5 T exerts a pressure of more than 22 MPa, most of which will be transmitted through the windings to a support structure outside the coil case (see Fig. 9). The conductors will restrain part of these forces, however, and because the crushing stress is expected to approach the yield strength of annealed copper, we are directing some fabrication effort toward increasing conductor strength. The addition of other materials or the use of partially hardened copper are two possibilities.

For reliability, we propose using a cryostatically stabilized Nb-Ti conductor in "pool" boiling helium at 100 kPa for the coils. One possible conductor configuration is shown in Fig. 10. All the superconducting filaments here are embedded in quadrant 4; the other three quadrants of OFHC copper provide the normal conductor needed for cryostatic stabilization. Grooves previously made in quadrant bars 1 and 3 form internal cooling channels. The ratio of superconductor to copper in quadrant 4 is about 1:1.

Explosive Joints in Superconductors. The maximum length of conductor available to us restricts the design

Fig. 10. Potential configuration for a cryogenically stabilized MX conductor.

and construction of large superconducting magnets. This length is limited mainly by the maximum billet weight (~270 kg) that can be handled with existing equipment; because unavoidable breakages do occur, manufactured lengths may be even smaller than this. The large magnets for future CTR experiments and reactors will require many tonnes of conductor and, therefore, many joints.

In conventional joints, the conductors are overlapped and then soldered, bolted, or both soldered and bolted. Soldering provides the low resistance, and bolting supplies mechanical strength. However, because these joints occupy considerable space, they upset the lie of conductors in the winding; special arrangements must be made to accommodate the joints. This can be expensive and time-consuming.

What is needed is a joint that occupies no extra space, permitting effectively infinite conductor length, and one that can be safely made near the coil during the winding process. Explosive joints appear suited to this application. Some work has already been done in Europe on explosively joining conductors, and the technique has been used successfully in several coils.⁶ The resulting scarfed (tapered) joint takes no extra space and has excellent mechanical strength and very low electrical resistance. Working with Battelle Columbus Laboratories, we recently completed a preliminary study of explosively joined Nb-Ti/Cu composite superconductors.⁷

The study commenced with experimental joints in solid-copper conductors; the impact of various parameters such as scarf angle and position and the quantity of explosive used was explored. Work then progressed to joining a composite conductor. The superconductor for these experiments had a 6 X 6-mm cross section with 500 Nb-Ti filaments and a copper-to-superconductor ratio of 1.2:1; this was the available conductor most like that envisaged for the MX conductor (Fig. 10). After a few trials, we found that the arrangement shown in Fig. 11a produced consistently satisfactory joints. Figure 11b shows the finished joint.

Mechanical tensile tests indicated that joint strength was about 475 MPa, 8% that of the basic conductor. Figure 11c shows a joint cross section after tensile fracture; as can be seen, the trailing edge is not fully bonded. We believe, however, that minor modifications can be made to the joint assembly that will overcome this problem and result in a joint strength equal to that of the conductor.

Fig. 11. Explosive-joint assembly and product: (a) assembly schematic for arranging component parts of an explosive joint; (b) finished joint; (c) photomicrograph of a test joint after tensile fracture. The fracture indicates incomplete bonding at the trailing edge; slight adjustments in our welding assembly should eliminate this flaw.

The results of electrical tests on a typical explosive joint are shown in Fig. 12. The joint has some superconducting properties; even at relatively high currents and fields, the resistance is less than 10^{-9} ohms. Many such joints would be acceptable in a large magnet system such as MX. With them, the type of conductor shown in Fig. 10 is obtainable in virtually unlimited lengths.

Insulation Development. Selection and fabrication of electrical insulation could be one of the most

time-consuming and costly factors of the MX magnets. Interturn and interleaver insulation for superconducting magnets serves as both a coolant network and an electrical barrier. When these functions are coupled with a multiaxis magnet geometry and fast-neutron radiation exposure, design and material selection pose a complex engineering problem. This is especially true for interturn insulation, which must bend not only normal to the face of the insulation strip but about the edge as well. Interturn insulation for Baseball II was difficult to obtain, costly to fabricate, and tedious to apply. For these reasons, we are now working to develop a more proficient scheme for the upcoming magnets.

