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Scientific Editors:

Robert C. Haight
Henry D. Shay

BRIEF

ii

LNG Safety Research at LLL.

General Editors:

Paul Adye
Richard B. Crawford
Judyth K. Prono
Jane T. Staehle

BASIC RESEARCH ON HIGH-EXPLOSIVE INITIATION

1

New instruments and experimental techniques are helping us discover the basic physical and chemical processes behind high-explosive detonation.

THE NATIONAL MFE COMPUTER CENTER: INCREASED CAPABILITY IN 1978

11

The capabilities of the MFE computer center at LLL continue to expand with the installation of the Cray-1 computer and its peripheral devices and with continued software development.

RAPID NUCLEAR CHEMISTRY FOR DETERMINING THE PROPERTIES OF SHORT-LIVED FISSION PRODUCTS

19

We have developed batch- and continuous-mode systems for the automatic chemical isolation and spectroscopic analysis of short-lived fission products.

MIRROR FUSION REACTORS

31

We have conducted conceptual design studies of fusion and fusion-fission hybrid reactors based on the three mirror confinement schemes—standard, tandem, and field-reversed mirrors—now being investigated at LLL.

AC 4

BRIEF

LNG SAFETY RESEARCH AT LLL

Liquefied natural gas (LNG) technology, an energy-crisis offshoot that promises to alleviate temporarily the U.S. natural gas shortage with the waste by-product of remote oil fields, also carries with it the threat of unforeseen industrial and community hazards. LNG is kept liquefied only by chilling it to 113 K (-160 °C); any break in the containment vessel releases the liquid into a warm environment. The huge vapor cloud so formed warms up only slowly; it hugs the ground and spreads due to gravitational and atmospheric forces. It poses the familiar fire hazards associated with household natural gas releases, but on a large scale.

The prospect of such occurrences poses many questions, the answers to which are at present very uncertain. For example, existing models disagree by over an order of magnitude on how far the vapor cloud from a particular large spill will travel downwind. Very little work has yet been done on scaling relationships that would allow us to extrapolate from the results of small experiments to predict full-scale effects. There is no existing facility at which large LNG spill experiments can be carried out reliably and safely under the variety of circumstances necessary to validate numerical models.

We have been asked to participate in a DOE program of LNG safety research. Among our responsibilities will be selection of a safe site and design and construction of a research facility dedicated to study of this problem. We will also be developing and verifying a group of analytical models that describe the phenomena involved in the accidental release of LNG into the environment. This will mean an extensive experimental program to measure vaporization rates, dispersion patterns, ignition characteristics, flame propagation rates, and external damage effects. We will need to develop a sensing and data-collection system capable of detecting methane, ethane, and propane with enough resolution to observe the characteristics of turbulent mixing and with enough scope to map a cloud perhaps 4 to 5 km long. We envision experiments that release up to 1000 m³ of LNG.

We expect that this program will require between 50 and 100 experiments at the large-scale facility over a two-year period. Until the large facility is ready we will participate in smaller experiments at the Naval Weapons Center, China Lake, California.

Contact William J. Hogan (422-7365) for further information on this subject.

Basic Research on High-Explosive Initiation

Our detonation physics program is investigating the physical and chemical processes involved in initiating a high-explosive (HE) detonation. Increasingly stringent safety requirements, ever more sophisticated applications, and the unique initiation and detonation properties of the new, insensitive HE's are forcing us to seek a more fundamental understanding of HE behavior to meet future Laboratory requirements. Our new experimental techniques have already produced promising results and point toward significant advances in our capabilities. The results of the program will help us to design with a great measure of HE safety, to model HE initiation accurately, to predict HE response to unintended stimuli, and to achieve possible major improvements in our HE systems.

Although the properties of explosives have been studied intensively for many years, little is known about the complex physics and chemistry of initiation. Most of the data on HE initiation are from such measurements as skid tests or drop tests. These tests give useful information on HE handling or on detonator performance, but they use stimuli that are too complex to yield information of any predictive value. Somewhat more useful data from one-dimensional (1-D) shock initiation experiments are available in the form of distance-time measure-

ments on shock fronts and free surfaces.

Recent advances in diagnostics include laser velocity interferometers, embedded stress and particle-velocity gauges, and fast infrared radiometers for temperature measurements. Computer modeling of the new data from these diagnostics will test our understanding of the physics and chemistry of initiation and will suggest further critical experiments to advance our knowledge.

Nuclear weapons can employ one of the most complex and sophisticated applications of high-explosive technology. An increased understanding of fundamental HE behavior will have a direct impact on initiation system design and weapon safety. Clearly, we must be able to perform and understand one- or two-dimensional experiments that use simple stimuli before we can address many of the more complex safety problems, such as HE response to multiple stimuli like shock, heat, or fracture.

In our initial work we are concentrating on two representative HE's, PBX 9404 and TATB. PBX 9404 is a high-energy explosive with moderate shock sensitivity. TATB gives about 67% as much detonation pressure as PBX 9404, but it is remarkably insensitive to severe impact and thermal environments, making it much safer to handle. To understand the differences in the shock sensitivity of these two explosives, we are studying the details of the hydrodynamic flow as an initial stimulus builds up to a detonation.

Most shock initiation tests are designed to collect

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engineering data rather than to probe the fundamental physics and chemistry of initiation. In the standard skid test, for example, a hemispherical mass of explosive mounted on a pendulum falls from a measured height and strikes a target at an oblique angle. Observers record the result in one of six categories, ranging from "no reaction" through "puff of smoke" to "complete detonation." In this test, the specimen experiences both concussion and friction stimuli. Furthermore, the measurement criteria are somewhat subjective: there is no hard and fast measure of how much smoke constitutes a puff. The test is useful in finding out how a particular explosive may behave when accidentally dropped, but it will not determine how the explosive will react to concussion alone, for example.

The most important and sophisticated standard initiation test is the wedge test.¹ A sustained pressure pulse of known amplitude (produced by an explosive plane-wave lens) enters the wedge-shaped charge through a buffer plate, while a high-speed, rotating-mirror camera records the progress of the shock front across the wedge. Detonation appears as an abrupt acceleration of the shock front to detonation velocity. Wedge tests are performed at various input pressures, and the results are usually displayed as a plot of run-distance to detonation vs input pressure.

One condition for the validity of an initiation model in a hydrodynamics code is that the model correctly reproduce the wedge-test data. However, this condition alone is not enough. Two models us-

ing drastically different chemical reaction rates can still both correctly reproduce wedge-test data. Only with more detailed knowledge of the hydrodynamic flow can we judge which model is more nearly correct.

LAGRANGIAN GAUGE EXPERIMENTS

We are beginning to measure hydrodynamic flow variables with thin transducers (called Lagrangian gauges because they move with the flow) embedded in the HE specimen. Such a gauge can give a continuous record of particle velocity or stress in a particular element of the initiating and detonating explosive. Development of reliable Lagrangian gauges has been a major thrust of our detonation physics program.

A good example is the Lagrangian manganin stress gauge. Manganin is a good stress transducer because its resistance varies directly with stress and because its temperature coefficient of resistance is small, making it relatively immune to shock heating effects. Manganin stress gauges have been used extensively in static high-pressure research and in shock wave studies on chemically inert materials, but they could not be used in HE studies because the hot reaction products short-circuited the gauge.

One of our first tasks was to develop a method of protecting manganin gauges from the reacting-HE environment. We have found that a gauge package consisting of a 25.4- μ m-thick manganin element protected with 250- μ m Teflon on each side is usable at all stages during the buildup to detonation from an initial stimulus. Figure 1 depicts the gauge package and a typical target assembly.

In an extensive series of experiments using manganin stress gauges embedded in explosive samples shocked by projectiles from our 102-mm light-gas gun, we have observed significant differences in the initiation behavior of PBX 9404 and TATB.² Figure 2 shows the resulting manganin gauge records. In the PBX 9404 targets, the stress at the shock front stayed at a nearly constant level until just before detonation, when the shock front was engulfed by a pressure wave from behind. In contrast with the PBX 9404 behavior, the stress profile in the TATB shows significant growth at the shock

front over the run to detonation. By putting appropriate reaction-rate terms in our 1-D hydrocode initiation models, we are able to model the observed stress-time profiles. Analysis of the data to determine energy-release rate awaits the results of a series of calibration shots to determine accurately the piezoresistive response of the manganin foil used in the gauges.

The response of large blocks of explosives to low-amplitude shocks is extremely important for safe handling and security considerations. We have applied the manganin gauge technique to determine the stress history of PBX 9404 subject to low-amplitude shockwaves.³ A 155-mm gun propelled 51-mm-thick copper flyers into 114-mm-thick PBX 9404 samples. Results from an experiment with an input stress of 0.38 GPa are indicated in Fig. 3.

A notable feature of these curves is the degradation of the shock front by a precursor wave. If the initial wave front pressure is greater than 1.2 GPa, it grows in amplitude as it traverses the sample, and manganin records from all experiments reveal increasing pressure behind the front. Experimental curves from higher input stresses exhibit increasing slopes behind the wave front as one would expect if the amplitude of the initial wave determines the rate of later reactions.

The data indicate that even a 0.38-GPa shock will result in a detonation if the sample is large enough, although the reaction is initially very slow at such a low pressure. Furthermore, gauge data from input stresses in the 1.3- to 1.4-GPa range indicate run distances to detonation much longer than would be predicted by an extrapolation of available sustained pulse initiation data.⁴ The ultimate low pressure limit for a sustained pulse that will result in detonation has not been reached but must be less than 0.38 GPa.

Another type of Lagrangian gauge measures the velocity of the material moving in a hydrodynamic flow. The simplest such material-velocity gauge (MVG)⁵ consists of leads attached to a conductor oriented perpendicular to an applied magnetic field. The flow velocity is determined by measuring the voltage induced as the conductor cuts magnetic field lines. A number of experiments now in progress use

Fig. 2. In a typical shock-initiation experiment (top right), the impact of a gun-accelerated flyer plate sends a shock wave through the target. Gauges embedded at various depths in the target (bottom right) produce the stress-time records displayed. Stress measurements were obtained in both PBX 9404 and TATB. The input stress has been adjusted to give about the same run to detonation in both materials. We plot an approximate stress, as we have not yet finished calibrating the manganin gauge foil.

MVG's to measure flow in initiating and detonating PBX 9404 and TATB. Information from velocity gauges is complementary to stress-gauge information, providing a valuable cross check on the validity of the stress-gauge records.

