D
-20-63
W.B.

Dr. 1342

I-8924

Prepared for DOE under contract
No. W-7405-Eng-48

About the Cover

Computer-simulation of a steel spherical projectile (2.5 cm in diameter and traveling at 1.5 km/s) normally impacting a disk of PBX 9404 high explosive that is covered by a uranium-238 plate. The calculation was performed using the DYNAS2D computer program which incorporates our latest shock-initiation model. The colors are computer generated: blue indicates unpressurized explosive, red denotes any pressure greater than 3.0 GPa, and the other colors show intermediate pressures. This problem illustrates how complex problems involved with the use of high explosives can be successfully treated with our shock-initiation computer model. The model was developed from data acquired using state-of-the-art experimental techniques. For further information about shock initiation in high explosives, see the article beginning on p. 1.

About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to conduct nuclear weapons and controlled thermonuclear reaction research. Today, about 60% of our resources are devoted to defense programs, which include weapons and laser fusion research. Other major areas of focus are: magnetic fusion energy; laser isotope separation; chemistry, engineering, and physics research; biomedical and environmental sciences; applied energy technology; and work for other Federal agencies. The *Energy and Technology Review* is published monthly to report on accomplishments in unclassified programs. A companion journal, the *Research Monthly*, reports on weapons research and other classified programs. Titles from recent issues of the *Energy and Technology Review* are listed opposite the inside back cover.

Scientific Editor

Paul S. Brown

General Editors

Richard B. Crawford
Mary Ann Esser
Patricia L. Lien
Eleanor M. O'Neal
Palmer T. Van Dyke

Graphics Designers

John Schuster
Paul M. Harding

Production Staff

Louisa Cardoza
Kim Osterhoff

0/20-83
w.B.

UCRL--52000-83-2

DE83 010360

E&TR

Energy and Technology Review

Lawrence Livermore National Laboratory

February 1983

Shock Initiation of High Explosives

1

In recent years, we have made advances in our experimental and computer modeling techniques to greatly improve our understanding of the response of various high explosives to an initiating impulse.

Diamonds: Powerful Tools for High-Pressure Physics

11

Diamonds, prized for their brilliance and sparkle, have many other unique properties. Their hardness and transparency make them especially valuable as anvils in investigations of the high-pressure behavior of various materials.

Neutron Diagnostics for Magnetically Confined Plasmas

20

We have developed spectrometers for measuring neutrons emitted by hot plasmas, enabling us to obtain information on mean ion energies and other parameters of interest in magnetic fusion experiments.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

PORTIONS OF THIS REPORT ARE CLASSIFIED

It has been reproduced from the best available copy to permit the broadest possible availability.

UCRL-52000-83-2
Distribution Category UC-2
February 1983

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

sample of explosive. These tests were essentially "go" or "no go"; the explosive either did or did not react, and the data consisted of statistics. Similar experiments by another investigator might or might not agree; there was very little basis for preferring one set of data over another.

The same could be said of the inert-gap test, in which we made the shock from a detonator pass through a layer of plastic or other inert barrier material before it reached the high explosive being tested. The minimum barrier thickness required to prevent detonation of the sample was, by definition, the "gap sensitivity" of the sample explosive. As long as we kept all the other elements of the test constant and changed only the thickness of the barrier, we could use the results as a measure of the explosive's sensitivity. The input shock stimulus was poorly characterized, however, and if we changed one parameter we would have to repeat the whole series of tests. Again, there was no general theory that would enable us to predict reliably the effect of an experimental variation.

The most useful tests available were those in which we measured the run distance to detonation. We established a reactive shock with a given pressure input at one face of a block or wedge of explosive material and allowed it to propagate. At some point, the shock would turn into a detonation front; the run distance before the onset of detonation was recorded with a streak camera. A plot of run distance vs input pressure is a very important measure of the explosive's sensitivity. Here again, however, the test results were strongly dependent on experimental conditions, and they provided no indication of the mechanism of initiation.

In late 1977, we started to acquire an entirely new class of explosive initiation data.¹ We began to study explosives with embedded stress and particle-velocity gauges and to record temperature changes with fast infrared radiometers. These experiments provided an insight into a variety of phenomena taking place in high-explosive initiation.