Future insulation will have to provide a network of equally spaced disks offering about 50% bearing area between conductors and, in the remaining space, allowing for adequate surface cooling of the conductor.

Because the conductor must bend about two mutually perpendicular axes, these disks and their carrier must also be flexible in two directions. Finally, relatively short runs of insulation will be needed for test magnets. Because commercial suppliers for such insulation are unlikely to be forthcoming, we are designing our own fabrication machinery for its production. This will give us the flexibility either to produce short in-house runs or provide the machinery for fabrication by industry.⁸

Research Directions

We are continuing to run tests on short lengths of Nb_3Sn conductor supplied by AIRCO to study the effects of varying filament size, heat treatment, strain, and stabilizing techniques. Within the next six months or so, we also expect to extend these tests to Nb_3Sn conductors fabricated by an internal bronze technique.

Fig. 12. Electrical test results for an explosive joint: (above) critical current of joint and base conductor; (right) joint resistance, which is acceptably low for joints in the proposed MX magnet system.

This approach, being developed by Supercon, Inc., Natick, Massachusetts, involves drawing down a three-component billet consisting of bronze-filled niobium tubes in a copper matrix and then reacting the tin to form Nb_3Sn on the tube's inner surfaces.

To extend our coil-test capability to the field regimes needed for proving tests on the MX conductor, and to enable us to carry out tests on larger Nb_3Sn conductors in coil form, we have proposed construction of a 1-m-bore, 8-T test facility. The design of this facility calls for a Nb-Ti backing coil capable

of producing a field of 8 T with a Nb_3Sn insert to boost the central field to 12 T. The cryostat needed for the coils will be assembled in the pit in our present cryogenic laboratory. This high-field test facility will be a major stepping stone toward showing that superconducting materials like Nb_3Sn can operate reliably in the coil shapes and sizes needed for magnetically confined fusion research.

Key Words: Magnet; MX; niobium-tin superconductors; niobium-titanium superconductors; superconductors; FFRF.

DIGITAL IMAGE PROCESSING: A FLEXIBLE DIAGNOSTIC TOOL

Digital image processing is a flexible diagnostic tool with wide-ranging applications in basic research. A major area of image-processing activity at LLL is diagnostic radiography, with two main objectives: to remove imaging distortions and artifacts incident to radiographic measurements, and to compensate for the low contrast sensitivity that characterizes much of the imagery. To achieve these objectives, we have developed complex mathematical techniques for image enhancement and restoration and, ultimately, for extracting quantitative data from digitized images. Our work is strongly applications-oriented.

The image-processing capability developed at LLL features an interface to the Laboratory's extensive OCTOPUS computer network and provides for considerable man-machine interactivity. The speed and memory of the OCTOPUS system permit us to routinely process large data arrays containing up to 2048×1048 picture elements. Consequently, we have been able to pursue research into the uses of sophisticated and complex processing algorithms for large-scale problems. The man-machine interaction allows us to exercise human judgment while processing image data, an important capability when dealing with measurements obtained from state-of-the-art physics research.

Our image-processing flow is diagrammed in Fig. 13. We start by digitizing the original continuous image (typically an x ray). Although several devices are available for reducing photographic transparencies to numerical values of intensity on a square grid, the usual

method is to measure the opacity of the transparency by a microdensitometer. The record of opacity and location is recorded on magnetic tape and read into the OCTOPUS network. Interactive processing then commences by means of the image display system and a high-resolution color monitor. From the system console, we can retrieve the image file, transport it to a worker computer, and have it processed according to a chosen processing scheme. In tens of seconds, the processing is complete, and the digital image (a digital picture) is available for display and inspection. The display system allows us to evaluate a high-quality playback of the picture and, if necessary, modify the processing algorithm and reprocess the image, thereby closing the interactive man-machine loop.⁹

The mathematical techniques used in image processing are best defined as belonging to two general

Fig. 13. Schematic of the interactive digital image-processing system at LLL.

