Energy and Technology Review

Lawrence Livermore Laboratory

March 1978

THE COVER

Photographic montage of Octopus, the Laboratory's interactive computing utility. Octopus is an extensive network of computers, storage media, input/output devices, and communication channels that provides Laboratory personnel with computational services in their offices. The network is built around six large computers, four CDC 7600's and two STAR-100's, with numerous smaller computers carrying out a variety of processing tasks to support the main computers and other network services.

The major storage media include an IBM photodigital store and CDC 38500 mass storage facility—each capable of holding over one trillion bits—as well as some 40 000 magnetic tapes. Input/output devices range from keyboard terminals and video display monitors in users' offices to two Honeywell nonimpact printers that can print 18 000 lines per minute. Finally, a variety of communication channels—some moving information at tens of millions of bits per second—interconnect all facilities into a single network of computing resources.

For a fuller description of Octopus and of its impact on research at LLL, see the article beginning on p. 1.

ABOUT THE JOURNAL

The Lawrence Livermore Laboratory is operated by the University of California for the United States Department of Energy. The Laboratory is one of two nuclear weapons design laboratories in the United States. Today nearly half of our effort is devoted to programs in magnetic and laser fusion energy, biomedical and environmental research, applied energy technology, and other research activities.

The *Energy and Technology Review* is published monthly to report on accomplishments in this energy and environmental research and on unclassified portions of the weapons program. A companion journal, the *Research Monthly*, reports on weapons research and other classified programs. Selected titles from past issues of the *Energy and Technology Review* are listed opposite the inside back cover.

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BRIEF

MECHANICAL ENERGY STORAGE PROJECT

In September 1977, the ERDA Division of Energy Storage Systems asked LLL to develop and evaluate the technology of mechanical energy-storage systems for application to electric and hybrid vehicles, and a new Laboratory program was initiated: the Electric and Hybrid Vehicle—Mechanical Energy-Storage Technology Project. The project supports the Electric and Hybrid Vehicle Act of 1976 and is expected to continue through FY 1982 with a total expenditure of nearly $8 million.

Sandia Laboratories is responsible for guiding component development. Our role is to develop and evaluate energy storage systems technology for applications to vehicles. We are currently in final negotiations with two major contractors, and at the end of March we sent out invitations for proposals to other prospective contractors for subsystem development. Although our primary responsibility is one of technical management, our effort complements other LLL projects such as those concerned with the characterization of composite materials, the design of flywheel rotors, and the assessment of transportation systems. (See the June 1976 and June 1977 issues of *Energy and Technology Review*—UCRL-52000-76-6 and UCRL-52000-77-6—for discussions of LLL work in transportation systems.)

Including flywheels or other mechanical energy-storage devices in electric and hybrid vehicles can enhance vehicle performance by improving acceleration, increasing range, and extending battery life. Because mechanical energy-storage systems can accept and deliver energy at very high rates, they can augment the battery during periods of high power demand. Current analyses indicate that the life-cycle cost of a vehicle may actually be reduced when a mechanical energy-storage unit is included in the drive train.

Before mechanical energy-storage systems can find widespread application in vehicle systems, their efficiency will have to be improved. These improvements will include advances in flywheel rotor design and construction, in the effective use of lightweight fiber-composite materials, and in the technologies of bearings, seals, vacuum systems, and other components. Under the management of LLL and Sandia Laboratories, DOE's Energy Storage Technology program will guide development of these individual components and their integration into systems for use in electric and hybrid vehicles.

Contact T. M. Barlow (422-6434) for further information on this subject.

Octopus: LLL's Computing Utility

The Laboratory's Octopus network constitutes one of the greatest concentrations of computing power in the world. This power derives from the network's organization as well as from the size and capability of its computers, storage media, input/output devices, and communication channels. Being in a network enables these facilities to work together to form a unified computing utility that is accessible on demand directly from the users' offices. This computing utility has made a major contribution to the pace of research and development at the Laboratory; what we now regard as an adequate rate of progress in our research could not be achieved without it.

LLL is only slightly younger than the modern digital computer, and our history is closely tied to that of the computer industry. We have always been a leader in applying computers to scientific activity and have one of the world's most extensive, up-to-date computer installations.

This preeminence has come about primarily because of the needs of the Laboratory's principal program, nuclear weapons research, which has used detailed numerical simulations of physical processes as a partial substitute for experiments. This substitution must be partial because, unlike experiments, numerical simulations cannot discover the fundamental characteristics of matter and energy but can only determine the effects of known or extrapolated characteristics. To the extent that they can be used, however, simulations have several advantages over experiments:

- They can be carried out much more rapidly; an idea can be tested within a few hours, often within a few minutes, and there is no need for months of preparation involving hundreds of individuals and travel to remote sites.
- They are much less expensive.
- They create no concerns about safety, public health, environmental impact, or legal obligations.

Without the computer, advances in nuclear explosives technology would have been much slower, more costly, and more difficult.

Progress in technological fields other than nuclear explosives also requires extensive use of computers; our laser and magnetic fusion programs, for example, depend heavily on simulations, and other fields of energy research are not far behind. Thus no matter how the Laboratory's programs change in the future, the need for powerful computing facilities will remain and will grow.

SOFTWARE DEVELOPMENT

Computers are tools of the scientist's trade, but unlike other tools, proper hardware installation alone is not enough for their efficient operation. Software is also required: a set of basic computer programs supporting the user-generated programs, such as simulations.

As a rule, computer manufacturers sell software

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along with their hardware, but their software is usually unsuitable for use at LLL, for several reasons. First, we often acquire a new computer model before the manufacturer has had time to develop complete software. Second, our needs differ from those of the financial institutions and other commercial enterprises that form the bulk of the manufacturers' customers and for whom their software is designed. Third, we prefer to keep the software of all our computers similar, so that our users are not burdened with learning an unnecessarily complex variety of computer behaviors; however, software from different manufacturers is seldom similar. Finally, manufacturers' software seldom satisfies our security requirements. Therefore, we have had to develop most of our own software and have acquired a staff

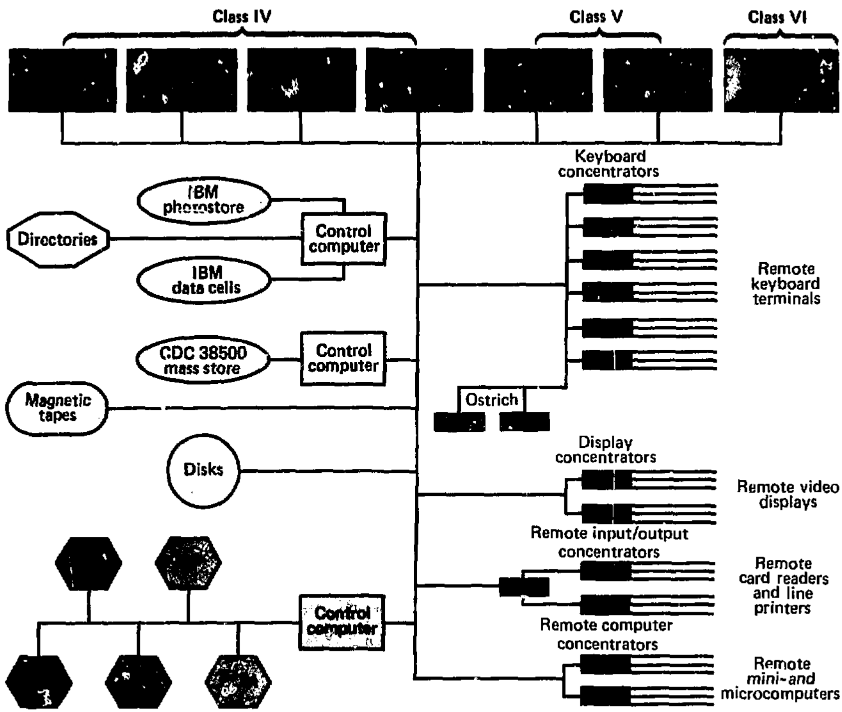

Fig. 1. The Octopus facilities are interconnected to form a single computing utility. In this simplified schematic representation, which includes equipment to be installed before 1980, each facility is color-coded to the service that it primarily supports. Red indicates processing—running simulations and other computer programs for the users. Yellow indicates storage—retaining information for a period of time. Blue indicates input/output—converting information between human-oriented and computer-oriented forms. The two major centralized devices here are the nonimpact printers (NIP) and computer-output-to-microfilm recorders (COM). Black indicates communication—transmitting information through the network. Most concentrators are DEC PDP-11's; the remote computer concentrators are SEL 32/75's. Ostrich verifies all users' combinations (that is, the secret word, known only to a user and Ostrich, that allows him to access Octopus).

of computer scientists to design and implement it. We also have a staff of engineers and technicians who design and build specialized hardware.

This staff of computing experts has enabled the Laboratory to be a leader, not only in scientific computer applications, but also in computer system design. To give our users the best possible service, useful new software concepts, whether invented here or elsewhere, are incorporated into our computers as quickly as possible, often years before they are generally available commercially.

Many of these advanced concepts are parts of one more encompassing idea, namely, that the Laboratory's computing resources shall constitute a *single* computing utility. This utility, called Octopus, delivers computational services directly into the users' offices, making computer access as convenient as turning on a light or placing a telephone call. Compared with public utilities, however, a computing utility like Octopus makes available to its customers—or users—a much greater variety of services. As shown in Fig. 1, services can be conveniently divided into four major categories: processing, storage, input/output, and communication.

PROCESSING

Processing is the transformation of data into a different, more useful form. In the case of the simulations carried out at the Laboratory, a description of the initial configuration of a physical entity or process is typically transformed, step by step, into a description of its later behavior and a summary of its characteristics. For example, a description of an explosive device at the moment of detonation is transformed into a history of the resulting explosion, including values, both total and as a function of time, for its various outputs (neutrons, electromagnetic radiation, etc.).