Most of these experiments were done in simple one-dimensional geometries, which simplified data collection and analysis. We now have accumulated a large body of data using ever-improving techniques. This data base has contributed substantially to the development of a comprehensive shock initiation model that we use to perform computer-simulation studies of intentional initiation, accidental initiation, vulnerability to enemy or terrorist destruction, and performance under a variety of environmental conditions.

A measure of the success of the model is its ability to describe the sometimes anomalous behavior of the important new insensitive high explosives (IHEs). The remarkable insensitivity of TATB (triaminotrinitrobenzene), the principal component of IHEs, to a large variety of accidental stimuli has given it an increasingly important role in improving weapons safety. We are now in a position to understand other practical and more complicated initiation situations, both deliberate and accidental.

Hot spots, small regions of high temperature resulting from shock interactions at voids and other discontinuities in the high explosive, are now recognized as the primary mechanism for heterogeneous shock initiation. To understand the effects of particle-size distribution, ambient temperature, porosity, and other important physical properties, and to account explicitly for these in our model, we need to know how these properties affect the ignition and subsequent growth of hot spots. The use of infrared radiometry and embedded gauges allows us to observe the evidence for hot-spot ignition and evolution with two diverse techniques, one measuring temperature and the other measuring stress or particle velocity. Simultaneous application of these techniques should enable us to characterize these hot spots so that we can determine how the shock-initiation model depends on the physical and chemical properties of the explosive.

Even though we have not yet reached our ultimate goals, we now have a large body of knowledge and

experience that allows us to approach many complex practical problems in initiation. The following sections tell of our progress in this direction, driven by applications of high-explosive technology to weapons programs.

Embedded Gauges to Measure Stress and Particle Velocity

In the last five years, we have greatly expanded the scope, quantity, and quality of the results obtained from embedded manganin stress gauges. We have been using these gauges in studies of LX-17 (a formulation of TATB and a polymeric binder), RX-26-AF (a nearly equal mixture of TATB and HMX plus a binder), and PBX 9404 (a conventional, moderately sensitive plastic-bonded explosive consisting mainly of HMX). Table 1 compares some properties of these explosives. LX-17 is extremely insensitive but possesses low energy. RX-26-AF is an attempt to combine the good features of both HMX and TATB.

Figure 1 shows experimental pressure histories for PBX 9404 and LX-17.

The PBX 9404 data (Fig. 1a) show the characteristic build-up to detonation from a low-pressure shock of a conventional explosive. The corresponding LX-17 data (Fig. 1b) show that a much higher initiation shock amplitude is required for build-up to detonation in about the same run distance and that this build-up occurs at the shock front, not behind it as in the PBX 9404.

To provide the data that will enable us to determine the amounts and rates of explosive reaction, we performed a number of one-dimensional experiments in the target chamber of a 101-mm single-stage gas gun. The data also will be useful for testing our shock-initiation model (discussed later). We used flat projectiles to induce planar shocks in the high-explosive targets, and we embedded numerous electromagnetic particle-velocity gauges in the targets to record the flow of the material under shock.

Figure 2 shows the experimental arrangement of these particle-velocity gauges and a typical set of data. A homogeneous, externally applied

Reactive Flow Lagrange Analysis

Reactive flow Lagrange analysis (RFLA)² requires that the particle-velocity derivatives be used to calculate the flow fields using the conservation of mass, momentum, and energy. For the conservation of mass, we write:

$$V(h,t) - V(h,\tau) = V_0 \int_{\tau}^t \left(\frac{\partial u}{\partial h} \right) dt, \quad (1)$$

where V is the specific volume; u is the particle velocity; h is the Lagrange distance (original location of the gauge); τ is the Lagrange time (when the gauge first sees movement); t is the absolute time; and the subscript 0 denotes the uncompressed material in front of the wave and H refers to the shocked state.

For the conservation of momentum, we use the equation:

$$V_0 [P(h,t) - P(h_H,t)] = \int_{h_H}^h \left(\frac{\partial u}{\partial t} \right) \partial h, \quad (2)$$

where h_H is the location of the shock front. If we already have measured the pressure and velocity histories, this equation provides an independent check of

the pressure and confirms that our gauges are accurately recording the build-up process.