Contact John W. Woods (Ext. 8022) for further information on this article.

classes: point and area operations. Point operations act on each image point independently and, hence, represent the smallest load for digital-picture processing, each output point being calculated from only one image point. The techniques for such operations, discussed below, include histogram improvement, grey-scale mapping, and pseudo-coloring. By comparison, area operations act jointly on sets of picture elements and are more complex, possibly involving all the image points in calculating individual output points. Area operations, also discussed below, include image estimation, statistical deconvolution, and edge enhancement.

Point Operations

With our display system, each picture element is resolvable into 64 grey levels of brightness. The digital picture can be analyzed to determine the relative frequency of occurrence for each grey level and the results then plotted. Such a plot is called a histogram. If the histogram is bunched into a small segment of the available display range, we can improve it by stretching the bunched region to the full range of display. This is accomplished by a nonlinear point operation on the digital image values. The visual effect is a contrast enhancement for typically low-contrast images.

A second point operation is grey-scale mapping. This technique is often used to emphasize an object of particular interest in the picture. In this way, the full display range can be utilized for a portion of the image that would otherwise use only part of the display range. Grey-scale mapping can also quantify a slowly varying image field (one varying slowly in density). By identifying similar grey levels at various locations, this process produces a contourlike plot. The visual effect is to magnify the distinctions between the grey levels, making very fine gradations appear more prominent.

Pseudo-coloring transforms a black-and-white or grey-scale image into a color display. This is accomplished by assigning 1 of 4096 arbitrary colors to the grey level of each picture element. We have found this method very useful in a wide range of applications because the additional dimension of color transfers more information to the observer than can a single grey-scale image. Many different pseudo-color schemes have been developed to enhance various aspects of digital images.

The improved image clarity obtained with pseudo-coloring is illustrated in Fig. 14, where the

technique is applied to laser-fusion research. The laser-plasma-interaction group at LLNL has been using laser pulses to implode glass-shell targets filled with deuterium-tritium fuel. A major purpose of their work is to develop an accurate model of pellet implosion.¹⁰ In their experiments, one or more 90-ps, 14-J laser pulses impinge on a target, and an x-ray microscope images the ensuing implosion on film. This radiograph is then digitized on a microdensitometer for computer processing. An example of the resulting grey-scale image of an implosion is shown in the top photograph of Fig. 14; the bottom photograph shows this same image after a pseudo-color scheme has mapped the grey onto a range of distinct colors. The color image has also been smoothed with a spatial low-pass filter. The

Fig. 14. Grey-scale image (top) of an imploded laser target and corresponding pseudo-color transformation (bottom). The colored contours of the lower image provide a much clearer picture of compression symmetry.

contour effect of the lower photograph more clearly shows the compression symmetry resulting from various target designs, thus helping to optimize such designs.

Area Operations

Image processing that involves more than one input point in the computation of each output point falls into the class of area operations. For example, a local average or smoothing, or a first- or second-order difference, is an area operation. The latter is often used to detect edges in pictures. Edge information may be very useful for dividing an image into regions of interest before further processing. Also included in this class of operations is the removal of surfaces attributable to uneven source illumination of an object. More sophisticated area operations involve a large number of input points in determining each output point; image estimation and statistical deconvolution are two examples.

Image Estimation. When our original image is noisy or perturbed by random disturbances, such as can happen in a flash radiograph, image estimation is necessary. Our objective is to form an estimate of the signal, or noise-free image, from the noisy image. Image estimation here becomes a standard problem in communication theory, and standard methods — Wiener or Kalman filters, least-square and constrained least-square methods — are at hand to minimize the weighted mean-square error in our estimate. The essential new item in transferring these techniques to image processing is the two-dimensional nature of image data. For two-dimensional as compared with one-dimensional images, the amount of data to be stored is squared: that is, 1 million points for a two-dimensional 1024×1024 digital image. Such images require the writing of a very tight code to implement the needed algorithms in a reasonable amount of computer memory and running time.