Processors can be classified in several ways. One is to divide them into micro-, mini-, midi-, and maxicomputers. These designations are relative, comparing computers in terms of their speed, storage capacity, and cost. Thus, today's maxicomputer is tomorrow's midicomputer, and so on. Over the years, computers have also been grouped into classes of increasing capability. These designations are fixed, with new classes being added as more advanced computers are developed.

The earliest major computers had only the capability of today's minicomputers and fall into class I. Class II is typified by the IBM 7094 and CDC 3600, which today would be regarded as midicomputers. Class III includes the CDC 6600. Today's maxicomputers include the class IV CDC 7600 and the class V CDC STAR-100. Octopus includes four 7600's and two STAR-100's (Fig. 2). Each of these can perform 3 to 10 million arithmetic operations in one second. Except for maintenance, they operate 24 hours a day, every day of the year. Yet they cannot carry out all the computations LLL scientists would like to do; future plans call for acquiring still more powerful computers as they become available. Our next acquisition will be a class VI computer with performance in the range of 20 to 60 million arithmetic operations per second. We are also planning for class VII computers in the early 1980's.

Beginning with class V, we find the introduction of vector capability—the rapid processing of many successive data elements upon the execution of a single instruction. This is contrasted with the scalar processing of earlier classes, which involves only one, two, or three data elements per instruction. We also find that successive classes exhibit a growing degree of parallelism, which allows several computational activities to take place simultaneously within a single computer (Fig. 3).

The users' programs on the six major Octopus computers are not limited to simulations. They include programs for preparing input for simulations and editing their results, for generating documents, for developing new computer programs, and for most of the other processing tasks, both scientific and nonscientific, required by our users. In addition to these maxicomputers, Octopus also includes numerous midi-, mini-, and microcomputers that carry out a variety of processing tasks in support of the maxicomputers and of the network's storage, input/output, and communication services. In fact, every computational service requires a processor to control it.

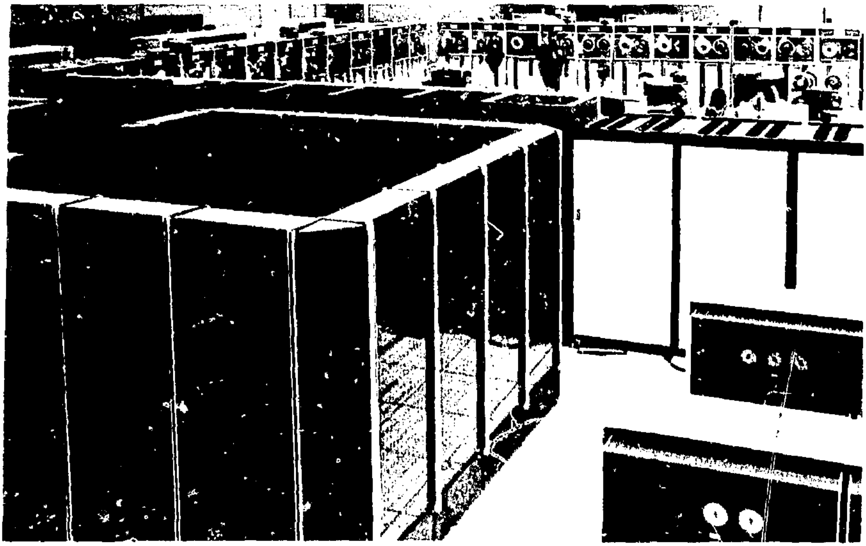

Fig 2. One of the four Octopus CDC 7600 computers with tape farm in the background.

STORAGE

Storage media retain information for a period of time so that it can be recalled on demand. Some storage devices—the main memories and magnetic disks of the various Octopus computers—directly support processing by holding initial, intermediate, and final values of computations in progress. Similarly, other storage devices directly support input output and communication services. However, there is a considerable need at LLL for permanent storage that can hold a user's information for days, months, or even years until he needs it again. This need reflects the fact that scientific research and development is a cumulative activity.

Storage devices are measured in terms of bits, the fundamental unit of information. A bit is what can be stored in an elementary hardware component that has two states, on and off. About 35 million bits are needed to store the Bible in a computer.

While some permanent information in Octopus is stored on magnetic disks and other devices with capacities of up to several billion bits, the bulk of it is stored on about 40 000 magnetic tapes and on two devices, each holding over one trillion bits: the IBM photodigital store (photostore) and the recently acquired CDC 38500 mass storage facility. Including shelved film that has been removed from the photostore, Octopus currently stores about ten trillion bits, or the equivalent of one-third of a million Bibles.

Future plans call for adding an automated facility to handle magnetic tapes, which must now be hand-carried back and forth between a storage vault and the computers. At the same time, we will begin converting to a new high-density tape that can hold about a billion bits per tape—ten times the capacity of our present tapes. Further plans are to acquire still more storage capacity in the form of a single device holding at least ten trillion bits; such devices are expected to become available in the early 1980's.

Permanently stored information is logically divided into units called files. Files vary in size from a

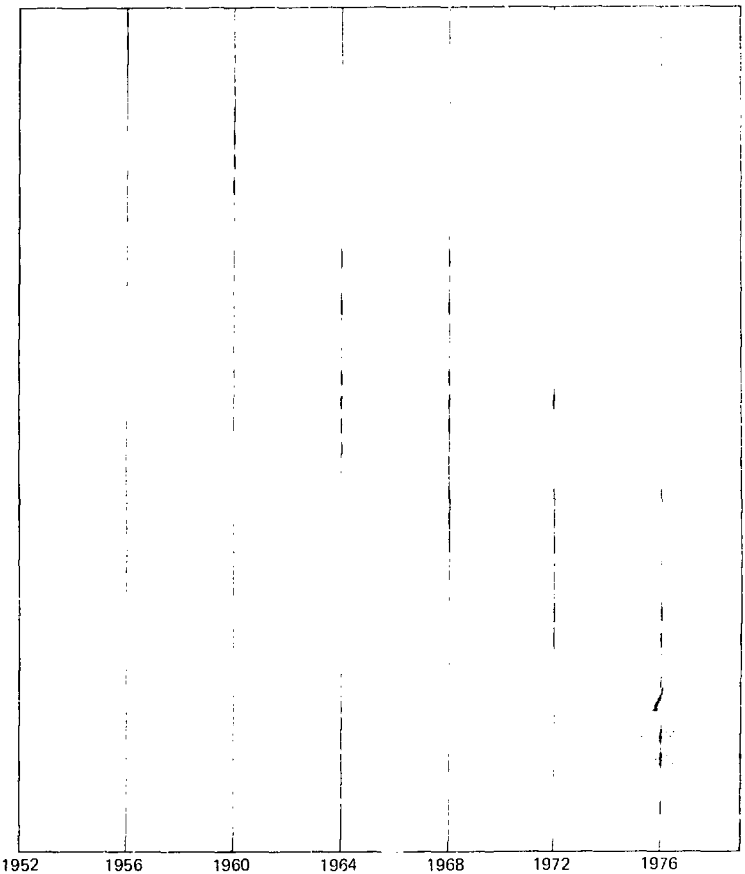

Fig. 3. History of large computers at LLL. *The color coding groups these computers by class:* I – blue, II – green, III – yellow, IV – orange, V – red. The last letter in a computer designation is its LLL symbol. If the power of these computers is compared with that of the class IV CDC 7600 (assigned a value of 1), then the power of the class I computers would be about 10^{-3}, class II would be 10^{-2}, class III would be 10^{-1}, and class V would be 2. *In general, the total power of large computers at LLL approximately doubled* every year through 1964 and has been doubling every four years since then. Of the large computers now at Livermore, all are incorporated into the Octopus network except for the CDC 6600 G, which is part of a separate unclassified network, and the CDC 7600 X, which is part of the National MFE Computer Center network (*operated by LLL*).

few bits to tens of millions of bits; the average at LLL is about two million bits. Each file belongs to a user or is shared by a number of users. Public files (usually program files) are shared by all users. A user refers to a file by its name.

The system used in Octopus for naming files stored on the large storage devices and for naming other permanent computing resources is based on directories, computerized records in the form of lists. Each entry in a directory list consists of two parts: a name and information that enables Octopus to uniquely identify and locate the resource denoted by that name. The user has no direct interest in the second part of an entry; all he needs to know is that giving the name enables Octopus to find the corresponding resource. (As used here, *resource* is defined as a body of information or an entity that can process, store, input/output, or communicate information.)

A directory is itself a resource. The names in one directory may refer to other directories. Each user, starting at a particular directory that Octopus knows belongs to him, called his root directory, may give a succession of names leading from directory to directory and culminating in the name of the desired resource. The structure of directories named in other directories can be as simple or complex as the user desires (Fig. 4).

Naming and locating resources through the use of directories has two important advantages. First, each user can categorize the files and other resources available to him in a way that he finds most convenient. For example, the names in his root directory might refer to other directories, each associated with a project on which he works. The names in one of these project directories may refer to directories associated with phases of the project. The names in a phase directory might refer to files used during that phase, or the sequence might continue, involving more directories.