RADIATION TEMPERATURE MEASUREMENTS

In a separate series of experiments we have been investigating the "hot spot" theory of HE initiation.

Hot spots, small regions of high temperature arising from shock interactions at voids and other discontinuities, have long been postulated to explain snook initiation in heterogeneous explosives.⁶ Their exact nature and function have been the subject of extensive speculation and debate. Theory suggests, however, that the single most important parameter governing the early stages of initiation in most explosives is hot-spot temperature, since this determines whether a self-sustaining reaction will

Fig. 3. Stress histories from a 0.38-GPa impact experiment on PBX 9404. We embedded one 8- Ω and two 50- Ω gauges at each level. Gauge levels A and B are 12.9 and 64.1 mm, respectively, from the impact surface. (All experiments at higher input stress used at least three gauge stations.) We measured shock transit times with piezoelectric pins set flush with the impact surface and at the downstream surface. Transit times combined with the gauge data allowed us to estimate run distances to detonation for the higher stress experiments discussed in the text. The agreement between the 8- and 50- Ω gauges suggests that no shorting between gauge leads is occurring through the HE explosion products.

develop before the pressure is released.

We have developed a technique to infer hot-spot temperature in PBX 9404 by measuring infrared emission. Fast-responding solid-state detectors with enough sensitivity for this study have only recently become available. Even when true temperatures could not be obtained from the data, time-resolved radiance measurements yielded histories of hot-spot development under various conditions of shock loading.

Figure 4 shows the experimental arrangement, together with the results of a series of gun-launched projectile impact experiments. The temperature peaks occurring near the shock arrival time at the surface of the explosive were caused by heat release from chemical reaction and not by air shock or any artifact of the experimental arrangement. This was

confirmed by dummy experiments with mock explosives in which no such peaks were observed.

The curves in Fig. 4 are from single-band temperature measurements and apply to average temperatures over the entire field of view of the detector. They were taken in two different wavelength bands, however. Such double-band measurements permit us to derive a ratio temperature, which applies to the hottest part of the field of view. If the single-band and double-band temperatures were the same, it would mean that the object viewed had a uniform temperature. If the ratio temperature is much higher than the single-band temperature, it indicates a nonuniform temperature distribution (hot spots). The derived ratio temperature of 800°C for this experiment is the first experimental measurement of hot-spot temperature in HE initiation.⁷

The other interesting observation from this experiment is the difference in shape between the two 3.8-GPa curves. This effect is not well understood, but may have something to do with the discrete nature of molecular band emission. After the hot spots begin to cool from their peaks, the individual curves may reflect differences in molecular vibrational emission frequencies among the constituents of the partially reacted explosive. We plan more refined measurements in this promising area, using narrow-band filters to isolate and follow the development of individual molecular species.

Multiple-band infrared radiometry seems to be a generally applicable tool for the study of initiation. Since the temperature achieved in hot spots must be intimately related to the shock sensitivity of explosives, temperature measurement as a function of material and shock-wave parameters will lead to a better understanding of the factors affecting sensitivity.

REACTION-ZONE STUDIES

Current hydrodynamic codes treat steady detonation-wave propagation by assuming that all of the chemical energy of the explosive is released at the shock front. This approach is adequate for PBX 9404, in which a detonation wave spreads out from a point of initiation as an expanding spherical shell. However, it is less useful to describe propaga-

tion in TATB or other insensitive explosives, where detonation waves may spread out or not, depending on the conditions of initiation. At present we compensate for the nonideal character of an insensitive

explosive by normalizing the code parameters to the results of appropriate experiments, but this is unsatisfactory because it provides no way to extrapolate from a satisfactory solution to a different

Fig. 4. Representative apparent-temperature vs time curves for PBX 9404 at various input stresses, derived from infrared radiometer signals. The inset schematically depicts the experimental arrangement at the target end of the 102-mm-diam gas gun used to generate the initiating shock. Thick aluminum flyer plates (6 to 12 mm) provided flat, sustained pressure pulses into sample disks of PBX 9404 about 5 to 8 mm thick. The two radiometers contained liquid-nitrogen-cooled indium-antimonide detectors. Both radiometers had identical 3-mrad fields of view covering identical areas of the explosive, about 4 mm square. A 4.0-μm "cut on" filter on one radiometer caused it to view a different wavelength band than the other radiometer. Radiometer response time was about 0.5 μs.

set of conditions.

Theorists have suggested that the anomalous behavior of TATB and other insensitive explosives could be explained if the reaction zone has a finite thickness behind the detonation front. We have developed a way to infer reaction-zone thicknesses from laser-interferometer velocity measurements,⁸ qualitatively confirming the theoretical predictions. Improved measurements, together with a broader understanding of the physical phenomena occurring in the reaction zone, will lead to more accurate codes that can be applied over a wider range of physical conditions.

Figure 5 shows the decay of a plane (1-D) detonation wave as it passes out of the explosive and through a metal plate. The wave consists of a sharp pressure spike associated with the reaction zone and a long, gradually sloping ramp following. The sharp spike has a constant shape and amplitude in the explosive (the chemical energy of the detonation sup-

ports it) and then decays in the metal plate, although the ramp is relatively unaffected. The rate of decay depends on the narrowness of the spike, and hence on the thickness of the reaction zone.

If some of the pressure spike is still present when the wave reaches the free surface of the metal plate, it will influence the velocity of the free surface. Figure 6 presents a diagram of the laser Doppler interferometer with which we can measure the front-surface velocity, together with velocity measurements on the front surfaces of 0.5-mm-thick plates exposed to detonations of PBX 9404 and TATB. The plate on the TATB starts out with the higher velocity, although the plate on the PBX 9404 eventually catches up and surpasses it. This indicates that the pressure spike was still present in the TATB wave and not in the PBX 9404 wave, although both had decayed over the same distance in the aluminum plates.

This observation supports the theory that the

Fig. 5. Idealized stress-wave profiles as a 1-D detonation shock passes from left to right through an explosive and an inert metal plate. The sharp spike at the leading edge of the wave defines the reaction zone. This spike decays in the metal plate because there is no more reaction energy supporting it. The velocity of the free surface of the metal plate will depend in part on how much of the pressure spike is left when the shock wave reaches it.

reaction zone in TATB is much thicker than in PBX 9404. More refined measurements will be needed to determine the shape of the pressure spike on the TATB detonation wave, and, hence, the

structure of the reaction zone.

The reaction zone structure of TATB influences the explosive's behavior in two very practical ways. First, there is the propagation of detonation waves,

Fig. 6. Laser Doppler interferometer and free-run-plate experiment used to probe reaction-zone structure (right). An explosive lens initiates a plane detonation wave in a 50-mm-thick test specimen. Laser light scattered from the free surface of a thin metal plate on the test specimen is collected and analyzed by a laser velocity interferometer. (left) Velocity histories taken at the free surfaces of 0.5-mm aluminum plates placed on detonating charges of PBX 9404 and TATB. The curve for TATB starts out higher than that for PBX 9404, even though it later falls behind, indicating that the TATB initial spike was higher than that for PBX 9404 after traversing the same thickness of aluminum. More refined measurements along the same line will enable us to reconstruct the reaction-zone profile in TATB and other insensitive explosives.

already mentioned briefly above. In an ideal explosive like PBX 9404 the detonation wave front can be calculated from the wave front at some earlier time by superposing spherical wavelets emanating from each point in the earlier wave front. In TATB this Huygens construction is completely inadequate. Convex Huygens wave fronts must always diverge. In TATB, a detonation wave may ultimately fail, even if it is fully detonating at the center, if initiation took place over too small an area.

Furthermore, even a diverging detonation wave front in TATB does not propagate as a Huygens wave front. The speed of propagation depends markedly on the curvature of the wave front. This very nonideal behavior of TATB traces back to the thickness of the reaction zone.

The second manifestation of reaction-zone structure is in the minimum charge diameters and the minimum areas over which TATB must be initiated in order to sustain a steady detonation. In initiation experiments using small, high-speed flyer plates, we found that the minimum energy necessary to produce a detonation in TATB increases sharply for flyer diameters less than 10 mm. PBX 9404, on the other hand, can be initiated by flyers about 1 mm in diameter. There is a similar order-of-magnitude difference in the minimum propagating diameter of PBX 9404 and TATB charges. Both of these effects are also traceable to the difference in reaction-zone thickness between PBX 9404 and TATB.

NUMERICAL SIMULATION OF REACTIVE HYDRODYNAMIC FLOW

One of the best tests of a theory is whether it is complete enough to enable one to simulate observed phenomena on the computer. In addition, the numerical simulation can be used to refine the theory. With the simulation we predict the result of an untried experiment and then compare the experimental results with those predicted. The differences between the two serve both as a measure of the accuracy of the simulation and as an indication of the nature and extent of the required adjustments in the theory.

Starting with a 1-D hydrodynamics code, we have

constructed codes that enable us to simulate 1-D reactive flow in PBX 9404, TATB, cast TNT, and PETN. We found it impossible to fit our Lagrangian-gauge data without incorporating rate laws that depend upon two distinct processes, an ignition step and then growth of the reaction to consume the material. The ignition step is consistent with our understanding of the role of hot spots in shock initiation. The rate of the subsequent reaction depends on pressure.

New data are needed over a wider range of conditions to further test these models. We already have qualitative agreement between the simulation and the experimental results. Quantitative comparison awaits completion of the manganin foil calibration.

Our initial success with 1-D simulation encourages us to attempt a 2-D simulation. A 2-D hydrodynamics initiation code is vital to understanding the behavior of TATB and other nonideal explosives. We have begun work on incorporating an initiation model into a 2-D hydrodynamics code.

Much work remains to be done to meet our program objectives. The new techniques described here must be applied to a wide variety of explosive materials, both to learn directly about these materials and to provide data for improving our computer models. However, recent advances in our understanding of the properties of PBX 9404 and TATB make us very optimistic about future prospects.

Key Words: detonation; infrared radiation—detection; initiation; KO (code); Lagrangian gauges; laser interferometry; PBX 9404; TATB.

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The National MFE Computer Center: Increased Capability in 1978

The National Magnetic Fusion Energy Computer Center at Livermore is greatly increasing its computing power and versatility through hardware acquisitions and concurrent software development. Most significant has been the arrival of the Cray-1 computer in April 1978, with its one-million-word semiconductor memory and vector processing rate of up to 250 million floating-point operations per second. Additional equipment now being installed includes a new 500-billion-bit CDC 38500 mass storage device, a Dicomed D48 graphic film recorder, and Systems Concepts 3350 staging disks.