For the conservation of energy, we have:

$$e(h,t) - e(h_H,t) = -V_0 \int_{\tau}^t P \left(\frac{\partial u}{\partial h} \right) dt, \quad (3)$$

where P is the pressure and e is the energy. Then, we use suitable equations of state for the products (p) and the unreacted explosive (x),

$$e_p = e_p(P, V_p), \quad (4)$$

$$e_x = e_x(P, V_x),$$

where

$$V = (1 - \lambda) V_x + \lambda V_p, \quad (5)$$

$$e = (1 - \lambda) e_x + \lambda e_p,$$

Knowing $u(h,t)$ and $P(h,t)$ at one of the gauge locations from experiment, we use Eq. 1 to determine $V(h,t)$ and Eq. 2 to determine $P(h,t)$. We then solve Eqs. 5 for λ , the extent of reaction.

Table 1 Energy and sensitivity of PBX 9404, LX-17, and RX-26-AF. PBX 9404 is a conventional (moderately sensitive) explosive, almost pure HMX. LX-17 is an insensitive high explosive, almost pure TATB. RX-26-AF is a blend of HMX and TATB, with intermediate properties.

High explosive	Initial density, g/cm ³	Chapman-Jouget pressure, ^a GPa	Energy per unit mass, ^b (km/s) ² /2	Run distance to detonation for 10-GPa input shock, ^c mm
PBX 9404 (94% HMX + binder)	1.84	37.0	1.295	1.5
RX-26-AF (47.5% HMX, 48.7% TATB + binder)	1.84	32.5	1.076	2.2
LX-17 (92.5% TATB + binder)	1.89	30.0	0.870	20

^aThe steady-state pressure attained at the leading edge of a sustained detonation wave in the high explosive.

^bThe kinetic energy delivered to a cylindrical copper wall containing the high explosive, which has detonated and reached a volume expansion of 2.4.

^cDistance of travel for a sustained shock pulse before detonation. This is a measure of the shock sensitivity; the smaller the number, the more sensitive the material is to shock.

Fig. 1

Experimental manganin stress histories for a sustained shock pulse in high explosive. Each curve represents the output of a gauge at a different depth (noted at the base of the curves) from the impact surface.

(a) PBX 9404, with an input pulse of 2.5 GPa. (b) LX-17, with an input pressure of 11.6 GPa (chosen to give approximately the same run distance to detonation, as in PBX 9404).

magnetic field must be provided perpendicular to the direction of material flow. The gauge elements are oriented at right angles to the field and the gauge leads are parallel to it. The gauge

Fig. 2

Particle-velocity experiment and results. (a) An exploded view of an arrangement of multiple particle-velocity gauges sandwiched between cylinders of high explosive. Notches cut from rim of the flyer are intended to minimize signal distortion at the leads. (b) A set of experimental particle-velocity histories for RX-26-AF (a mixture of HMX, TATB, and an inert binder). The numbers alongside the curves refer to the depths of the gauges from the impact plane, in millimetres. The impact pressure is 2.7 GPa.

is thin enough that it moves promptly with the material flow when the shock arrives, with a rise time of about 30 ns in the induced voltage on the moving element.

The voltage in this moving element is directly proportional to its velocity. With a rise time of about 30 ns, the 25- μm -thick aluminum gauges cause only minimal flow perturbation. (For full detonation experiments, as opposed to this experiment involving building to detonation, we have found it necessary to add an insulating coating around the gauge element to protect it from the harsh detonation environment.)

As a cross check on our measurements, we can calculate the pressure history from the measured particle-velocity flow field and compare the result with an experimental pressure history. Such correlations are highly consistent, indicating that our gauges are accurately recording the build-up process.³

To derive reaction histories, we use a technique called reactive flow Lagrange analysis (RFLA) in which we need both a suitable equation of state and high-quality particle-velocity flow histories (see the box on p. 2). From the data obtained for RX-26-AF, we have calculated the fraction-reacted history shown in Fig. 3. The unusual feature of this history is that it shows two separate regions of increasing reaction rate, which may indicate the separate initiation behavior of HMX and TATB.