The second advantage of directories is that users can share resources with as many or as few other users as they desire. Sharing occurs whenever a succession of names starting in one user's root direc-

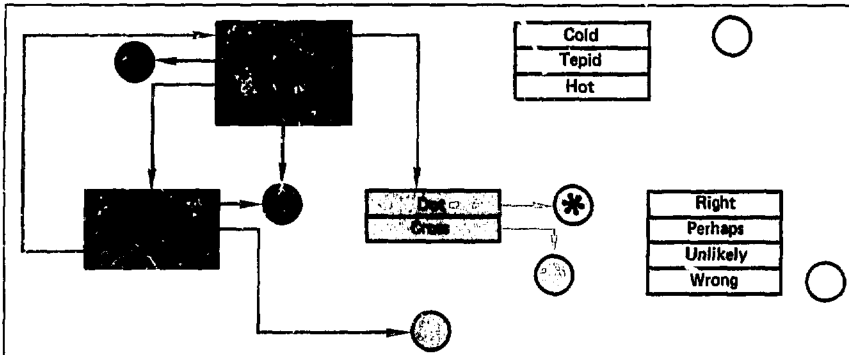

Fig. 4. The Octopus directory structure enables each user to organize his computing resources in a convenient manner and to share them with others to the extent that he wishes. In this schematic, a directory is represented as a rectangle divided into smaller rectangles representing entries. Each entry contains a name that refers to the resource pointed to by the arrow from that entry. Resources other than directories (that is, files) are represented as circles. The structure shown here is purely hypothetical. The top directories are the root directories of two users, color-coded here as blue and yellow. Green denotes their shared resources. Note that the same name may be repeated but not within a single directory, that a resource may have more than one name, and that closed loops may occur. (In a closed loop, a name starting in one directory eventually leads back to that directory. Here, for example, the sequence *Up Triangle* starting at the blue root directory refers to that same directory.) The resource marked with the asterisk is identified by the blue user with the sequence Right Dot, while the yellow user has two names for it, Hot Dot and Tepid Right.

tory locates the same resource as a succession of names starting in another's root directory. As shown in Fig. 4, users sharing a resource may give it different names.

The directory system is also a valuable tool for carrying out an important duty of the Octopus utility, namely, guaranteeing the privacy of its users' files and other resources. Each user is permitted to access only those resources, whether private or shared, located by a succession of names starting at his root directory. This requirement fulfills the need-to-know security requirement.

INPUT/OUTPUT

Input/output devices translate information between the human world and the computer world. Input is generally much less voluminous than output. In fact, whenever it appears that a computer program is going to require a large amount of input, a second program is often written to generate that input from a compact description. Therefore, input into Octopus tends to be conventional: punched cards, keyboards, devices that can point to a location on a video display, and magnetic tapes (for information carried to Octopus from non-Octopus computers).

For output, the Laboratory has two Honeywell nonimpact printers, each of which can print 18 000 lines per minute with 132 characters per line. Alternatively, they can print an equivalent number of pages of graphical output. We also have three Information International Inc. computer-output-to-microfilm recorders that can output on microfiche, 35-mm film, and 105-mm film. The total output to both paper and film is currently about 10 million pages per month. This huge volume, like the volume of data stored in Octopus, is a natural consequence of the huge volume of computer processing that is going on.

These high-capacity, centralized output devices are only part of our input/output capacity. Equally important are the lower capacity printers, card readers, paper tape devices, tape cassette devices, video displays, and keyboard terminals that are distributed around the Laboratory in or near the users' offices. It is these that help make Octopus into a true utility, bringing computing service to the user where he works.

Currently, the Laboratory has about 1300 teletypewriters and other keyboard terminals, many with paper tape or magnetic tape cassette devices, and about 1000 video display monitors. Most are in users' offices. We also have 30 to 40 card reader/line printer stations throughout the Laboratory.

Obviously, all output is not examined in detail. A large amount of it is kept as insurance, to be examined more closely only if the overall results require it. In general, a user will scan quickly through tens or even hundreds of pages of closely spaced columns of numbers that summarize the history of a physical process, looking for behavior patterns that characterize its interesting parts. When he finds them, he may then take note of a few of the tabulated values and discard or file the rest of the output. A great help in this process are presentation methods that are more compact and more readily grasped by the human mind.

Consequently, increasing emphasis is being placed on graphical and picture output instead of tables of numerical values, on color instead of black and white, on texture and shading instead of line drawings, on motion pictures instead of stills. All these techniques concentrate information so that it can be quickly assimilated, and they are all included in our plans for new output devices that print on both film and paper or that display on video monitors. Video displays are particularly valuable in that they provide a medium for immediately viewing the output from computations without waiting for the slower hardcopy devices.

COMMUNICATION

Octopus is a network: all its facilities are bound together with communication channels into a single web of computing resources. It is this interconnection that makes Octopus a utility and not just an unusually large concentration of computing power.

Interconnection brings several benefits. All the network's resources can be accessed and controlled from a terminal in the user's office, although each user can access only those resources to which he has a right. The resources of the network can also be used together in various ways, each becoming more useful because of the synergistic effects of interacting with other resources. Computational activities involving several devices, such as fetching data from storage, using it in a computation on a processor, and then outputting the results on a printer, become one, smoothly flowing process rather than a succession of steps punctuated by manual intervention. Finally, all the stored information forms one vast data base that can be readily shared as permitted.

Each facility in Octopus is not directly connected to every other facility; information communicated from one computer to another may have to move through a succession of intermediate computers. The communication channels between the facilities are varied. The channels presently connecting the large, centrally located facilities to one another move information at up to tens of millions of bits per second, but each channel connects only two facilities. We are also installing the Network Systems Corp. Hyperchannel, which will interconnect many facilities, with sophisticated hardware and software techniques smoothly interleaving transmissions between differing pairs of facilities as they contend for the shared channel. Channels between the central portion of the network and remote facilities in or near the users' offices include both simple pairs of wires and coaxial cables.

An important new development is starting to take place in regard to remote facilities. No longer do they consist solely of input/output devices such as keyboard terminals and printers. The rapidly falling cost of mini- and microcomputers and their associated peripheral gear now makes it economical to have processing and storage capability in some of the users' offices. This trend is a natural evolution of Octopus and is expected to continue. That is, some of the computing resources available to a user in his office are in fact located in his office. Others, because of their size and cost or because, as with stored data, of the benefits of sharing, are available from the central part of the network over communication channels. The network also provides a means for the computers in users' offices to communicate with one another.

Interfaces to Octopus especially tailored for remote minicomputers are now being developed to supplement those tailored to input/output terminals. When they are in place, we expect that a majority of the Laboratory's minicomputers, which now number about 250, will become attached to the network. A few dozen are already connected and perform a wide variety of functions. Some, for example, transmit experimental digital data directly to the Octopus network without intermediate input/output devices. Others monitor the progress of long simulations and regulate allocation of computer time within a group.

NETWORK CAPABILITY

The kind of computing activity that Octopus makes available to its users may be illustrated by the following account of a fictional but not atypical user.

An applications programmer has just received a telephoned complaint that the STRAIN code (computer program) for calculating the distortion of stressed mechanical parts is giving unreasonable answers to certain problems. The programmer, who is responsible for maintaining STRAIN, is asked to fix the bug (error) in the code. The caller states that he has given the programmer a file called TESTDATA containing a set of input parameters for one of the problems giving difficulty. As soon as he hangs up, the programmer begins typing at his keyboard terminal. His first entry is an identification line that indicates which major computer is to be used and identifies the programmer to the system. It includes a combination, a secret word known only to the programmer and to Ostrich, a special computer in Octopus that verifies combinations. The combination is checked by Ostrich and found to be correct; Octopus is then certain with whom it is dealing, and therefore permits the programmer to access his root directory.

Our programmer asks that the file TESTDATA be copied from the photostore to the computer he is using. The full name that he gives for the file includes the name of a special directory in which are listed all computing resources given to him by others. The file containing the STRAIN code is also fetched from photostore.

The programmer then executes STRAIN with TESTDATA as input. He asks that the output file be displayed in graphical form on the video screen in front of him. The caller was right: the distortion of the displayed shape for the part is counter to the direction of the applied stress. The programmer invokes an editing program and uses it to modify some of the data in TESTDATA, runs STRAIN using the modified input, and examines the results on his video display. He does this several times. Within a few minutes, he has seen enough examples of the aberrant behavior of STRAIN that he can speculate where the trouble is in the program.

He now uses another editing program, one designed not for examining data files but specifically suited to programs written in the FORTRAN language used to write STRAIN. He commands the editor to display the program listing of one of STRAIN's subroutines. The subroutine is several pages long, and he must ask for a few of them in succession before he sees the one he wants. Shortly he sees that the minus sign has been omitted from a parameter that is used only when the stressed part is asymmetrical. Apparently computations involving such unusual parts have never been done before and were overlooked when the code was tested.

The programmer corrects the bug using the editor and then calls on the FORTRAN compiler (language processor) to generate a new version of STRAIN. He executes the new code with TESTDATA as input and views the result, which is now properly shaped. After he runs several more test cases, the new code (both the source version written in FORTRAN and the executable version generated by the compiler) are sent to the photostore. The executable version replaces the faulty previous version as a public file. The new STRAIN listing is sent to a printer located down the hall from the programmer; he will pick it up the next time he goes out. He types a BYE line to terminate his session with Octopus and telephones to tell the person who made the complaint that the bug is fixed. About an hour has passed.

Although this example is fictional, it illustrates a basic truth: the interactive computing possible with a computer utility like Octopus greatly reduces the turnaround time (the time between the submission of a problem and the return of the result) for many computing activities. This creates the possibility of quickly shifting between computing and thinking, so that there is a man–machine symbiosis that is much more productive than if they must act separately.

Key Words: computers; multiple access computer system; Octopus; Octopus system—design; time-sharing.

Magnitude Corrections for Attenuation in the Upper Mantle

Since 1969, a consistent discrepancy in seismic magnitudes of nuclear detonations at NTS compared with magnitudes of detonations elsewhere in the world has been observed. This discrepancy can be explained in terms of a relatively high seismic attenuation for compressional waves in the upper mantle beneath the NTS and in certain other locations. We have developed a correction for this attenuation based on a relationship between the velocity of compressional waves at the top of the earth's mantle (just beneath the Mohorovičić discontinuity) and the seismic attenuation further down in the upper mantle. Our new definition of body-wave magnitude includes corrections for attenuation in the upper mantle at both ends of the teleseismic body-wave path. These corrections bring the NTS observations into line with measurements of foreign events, and they enable us to make more reliable estimates of yields of underground nuclear explosions, wherever the explosion occurs.