The Cray-1 computer is already significantly affecting computational physics in the magnetic fusion energy community. For example, one magnetohydrodynamics code, after conversion to the Cray-1, runs five times as fast as it did on the CDC 7600. The center's expanded capabilities now make possible new ways of visualizing plasma physics problems and more refined estimates of hard-to-measure physical parameters.

The National Magnetic Fusion Energy Computer Center (NMFEC) was created in 1974 to provide a centralized computing facility for national laboratories, contractors, and universities involved in magnetic fusion energy research and development. Initially, five laboratories (Princeton Plasma

Physics Laboratory, Oak Ridge National Laboratory, Los Alamos Scientific Laboratory, Lawrence Livermore Laboratory, and General Atomics Corporation) were connected to a central CDC 7600 computer system with high-speed (50-kilobit-per-second) transmission lines. At each of the sites a DEC KI-10 computer was installed to run the local printer, tape drives, and card reader, and to provide a local capability for running smaller physics problems. Additionally, a communication processor (PDP-11/40) was installed at each site to interface the KI-10 with the communications network. This combination of minicomputers at each major site constitutes a user service center. Figure 1 shows the original magnetic fusion energy network.

GROWTH AND EXPANSION OF THE NMFEC COMPUTER CENTER IN 1978

Quite early in the operation of the MFE network, researchers could see the need for much more computational capability. Many important physical phenomena took long times to simulate or required more memory than even the CDC 7600 could provide. The complex computational plasma physics that is vital to MFE research programs justified the purchase of a Class VI computer two to five times faster than the 7600.

The Class VI computer, delivered at the end of April 1978, is a Cray-1 computer system. Its basic configuration, shown in Fig. 2, consists of a central processing unit (CPU), a maintenance control unit

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Fig. 1. The original MFE computer network as it was in 1974. The computer center at LLL was connected with stations at four other laboratories via high-data-rate transmission lines.

for performing hardware diagnostics, and a dynamic disk subsystem to control sixteen DD-19 disk storage units. The storage capacity of each of the disk storage units is on the order of 2500 megabits of information.

The Cray-1 CPU is divided into three sections: a million-word (64 bits per word) semiconductor memory with a maximum transfer rate of 80 million words per second, a computational section with functional units and registers, and an input-output section with a maximum transfer rate of 10 million words per second. The memory has twice the capacity of the CDC 7600 large-core memory and allows rapid access comparable to the CDC 7600's relatively small semiconductor memory.

The computational section of the Cray-1 CPU

consists of scalar and multielement vector registers, address registers, and twelve functional units. The functional units are divided into four equal groups serving address functions, vector operations, scalar operations, and floating-point operations. The computational section's architecture permits a technique called chaining, providing speeds up to 250 million floating-point operations per second (250 Mflops). (The CDC 7600 performs about 20 Mflops.) Chaining is fast because the vector functional units, in combination with scalar and vector registers, can store intermediate results, eliminating much addressing of memory.

The Cray-1 system has been integrated into the existing MFE computer systems with a direct connection to the CDC 7600, to the file management

Fig. 2. The basic configuration of the Cray-1 computer system. The main divisions of this system are the central processing unit (CPU), the maintenance control unit for internal checking of system hardware, and a mass storage subsystem consisting of 16 DD-19 disk storage units.

system (FILEM), and to the staging disks controlled by the file management computer. Making these physical connections is only the first step in integrating a new computer into the system, however. The Cray Operating System, acquired with the Cray-1, provides only limited batch processing of jobs. This is far short of the MFE community's need for both a timesharing and a multijob batch processing system.

This year we have adapted a version of our Livermore Timesharing System (LTSS) to the Cray-1; the

the new version is called CTSS. The basic CTSS system and several of the utility routines were converted to the Cray-1 by early August of this year. The Cray Fortran compiler was also converted to run under CTSS at this time, making available both batch processing and limited timesharing. Full timesharing is expected by the end of 1978.

In addition to the memory capacity built into the computers, there is a large and growing need for long-term and short-term file storage. Files are long lists of numbers, such as values of the magnetic field

at each of a series of points distributed throughout a volume, that need to be recalled from time to time in various calculations. We are installing multilevel storage to give our users a high-performance, reliable system for storing files at minimum cost.

The first level of file storage, for the most frequently needed files, is the System Concepts 3350 array of high-performance staging disks. Each computer in the network independently processes files through the staging disks, providing the benefits of redundancy. The total capacity of this first-level system is 2400 megabytes, with an access time of about 75 ms.

The second level of the file storage system is the CDC 38500 mass storage system installed early in 1978. This is a cartridge system with a total installed capacity of 0.5 trillion bits and a potential for expanding to twice that size. Access times are on the order of 15 s. We estimate that between 95 and 98% of all accessed files will reside on either the staging disks or on the mass storage system.

The final archival level of file storage we are acquiring is the Automated Tape Library (ATL). The ATL is a box-like enclosure that stores very high-density tape reels (6250 bits per inch). Each basic module of the five in the system holds almost 400 reels of magnetic tape, a reel selection mechanism, and four automatic reel mounting units that service four tape drives. We expect that ultimately 75% of all stored files will reside on these tapes. Under control of the file management computer, the ATL will be able to mount a tape automatically in about 15 s. Total access time (including time to mount the tape) will be about 2 minutes. The system eliminates manual intervention to ensure system reliability and physical security for the data. Table 1 presents the operating parameters of the various levels of file storage.

One index of user acceptance is the growth rate of demand for file storage. Figure 3 shows how this demand has steadily increased since the FILEM was placed in operation. Clearly the 1.5-trillion-bit capacity of the ATL is appropriate.

An important aid to understanding the results of our computations is the ability to present them pictorially. In addition to such graphic display equip-

ment as cathode-ray tubes and printer-plotters at the various user service centers, we have acquired a Dicomed D48 film processor. This unit can process 16- and 35-mm film in both black and white and full color, as well as 105-mm microfiche. The D48 system produces high-definition vectors and characters for graphic microfilm output and also provides equivalent gray-scale images.

Meanwhile, the network continues to grow. More than 30 university research groups, as well as small fusion groups at other laboratories, have been allocated time on the CDC 7600. The MFE computational workloads from the University of California at Berkeley and the University of Texas at Austin have increased to the point that each has

Table 1. Capacities, access speeds, and costs per megabyte for the various storage levels of the new NMFECC mass storage equipment.

Storage level	Gross storage capacity, Mbytes ^a	Access speed, ms	Cost, \$/Mbyte
Disk	2 400	75	105
Mass store	62 500	15 000	16
Archival	187 500	120 000	2

^aOne byte = 8 bits.

Fig. 3. Growth in demand for file storage since the file management system (FILEM) was placed in operation. Additional file storage capacity now being installed is expected to satisfy user demand for several years to come. This graph can be interpreted in terms of bits with the average file size being about 1.8 megabits.

ago. An investment in computer time now provides a much greater return in terms of output data that can reasonably be expected to predict the behavior of an experiment.

These advances in theoretical models and numerical techniques have been necessary to keep up with magnetic confinement experiments, which have become more complex. In the LLL mirror program, for instance, the axisymmetric devices of the 1950's have been superseded by the minimum- B configurations of current experiments. These latter configurations have no symmetry coordinate, making it necessary to describe the plasma in three dimensions instead of two.

Of the various kinds of numerical models for describing plasma behavior, time-dependent magnetohydrodynamic (MHD) codes, normal-mode MHD calculations, and particle codes are among the largest and longest-running codes within the MFE network. For this reason we selected five of these physics codes for conversion as an acceptance test of the Cray-1. The five codes we chose were:

- PEST (MHD normal-mode calculation)—Princeton Plasma Physics Laboratory.
- ERATO (MHD normal-mode calculation)—Oak Ridge National Laboratory.
- ICED-ALE MHD (three-dimensional nonlinear MHD)—Los Alamos Scientific Laboratory.
- SUPERLAYER (a two-and-a-half dimensional particle code)—Lawrence Livermore Laboratory.
- GAQ (MHD equilibrium solver)—General Atomics Company.

All of these codes work properly on the Cray-1. Typically, codes run on the Cray-1 are faster by factors of 2 to 5 than when run on the CDC 7600.

RECENT COMPUTATIONAL RESULTS

Magnetohydrodynamics. This is the study of how a conducting fluid (in this case a plasma of ions and electrons) behaves in a magnetic field. The most general MHD problem requires us to solve eight simultaneous nonlinear partial differential equations. This calculation in two dimensions has become fairly routine, though often time-

consuming.¹ We have also carried out some three-dimensional calculations, but they are very difficult to do on the CDC 7600. One important calculation of this type done on the CDC 7600 was the numerical simulation of the Scyllac experiment using the ICED-ALE MHD code.² This simulation helped theorists identify the origin of the force imbalance that prevented plasma confinement in this experiment. With the Cray-1 system, it is now possible to perform these calculations much faster and with better resolution.

To simplify the calculations, it is possible to avoid solving the complete set of MHD equations in some cases. For example, physicists at Princeton and Oak Ridge were able to reduce the equations describing some aspects of tokamak operation to two coupled nonlinear equations in two dimensions. This approximation was valid because the poloidal magnetic field is usually weak compared to the toroidal field. (The poloidal and toroidal directions refer to the short way and the long way, respectively, around the toroid-shaped plasma.) Extensive work with this and other computational models enabled theorists to explain the "sawtooth oscillations" seen in the core of tokamak plasmas in terms of a combination of MHD instabilities.³

To investigate other instabilities, plasma researchers are often forced to consider three-dimensional configurations. For example, another mode of plasma behavior sometimes seen in tokamaks is the "major disruption," an expansion of plasma toward the wall of the containment vessel. Some of the same types of instabilities considered in the explanation of sawtooth oscillations were thought to be at work in the major disruption, but two-dimensional calculations were not able to verify this.

A weakness of the two-dimensional calculations was that they assumed that all plasma perturbations had the same helical pitch around the plasma column. It was therefore impossible to include interactions between modes of different helicity in a two-dimensional calculation. Extending the model involving the reduced equations to three dimensions enabled researchers to discover a plausible explanation for the major disruption.⁴ Computational

physicists at Oak Ridge have converted this particular three-dimensional code, called RS3, to the Cray-1 computer, and it now runs five times faster than on the CDC 7600. It still has many uses in studying the major disruption and other MHD phenomena to which it applies. For other applications, however, we will still need to solve the complete set of MHD equations in three dimensions.