We are also developing miniature manganin stress gauges, scaled down to a fraction of the regular size, for measuring diverging shocks in a large sample of high explosive initiated by a hemispherical detonator. The goal of the experiments is to determine how a small hemispherical charge of a sensitive, energetic explosive initiates an IHE sample such as TATB. The reduced gauge size allows us to place several gauges close together on the same experiment and to define more precisely the location at which the stress is being measured (important in the diverging flow pattern). The results indicate that this technique may become an important new application of manganin

gauges to detonator technology, which is of crucial importance to weapons performance. However, further work is necessary to arrive at the exact gauge cladding required to withstand the highly disruptive environment of violently reacting or detonating explosive while, at the same time, faithfully reproducing the flow.

Direct Measurement of Hot Spots

Within the past few years, our technique of directly observing hot-spot formation in shocked explosives by means of their infrared emission has become routine for studying fundamental processes of initiation. One of the best approaches has been to use an impedance-matching, infrared-transmitting window to simulate the interior of a block of high explosive. If the window is a good impedance match (i.e., has a density and shock velocity similar to that of the explosive), then in principle, the shock velocity is not affected by the interface between the explosive and the window. With such a window, the explosive material is inertially confined, and the infrared emission collected depends on the energy released within a layer of the explosive by the shock-induced reactions of interest. (In practice, the results are somewhat dependent on careful and consistent preparation of the high-explosive surface.)

An important feature of this technique is that we measure the emittance in two separate wavelength bands, (as a function of time). Since the emittance depends primarily on the fractional area of any hot spots presented to the detector and on their emissivity, the emittance is a measure of the fraction of the material consumed by reaction at any given instant (see the box on p. 6). Furthermore, the use of two wavelength bands allows us to infer the "color" of the radiation and hence the temperature.

Figure 4 shows several fraction-reacted histories derived in this manner from time-resolved radiance measurements in PBX 9404. The slopes (reaction rates) depend strongly on time (see also

Fig. 3

Fraction-reacted history for RX-26-AF at a depth of 6 mm and an impact pressure of 2.7 GPa, calculated by means of reactive flow Lagrange analysis. This calculation takes place in two steps; starting with the gauge records, the code first integrates the equations of motion to determine the flow fields and then calculates a reaction rate using these flow fields and an equation-of-state relationship for the explosive. The changes of slope in this curve may indicate two separate reactions.

Fig. 4

Infrared radiometer measurements for several 101-mm single-stage gas gun impact experiments at a variety of input shock pressures (in GPa). The PBX 9404 targets were viewed through potassium chloride windows. Data are reported as the ratio of the observed radiance signal to the signal that would have resulted if the entire explosive surface were a blackbody. These curves are noteworthy for the rapid increase in slope (reaction rate) with time. There is also an extreme dependence of the initial slope on input shock pressure, although this is less easily seen from these plots.

Fig. 5

Emittance histories for several 101-mm gas gun impact experiments on two kinds of TATB with potassium chloride windows: fine grained TATB, red curves; coarse TATB, blue curves, (input shock pressures in GPa). The fine-grained TATB had a mean particle size of 9 μm ; the coarse, 58 μm . Each was pressed to the same nominal density, 1.86 g/cm^3 . Comparison of the pair of curves near 5.1 GPa and the pair near 7.5 GPa reveals that, in both cases, the coarse TATB initiates before the fine, but the initial reaction rate (slope) is higher in the fine TATB.

the pressure histories in Fig. 1); the initial slopes depend strongly on the initial shock stress. The former dependence results in a linear relationship between reaction rate and pressure. The latter observation implies a large power dependence of the initial reaction rate on input shock strength. We conclude from this that the initial number or volume of hot spots is extremely dependent on shock strength. These two observations taken together imply separate mechanisms for ignition and subsequent growth of the hot spots.¹

We assume that the increase in measured pressure using the manganin gauges in PBX 9404 is directly proportional to the fraction of explosive that has reacted. The rate of pressure increase initially measured following the shock is strongly dependent on input pressure, while the slopes of each experimental curve increase less strongly as the measured pressure increases. (As shown in Fig. 1, the pressure increases

at the deeper gauge locations because the reaction is building up at the shock front.) The similarity of the conclusions derived from two diverse experimental techniques (radiometry and pressure measurements) is strong evidence for their validity, and it represents the best experimental evidence yet for the hot-spot initiation concept.