Under the Threshold Test Ban Treaty (TTBT), both the U.S. and the U.S.S.R. agree to limit the yields of their underground nuclear tests to 150 kt (630 TJ). They also agreed to use "national technical means" for verifying each other's compliance. In practice, this means relying on seismic measurements for our yield estimates.

Seismic monitoring for the TTBT includes detection, location and identification of seismic events, and (for events identified as explosions) yield estimation. One method for distinguishing explosions from other seismic events is the m_b:M_s discriminant (see box on page 11). This discriminant is based on the observation that, for a given value of the surface-wave magnitude, M_s, the value of the body-wave magnitude, m_b, is generally one or two units greater for explosions than it is for earthquakes.

In analyzing m_b:M_s plots, seismologists first noted in 1969 that the m_b:M_s data for explosions in the Western United States are anomalous with respect to data for the Aleutians and the U.S.S.R.[1] The anomaly, which has been frequently confirmed, could be ascribed to unusually high M_s values, unusually low m_b values, or a combination of the two effects.

An illustration of this anomaly appears in Fig. 1. This chart presents the correlation between M_s and m_b for 28 U.S. events, 26 of which were at NTS, and 28 Soviet events, 22 of which were at the principal test sites in Kazakhstan (20) and Novaya Zemlya (2). The data fall clearly into two groups with widely diverging slopes.

One proposed explanation for the anomaly is that the release of tectonic strain (strain caused by distortions in the earth's crust) accompanying the explosions at NTS produces the enhanced M_s values. The available evidence does not support this explanation, since tectonic strain release alone is insufficient to account for the anomalous m_b:M_s relation.[2]

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SEISMIC MAGNITUDE DETERMINATION

Seismic magnitude is an empirical measure of the strength of a seismic event, either an earthquake or an explosion. It is defined by an equation of the form

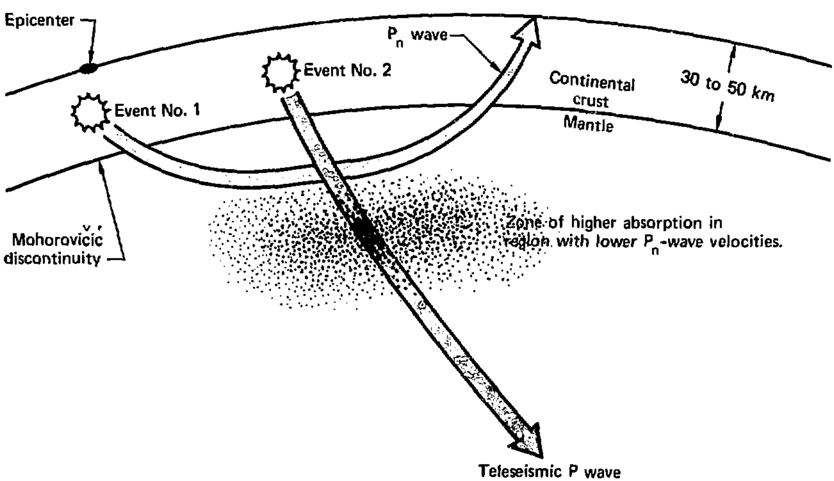
$$m = a + \log_{10}(A/T) + B(\Delta) ,$$

where m = magnitude, a = empirical constant, A = signal amplitude, T = signal period, and B = empirical function of Δ, the epicentral distance between source and receiver.

Two types of waves are of major importance in teleseismic (more than 2 000-km) monitoring of explosions and earthquakes: the P or body wave, a compressional wave that travels through the body of the earth, and the Rayleigh wave, a wave that propagates along the surface of the earth. We determine the body-wave magnitude, m_b, by measuring the amplitude of the P wave, and the surface-wave magnitude, M_s, by measuring the amplitude of the Rayleigh wave. The m_b:M_s discriminant, used to distinguish between explosions and natural earthquakes, is the relation between these two magnitudes.

In correcting magnitudes for attenuation in the upper mantle, we distinguish two types of P waves. One is the P_n wave that is generated by shallow events in the crust and is refracted just below the Mohorovičić discontinuity between the crust and the mantle. We have discovered that the velocity of this wave appears to be an indicator of the seismic absorption conditions at greater depths in the upper mantle, and we can use it in estimating attenuation coefficients for subsequent events in the same region.

The teleseismic P wave, on the other hand, penetrates hundreds of kilometres into the mantle before it is refracted back up to the surface thousands of kilometres from the source. The attenuation deeper in the mantle is much less than that in the upper mantle near the Mohorovičić discontinuity. Hence, a teleseismic P wave is subjected to the greatest attenuation only as it propagates through the shallow portions of the mantle.



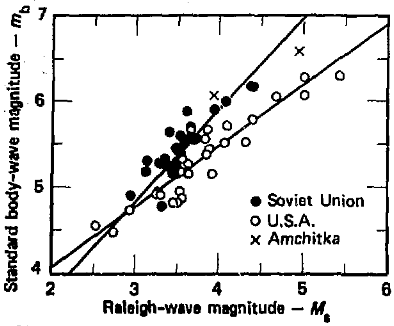


Fig. 1. A plot of surface-wave magnitude, M_s, vs the conventionally defined body-wave magnitude, m_b, for 56 different explosions, equally divided between U.S. and Soviet shots (of which 26 were at NTS, 20 at the Soviet proving ground at Kazakhstan, and 2 at Novaya Zemlya in the Arctic Ocean). The data clearly fall into two categories, with the NTS explosions in one group and the Soviet explosions in another. Anomalous attenuation of the body waves in the upper mantle beneath NTS appears to account for most of the difference between the two sets of data.

Another explanation, for which considerable seismic evidence exists,[3] is that there is unusually high body-wave attenuation in the upper mantle beneath the Western United States, depressing the m_b values for NTS explosions. If we assume that this is the case, we can formulate correction factors that compensate for the attenuation, bringing the NTS data into line with data from the rest of the world.[4] In this article we examine the evidence for this explanation, develop a body-wave magnitude definition that corrects for regional variations in attenuation, and apply this correction to seismic data for a worldwide set of explosions.

EVIDENCE FOR REGIONAL VARIATIONS OF ATTENUATION IN THE UPPER MANTLE

Many studies of the amplitudes and frequencies of body waves have detected anomalously high seismic-wave absorption in the upper mantle in the Western United States.[5] These studies consistently report higher attenuation in the Western United States than in the Eastern, sometimes by a factor of three. There also appears to be a correlation between the unusual attenuation and observed patterns of P- and S-wave slowing (late arrival times), upper-mantle electrical conductivity, and heat flow.[6]

Regional variations in upper-mantle absorption are also found elsewhere, as in the Baikal Rift region and the transitional zone between Asia and the Pacific Ocean. Like the Western United States, these two regions have a thin crust, high heat flow, high electrical conductivity, low density, and low seismic velocities in the upper mantle.

We explored the interrelations among some of these parameters and found a useful empirical relation between seismic velocity and seismic attenuation. This is illustrated in Fig. 2, a composite plot that presents curves of body-wave-magnitude residuals (the deviations of specific body-wave magnitude measurements from the average) and of average attenuation factors versus P_n-wave velocity and P-wave velocity, respectively. Note that there is a sudden change in each of these curves at a velocity of 8.1 km/s. Thus, although the reasons for the correlation between P_n-wave and P-wave velocities and body-wave attenuation are unknown (in the sense that we are unable to calculate the effect from first principles), we have strong evidence that such a correlation does exist, that there are regional variations in body-wave attenuation, and that we can use the measurable variations in P_n-wave velocity to estimate the rate of attenuation.

CORRECTION METHOD

Our first step in applying this new correction technique was to formulate a new definition of body-wave magnitude, designated m_Q to distinguish it from the standard body-wave magnitude, m_b. The corrected body-wave magnitude is defined by the equation

$$m_Q = m_b + RC + SC + DC .$$

In this expression RC is the correction for attenuation in the upper mantle at the receiver end of the wave path, SC is the similar correction for attenuation near the source of the disturbance, and

DC is the correction for the depth of the source. Separating the correction into parts serves to emphasize that the values of the correction terms are different in different parts of the world and for different depths of the source. The attenuation is also greatest in the upper mantle and negligible over most of the deep portion of the wave path—hence the separate corrections at the source and receiver ends of the path.

Ideally, the basic datum needed for calculating each of these correction terms is the value of the specific dissipation factor, Q_α, at every point in the wave path. This ideal is unattainable; in fact even average dissipation factors, $\overline{Q}_\alpha$, are unavailable for much of the world. Our new correlation between P_n-wave velocity and upper-mantle attenuation enabled us to estimate $\overline{Q}_\alpha$ for many additional regions. We limited our data set to recordings of events for which we could estimate $\overline{Q}_\alpha$ at both the source and the receiver ends of the path.

To derive profiles of Q_α vs depth, we used various published profiles of P-wave velocity vs depth for different parts of the world and for the world average, together with the curve in Fig. 2. Step-by-step calculations of the attenuation down to 700 km into the mantle produced values for $\overline{Q}_\alpha$ of 800 for shield and stable-platform areas (most of the continental areas including the Eastern United States) and of 275 for the Basin and Range Province where NTS is located. (Note that a larger value of Q_α corresponds to a lower attenuation. Q_α for a nonattenuating material would be infinite.) These values of $\overline{Q}_\alpha$ enabled us to compute correction factors for every source-receiver pair, yielding new body-wave magnitudes, m_Q.