The main interest in studying instabilities is to follow plasma perturbations as they grow and become nonlinear. Only in this way can we determine whether an instability saturates before it spoils confinement. Many such problems, previously beyond the capacity of our system, are now being attacked vigorously on the new machine.

Another approach to the determination of MHD behavior is the study of linear normal modes. These are natural modes of oscillation excited by small perturbations from equilibrium. The PEST⁵ and ERATO⁶ codes do this by calculating an equilibrium and then obtaining the structure and frequencies of the normal modes by formulating and solving a matrix eigenvalue problem.

These codes have made vital contributions⁷ to the understanding of the dangerous "kink" and "ballooning" instabilities, as well as other MHD modes in tokamaks. This information permits physicists to determine limits on the ratio of particle pressure to magnetic field pressure (β). For example, the PEST code has had a major impact on experimental design, particularly in the case of the Princeton PDX experiment in which coils were rewired on the basis of equilibrium and stability studies.

The PEST code runs 3.7 times faster on the Cray-1 than on the CDC 7600. With this greater speed we may undertake to develop more sophisticated versions of these codes, with better resolution of the plasma and coil configurations. The improved codes may provide vital input to the investigation of future experiments and reactor configurations.

Particle Codes. In many cases, however, MHD and other fluid models cannot adequately describe plasma behavior. In such cases the calculations must include microscopic effects (how individual particles move, how their velocity distributions

change, and how these motions and changes affect the plasma).

Although ideally such a calculation should follow every particle in the plasma, in practice particle codes follow the motions of a large number of "superparticles" that behave like individual ions and electrons but actually represent many individual particles. These superparticles move because of forces exerted by the electromagnetic fields in the plasma, which are in turn determined by the charge densities and currents due to the particles. The calculation must proceed self-consistently, constantly assessing the effects of the fields on the particles and of the particles on the fields.

We used the LLL particle code SUPERLAYER^{8,9} in the Cray-1 acceptance test. SUPERLAYER is a two-and-a-half-dimensional code: it assumes that quantities vary only in the radial and axial directions (cylindrical symmetry), but that particles may have velocities in all three coordinate directions. SUPERLAYER accounted reasonably well for the failure to achieve field reversal in the cylindrical Astron experiment.¹⁰ We are now using it extensively to interpret results of the 2XIB experiment at LLL and of ion ring experiments at Cornell, and in the design and simulation of the TMX and MFTF experiments. Its main application at present is to investigate possible field-reversed configurations in 2XIB and MFTF.⁹

SUPERLAYER has been used in many important calculations, but it also has significant limitations. Even in modeling asymmetric mirror devices it assumes cylindrical symmetry. In many cases it forces us to accelerate artificially the rates for some physical processes, and the code is still unable to account for all the effects of space charge, electron currents, and rf diffusion. Even the Cray-1 will not allow these difficulties to be resolved completely, but it will permit great improvement in the accuracy of the simulation.

In addition to simulating specific experiments, particle codes have become extremely useful for verifying general plasma theory: an experiment to verify a theoretical idea may be very difficult and expensive, but a particle code can describe how an ideal plasma would behave under given cir-

circumstances at relatively low cost. We can also program in any desired diagnostics in a calculation without perturbing the plasma, a feat that is often impossible in an experiment.

However, just as with the MHD calculations, we must often resort to three-dimensional formulations to simulate the most interesting plasmas. Three-dimensional particle codes have so far been only marginally successful. We expect that with the added computing power of the Cray-1, three-dimensional particle models will become important theoretical tools.

OUTLOOK

Clearly, the current expansion of the MFE network will allow more physics to be included in very large multidimensional fluid and particle codes. Furthermore, it will now be possible to develop more sophisticated hybrid codes, i.e., plasma simulations which combine, for example, fluid and particle models that interact with each other. Such sophistication will be an absolute necessity for the design of future experiments and eventual fusion reactors.

Key Words: Cray-1; ERATO; GAQ; ICED-ALE MHD; magnetic fusion; magnetohydrodynamics (MHD); National MFE Computer Center; PEST; National MFE Network; plasma physics; SUPERLAYER.

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Rapid Nuclear Chemistry for Determining the Properties of Short-Lived Fission Products

We have developed automatic systems for rapid chemical isolation and spectroscopic analysis of short-lived fission products. Using both batch- and continuous-mode systems, we are able to measure nuclear properties with a speed and accuracy unattainable by conventional chemistry. From the data bases thus obtained, we are deriving new information on decay properties and fission yields that is applicable to nuclear power safety, explosion diagnostics, and understanding of fundamental nuclear properties.

We have known fission for over four decades, yet it continues to present challenging problems both as to its fundamental nature as well as to its optimal use as an energy source for civil and military applications. Many of these problems can be attacked if the fission products are studied in detail. For years the long-lived fission products, which can be isolated by traditional chemical techniques, have been investigated. However, we have been quite ignorant of the short-lived nuclides with half-lives up to a few hundred seconds, mainly because the techniques of chemical isolation have required times far in excess of the decay half-lives; hence, these nuclides decayed before they could be measured.

For fundamental studies of fission, two important types of information come from the study of

short-lived fission products. The first is the abundance of each particular nuclide shortly after the fission event. These data should be explained by theories of the fission process. The other type of information is about the fission products themselves: their masses, nuclear structure, and decay properties. These fission products have many more neutrons than the stable nuclides of the same mass number, and so they offer tests of nuclear theories in unusual nuclides. Because fission produces these neutron-rich nuclides, we must understand them before we can understand more about the process that produced them.

The data on short-lived fission products also bear on several problems of fission reactors, in particular on loss-of-coolant accidents and the associated problem of decay heat from radioactive decay of the fission products. The general design of heat transfer loops is also influenced by the amounts of beta and gamma rays from the radioactive decay of these products.

In the area of weapons testing, the fission products are indicators of device performance. The post-detonation chemistry, which is one major cause of fractionation, is strongly influenced by the short-lived products.

To study short-lived fission product nuclei in detail, we have developed techniques of rapid chemical isolation and spectroscopy for these fission products. Because of the very short half-lives, the useful measurement period resulting from a single chemical isolation is very short, and only a

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(a) From periodic table of the elements:

IV-A	V-A	VI-A	VII-A
6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine
14 Si Silicon	15 P Phosphorous	16 S Sulfur	17 Cl Chlorine
32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine
50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine
82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine

Fig. 1. Abstracts from the periodic table of the elements and the chart of the nuclides for those elements or isotopes of interest in our program to develop techniques for rapid separation of fission-product isotopes of the group V-A and VI-A elements. Mass chains are all those nuclides with a given atomic mass number. For example, the mass-133 chain consists of ^{133}Sn , which decays to ^{133}Sb , which decays to ^{133}Te , and so forth.

(b) From chart of the nuclides:

1133 9s 20.8h	1134 3.6m 52.6m	1135 6.585h	1136 46s 85s	1137 24.6s	1138 6.5s	1139 2.4s
Te132 78h	Te133 55.4m 12.5m	Te134 42m	Te135 19.2s	Te136 21s	Te137 ~3.5s	
Sb131 23.0m	Sb132 4.1m 2.1m	Sb133 2.4m	Sb134 11.3s	Sb135 1.70s		
Sn130 3.7m	Sn131 63s	Sn132 40s	Sn133 34s			

Key for isotopes of interest:

☐	$t_{1/2} \leq 10 \text{ s}$
☐	$10 \text{ s} \leq t_{1/2} \leq 30 \text{ s}$
☐	$t_{1/2} \geq 30 \text{ s}$

Kr83 1.86h 11.5	Kr84 57.0	Kr85 4.48h 10.72s	Kr86 17.3	Kr87 76m	Kr88 2.84h	Kr89 3.15m	Kr90 32.3s	Kr91 8.8s	Kr92 1.84s	Kr93 1.28s
Br82 6.3 31.6m	Br83 2.40h	Br84 6.0m	Br85 2.87m	Br86 55.5s	Br87 56.1s	Br88 16.4s	Br89 4.4s	Br90 1.8s	Br91 0.6s	Br92 0.36s
Se81 57.3m 18.5m	Se82 9.2	Se83 69s 22.3m	Se84 3.3m	Se85 31s	Se86 15s	Se87 5.6s	Se88 1.5s	Se89 0.41s		
As80 16s	As81 33s	As82 13.7s 19s	As83 13.4s	As84 ~0.65s 5.3s	As85 2.03s	As86 0.9s	As87 ~0.3s			
Ge79 42s	Ge80 29.5s	Ge81 10s	Ge82 4.6s	Ge83 1.9s	Ge84 1.2s					

small fraction of the necessary data can be obtained by an individual measurement. We therefore repeat exactly the same measurement many times to build the statistical base. Furthermore, since the nuclide species of interest represent a small fraction of the total radioactivity, we separate that nuclide from the highly radioactive collection of fission products by remote means. Our facility includes both an automatic batch system (autobatch) and a system for continuous isolation of single-element fission products.

We have developed, in particular, rapid techniques to separate fission-product isotopes of the group V-A and VI-A elements (Fig. 1). We use gaseous hydride separation and transfer techniques for the antimony and arsenic isotopes. For bromine production we have used its precursor, selenium, followed by extraction of the daughter bromine, a technique that allows enhancement of 55.5-s ^{86}Br over 56.1-s ^{87}Br by more than a factor of 25, which compares with the approximate ratio of 1 produced by isolation of bromine from fission products. The isolation of tellurium from fission products has been done by a combination of hydride production followed by extraction in xylene. The half-lives we study for the Sb isotopes range from 11 s to a few minutes. The study of the As and Br isotopes is challenging because of the similarity in half-lives of ^{86}Br and ^{87}Br as well as 16.5-s ^{80}As , 19-s $^{82}\text{As}^{\text{m}}$, 13.3-s $^{82}\text{As}^{\text{g}}$, and 13.5-s ^{83}As .

AUTOBATCH

Since we wish to study neutron-induced fission products, we need a pneumatic tube to transport samples rapidly in and out of a neutron source, such as the Livermore Pool-Type Reactor (LPTR).¹ Next, within a few seconds or less, we must be able to extract the fission products from the transportation container (called a rabbit) and to isolate chemically the nuclide of interest. Once it is isolated, we must quickly measure its characteristic radiations before its level of activity drops too low. (Typically, for a species whose half life is 5 s, we have only 10 to 20 s in which to make a useful measurement; after that, the activity of the sample has dropped to such a low level that other species

Table 1. Improvements in the processing characteristics of our system to isolate shorter half-life fission products.