Recent infrared work on TATB shows a similar dependence of fraction-reacted histories on pressure, but we also discovered a large effect of particle-size distribution (Fig. 5). In these fraction-reacted histories for each of two different TATB particle-size distributions pressed to the same density (and hence the same porosity), there are two obvious differences. First, signals arise sooner in the coarse-grained material; second, the extent of reaction is initially much greater in the fine-grained material for similar input shock pressures.

Our interpretation of these data⁵ is that the hot spots of the coarse TATB are larger because the particles are larger. Larger hot spots lead to more immediate reaction, accelerating the shock wave, but, because the specific surface area is less in this material than in that composed of fine particles, the reaction rate is initially slower. On the other hand, the smaller hot spots of the fine TATB yield less pressure and velocity increase in the shock front, but, because the specific surface area is much greater, the reaction rate builds rapidly. In other words, the reaction builds faster at the shock front in the coarse TATB but faster following the front in the fine material. This interpretation is consistent with the results on PBX 9404, namely, that a larger initial reaction rate implies a larger number of hot spots.

We have recently developed even faster infrared radiometers (with rise times of 5 ns) for use in reactive flow diagnostics. They have given us the added capability of resolving the heating near the shock front from that in the following reaction. Preliminary data on TATB have confirmed the general conclusions arrived at with the slower radiometers.

Infrared Radiometry

The emittance is defined as the ratio of the observed radiance signal to the signal of a blackbody at the same temperature. Because the true blackbody temperature is not known, we use the two-band signal ratio to estimate the blackbody temperature. Then, we use the equation,

$$\epsilon_i = \epsilon^b \cdot f = \frac{W_i^{\text{obs}}}{W_i^{\text{bb}}},$$

to evaluate the fraction reacted, where ϵ_i is the emittance of the i th band fraction of high explosive burned, ϵ^b is the emissivity of the hot spots (assumed to be unity), f is the extent of coverage of the hot spots expressed as a fraction, W_i^{obs} is the observed radiance signal, and W_i^{bb} is the blackbody signal expected at the inferred "color" temperature.

Computational Results

Five years ago, we had just begun to incorporate into our hydrocodes a reactive flow model based on the concept of separate mechanisms for ignition and growth.¹ At the time, we had two models; since then, we have condensed our two model versions into one. We have further improved the model by revising the high-pressure description of the unreacted explosive, by taking into account the shear modulus and yield strength of the explosive, and by changing parameters of the rate law. The improved version is:

$$\frac{\partial F}{\partial t} = I(1-F)^{2/9} \left(\frac{p_s}{p_0} - 1 \right)^4 + G(1-F)^{2/9} F^{2/3} P^z, \quad (1)$$

where F is the fraction reacted, p_0 and p_s are the initial and shocked densities, respectively, P is the pressure, and I , G , and z are adjustable constants.⁶ In this expression, the first term controls the ignition of a small amount of explosive by the shock wave. The second term, which represents the subsequent

spherical expansion of the hot spots, dominates at higher pressures. For each of the very different explosives studied (PBX 9404, TATB, cast TNT, and PETN), we were able to derive a set of constants that characterize that material. Using this rate equation, we successfully matched both gauge measurements and the run distances to detonation as a function of shock pressure at various initial densities for the various explosives.

In Fig. 6, we compare the results of calculations based on this rate equation with the experimental results for PBX 9404 and LX-17 (from Fig. 1). The quantitative match in the early part of the records is excellent; however, near the pressure peaks, these calculated histories are somewhat too high, perhaps because the gauges, the model, or the assumed equations of state may be unreliable in this region. The overall match is quite good and the ability to predict the two widely diverse build-up mechanisms exhibited by PBX 9404 and LX-17 demonstrates the versatility of the model. Also, calculated fraction-reacted histories for PBX 9404 agree

Fig. 6

Comparison of computer calculated stress histories with the experimental manganin stress histories from Fig. 1 for a sustained shock pulse in high explosive. Each pair of curves corresponds to the output of a gauge at a different depth from the impact surface; the point "CJ" is the Chapman-Jouget pressure. (a) PBX 9404, with an input pulse of 2.5 GPa. (b) LX-17, with an input pulse of 11.6 GPa (which gives about the same run distance to detonation as for PBX 9404 with an input pressure of 2.5 GPa).