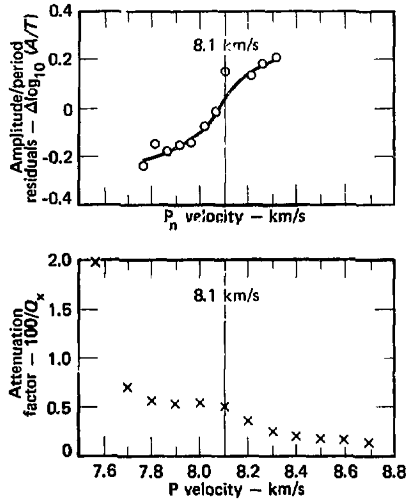


Fig. 2. A composite plot combining data on body-wave magnitude residuals (individual variations from the average of a number of separate measures) vs P_n-wave velocity, and the specific dissipation factor (a measure of attenuation) for P waves, Q_α, plotted vs local P-wave velocity. The two sets of data are from separate measurements, yet they both show a break at a velocity of 8.1 km/s. This is strong evidence for a real connection between P-wave velocity and Q_α.

APPLICATIONS OF m_Q

The main applications of our new definition of body-wave magnitude are to remove a regional bias in standard magnitude measurements of distant seismic events and to improve our yield estimates of distant nuclear events. To this end we have analyzed the seismic records for a worldwide set of 46 nuclear and 2 large chemical explosions and determined m_b and m_Q values for each of them. We have also determined M_s values for 43 of the 46 nuclear explosions. Of these 48 explosions, 38 were detonated by the United States (32 of them in the Western United States), 7 by the U.S.S.R. (including the 2 chemical explosions), 2 by France, and 1 by India.

The yields, depths of burial, and other data have been published for the 38 U.S. explosions and can be inferred from published data for the other events. Figure 3 is a plot of this data (omitting four Yucca Valley events) in terms of the relation between m_Q and yield. As may be seen, the data points fall fairly close to a single line determined by regression analysis (least-squares fitting).

Figure 4 is a plot of m_Q vs M_s for the same set of 56 explosions plotted in Fig. 1. Using the corrected body-wave magnitude in place of the standard m_b merges the two divergent groups of data points almost into one.

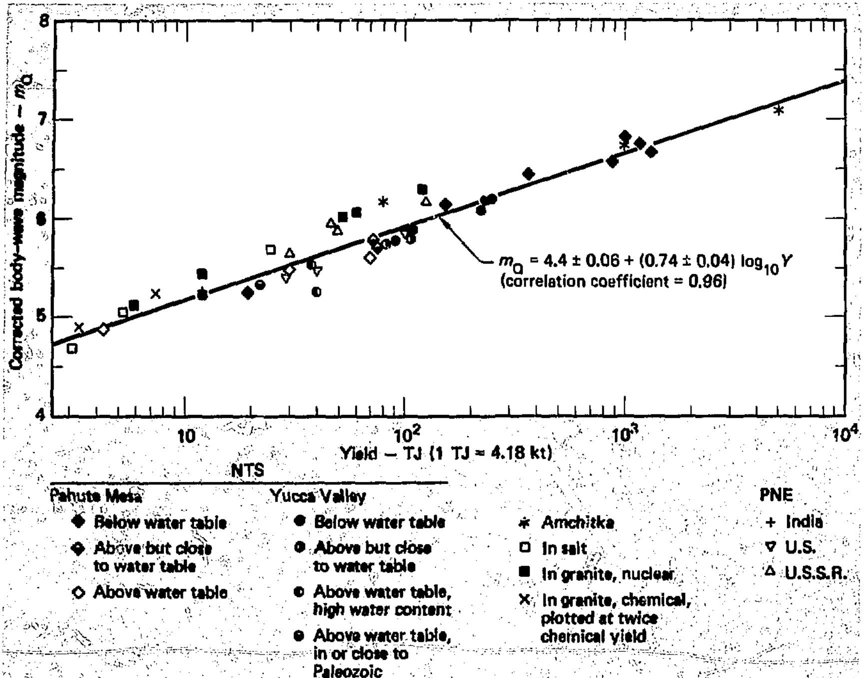


Fig. 3. A plot of corrected body-wave magnitude, m_Q, vs yield for 44 nuclear events, 25 of them detonated at NTS, 9 others elsewhere in the United States, 7 by the U.S.S.R., 2 by France, and 1 by India. A single least-squares-fitted line adequately represents the data.

SUMMARY AND CONCLUSIONS

The m_b:M_s relation, commonly used for distinguishing between explosive events and earthquakes, is anomalous for explosions in the Western United States compared with the relation for explosions in other testing areas of the world. There is considerable evidence that relatively high body-wave attenuation in the upper mantle beneath the Western United States is a principal cause of the different m_b:M_s relation for NTS explosions.

We have detected a strong correlation between seismic absorption in the upper mantle and the velocity of P_n waves just below the Mohorovičić discontinuity. We have developed an empirical method of body-wave magnitude correction that includes corrections for attenuation at the receiver and at the source, plus a source-depth correction to account for interference effects in the P-wave arrival. We designate the resulting corrected body-wave magnitude m_Q, to distinguish it from previous definitions of body-wave magnitude, m_b.

We have determined m_Q values for a worldwide set of large explosions for which yield data are available. We found that a single m_Q:yield relation is a fair fit to the data for all explosions with high seismic coupling, but that two m_Q:yield relations are a

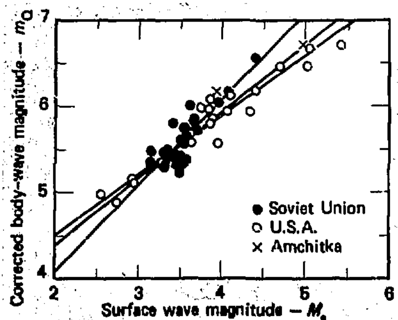


Fig. 4. A plot of corrected body-wave magnitude, m_Q (as distinguished from m_b), vs surface-wave magnitude, M_s, for the same 56 events plotted in Fig. 1. The two formerly divergent groups of data points are now merged and nearly indistinguishable.

better fit to the data. The differences in the two sets of explosions appear to have more to do with coupling than with attenuation in the upper mantle.

Finally, we found that the explosions in our data set, including those at NTS, have a common m_Q:M_s relation with explosions in other parts of the world. We also reexamined previously published studies that showed anomalous m_b:M_s relations for NTS explosions compared to explosions on Amchitka and in the U.S.S.R. and showed that they too have a common m_Q:M_s relation. These observations suggest the possibility of a universal magnitude, useful in the analysis of explosions and earthquakes anywhere in the world.

Key Words: compressional (P) waves; Rayleigh waves; seismic detection and measurement; seismic waves—propagation.

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RTNS: A Tool for Studying Neutron Damage

The high fluxes of 14-MeV neutrons produced by fusion reactors cause materials damage problems that affect reactor feasibility, economics, and safety. Although a body of neutron damage data has been developed in the fission reactor program, we need still more information to guide materials selection for the first demonstration fusion reactor.

We have been studying damage processes induced by 14-MeV neutrons for approximately four years at LLL's RTNS-I (Rotating Target Neutron Source). The RTNS-I is the most intense 14-MeV neutron source in the world, producing 6×10^{12} 14-MeV neutrons per second. By extrapolating the technology of this source, we have designed a facility with two new neutron sources (RTNS-II) to produce 4×10^{13} neutrons per second. Construction of these sources and the research facility that houses them is nearing completion. The new facility will be operated by LLL as a national center for fusion reactor materials research.

The successes obtained with magnetic confinement of plasmas in tokamak devices, first in the Soviet Union and then in the United States, led in the early 1970's to the decision to accelerate the U.S. program to produce fusion power reactors. The resulting effort was structured into two subprograms: one to address the remaining physics uncertainties of plasma confinement and the other to address the engineering feasibility of fusion reactors. Of the engineering problems associated with fusion reactors, one of the most difficult to study without having a working fusion test reactor is the damage produced by the 14-MeV neutrons from the T(d,n) reaction.

In any of the currently proposed magnetic or inertial confinement fusion reactors, the flux of 14-MeV neutrons at the inner wall of the reactor will be about 10^{14} n/cm^2·s. Although this flux is over an order of magnitude below that typical in fission power reactors (1 to 3×10^{15} n/cm^2·s), the average energy of fission neutrons is so much lower (below 1 MeV even for fast breeder reactors) that the damage processes may be significantly different. This difference in energy prevents us from extrapolating confidently from fission reactor experience.

Neutrons damage reactor materials in several ways. Energetic atoms recoiling from collisions with neutrons produce cascades of vacancies and interstitial atoms in the material lattice. Helium and hydrogen are produced when neutrons interact with atoms of the material through (n,α) and (n,p) reactions. Vacancies may aggregate into voids, gas bubbles may form and grow, and interstitial migration may change alloy microstructure. These processes result in changes in the physical and electrical properties of materials. Materials such as superconductors may fail, or the strength of structural or radiological-containment components may be reduced below an acceptable level. Near the surface of the material, energetic recoil atoms may escape

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completely (sputtering) or the lids of gas bubbles may break off (exfoliation). Release of such material into a plasma could cool it and quench the thermonuclear burn. Gross modification of surface features causing increased gas absorption or release, insulator failure, or damage to the final optics of lasers could have similarly unacceptable results.