	Old system	New system
Transport time from LPTR to chemical lab, s	15	1.8
Time for chemical isolation, s	30	1.9
Shortest half-life studied, s	45	2.0
Minimum cycle time, s	480	30
Irradiations per 8-hr day	60	1000
Target-launcher capacity, number of rabbits	1	38
Time to deliver sample to detector, s	25 ^a	0 ^b

^aHand-carried.

^bPart of computer-controlled chemistry.

mask its characteristic radiations.)

We have had to improve considerably our original system, which was initially designed for the isolation and study of 2-min activities. Characteristics of the improvements are compared with the original system in Table 1; the improvements have come from our effort to automate fully both the chemical separation and the spectroscopy measurements.

The full cycle of operation for our automated system is diagrammed in Fig. 2. Rabbits containing doubly encapsulated 1-mg samples of U-235 in solution are shot into the reactor from an automatic rabbit launcher. A microprocessor controls the loading and firing from a magazine that holds 38 rabbits. A microprocessor loads and sends the rabbit through a pneumatic tube (activated by nitrogen gas) to the core of the LPTR. The sample is irradiated for a specific time, then the microprocessor sends it through a second pneumatic tube to a receiver located in a chemistry laboratory hood approximately 60 m from the core of the LPTR. Once in the receiver, the rabbit is punctured by a double concentric needle that ex-

Fig. 2. Full operating cycle for our automated system. (a) Automatic launcher sends rabbit to core of L.P.T.R. for irradiation; from L.P.T.R., rabbit is sent by pneumatic tube to chemistry laboratory. Fission products are extracted, and acid and carrier are added. As shown in (b), mixture is bubbled with nitrogen gas to purge fission-product gases, then sodium borohydride is added, producing group V-A and VI-A element hydrides. Gases flow through tube containing CaSO_4 into catcher made of inert substrate impregnated with potassium hydroxide in ethanol. Once Sb is on catcher, spectrometer is turned on. Simultaneously with measurement cycle, chemical separation parts of the system are cleaned. Once its measurement cycle is over, spectrometer is shut off, and catcher is cleaned and refurbished for next separation. Finally, rabbit is removed, and receiver block is ready for next rabbit.

tracts the fission product in a reaction vessel, adding acid and carrier (a small amount of antimony) in the process.

Purging with N_2 gas (see Fig. 2b) cleans out the gases produced during fission and precludes their daughter activities from being observed in subsequent spectroscopy measurements. The actual chemical separation of Sb from the other fission products is made by addition of sodium borohydride ($NaBH_4$) to the acidified fission products and carrier. The stibine and arsine (gaseous SbH_3 and AsH_3) are transported through a $CaSO_4$ trap that eliminates other hydrides produced by $NaBH_4$ reaction. The final step is destruction of the stibine with KOH in ethanol; the homologue AsH_3 passes through. This final step leaves the Sb on a substrate in front of a radiation detector. As soon as the final chemical step is finished, the microprocessor turns on the spectrometers for measurement.

An important feature of the microprocessor control is the capability for simultaneous operation. For example, spent reagents are cleaned from the chemistry system and new reagents replenished during the measurement period (Fig. 2). This reduces the cycle time and, hence, increases the number of measurements that can be made in an operational day. The actual number of measurements, then, depends only on the length of the measurement segment, which can vary from a short time—if gamma-gamma-time three-parameter coincidence measurements are being made on a short-lived activity such as 10-s ^{134}Sb decay—to 30 min in our experiments to measure the fission-yield isomer ratio of $^{132}Sb^g$ vs $^{132}Sb^m$. The measurement rate has been greater than 1000 isolation/measurement cycles in one 10-hour LPTR operating day.

We have developed a number of novel chemical techniques in our efforts to isolate rapidly some fission-product elements. For example, we have based some of our chemical isolations on the generation, transport, and selective absorption of the gaseous hydrides of class V-A and VI-A elements. We discovered that the mere injection of a caustic ($NaOH$) into the transport line isolated nearly pure As (see Fig. 3). (Although we had been

able to obtain excellent antimony separation on the time scale of 0.5 to 1 min using this same hydride technique combined with ion exchange, we found that the kinetics of ion exchange were too slow to be useful for the isolation of 10-s ^{134}Sb .) Also, we found that tellurium hydride could not be isolated by the gas-generation technique when a mass of tellurium carrier (typically 1 mg per separation) was added. However, we did obtain a good tellurium separation after we discovered that, in the gas phase, a massive amount of tellurium will decompose simultaneously by second-order reaction, much as its homologue sulfur does.

The study of some nuclides requires chemical separations on a time scale much less than their half-lives. For example, not until we were able to perform 10-s Sb separations were we able to study 850-s (12.5-min) $^{133}Te^g$ by itself (see Fig. 1). Several tellurium isotopes have half-lives in the range of 10 to 40 min. In order to isolate only $^{133}Te^g$, we had first to isolate antimony, allow it to decay, and separate the daughter tellurium. By selective timing of the separation steps, nearly pure $^{133}Te^g$ was obtained.

Since we must repeat our experiments for statistical significance, we want to assess the experiment's progress while we are taking data. Consequently, we have developed spectrometers that have the capability of on-line analysis of the data. One such spectrometer² allows nearly instant analysis of gamma-gamma coincidence spectra, instead of having a 2- to 7-day delay.

CONTINUOUS CHEMISTRY

When we want to study a species with a half-life of only a few seconds or less, the available measurement period is excessively small when compared to the amount of time required to process a discrete sample. A way to avoid such a low duty factor is to isolate the species of interest in such a way that our measurement apparatus observes an apparent steady-state source. This can be accomplished by taking a continuous-flow fission-product stream (solution) and selectively extracting the desired species from the solution into a second immiscible solvent. Until recently, the difficulty was that

several minutes have been required for phase separation of most immiscible pairs of solvents in minutes. This has been overcome by use of a high-

speed centrifuge.³ The technique was originally developed for the study of chemical kinetics and distribution coefficients.

This technique (called SISAK) has been developed around a centrifuge developed by Jan Rydberg and Hans Reinhardt of Chalmers Technical University in Gothenberg, Sweden. This centrifuge has a small (10-cm³) central bowl that rotates at approximately 20 000 rpm. At these speeds and volume, the residence time in the centrifuge is only 400 ms.

We have tested a dual centrifuge system and demonstrated the isolation of cerium on a short time scale. We are currently building a four-centrifuge system whose operation is diagrammed in Fig. 4. In Step 1, the fission products are extracted from a continuous fissioning source (target) by liquid or gas flow and then mixed with an aqueous stream; the stream is degassed to get rid of fission-product gases. In step 2, the aqueous phase is mixed with an organic solvent containing a chemical complexing agent (such as bis-2-ethylhexylortho-

phosphoric acid, HDEHP). In general, step 2 will extract more than one element. Hence, a selective second extraction (back extraction) is done in step 3 with the desired species in step 4. Further chemical purification and retention time for measurement can be obtained by choosing a suitable type of product collector (ion exchange, preformed precipitate, etc.). Step 5 is necessary to clean up the second organic phase and extractant of residual activity (daughter products, etc.) so that it may be recycled and used in step 3 again. Such a system has been used³ to isolate and measure activities as short as 800 ms.

DATA APPLICATIONS

Nuclear Power. In designing a power reactor, provisions must be made for several categories of hypothetical accidents. For example, if an accident causes the loss of the cooling water, automatic con-

Fig. 4. Diagram of four-stage centrifuge system currently under construction. Yellow shows organic phase; red, aqueous phase. (1) Gaseous or liquid fission-product stream is mixed with aqueous stream and then degassed. (2) Aqueous phase is mixed with organic solvent to extract elements. (3), (4) Since step 2 will extract more than one element, a selective second extraction (back extraction) is done in step 3 with the desired species isolated in step 4. (5) Second organic phase and extractant are cleaned of residual activity to be recycled and used again in step 3. This system can isolate and measure activities on the order of 1 s or less.

trois would instantly drop the reactor control rods back into the core, thereby stopping operation of the reactor and any further fission-product production. However, residual fission products holding a large amount of energy would remain. This energy could be converted into heat at a rate governed by the half-lives and by the decay energies of all the fission products present.

To design emergency cooling systems to compensate for this heat production, one approach is to identify those short-lived isotopes that produce the decay heat and then to calculate the rate of heat production. We have examined the contributions and their uncertainties from individual isotopes produced from ^{235}U fission products for a burst irradiation and for cooling times (t_c) of 10 and 100 s. For t_c of 10 s, more than 97% of the total decay power is due to about 84 isotopes. By summation of individual contributors, 26 isotopes account for 94% of the total energy variance. This data base is extremely useful for the flexible and efficient design of next-generation reactors.

Our first measurements for this application have been on the properties of the short-lived antimony isotopes 4.2-min $^{132}\text{Sb}^m$, 2.4-min $^{132}\text{Sb}^g$, 2.3-min ^{133}Sb , and 10-s ^{134}Sb . Our results show that even previously accepted average gamma-decay energy data are incorrect by as much as 45%. In Table 2, we compare our results with previous work.

Analysis of Underground Nuclear Explosions. The quantitative analysis of debris recovered from an underground nuclear detonation is complicated

because the residual reaction products used to measure various aspects of the fission process are not homogeneously mixed in the recovered samples. Following detonation, condensation and, subsequently, solidification occur in a nonuniform manner, such that volatile elements separate out differently than do refractory elements. Consequently, upon recovery we obtain nonuniform and nonrepresentative diagnostic samples due to the physical and chemical effects that segregate elements in the time between detonation and full underground equilibrium.

The temperature-pressure history that governs the fractionation during the condensation-solidification period is poorly understood. However, we can sometimes make predictions using computer modeling based on the thermal properties of the medium. The predictions can be checked by studies of the cavity gas composition at early times (a few minutes) and through correlation of species whose chemical nature is fixed during the course of condensation. Thermodynamic studies of the materials (present either as matrix material or as trace components) would lead to a better understanding of the phenomenology of chemical fractionation if the physical conditions were known and if the chemical nature of the fission mass chains later measured was known as a function of time. To know the nature of the mass chains, we must know the detailed properties of the rapid consecutive beta decay of the short-lived fission products that are changing the chemical composition with time along a fission product mass chain. The known properties must include not only fission yield values, half-lives, and decay characteristics (absolute gamma-ray intensities, etc.) but also beta-delayed neutron emission.