The striking correlations achieved thus far between the data obtained by infrared radiometry and by embedded gauges indicate that we should closely integrate both initiation endeavors.

well with those derived from the time-resolved infrared temperature measurements shown in Fig. 3.

New formulations based on mixtures of HMX and TATB are now being developed for certain weapons applications in the hope of achieving a trade-off between energy on the one hand and shock sensitivity and thermal instability on the other. One of these is RX-26-AF, which is presently undergoing a series of large-scale safety and vulnerability tests. We were able, computationally, to match the experimental pressure histories only after we modified the rate law to include two separate growth terms in Eq. 1. One term, representing the HMX, contributes at lower pressures, while the second, representing the TATB, takes effect only after the pressure is much higher.

Fig. 7

Demonstration of the ability of two-dimensional calculations, using our ignition and growth model, to simulate a peculiarity of TATB-containing explosives: the ability to detonate incompletely. The curved line marks the boundary between complete reaction and very little reaction. The flyer plate has struck the high-explosive sample from the bottom.

Time = 2.39 μ s
 Min (N) = -9.52×10^{-7}
 Max (X) = 3.35×10^{-1}

Time = 3.59 μ s
 Min (N) = -5.53×10^{-7}
 Max (X) = 4.50×10^{-1}

Time = 4.80 μ s
 Min (N) = -5.00×10^{-3}
 Max (X) = 3.47×10^{-1}

Fig. 8

Calculated pressure contours in a point-initiated, cylindrical RX-26-AF charge as the detonation wave traverses a dense inert barrier. The color contour shows the location of the detonation front. (a) The curved detonation front approaches the barrier. (b) The shock has entered the RX-26-AF beyond the barrier but has not yet initiated detonation. (c) The explosive has reinitiated in the center but not near the edges.

We have successfully modeled the unusual behavior of TATB, including its large failure diameter and sensitivity to flyer diameter in electric-gun initiation experiments,⁷ by incorporating our ignition and growth model into a two-dimensional hydrocode. We have even adequately calculated the most extreme example of the insensitivity of TATB, i.e., the detonation of a hole in a large block of TATB by a small diameter flyer.⁸ Figure 7 shows the results of this application of the model.

For RX-26-AF, the two-dimensional hydrocode with the model containing two growth-rate terms was capable of reproducing complex two-dimensional experiments to measure detonation transit times through inert barriers. These experiments were designed to simulate practical systems in which shock arrival times must be accurately known and in which calculation of these times is complicated by detonation and reinitiation. In Fig. 8, which shows the results of a calculation involving the curved detonation and reinitiation behind a barrier, the calculated transit times match the experiments almost exactly. Such simulations of complex experiments would be impossible if the model for initiation,

which must reoccur on the other side of the barrier, were unrealistic.

Future Work

The striking correlations achieved thus far between the data obtained by infrared radiometry and by embedded gauges indicate that we should closely integrate both initiation endeavors. If both techniques can reveal the same conclusions, real economy of experimentation can be achieved in many cases, and these two powerful methods can be more efficiently applied to the fundamental questions of high explosive initiation.

We have recently upgraded the experiment chamber at the 101-mm gas gun facility, increasing its capability from 200- to 400-g-equivalent of PBX 9404. With this larger capability, we can now observe much longer runs to detonation, including the complete run up to detonation in such important IHEs as TATB.

The extent to which low temperature decreases the sensitivity of IHEs below what we can account for by any density effect is a currently pressing problem in intentional initiation systems. We are planning experimental and modeling work on this problem as well

as on the effect of particle-size distribution and the combined effect of low temperature and particle size. We will also be investigating thin and multiple pulses and other more complicated pressure pulses with experiments and modeling in an attempt to understand the nature of hot spots and the response of high explosives to accidental stimuli.