Statistical Deconvolution. A related area operation is statistical deconvolution, which is needed when the data are not only noisy but there is some distortion of the signal, as well. Such a situation can arise when an image is out of focus because of aperture or diffraction limitations, or when it is blurred by motion, or aperture-encoded. We model the data as an ideal signal linearly transformed by a known distorting system and then couple the additive noise to the result. Two examples should serve to illustrate statistical deconvolution.

In x-ray astronomy, random pinhole arrays are used as a mask in imaging distant stars. The result is a coded aperture image consisting of the superposition of the mask shadows corresponding to each resolvable element of the source object. Superimposed on this image are photon noise, film-grain noise, and a fog level due to the nature of the photographic process. In support of one LLL project, we applied optimal linear signal processing to these coded aperture images.

An experiment was conducted using visible light to simulate the imaging process. Figure 15a shows the image of our random mask; Fig. 15b shows the coded image of a small letter E whose height is a few resolution elements. When we attempted to reconstruct the coded image optically (using the standard matched-filter method¹¹), the result was unacceptable. The mean background level (i.e., average brightness) due to the superposition of images made for an inferior matching. However, when we reconstructed the image digitally, subtracting this mean, the results were noisy but much improved (Fig. 15c). We then applied a Wiener deconvolution filter to the coded noisy image with the result shown in Fig. 15d. Note the increased resolution and also the reduction of artifacts, especially on the horizontal and vertical axes passing through the E.

Fig. 15. Linear signal processing applied to coded aperture images: (a) random mask; (b) coded image of the letter E used in the experiment; (c) initial digital reconstruction of the coded image; (d) final reconstructed image obtained after applying a Wiener deconvolution filter.

A second use of statistical deconvolution involves diagnostics on a method developed at the Laboratory for isentropically compressing soft materials into a 100-GPa pressure range.¹² A sample material to be compressed is placed in a cylindrical copper tube, which is vacuum-suspended in a stainless steel liner; the liner is placed in a 0.1-T magnetic field. A cylinder of high explosives around the liner is detonated, compressing the magnetic flux and inducing 100 GPa pressure on the copper tube and enclosed sample. It is of great interest to know the sample-volume compression at the peak pressures.

To secure these data, we take flash x-ray measurements. The x-ray source is a 200-ns burst of flux, which freezes the motion at a predetermined time. A typical resulting radiograph is shown in Fig. 16a; from it we would like to determine the boundaries of the sample, tube, and liner. The precision with which we can locate these boundaries in the radiograph, however, is limited. This is a

consequence of both the resolution limits of the radiographic system and the image's extreme noise level from the high-speed film used to accommodate the short time exposure.

To improve the boundary definition, we must improve the edge resolution and smooth the noise fluctuations. The method applied for this purpose involves expanding the enhanced image in a basis of "singular pictures" constructed using the singular vectors of the finite Laplacian operator. To form the image as a linear combination of singular pictures, we introduce a weighting array to facilitate the desired enhancement. By properly choosing these weights, we can partially compensate for the resolution limits of the imaging while effectively bounding the first-order variation of the image. This choice is generally based on *a priori* knowledge of the object and measurement noise, and on the physics of imaging.

A vertical scan line from processed data corresponding to the central portion of the radiograph

Fig. 16. Flash radiograph (a) of sample material under compression. We have only limited precision in locating the boundaries of sample, copper tube, and liner from this radiograph. To improve the boundary definition, we digitally process the image. A vertical scan line from the processed data is shown in (b); dots represent radiographic data points, and the smooth curve is a best estimate of these noisy data. From a sequence of such vertical scans, we can then construct a composite view of the boundaries (c), shown here for the central portion of the radiograph.

is shown in Fig. 16b. The structure of the density variation due to the copper tube and sample is retained (although not perfectly resolved), and the noise effects are considerably reduced. The transition regions are identified from such vertical scans, and the boundaries can then be constructed in the composite, as shown in Fig. 16c.