In the diagnostics using prompt-gas samples, particularly important is the mass-133 fission-product chain (see Fig. 5) in which not only chemical but physical changes occur. Unfortunately, little has been known of its exact properties. For example, literature values for the chain branching at antimony to tellurium vary by almost a factor of 100. In the past few years we have determined all the absolute values for the decay properties in the chain

Table 2. Changes in average γ -ray energies of isotopes associated with reactor-safety decay-heat isotopes.

Value	Isotope			
	$^{132}\text{Sb}^m$	$^{132}\text{Sb}^g$	^{133}Sb	^{134}Sb
E_γ , MeV/fission (previous work)	2.344	2.488	1.874	2.086
E_γ , MeV/fission (present work)	2.799	2.535	2.531	2.632
Percent change	19	1.9	45	26

Fig. 5. Properties of the mass-133 fission-product chain have been clarified by our work on these isotopes over the past few years. The absolute intensity of the major gamma ray associated with each isomer's decay is given (e.g., 2.5-min $^{133}_{51}\text{Sb}$ beta decays by 18% to $^{133}_{52}\text{Te}^m$ and 82% to $^{133}_{52}\text{Te}^g$, while the observed 1096-keV gamma ray represents 42% of all $^{133}_{51}\text{Sb}$ decay). The inserts show the change in percentage population of the various isomers from values previously in the literature to those measured by us. The left insert shows that the original ~20% population of ground state (g) and ~80% population of isomers (m) is actually 82% to the ground state and only 18% to the isomer. The right insert shows that previously the decay of 55.4-min $^{133}_{52}\text{Te}^m$ was thought to decay by 34% internal transition to the $^{133}_{53}\text{I}$ ground state and 66% to ground state. Instead we have discovered that there is beta decay to a 9-s ($19/2^-$) isomer in $^{133}_{53}\text{I}$ and that more than half the intensity ascribed to the internal-transition gamma ray belongs to transitions between high energy levels in $^{133}_{53}\text{I}$.

using our system. Our first experimental data² showed several unsuspected features in the properties of the decay chain that have been confirmed by our measurements. Particularly important are:

- The absolute intensity of the gamma rays from the $^{133}\text{Te}^m$ decay

- That 10% of all $^{133}\text{Te}^m$ decays go through a $9\frac{1}{2}^+ 19\frac{1}{2}^-$ isomer in ^{133}I at 1634 keV.

- That of the 334-keV gamma-ray intensity originally thought to be the isomeric transition for $^{133}\text{Te}^m$ decay to $^{133}\text{Te}^g$, only 60% represented the isomeric transition.⁴ The remaining 334-keV

Fig. 6 A partial decay scheme of $10s\text{-}^{133}\text{Sb}$ that we have constructed from our data is shown in the red portion of the figure and is compared to our theoretical calculations shown in the orange column. We have discovered an unsuspected influence on the lower energy-level properties of this closed-shell nucleus. Calculations with only the valence nucleons beyond shell closure fail to replicate the transition rates of the nuclear level decays. For example, our measured value of the $B(\beta^-; 6^+ \rightarrow 5^+)$ transition rates was more than an order of magnitude different than the predicted value (see inserted bar graph) using a simple model (calculation I). Only by including excitation of the core nucleons were we able to account for the experimental results (calculation II). The gamma transitions ending in square boxes are only observed in time-delayed coincidence, obtained in the three-parameter, gamma-gamma-time coincidence discussed previously.

gamma-ray intensity belongs to the unsuspected dominance of low-energy transitions at high excitation energy in ^{133}I .

These features are important for using the gamma-ray data to determine the yields of the early mass-133 fission-product chain. They will be used as the basis for our fission-yield measurements.

Fundamental Properties. During the course of obtaining the necessary metrology for nuclear power and explosion diagnostics, we are acquiring a large body of systematic information on the properties of highly unstable nuclei. These data allow us a unique opportunity to explore a number of fundamental problems of nuclear science. Among these are:

- New phenomena such as the extent and properties of beta-delayed neutron emission from nuclei
- Validity of statistical theories of nuclear fission.
- Statistical vs structural influence on beta-decay-strength functions at high excitation energies.
- Consequences of large neutron-to-proton ratios on nuclear properties such as shell structure, collective excitations, and coexistence of spherical vs deformed shapes.
- Search for dynamical symmetries in nuclei.

We have adopted a large-basis shell-model code that has been successful in describing nuclei that range from the light closed-shell nuclei to those in the $Z = 30$, $N = 82$ region.⁵ After testing gross nuclear properties, we have compared in detail the code's predictions against our results on the energy level properties of ^{132}Te , ^{133}Te , ^{134}Te , and ^{135}Xe . As an example, in Fig. 6, we compare our calculational and experimental results for ^{134}Te levels (as populated by the decay of 10-s ^{135}Sb). From these results we have discovered an unsuspected influence on the level properties of this closed-shell nucleus. Calculations with only the valence nucleons beyond shell closure fail to replicate the

transition rates of the nuclear level decays. Only by allowing the unsuspected influence of the closed-shell core nucleons were we able to account for the experimental results.⁵ Our measured value of the $6\frac{1}{2}^+ \rightarrow 6\frac{1}{2}^-$ versus $6\frac{1}{2}^+ \rightarrow 4^+$ transition rates was more than an order of magnitude different from the value predicted without the influence of the core nucleons.

CONCLUSION

We are continuing to improve our chemical isolation techniques and spectroscopic analysis of short-lived fission products. The observable half-lives of our original system have already been improved from 45 s to 2 s. With our new four-stage centrifuge system, currently under construction, we expect to further reduce the measurable isotope half-lives to under one second.

Key Words: automated chemical isolation; fission products; decay schemes; fission products; gamma emission; fission products—yields; nuclear chemistry; nuclear energy; nuclear properties.

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Mirror Fusion Reactors

We have carried out conceptual design studies of fusion reactors based on the three current mirror-confinement concepts: the standard mirror, the tandem mirror, and the field-reversed mirror. Recent studies of the standard mirror have emphasized its potential as a fusion-fission hybrid reactor, designed to produce fuel for fission reactors. We have designed a large commercial hybrid and a small pilot-plant hybrid based on standard mirror confinement. Tandem mirror designs include a commercial 1000-MWe fusion power plant and a nearer term tandem mirror hybrid. Field-reversed mirror designs include a multicell commercial reactor producing 75 MWe and a single-cell pilot plant.

To become a practical energy source, nuclear fusion must pass beyond the present research phase to scientific, engineering, and economic feasibility. Predicting the future course of fusion feasibility is risky, but the potential of fusion power is great. Ultimately, it promises low radioactivity and an inexhaustible fuel supply. In the nearer term, fusion neutrons can be used to breed tritium and fissile fuel. This fissile fuel can then be used to generate orders-of-magnitude more energy than from fusion alone by being burned in a fission reactor. We have developed a number of near- and long-term alternatives for tapping fusion power with reactors

based on three magnetic mirror-confinement concepts being studied now. This article describes these concepts and their potential reactor applications.

MIRROR FUSION DEVELOPMENT

Figure 1 depicts the evolution of mirror fusion concepts as seen by researchers at LLL. The early simple mirror proved to be an unstable plasma container and was replaced by the minimum- B mirror. From the center of a minimum- B magnetic field—produced either by a pair of solenoids and Ioffe bars, by a Baseball coil (shown in Fig. 1), or by a yin-yang coil—field strength increases in all directions and ensures gross (MHD) stability for the plasma. We have come to call the minimum- B configuration a standard mirror. Until 1976, this mirror concept was essentially the only one under study at LLL. Baseball II (now decommissioned), 2XIIIB (active), and the Mirror Fusion Test Facility (MFTF, presently under construction) are standard mirror experiments.

It is now clear, however, that end losses from a standard mirror severely limit its plasma Q (fusion power divided by trapped injected power). The search for enhanced- Q mirror machines has thus led to work on two new concepts: the tandem mirror and the field-reversed mirror.

By tandem mirror confinement, we mean three mirror cells on a common axis: two standard mirror cells are placed at either end of a series of cylindrical coils that make up a solenoid (Fig. 1). Each end cell provides a minimum- B magnetic field. Confinement

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Fig. 1. Evolution of mirror fusion concepts. The early simple mirror was subject to MHD instability and was replaced by the minimum- B mirror, now called the standard mirror. In such a mirror machine, the magnetic field strength increases in all directions from the machine's geometric center, providing MHD stability for the plasma. However, end losses limit the plasma Q (ratio of fusion power to injected power) of minimum- B mirrors. Thus, two Q -enhanced mirror configurations are now being investigated. In a field-reversed mirror, plasma is confined in a toroidal region of closed field lines generated by diamagnetic plasma currents in a nearly uniform background field. In a tandem mirror, a minimum- B mirror cell is placed at each end of a solenoidal cell. The electric potential of the two end-cell plasmas electrostatically confines the plasma in the solenoid.

in the solenoidal cell is enhanced by means of electrostatic stoppering provided by the plasma potential of the small end-plug plasmas. Our tandem mirror experiment, or TMX, is to be a proof-of-principle demonstration of the tandem mirror concept.

By field-reversed mirror confinement, we mean the confinement of plasma in a toroidal region of closed magnetic field lines generated by diamagnetic plasma currents in a nearly uniform background field (Fig. 1). So far, efforts to produce field reversal in the 2X11B facility by neutral-beam injection have not succeeded, although they have come very close.

Further experiments on this machine are planned. In addition, field reversal experiments will be conducted on TMX and MFTF.