Our modeling effort will be directed toward the prediction of particle size, initial temperature, and other material property effects which are presently beyond the capability of the pressure-dependent model. To introduce a microscopic description of the material, we plan to incorporate into the reactive flow model the best available data on hot-spot formation (temperature, size, etc.) and subsequent growth (kinetics, heat transfer, etc.), together with a statistical treatment of hot spots⁹ in which various size and temperature distributions are specifically designated.

Conclusions

We have substantially advanced the experimental and theoretical study of shock initiation in the past five years.¹ The current generation of our stress and particle-velocity gauges allows quantitative input to a predictive initiation model. Fast infrared radiometry has provided insight into the ignition and growth aspect of initiation and provided semiquantitative data on particle-size effects for inclusion into the model. This approach, combining experimental and theoretical studies, has already paid off in the design and modeling of our initiation systems, which are important to a weapon's safety and vulnerability as well as to its performance. ■

Key Words: high explosive; HMX; infrared radiometry; insensitive high explosive; LX-17; manganin stress gauge; particle-velocity measurements; PBX 9404; PETN; RX-26-AF; shock initiation; TATB.

Notes and References

1. The early work on hot-spot formation was described in *Energy and Technology Review* for September 1978 (UCRL-52000-78-9), p. 1.
2. M. Cowperthwaite and J. T. Rosenberg, "A Multiple Lagrange Gauge Study of the Shock Initiation Process in Cast TNT," in *Proc. Sixth (Intl.) Symp. on Detonation*, ACR-221, Office of Naval Research (August 1976), p. 786.
3. L. M. Erickson *et al.*, "The Electromagnetic Velocity Gauge: Use of Multiple Gauges, Time Response, and Flow Perturbations," presented at: Seventh (Intl.) Symp. on Detonation, U.S. Naval Academy, Annapolis, Maryland, June 1981.
4. W. G. Von Holle and C. M. Tarver, "Temperature Measurement of Shocked Explosives by Time-Resolved Infrared Radiometry—A New Technique to Measure Shock-Induced Reaction," presented at: Seventh (Intl.) Symp. on Detonation, U.S. Naval Academy, Annapolis, Maryland, June 1981.
5. W. G. Von Holle and R. McWilliams, "Application of Fast Infrared Detectors to Detonation Science," in *SPIE Proc.*, Vol. 366, San Diego, California, August 1982, in press.
6. C. M. Tarver and J. O. Hallquist, "Modeling Two-Dimensional Shock Initiation and Detonation Wave Phenomena in PBX 9404 and LX-17," presented at: Seventh (Intl.) Symp. on Detonation, U.S. Naval Academy, Annapolis, Maryland, June 1981.
7. The use of the electric gun in high-explosive detonation research was discussed in *Energy and Technology Review* for February 1980 (UCRL-52000-80-2), p. 28.
8. R. K. Jackson *et al.*, "Initiation and Detonation Characteristics of TATB," in *Proc. Sixth (Intl.) Symp. on Detonation*, ACR-221, Office of Naval Research (August 1976), p. 755.
9. S. G. Cochran, *A Statistical Treatment of Heterogeneous Chemical Reaction in Shock Initiated Explosives*, Lawrence Livermore National Laboratory, Rept. UCID-18548 (February 1980).

Diamonds, for centuries the symbol for enduring value, have begun to play a major role in scientific research. As the hardest material known, they make ideal anvils between which to compress specimens to very high pressures. We are using such cells to investigate the properties of materials under extremely high pressures.

The idea of using two flawless brilliant cut diamonds as anvils in a mechanical press to generate high pressures is not exactly new.¹ Over the past 20 years, the apparatus has undergone much refinement and development, however.^{2,3} Pressures attainable by this means now exceed 100 GPa, about one million atmospheres.

In addition to their hardness, diamonds are highly transparent to both x rays and visible light. This makes it possible to observe the sample under pressure, to irradiate it with a laser, and to probe its characteristics both optically and with x rays. Pressure-sensitive fluorescent materials (such as a ruby chip) enable us to monitor the pressure with a precision of $\pm 1\%$. Lasers can supply heat to raise the specimen temperatures to about 3000°C. At such temperatures, the ruby chip can be used as a pressure calibrant, provided it is displaced slightly away from the point of heating. X-ray diffraction measurements can be used to determine the crystal structure.