Alpha-rooting. In statistical deconvolution, the processor assumes that a statistical characterization of the images is known or can be estimated from the noisy image(s). When this is not the case, the procedure of alpha-rooting for edge enhancement often produces remarkable results. The idea here is to change the magnitude of the image's Fourier components by raising them to the power alpha (less than 1). This has the effect of raising the magnitude of the small, high-frequency components relative to the large, low-frequency components and yields increased spatial resolution - i.e., a sharper image. In this scheme, alpha is determined interactively to strike a proper balance between increasing the resolution and magnifying the (high-frequency) noise.

We have used alpha-rooting, coupled with pseudo-coloring, in nondestructive testing to obtain information that appears unavailable when initially inspecting a radiograph. The top photograph in Fig. 17 is a radiographic image of one test specimen - a cylindrical graphite ring. We are first interested in obtaining both a detailed overview of the density distribution and some information concerning its symmetry and rate of variation. We do this using our pseudo-color display, which produces a color transformation (middle photograph) of the original radiograph. With this technique of mapping slight density variations into abrupt color differences, the contours of constant density are more clearly identifiable.

We are also interested in locating defects in the graphite, though it is not apparent from the original radiograph that any exist. We zoom in on the top center portion of this radiograph, therefore, and apply a nonlinear alpha-root filter to compress the dynamic range of the image and to emphasize its detailed structure. The result of this filtering is shown in the bottom photograph of Fig. 17, which exposes large numbers of isolated defects in the graphite. These defects produce dark specks in the image because of their decreased transparency to the source radiation. From this filtered image, it is a relatively straightforward step to provide a frequency-of-defect measure for the specimen.

Fig. 17. Alpha-rooting and pseudo-coloring applied to nondestructive testing: (top) radiograph of the test specimen, a cylindrical graphite ring; (middle) pseudo-color display of the radiograph showing density distribution and symmetry; (bottom) detailed structure of the radiograph's top, center area after alpha-root filtering exposes defects in the graphite. The rectangular object visible in the two lower photographs is a penetrometer used to indicate the sensitivity of the radiographic measurements.

Processing Nonimage Data

So far we have discussed digital processing in terms of data originally in image format, such as radiographs. However, putting nonimage data into image format can also be beneficial. Just displaying these data as an image often aids their interpretation and thus their usefulness. Further, once so formatted, the data may then be digitally processed as described above. An ongoing acoustical imaging project at LLL illustrates the potential of processing nonimage data.

What was needed was information on the thickness of the human chest wall for use in studies relating external radiation readings to plutonium concentration

Fig. 18. Experimental setup (top) for imaging a vertical cross section of the chest. From one-dimensional data so obtained, a picture is built up (lower left); a curve-fitting routine is then used to quantify the interior and exterior edges of the chest wall (lower right). The coefficients of these two curves can be used to calculate various chest-wall parameters.

in the lungs. In this project, a directional acoustic probe was moved vertically along an individual's chest wall, producing an acoustic reflection record for numerous positions and angles of incidence (see Fig. 18, top). The location and direction of each of these records was digitized along with the reflection record itself and stored on magnetic tape. Later, these one-dimensional data were played back and a picture built up from the reflection records, as shown in the left photograph of Fig. 18. In this digital image, the chest wall stands out very well; one can also see indications of the ribs as well as the front surface of the lungs. A curve-fitting routine was then used to quantify the interior and exterior edges of the chest wall. The spline fit, determined from picking 10 points on the chest and lung boundaries, is shown in the lower right photograph. The coefficients of these two curves can be used to determine various chest-wall parameters: for example, average thickness, volume, and area.