The principles of a mirror fusion reactor are shown in Fig. 2. The deuterium and tritium fuel ions (D^+ , T^+) are magnetically confined in the center of the reactor. Those that fuse produce energetic neutrons and alpha particles ($^4He^{++}$). Unaffected by the magnetic field, the neutrons enter the energy-absorbing blanket. Neutron-lithium reactions in the blanket produce tritium makeup fuel for the reactor. The thermal energy deposited in the blanket is removed by the primary coolant (helium

Fig. 2. Principles of a mirror fusion reactor. Although this design suggests a tandem mirror reactor, the principles are the same for other mirror-confinement concepts. Deuterium and tritium fuel ions are confined in the center of the reactor (in a tandem reactor, the electrostatic stopping of the end plasmas enhances this confinement). Fuel ions that fuse yield neutrons and alpha particles ($^4\text{He}^{++}$). The neutrons enter the lithium blanket and react to produce tritium makeup fuel for the reactor. The blanket's thermal energy produces steam, which, in turn, is used to produce electricity. The energy of charged particles that leak out the ends is recovered by direct energy converters.

gas in Fig. 2). The coolant passes through a steam generator, and the steam produces electricity in turbine-generator units. Also shown in Fig. 2 is the end leakage of charged particles (unburned D^+ and T^+ as well as $^4\text{He}^{++}$), which occurs in all mirror reactors. The energy of this leakage can be recovered thermally or by direct energy converters, which decelerate the particles in an electric field and collect their charge on collector electrodes.¹

MIRROR FUSION EXPERIMENTS

Standard Mirror. The most important and successful mirror machine thus far has been the 2XIIIB experiment. Typical machine and plasma parameters for 2XIIIB are given in Table 1. For a reactor, plasma density in 2XIIIB is adequate and

ion temperature need only be increased tenfold, which is possible by neutral-beam injection at higher energies. However, confinement time must increase a thousandfold and is therefore the main issue.

The lifetime of ions (confinement time, τ) has been shown to scale with energy (ion temperature) to the 3/2 power. Simply raising ion temperature by a factor of 10 thus increases τ by 30. Another factor of 5 to 10 may result from raising the ratio of the mirror field to the central field and from considering the favorable mass effects of tritium, the heating due to alphas, and the diminished cooling due to cold plasma and cold electrons from the ends. This leaves an additional factor of 3 to 6 in confinement time to reach reactor conditions. As will be seen later, possible candidates to supply this factor are

Table 1. Typical 2XIIIB parameters.

Machine parameters	
Neutral beam	
Voltage, kV	20
Current, A	500
Duration, ms	10
Magnetic field	
Field strength B_{VAC} , T	0.7
Mirror ratio	2:1
Mirror-mirror length L , cm	150
Plasma parameters	
Density $\hat{n}$, cm ⁻³	1.5×10^{14}
Ion energy $\bar{W}_i$, keV	13
Electron temperature, eV	140
Beta ^a	1.7
Field reversal parameter $\Delta B/B$	0.7
$n\tau$ (cm ⁻³ · s)	10^{11}
Plasma size	
Radius R_p , cm	6
Length L_p , cm	16
Volume, litres	3.2
Vacuum gyro radius a_i , cm	3.5
R_p/a_i	1.7
L/a_i	43

^aRatio of plasma pressure to the pressure of the confining magnetic field.

the tandem mirror reactor and the field-reversed reactor.

Many problems have been solved in 2XIIIB, though many still remain. Gross motion of the plasma away from its equilibrium state (MHD instability) is completely suppressed even at remarkably high plasma pressures, where the plasma pressure averaged over the radial dimension is over 50% of the magnetic field pressure. Microturbulence due to the nonthermal ion energy distribution inherent in mirror machines has been largely suppressed by injecting relatively cold plasma along the open field lines to occupy the space outside the mirror confinement region. While this streaming plasma has suppressed microturbulence, however, it has also created another problem. The cold streaming plasma, which touches both the hot plasma and the end walls, requires power to sustain itself and cools the hot plasma it touches. This problem, called end-wall or electron thermal heat conduction, is now being studied.

Another solved problem is startup: creating and then building the density and temperature of a plasma to the desired steady-state conditions. Startup has been thoroughly demonstrated in 2XIIIB. We have also shown that impurities are not a problem experimentally because of the strong positive plasma electric potential that pushes out any impurity ion trying to enter. Also, the mirror plasma in 2XIIIB is quite tolerant of the rather high gas pressure—1.3 mPa ($\sim 10^{-5}$ Torr)—surrounding the hot plasma.

The success of 2XIIIB has led to a scaled-up experiment called the Mirror Fusion Test Facility (MFTF).² It is about two times larger than 2XIIIB in linear dimensions and its field, produced by superconducting magnets, is three times higher. The injection energy is scaled up to 80 keV from 20 keV, injection power will be raised to 60 MW from 8 MW, and neutral-beam time is 500 ms vs 10 ms. Besides scaling $n\tau$ with energy ($n\tau \propto T^{3/2}$), the radius of the plasma measured in ion gyroradii (as well as in centimetres) will be scaled up to 10 from 2 (30 cm from 7 cm). This radius scaling will test theoretical predictions that the important microinstability, called the drift-cyclotron-loss-cone mode, will become less vigorous as the radial density gradient is decreased.

Tandem Mirror. The electrical potential that naturally occurs in a standard mirror plasma can be used to confine plasma electrostatically in a solenoidal magnetic field by locating a mirror cell at each end. This concept looks so promising that a number of experiments, like our TMX,³ are being built to test it. The important advance embodied in this concept is a higher Q . It appears that Q can be 5 to 10, whereas the standard mirror has a Q of only 1 to 2. The concept's simple geometry, allowing modularity, is also noteworthy.

Tandem mirror experiments will address a number of problems. For example, gross stability is not guaranteed, because the solenoid is slightly unstable and is coupled to the stable end-plug magnetic wells with a transition magnetic field that is unstable by itself. The impurity problem could lead to pulsed operation to purge impurities, including the alpha particles resulting from D-T fusion. The

theoretically predicted electrical potential profile must also be verified.

Field-Reversed Mirror. The 2XIIIB machine contains so much plasma pressure that its diamagnetism comes very close to reducing the 9.7-T (7-kG) field to zero. With a factor-of-2 more confinement, the field would be reversed, which means the field lines would close on themselves. In principle, then, the lossy, open-lined standard mirror can become much less lossy, since losses would only occur across the field lines. The desired configuration is shown in Fig. 1. Such field-reversed states have routinely been attained with energetic electrons at Cornell University. The theta pinch at Los Alamos Laboratory has also achieved a field-reversed state composed of warm (100-eV) ions and lasting for 50 microseconds.

The field-reversed mirror reactor concept is based on field reversal sustained in steady state by energetic neutral-beam injection. The virtues of

such a configuration are a high Q (~ 5) and small size. The problems are how to create such a state and, once created, whether it will be stable and have a low enough loss rate.

STANDARD MIRROR REACTORS

Previous studies⁴ have shown that the standard mirror, as a fusion power reactor, would produce very expensive electricity. This is primarily because of the inherently low plasma Q of optimized reactor designs. (Q can be raised, for example, by depressing the central magnetic field strength and thus increasing the mirror ratio, but this decreases the fusion power density and shifts the design off-optimum, i.e., increases the cost of electricity still further.) More recent studies⁵ have shown, however, that the standard mirror in large sizes could be a fusion-fission hybrid reactor, breeding make-up fuel for fission reactors.

Commercial Hybrid. Figure 3 shows a standard

Fig. 3. Fusion-fission hybrid reactor based on the standard mirror. A yin-yang coil set (13-m mirror-to-mirror length) creates an 8.5-T magnetic field. The prestressed concrete reactor vessel (PCRV) houses the magnet, blanket, and primary heat-transfer loop. The plasma is heated and sustained by neutral beams.

mirror hybrid using a yin-yang coil set with a mirror-to-mirror length of 13 m and a maximum magnetic field strength of 8.5 T (permitting the use of niobium-titanium superconductors). With a Q of 0.64, this optimized commercial reactor produces 600 MWe of net electric power and 2000 kg/yr of plutonium, enough to provide makeup fuel for light-water reactors producing 6000 MWe of power. The estimated cost of electricity from this hybrid and its associated fission reactors is 30 mills/kWh, amortizing capital investment over a 30-year lifetime. Similar costs are obtained for this same hybrid design if the Th- ^{233}U cycle is used. By comparison, electricity from fission reactors being built today will cost about 25 mills/kWh.

The injector design for the hybrid reactor is based on the Lawrence Berkeley Laboratory's positive-ion injector. The reactor requires deuterium injectors with acceleration to 125 keV and tritium to 187 keV. The total injected power is 625 MW.

The blanket of the hybrid reactor contains U_3Si , a metallic alloy being used in fission reactors. Our reasons for this choice are its high uranium density, ease of fabrication, and comparatively high burnup capability (for a metallic fuel). Economic optimization of the fuel cycle for this reactor dictates a total fuel exposure of about 5 MW-yr/m² of 14-MeV neutron energy through the first wall. Table 2 lists the initial (beginning-of-life) and final (end-of-life) neutronic parameters of the U_3Si blanket.

Our mechanical design approach is to mount the

magnet, blanket, and primary heat-transfer loop all within a prestressed concrete reactor vessel (PCRV), like those developed for gas-cooled fission reactors. In the center of the vessel are the magnet and blanket; the steam generators and helium circulators are located around the periphery. The blanket is a spherical shell inside the magnet. In this way, the blanket and its cooling system are locked together so that no relative motion between them can occur, precluding the possibility of rupturing any of the coolant ducts. The reactor vessel also provides the main restraining forces for the magnet.

The blanket design concept avoids any major disassembly of the reactor during the blanket change operation by relying on remote assembly and disassembly of the blanket inside the reactor vessel. The blanket is made up of about 600 small, cylindrical modules, approximately 50 cm in diameter, with the blanket structure being suspended directly from the vessel's inside wall, as shown in Fig. 4. A refueling machine removes and replaces the blanket modules. It consists of a post that is inserted down through the center of the reactor and that has a pivoting arm to operate on the modules.

The local blanket multiplication and, therefore, local blanket power density increases by a factor of 2 over the life of the fuel (see Table 2). To limit the peak-to-average variation in the total blanket thermal power to about 10% (3600 MW average, 4000 MW peak), we have grouped the blanket modules into four quadrants. At intervals of one-quarter of the blanket life, the reactor is shut down and one quadrant of the blanket is refurbished with new fuel assemblies. In this way we will establish an equilibrium fuel cycle in which the four quadrants are each at a different exposure. The primary heat transfer and power conversion loop capacity are designed to accommodate the 10% power variation.

Pilot Plant Hybrid. Reducing the physical size of the commercial hybrid degrades its performance because of reduced Q and decreased blanket coverage. We have, therefore, designed a small, pilot-plant hybrid as a net power producer. That is, the power generated by a fission reactor using the bred fissile fuel exceeds the hybrid's electrical power input.

Table 2. Time-dependent U_3Si blanket neutronic parameters.