LLL's involvement with intense 14-MeV sources began in 1966 with the installation of the ICT (Insulating Core Transformer) accelerator (Fig. 1). As originally installed, this 400-keV air-insulated machine could produce an 8-mA beam of atomic deuterons (D^+). By bombarding a target of tritium absorbed in titanium, we could produce a 14-MeV

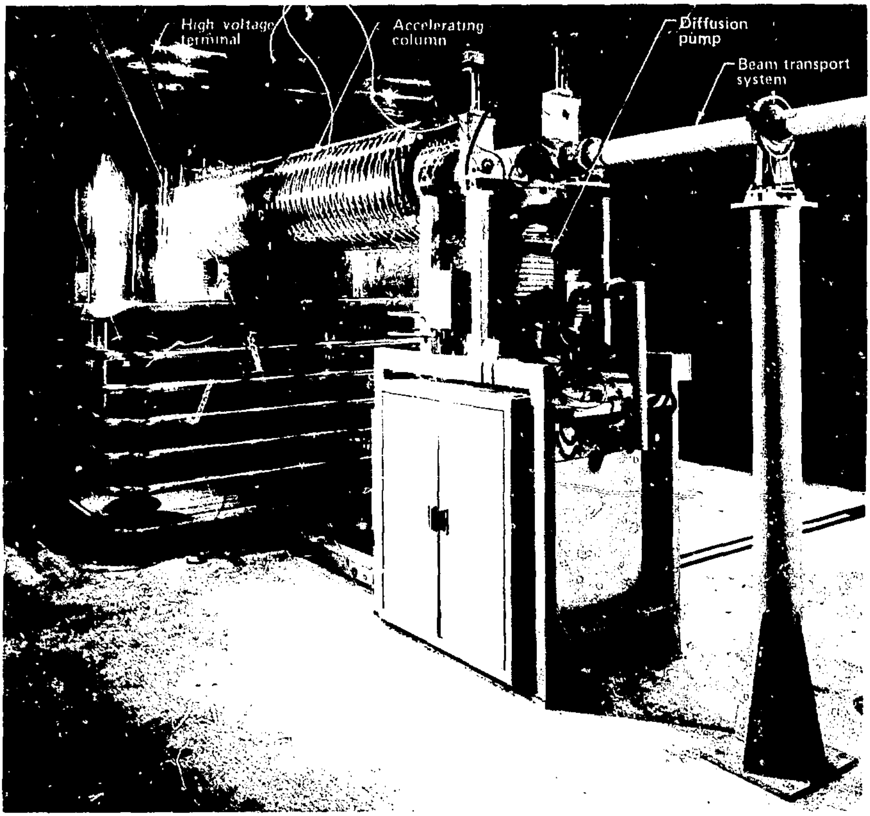

Fig. 1. Deuteron accelerator for the RTNS-I source. The large aluminum high-voltage terminal on the left contains the deuteron ion source and the power supplies that drive it. In operation, this machine accelerates a 400-keV deuteron beam through an accelerating column that is surrounded by cylindrical rings to produce a smooth electrostatic surface. The 400-keV deuteron beam then passes from the diffusion pump stand at the center of the picture through the evacuated-beam transport system out to the right to the target room in which the rotating tritium target is placed.

Table 1. Livermore neutron source parameters.

	RTNS-I 1976	RTNS-II 1978
Beam energy, keV	400	400
Target current, mA	25	150
Spot size, mm	6	10
Target diameter, cm	23	50
Target speed, rpm	1100	5000
Source strength, n/s	6×10^{12}	4×10^{13}
Maximum flux, $n/cm^2 \cdot s$	1.7×10^{12}	1.0×10^{13}
Target lifetime, hr	100	100

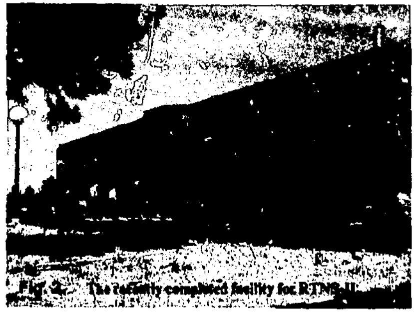

Fig. 2. The recently completed facility for RTNS-II.

neutron source strength of 2×10^{12} n/s. To prevent the power deposited in the target from raising the temperature to such an extent that excessive tritium is released, we rotate the target at 1100 rpm with its back surface in water. Although this source was developed primarily for weapons-related neutronics work, interest in fusion materials damage problems led to its upgrading in the early 1970's. By 1974, a source strength of 6×10^{12} n/s was produced with a peak flux of 1.7×10^{12} $n/cm^2 \cdot s$ available.

Using the RTNS-I source, experimenters from LLL and other laboratories measured sputtering coefficients, hardening of metals (measured by change in yield strength of sample), and change of critical current in superconductors resulting from 14-MeV neutron irradiation. The results of these measurements indicate that damage processes that depend on total defect production scale about as expected with neutron energy. Damage processes dependent on the type and distribution of clustered defects do not scale as expected. Change in lattice parameters, detailed microstructure, yield strength, superconducting properties, and optical absorption do not scale with damage energy deposited. Although these experiments were hampered by the low flux available (maximum fluence to date in an experiment has been about 2×10^{17} n/cm^2), their results demonstrated that simple extrapolation of fission reactor experience is inadequate for fusion reactor design decisions.

To provide for fusion neutron irradiations and to overcome the flux limitations of the RTNS-I source, in 1973 LLL proposed the construction of a new neutron source facility containing two improved sources based upon the rotating target technique. Design source strength was projected at 4×10^{13} n/s with a peak flux of 1.0×10^{13} $n/cm^2 \cdot s$. LLL proposed to operate this facility, called the RTNS-II facility, as a national center for fusion reactor materials research under the auspices of the Office of Fusion Energy.

The main parameters of the RTNS-II neutron sources are compared to those of the RTNS-I source in Table 1. The estimated cost of construction of the new facility and the neutron sources is $5 million. This funding was provided as a line item in the FY 1976 federal budget. Design of the facility began in March of 1976; procurement began in May of that year and construction started in August. We estimate that the project will be completed in July of 1978.

RTNS-II FACILITY

Physical Plant. The physical plant for the RTNS-II Facility serves two functions: to contain the primary and secondary radiation resulting from operation of the neutron sources and to provide control and support areas for work on both unirradiated and irradiated components of the sources and experimental apparatus. The facility is shown in Fig. 2. The primary radiation from the neutron sources will be contained by concrete walls 2.5 m thick around the target rooms in which neutrons are produced. (The door to one of the target rooms is shown in Fig. 3.) Access to the accelerators, target rooms, and hot work areas of the facility is limited and controlled by the source operators.

To minimize the dangers of handling irradiated equipment, we provide a hot cell and hot work room for servicing and storing these activated materials. Activated apparatus is moved from the target rooms to the hot cell by a remote handling system able to place a 3-Mg package with 0.5-cm accuracy. Because the tritium targets outgas approximately 370 GBq (10 Ci) of tritium per hour during normal operation, the exhaust of all vacuum systems on the accelerators must be collected and passed through a tritium scrubber. This scrubber converts all hydrogen isotopes to water and traps the water for safe disposal.

Accelerators. The major components in one accelerator and target room are shown in Fig. 4. A large high-voltage terminal contains the deuteron ion source plus the power supplies and vacuum pumps required to operate this source. The high-voltage terminal is raised to 400 kV by a 300-mA Cockcroft-Walton high-voltage supply. Power to operate the ion source and all the electronic components in the high-voltage terminal is provided by a 75-kW isolation transformer that feeds three-phase power from ground into the terminal. The ion source selected for these accelerators is a modification of the reflex arc MATS-III source developed at Livermore as an injector for magnetic confinement experiments. A 90° double focusing magnet is used following the source to separate the D^+ beam from the molecular beam components (D_2^+, D_3^+) that are also produced by the source. This arrangement allows the accelerating column and the beam transport system for the accelerator to be optimized for a

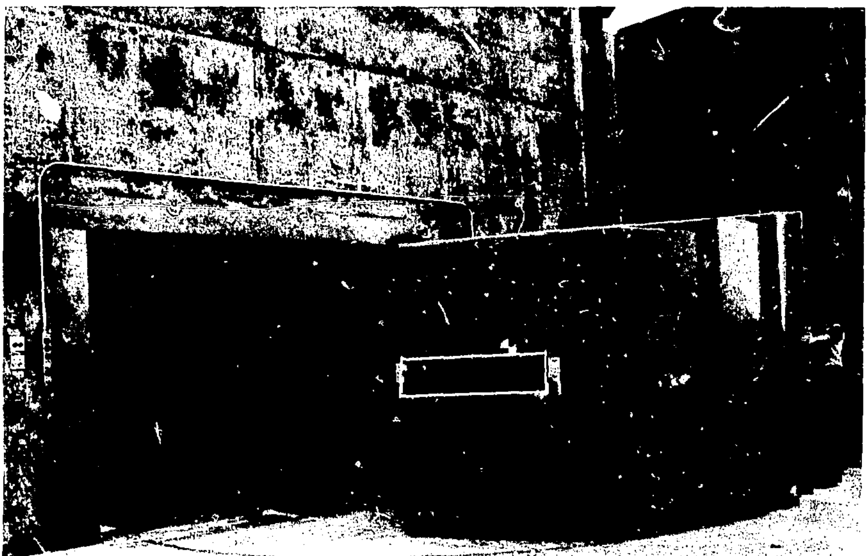

Fig. 3. Shielding door to one of the target rooms in the RTNS-II facility. The door is about 2.5 m thick, 3.5 m wide at the outside, and 2 m wide on the inside face. This door swings on hinges and weighs approximately 44 Mg. When in use, experimental equipment and target assemblies for the RTNS-II sources will be moved from a hot work area through this door into the target room for irradiation under remote control. During this process, the door will be operated from a remote location.