Concluding Remarks

In recent years there has been increasing interest in processing pictorial images digitally.¹³ Since the initial success of digital image correction in support of the space program, considerable effort has been devoted to developing image processing as a diagnostic tool for basic research. Our work on digital image processing at LLL has been strongly influenced by the online accessibility of several high-performance computers in OCTOPUS. The computing power and storage available at LLL have allowed us to develop and apply sophisticated algorithms, involving both statistical and deterministic characterizations of the data. With an interface to OCTOPUS and man-machine interaction, we are able to handle large-scale image problems with the versatility, accuracy, and reliability intrinsic to digital processing, and with the speed and storage capacity previously reserved for optical processing systems.

Future work will center on developing improved processing schemes that incorporate more accurate image models. We plan to develop processing algorithms particularly suited to the CDC STAR 100 and other large vector processing computers. At the same time, however, we are pursuing other algorithms suitable for both minicomputer and special-purpose hardware implementation.

Key Words: digital image processing; image enhancement; image processing; image restoration.

Notes and References

1. "Fusion Power: Potential and Progress," in the November 1975 *Energy and Technology Review* (UCRL-52063-75-11), p. 2.
2. *Fusion Power Research and Development Program Projections*, U.S. Energy Research and Development Administration, Division of Controlled Thermonuclear Research, Washington, D.C. (May 1975) (to be published).
3. *The Application of Computers to Controlled Thermonuclear Research*, U.S. Atomic Energy Commission Rept. WASH-1296 (1973).
4. J. Killeen, *Nucl. Tech.* **27**, 107 (1975).
5. J. Zbasnik, L. Vandervoort, C. Taylor, D. Ping, and D. H. ... "Test on Multifilamentary Nb₃Sn Superconductors," in *Proc. Sixth Symposium on Engineering Problems of Fusion Research, San Diego, November 18-21, 1975*.
6. See, for example, A. Berruyer, R. Blondet, G. Bronca, J. Holtz, J. Krikorian, and J. Neel, *Advances in Cryogenics Engineering* **15**, 158 (1969).
7. D. Cornish, J. Zbasnik, and H. Pattee, "Explosive Joints in Nb-Ti/Cu Composite Superconductors," in *Proc. Sixth Symp. Engineering Problems Fusion Research*.
8. For progress to date on designing insulation for MX and FERF, see A. Harvey and J. Rinde, "Electrical Insulation for Large Multiaxis Superconducting Magnets," in *Proc. Sixth Symp. Engineering Problems Fusion Research*.
9. L. Hatfield and C. Journeay, "Advanced Interactive Picture Processing System," presented at *Society for Information Display Seminar, San Diego, May 1974*; also Lawrence Livermore Laboratory Rept. UCRL-75710 (1974).
10. H. Ahlstrom and J. Holzrichter, *Laser Focus* **11**, 39 (1975).
11. R. Dicke, *Astrophys. J.* **153**, 1101 (1968).
12. R. Hawke, D. Duerre, J. Huebel, H. Klappen, D. Steinberg, and R. Keeler, *J. Appl. Phys.* **43**, 2734 (1972).
13. J. Aggarwal and R. Duda, Eds., Special Issue on Digital Filtering and Image Processing, *IEEE Trans. Circuits and Systems*, **CAS-22** (1975).

Cumulative Index

April Through December 1975

The following index is a cumulative table of contents covering the nine issues of *Energy and Technology Review* from April (the first issue) through December 1975:

<u>Month</u>	<u>UCRL No.</u>
April	52000-75-4
May	52000-75-5
June	52000-75-6
July	52000-75-7
August	52000-75-8
September	52000-75-9
October	52000-75-10
November	52000-75-11
December	52000-75-12

The righthand column of the index gives the month and the page where information about an indexed item can be found (e.g., *Apr-1* means page 1 of the April issue).