	Initial	Final
Exposure, MW-yr/m ²	0	0
Blanket energy multiplication	8.8	18.4
Plutonium atoms produced/neutron	1.85	1.75
Percent heavy metal converted to plutonium	0	2.3
Percent heavy metal fissioned	0	0.75
Tritium atoms produced/neutron	1.05	1.42

Fig. 4. Cutaway of the blanket and shield for a standard-mirror fusion-fission hybrid reactor. The blanket, suspended from the inside wall of the prestressed concrete reactor vessel, consists of some 600 cylindrical modules. Every quarter of the blanket life, a refueling machine removes and replaces the modules in one quadrant of the blanket.

Solenoidal magnets and four Ioffe bars create the minimum- B magnetic well (Fig. 5). Because of the reduced constriction at the mirror throat, we were able to design a smaller reactor with this magnet than with the spherical yin-yang magnet. The mirror-to-mirror length is 5 m, the inside radius of the solenoidal magnets is 1.4 m, and the radius to the outside of the Ioffe bars is 2.5 m. The central magnetic field strength is 2 T, the mirror field is 4 T,

Fig. 5. Magnet for a small, pilot-plant hybrid reactor based on the standard mirror. The reactor would be a net product producer—i.e., the power generated by its associated fission reactor using C-26 bred fissile fuel would exceed the electrical power input to the hybrid.

and the maximum field at the conductor is 8 T, allowing the use of niobium-titanium superconductor (as in MFTF and the commercial hybrid).

The neutral-beam injection energies are 50 keV (D) and 75 keV (T). The predicted plasma parameters are a plasma radius of 34 cm, a Q of 0.18, and a fusion power of 3.7 MW. The peak first-wall neutron loading is 0.24 MW/m^2 .

The predicted performance of this hybrid pilot plant with a U^{235}Si blanket is given in Table 3. Note that the reactor meets its net power production criterion with no recovery of the plasma end leakage.

FIELD-REVERSED MIRROR REACTORS

We have developed a plasma model for the field-reversed mirror based on very limited experimental and theoretical knowledge. Basic to our model is the assumption that a stable field-reversed plasma can be sustained by injection of a neutral-beam current sufficient to balance the particle loss rate. We assume a long, fat toroidal plasma. We also assume

Table 3. Power balance in MWe for the standard mirror hybrid pilot plant.

Output	
Hybrid electric power	8.7
Equivalent electric power produced from plutonium (18.0 kg/yr)	57.9
Gross electric output power	66.6
Input	
Injector power ^a	-34.7
Net electric power ^a	31.9

^aHybrid and fission reactors.

that the particle confinement time is proportional to the ion-ion scattering time and that the size of the field-reversed plasma, measured in terms of minor radius divided by ion gyroradius, is limited by stability to about 5. As a result of this latter assumption, the field-reversed plasma layers are predicted to be quite small, usually producing tens of megawatts of fusion power.

For a commercial power reactor, we have proposed a multicell arrangement wherein a series of field-reversed plasma layers are arranged along the axis of a long superconducting solenoid that provides the background magnetic field. We have optimized the parameters of such a reactor based on the coupling of our plasma model to an analytic model of a field-reversed mirror reactor cell (blanket, shield, and magnet coils), on a power balance analysis, and on a cost estimate. The design calls for an 11-cell reactor producing 75 MWe net electric power. Reactor parameters are listed in Table 4; one cell of the reactor is shown in Fig. 6.

One of the complications of a multicell, field-reversed mirror is that the attractive force between two adjacent plasma toroids (due to their field-reversal currents) must be resisted by an axial magnetic well in each cell. We propose to produce these axial wells by placing a circular mirror coil between every two cells at the first-wall radius. The mirror coils are resistive copper coils.

We anticipate that stability of the field-reversed mirror plasma may require a radial magnetic well in each cell. We propose to produce these radial wells

Table 4. Field-reversed mirror reactor parameters.

Performance	
Net power, MWe	75
Fusion power, MW	220
Plasma Q	5.5
Average neutron wall loading, MW·m ⁻²	1.7
Recirculating power fraction	0.46
Plant efficiency	0.29
Physics parameters	
Injected current into each cell, A at 200 keV	18
Beta ^a	1.5
Plasma minor radius, m	0.07
Plasma major, radius, m	0.14
Plasma length, m	1.0
Peak plasma density, cm ⁻³	6.5×10^{14}
Technology parameters	
B/VAC , T	4.1
Injection energy, keV	200
First wall radius, m	0.73
Cell length, m	2.0
Number of cells	11

^aRatio of plasma pressure to the pressure of the confining magnetic field.

with a set of four Ioffe bars passing axially through the reactor. These coils are also made of copper and placed at the first wall.

We have designed a single-cell version of the above reactor as a fusion pilot plant. For this single-cell reactor, which closely resembles the cell shown in Fig. 6, the magnet consists of a pair of large superconducting solenoids and a set of copper Ioffe bars placed at a radius of 60 cm. (In this design, the solenoids will create the axial well, and thus no mirror coils will be needed.) The blanket and shield are between the Ioffe bars and the solenoids. The vacuum magnetic field strength at the center of the cell is 4.1 T. The maximum magnetic field strength at the conductor is 7.5 T, within the capability of niobium-titanium superconductor. The resistive loss in the Ioffe bars is 3.3 MW. In addition, neutron attenuation by the Ioffe bars causes an additional heat deposition in the copper equal to 1.9 MW.

The fusion power of this single-cell reactor is 20 MW. Taking the blanket energy multiplication to be 1.2 and the thermal conversion efficiency to be

Fig. 6. One cell from our field-reversed mirror reactor. The design calls for 11 field-reversed plasma layers arranged along the axis of a superconducting solenoid sustained by neutral-beam injection. Copper mirror coils on both ends of each toroidal plasma produce axial magnetic wells to resist the attractive force between adjacent plasmas. A set of four copper Ioffe bars, placed at the first wall, produces radial wells to enhance the plasma's stability. The magnet for our single-cell field-reversed mirror reactor is the same except that the two mirror coils are not needed.

0.35 and including the effect of neutron attenuation in the Ioffe bars, we calculate the gross electric power from the blanket to be 5.9 MW. Another 5.2 MW comes from the end-leakage direct converters (including thermal conversion of their rejected heat). The neutral-beam injectors (efficiency 0.7) require 5.3 MW input power, and the power requirement of the Ioffe bars is 3.3 MW. Thus, the net electric power for this pilot plant is 2.5 MWe.

TANDEM MIRROR REACTORS

Typical parameters for our tandem mirror reactor are given in Table 5; the reactor design is shown

in Fig. 7. The reactor concept came out of an intensive search for a Q -enhanced mirror reactor. Its striking features are a high Q (~ 5) and the simplicity of the basic cylindrical geometry, which allows modular construction of the first wall, blanket, and magnet.

The end-plug plasmas are maintained by the continuous injection of 200 MW of 1.2-MeV D^0 into each plug. The superconducting magnet to hold the high-density, high-energy plasma must produce a magnetic well with a central field strength of 17 T. The plasma that leaks out of both the plug and solenoidal regions is magnetically guided into the end expander tanks, where direct conversion by a set of grids resembling a triode vacuum tube is accomplished.

We have identified two problems with this design: (1) the feasibility of a neutral-beam injector that will run continuously, reliably, and efficiently at 1.2 MeV, and (2) the means for keeping the concen-

Table 5. Tandem mirror reactor parameters.

Performance	
Net power, MWe	1000
Fusion power, MW	2500
Plasma Q	4.8
Neutron wall loading, MW·m ⁻²	2
Recirculating power fraction	0.43
Plant efficiency	0.34
Physics parameters	
Trapped current into each plug,	
A at 1.2 MeV	220
Plug beta ^a	1.0
Plug plasma radius, m	0.48
Plug particle nr, s·cm ⁻³	2.5×10^{14}
Central-cell fueling current (cold), A	1100
Central-cell beta	0.7
Central-cell plasma radius, m	1.2
Central-cell plasma density, cm ⁻³	8.6×10^{14}
Central cell particle nr, s·cm ⁻³	7.7×10^{14}
Technology parameters	
Plug B_{VAC} , T	16.5
Plug B_{mirror} , T	17.6
Central cell B_{VAC} , T	2.4
Plug injection energy, MeV	1.2
First-wall radius, m	1.6
Central cell length, m	100

^aRatio of plasma pressure to the pressure of the confining magnetic field.

Fig. 7. Core of our tandem mirror reactor. The central cell is 100 m long; the first-wall radius is 1.6 m. Continuous neutral-beam injection maintains the end plug plasmas. Plasma leakage from the end cells and solenoid is guided magnetically into end expander tanks containing direct converters. Advantage of this reactor design include a high Q (~ 5) and modular construction of the first wall, blanket, and solenoid magnet.

tration of alpha particles low, since these particles can prevent steady-state burn. An improved magnet and shield for the end plugs is required. Likewise, means for getting higher Q 's and for coping with recirculation power more efficiently and cheaply are needed.

Crucial physics data, which may strongly affect the reactor design, are also needed. The power required to maintain a stable plasma in the plug cell is a critical factor. Another crucial issue is the suppression of electron thermal heat conduction to the end walls. The grids of the direct energy converter are predicted to handle this suppression. Gross stability of the solenoidal plasma by the plug plasmas must also be verified.

The use of the tandem mirror concept for the production of fissile material (^{233}U or ^{239}Pu) results in design parameters that are much less demanding than those for the direct production of electricity. For such a fusion-fission hybrid reactor, the two-component operating mode is used. That is, tritium at low energy is electrostatically confined in the solenoid, and deuterium at 100–200 keV is injected

into the tritium plasma. Some of the deuterium ions fuse while slowing down. Because the tritium is relatively cold, a greater leak rate than for the tandem mirror reactor occurs, providing a greater streaming plasma in the end plugs, which will enhance stability. The lower electron temperatures result in lower potential plugging barriers, which greatly alleviate the end plugs' tendency to confine alpha particles.

CONCLUSIONS

Both the tandem and the field-reversed mirror appear promising as fusion power reactors because their Q values are five or more times higher than for the standard mirror. Both mirrors also hold the promise of making relatively simple reactors. In fusion-fission hybrid configurations, this simplicity implies much nearer term applications. Of course, many physics and technology questions remain to be answered before mirror fusion reactors become a reality. Current and future experiments at LLL—on 2XIIB, TMX, and MFTF—are addressing these questions.

Key Words: field-reversed mirror reactor; magnetic mirrors; MFTF; Mirror Fusion Test Facility; mirror machines; nuclear reactors; power reactors; reactors—design; Tandem Mirror Experiment; TMX; thermonuclear reactors; Two X.

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