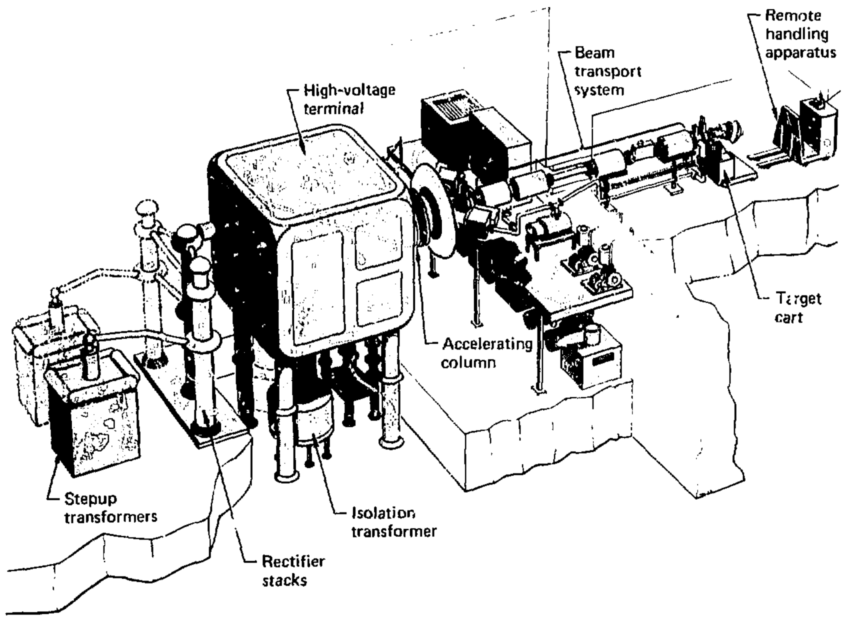

Fig. 4. Major components of a single neutron source in the RTNS-II facility. On the left (in the machine room housing the accelerator) are the stepup transformers and rectifier stacks, the high-voltage terminal containing the deuteron ion source for the accelerator, and the accelerating column and beam transport system. In the cutaway room at the right of the figure are located the rest of the beam transport system, the rotating target, and the cart on which the experimental package is placed. Shown at the extreme right is the remote transport system that moves experimental and target packages to and from the target room. Components shown in dashed lines can be added to upgrade the high-voltage supply to 500 mA rating.

single ion species.

A cutaway view of the high-voltage terminal (Fig. 5) shows the ion source and the accelerating column through which the ion beam passes as it moves from the 400-keV terminal to ground. The vacuum envelope of the acceleration column was fabricated at LLL by vacuum-brazing alumina insulating rings to copper electrodes. The active length of the column (the region through which the beam actually accelerates) is shorter than the outside length of the envelope (25 cm vs 80 cm). Intermediate electrodes of copper coated with chrome are used to connect the outer copper electrodes (to which the resistor string is connected) to the inner molybdenum electrodes that shape the field in which the deuterons are accelerated.

A major design problem in the construction of the RTNS-II neutron sources is to minimize the possible consequences of the ion beam from the accelerator being misdirected onto a component of the accelerator. Since the power density of this beam is 75 kW/cm^{-2}, the beam will melt any material on which it is directed except for the rotating target. Our solution to the problem is to design the acceleration column and beam transport system to deliver to the target virtually all of the ion beam in-

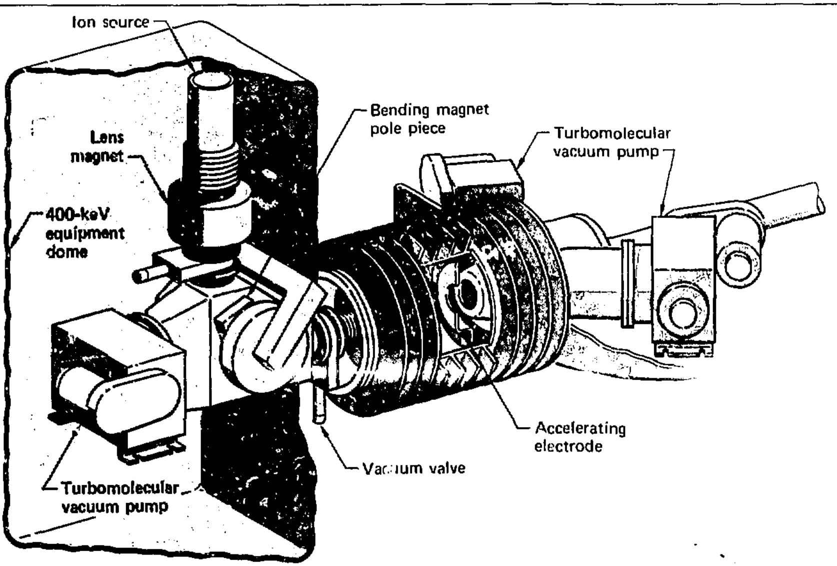

Fig. 5. Major components of the ion source and acceleration tube of the RTNS-II sources. The ion source is mounted vertically to allow installation of a 90° bending magnet that separates unwanted molecular components of the beam from the atomic components. After this separation the deuteron beam accelerates from the extraction voltage (15 keV) to the full 400-keV energy by passing through the accelerating column of the machine. The large gas load from this ion source (approximately 10 to 20 cm^3/min at standard temperature and pressure) is removed from the vacuum system by three turbomolecular pumps—each with a capacity to pump 2000 litres of air per second.

jected into the accelerating column. Limiting apertures of pyrolytic graphite are used at places in the beam transport system where the ion beam is diffuse. These apertures can stand power deposition of a few kW/cm^2 and are thus useful to limit the outer edge of the ion beam. Diagnostic devices that determine the beam current and beam position without interacting with the beam have been developed. Beam current is monitored by measuring the dc magnetic field produced by the beam. Beam position is determined by viewing the recombination radiation produced when the beam ionizes residual gas in the beam transport system.

To test the design of the many accelerator subsystems, we conducted a full-scale test with one accelerator (Fig. 6). Because the test enclosure does not have neutron shielding, the beam accelerated must be H_2^+ rather than D^+ (For purposes of testing the accelerator, these two beams are equivalent.) Tests of all accelerator systems to date have been successful. Ion beams of up to 50 mA have been produced at energies up to 250 keV. Noninteractive beam-monitoring devices have been tested successfully, as has the design of the ion source acceleration column and beam transport system. Tests using a deuterium-loaded rotating target are to begin shortly.

Target System. Although we are investigating materials with better hydriding and thermal properties, the initial neutron source for the RTNS-II will be the tritium-in-titanium material used on RTNS-I. To ensure that this material operates in

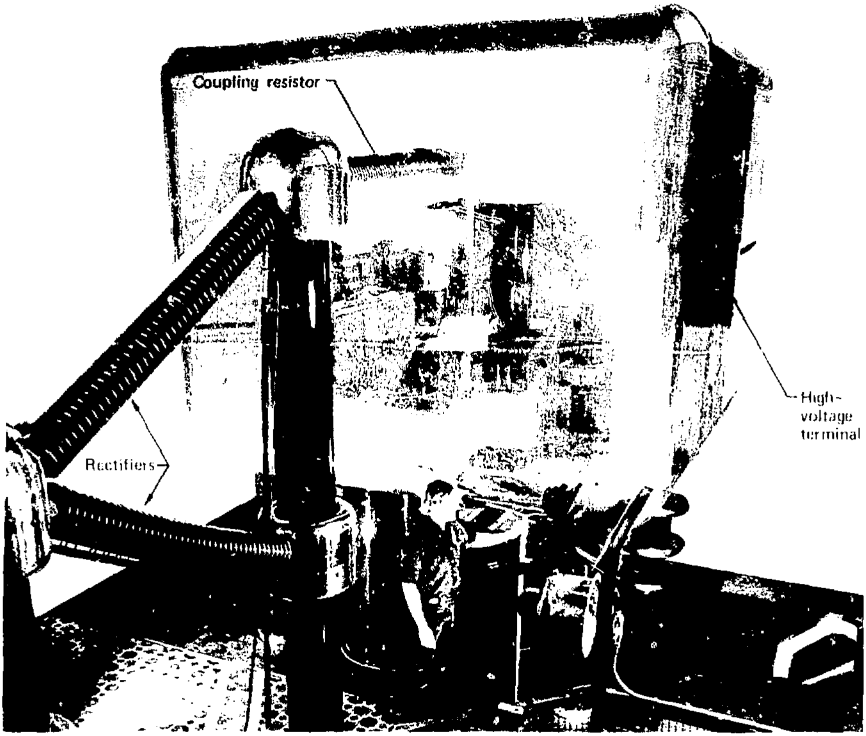

Fig. 6. High-voltage terminal and power supplies of the prototype accelerator. To the left are the insulating legs, capacitors, and rectifier stacks that comprise the Cockcroft-Walton power supply. This power supply is connected to the skin of the high-voltage terminal by a high-power 10 000-Ω resistor, which decouples the terminal from the power supply during sparks. The acceleration column and beam transport system (not shown) for this prototype accelerator are located behind the high-voltage terminal at the back of the enclosure.

the same thermal cycle on RTNS-II, we have modeled the thermally driven process of tritium dissociation and diffusion in the target. Time-dependent temperature profiles of the energy deposition in the target were calculated using the power density of the beam, the dwell time of the beam on the target element, and the thermal conductivity of both target material and backing. Using these profiles, we calculated the dissociation of titanium tritide and the diffusion of tritium through the target to its front surface. To normalize this calculation to the target lifetimes observed on RTNS-I, we added to the calculation a measured surface barrier to tritium release. The condition under which the target must be operated on RTNS-II was determined by adjusting the speed of the beam past each target element until the tritium release over each thermal cycle was the same as that calculated for RTNS-I. To accommodate the increase in power density from 30 kW cm^{-2} on RTNS-I to the planned 75 kW cm^{-2} on RTNS-II, we had to increase the target speed from 1100 cm/s to 10 000 cm/s.