ADVANCED ENERGY SYSTEMS

Aerial Prospecting for Geothermal Resources	May-1
CDC-7600 Goes Online at CTR Computer Center	Oct-ii
Field Work Under Way for Solar Energy Project	Sep-ii
Gas-Embedded Z-Pinch: New Approach to an Old Concept	Jun-1
Geothermal Energy Development Project: Status Report	Aug-1
Heavy Water Production: New LLL Studies	Oct-1
Lithium-Water-Air Batteries for Automotive Energy	Sep-20
LLL to Assess Wind Power Potential	Dec-ii
Major Advance in CTR Research	Jul-ii
Mirror Reactor Concept for a Fusion Engineering Research Facility	Apr-1
National CTR Computer Center	Dec-1
Shallow Solar Ponds: An Economical Approach to Industrial Process Heat	Apr-4
2XIB: Heating and Containing Magnetically Confined Plasmas	Nov-1

ENERGY PERSPECTIVES

Energy -- A Plan for Action	Jul-1
Energy Research and Development Priorities	Sep-1
Nonelectrical Uses of Geothermal Resources	Nov-18

ENVIRONMENT, HEALTH AND SAFETY

ARAC: Real-Time Prediction of Hazards Due to Radioactive Releases	Aug-12
Dynamite Tagging Study Completed	May-ii
Flow Microfluorometry: Analyzing Sperm DNA Content	Oct-14
Health and Environmental Effects of Methanol as an Automotive Fuel	Sep-17
Livermore Regional Air Quality (LIRAQ) Models: Tracing Pollutant Concentrations	Aug-9
New X-Ray Fluorescence Excitation Analyzer Expedites Blood Tests	Sep-ii
Radionuclide Accumulation in Oysters	Jun-15
Radon Sealants for Uranium Mines	May-9
Safety Limits of Half-Mask Respirators for Organic Solvent Vapors	Oct-11
Seismic Response Analysis of a Nuclear Fuel Fabrication Plant	May-5

FOSSIL ENERGY

An Overview of the LLL <i>In Situ</i> Coal Gasification Program	Apr-8
Hoe Creek Coal Gasification Experiments Under Way	Nov-ii
Methanol from <i>In Situ</i> Coal Gasification	Sep-9
Progress in LLL Oil-Shale Research	Jun-10
RISE: An LLL Concept for Extracting Oil from Oil Shale	Jun-6
Rock Mechanics: A Review of Current Research	Jul-18

LASERS AND LASER APPLICATIONS

Deuterium Enrichment Achieved with Lasers	Aug-ii
Laser Isotope Separation of Uranium	Jul-9
Laser Program Achieves Record Neutron Yields	May-ii
Narrowband Fluorescer Used to Drive an Iodine Photodissociation Laser	Nov-7
Progress in the Calculation of Laser-Plasma Coupling	Apr-14

NATIONAL SECURITY

New Hard Shell Munition Successfully Tested	Aug-ii
Nuclear Silo Counterforce: Calculating the Soviet-U.S. Balance	Jul-13
X-Ray Fluorescence Analysis for Nuclear Materials Accountability	Aug-17

SCIENCE AND TECHNOLOGY

Adapting the Automobile to Methanol: One Practical Approach	Sep-13
Computer-Controlled Multiple-Actuator Shaker Offers Unique Test Capabilities	May-12
Digital Image Processing: A Flexible Diagnostic Tool	Dec-15
Fluid Jets: Enhanced Cutting in the Far Zone at Lower Pressures	Nov-11
High-Field Superconducting Magnets for Fusion Research	Dec-8
Hydrogeochemical Survey to Locate Uranium Sources	May-ii
Nuclear Chemical Mining for Copper Recovery	Oct-20
Piezoelectric-Supported Thrust Bearing for Diamond Turning Machine	Apr-ii
Search for Antineutrino Decays Proves Fruitless	Jun-ii
Spatial Distribution of the Crab Nebula X-Ray Source	Apr-18
Uranium-235 Fission Cross Section Accurately Determined	Jun-ii

TRANSPORTATION RESEARCH AND DEVELOPMENT

Adapting the Automobile to Methanol: One Practical Approach	Sep-13
Health and Environmental Effects of Methanol as an Automotive Fuel	Sep-17
Lithium-Water-Air Batteries for Automotive Energy	Sep-20
Methanol from <i>In Situ</i> Coal Gasification	Sep-9