This tenfold increase in target speed was accomplished in two steps. The first was to increase the speed of target rotation from 1100 rpm to 5000 rpm

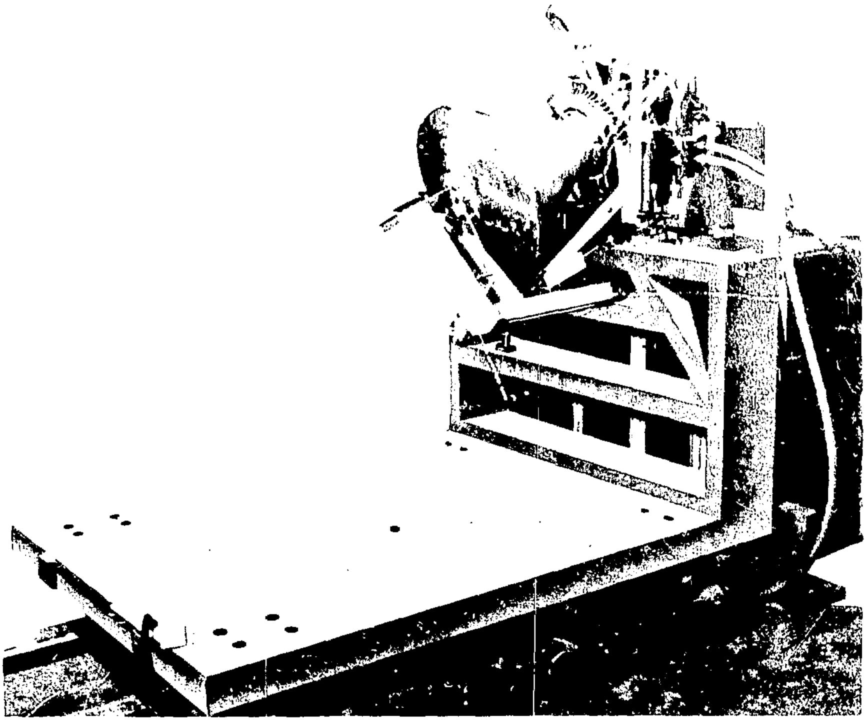

Fig. 7. **Prototype of the 50-cm, 5000-rpm target system. The test target is mounted on the cart that will be used to carry the target system and experimental apparatus to and from the target room. During irradiation the target assembly is aligned to within 1 mm of the target surface, which is moving at 5000 rpm.**

by replacing the present rotating vacuum seal of stainless steel on plastic with a differentially pumped air-bearing seal. The second step in increasing the target speed was to double the target diameter to approximately 50 cm. A full-size test of this system is shown in Fig. 7. The test target is mounted on a prototype of the cart that will be used to carry experimental apparatus and the target to the target room.

To circulate cooling water across the back of the target, we placed the water within etched channels in the back of the target. A section of the mask used to etch these channels is shown in Fig. 8. After etching, another sheet of copper is bonded over the channels, and the target is then hydroformed to the desired shape. Target backing materials and the processes of etching, bonding, and hydroforming have been extensively tested in the past two years. All steps of the sequence required to produce 50-cm targets have now been demonstrated.

One remaining detail of the tritium-in-titanium target is poorly understood. During the 100-hour usable lifetime of the target, over twice as much deuterium is injected into the titanium by the deu-

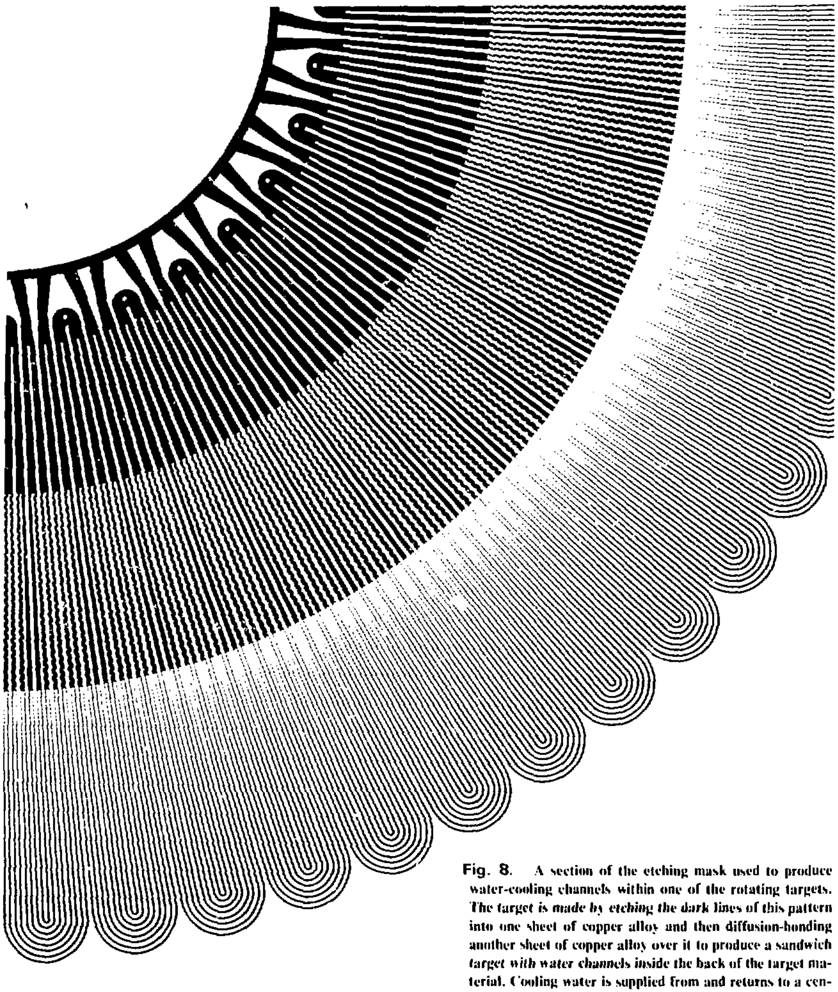

Fig. 8. A section of the etching mask used to produce water-cooling channels within one of the rotating targets. The target is made by etching the dark lines of this pattern into one sheet of copper alloy and then diffusion-bonding another sheet of copper alloy over it to produce a sandwich target with water channels inside the back of the target material. Cooling water is supplied from and returns to a central hub. To remove the 60 kW of power that the ion beam deposits on the tritium target, water must be forced through these channels at a rate of approximately 1 litre/s. The convoluted channels enhance heat transfer to the coolant.

teron beam as the original tritium inventory of the target. However, deuterium is released from the target by diffusion at a rate over 10 times that at which tritium is released. The distribution of tritium remaining in the target is quite nonuniform as a function of depth in the target and is not that expected from any simple model in which equilibrium mixing and diffusion of hydrogen isotopes is assumed. Successful operation of the RTNS-II sources depends upon the persistence of this behavior at the higher deuteron dose levels the target will experience on RTNS-II.

OTHER NEUTRON SOURCES

Two alternative neutron sources for fusion materials studies are currently being considered by the Office of Fusion Energy. The first, referred to as INS (Intense Neutron Source), has been authorized for construction at the Los Alamos Scientific Laboratory. This source would focus a 1.5-A beam of T^+ on a supersonic target of D_2 gas to produce a total neutron source strength of 1×10^{15} n/s. Construction of this neutron source was authorized along with RTNS-II in the FY 1976 federal budget. However, because of budgetary limitations, construction of the INS has not yet began. The current estimated cost of the INS project is $30 million.

Another neutron source, using a different source reaction, was authorized in the FY 1977 federal budget for construction at the Hanford Engineering Development Laboratory at Hanford, Washington. This source would use a 35-MeV deuteron linac and a liquid-lithium target. Bombarding the lithium target with a 100-mA beam of deuterons can produce a total neutron source strength in excess of 10^{16} n/s. The neutrons produced range in energy from less than 1 MeV up to a maximum of about 45 MeV. However, the neutron spectrum has a mean energy of about 14 MeV with a broad maximum near that energy. Such a neutron spectrum may be an acceptable approximation to the spectrum in a fusion reactor. The projected cost of this neutron source is $83 million. Operation is scheduled for five years from the start of construction, which has not yet begun.

These sources may be compared by noting that the experimental volume of the RTNS-II sources is 2 cm^3, that of the INS is 10 to 50 cm^3, and that of the Li(d,n) source is 1000 cm^3. Construction of the latter two sources will require advancing the technology of accelerators, beam transport and beam diagnostics, and targets.

FUTURE DEVELOPMENTS

With initial operation of the first of the two neutron sources in the RTNS-II Facility scheduled for July of this year, the experimental program in the new facility will begin. First regularly scheduled materials experiments are planned for October of 1978. The size and extent of this experimental program will depend upon future budgets for the fusion program. The RTNS-II sources were designed with options that allowed them to be upgraded to source strengths of 10^{14} n/s. Such upgrading would extend the period of usefulness of these sources to the late 1980's.

If the neutron sources are not used to capacity by the fusion materials program, experiments in areas such as neutron cancer therapy or technology development for other accelerator-related programs may be possible. The design tools and diagnostic concepts developed during the RTNS-II project may be applicable in areas as diverse as the development of neutral beam sources or direct energy conversion devices for fusion reactors, or the production of high-current pulsed injectors for radiotherapy or spallation breeding accelerators. Operation of these neutron sources and participation in the new and unique materials work to be done with them will give LLL a lead role in a new area of technology.

Key Words: fusion reactors, neutrons—radiation effects, reactor materials, Rotating Target Neutron Source, RTNS

FOR FURTHER READING

Readers wishing additional information on intense sources of high-energy neutrons should see the special issue of *Nuclear Instruments and Methods* "High Energy and High Intensity Neutron Sources," *Nucl. Instrum. Methods* **145**, No. 1 (1977).

PAST TITLES

Articles in the *Energy and Technology Review* have been organized into subject areas approximately corresponding to the Assistant Secretaries' areas of responsibility in the Department of Energy. These subject areas are listed below with references to some recent articles in each category. (A semiannual index appears in the June and December issues.)

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