The diamond-anvil high-pressure cell has many advantages over lower pressure devices. Because diamond is so brittle, anvils made from it generally tend to break before they deform. Thus the pressure distribution, assuming the diamond is not strained beyond its breaking point, tends to be completely reproducible over a series of measurements. As a result, the diamond-anvil apparatus has become a versatile tool to investigate high-pressure and high-temperature phenomena in physics, chemistry, and the earth sciences.

In the earth sciences, for example, the pressure and temperature capabilities of the diamond-cell apparatus have made it possible to investigate the mineral reactions that take place at conditions representative of the earth's

core-mantle boundary, hundreds of kilometres beneath the surface. Before, geophysicists and geochemists had to guess at the nature of these transformations from seismic-wave data or by studying analogous reactions in materials amenable to experiment with less highly developed, static pressure devices such as piston-cylinder and simple squeezers.

For example, many studies have been made of germanium compounds that have transformations comparable to those in silicon compounds but which take place at much lower pressures. In particular, we are interested in how terrestrial seismic profiles vary as a function of compositional and structural transformations of silicate minerals inside the earth. Among these are the olivine-spinel transformations, the disproportionation of garnet and pyroxene, and the stability of the perovskite structure under the conditions believed to exist in the earth's mantle.

Equipment

The diamond-anvil apparatus (Fig. 1) consists essentially of two small brilliant cut type I diamonds in an opposed anvil configuration. The design achieves tremendous sustained pressures by concentrating a moderate force on a tiny area (the culet face) where the points of the pavilion faces of the two diamonds come together. We use a laser-fluorescence method to measure the resulting hydrostatic stress on the specimen and x-ray diffraction to determine its crystal structure.

In the diamond-anvil device, the two diamonds are mounted over zirconium pads (to distribute any concentrated forces caused by surface imperfections) on a pair of tungsten carbide rockers, hemicylinders with their axes at right angles, that can be tilted to align the culet faces perfectly parallel. [The culet face is a small flat area, parallel to the front or table face, that truncates the apex of a brilliant-cut diamond. We make it 16-sided (approximately circular) by eight additional cuts along the edges of the pavilion faces.] The diamonds we use range from an eighth to a half carat, and the culet faces range

Fig. 1

Diamond-anvil pressure cell for studies of crystal structure at high pressures. (a) Disassembled to show diamonds and x-ray collimator. (b) Cutaway view showing how the various components fit together.

from 200 to 1000 μm in diameter (Fig. 2).

Once perfect alignment has been achieved, we remove the tight-fitting piston that holds one of the two diamonds and start the sample-mounting procedure. On the culet face, we place a prepressed stainless-steel gasket 250 μm thick with a hole 120 to 150 μm in diameter in its center. In the hole we place the sample, together with a very small ruby chip, and add the pressure medium, which may be a liquid or a gas (Table 1). In the case of a gas, this is accomplished by remotely assembling the apparatus in a pressure vessel filled with the gas to be used.

The ruby chip serves as a pressure sensor and indicates when the applied stress becomes nonuniform. Figure 3 shows the apparatus for using the pressure sensor. Under illumination by a helium-cadmium laser, the ruby chip emits fluorescent light at two characteristic frequencies. The wavelengths of these two sharp spectral lines (R_1 and R_2) vary as a well-calibrated function of the pressure. When the pressure ceases to be hydrostatic because the fluid pressure medium transforms into a solid or becomes very viscous on compression, the nonuniformity of the resulting stress broadens the fluorescent lines.

Fig. 2

Flawless, brilliant-cut gem-quality diamonds used in our studies of crystal structure under high pressure. (a) Standard American brilliant cut and (b) the way we modified it (by making 8 additional cuts along the bezel and 16 extra cuts on the culet) to reduce the likelihood of chipping. (c) Top view of a diamond to be mounted in the diamond-anvil pressure cell. (d) Diamond that failed in service by chipping.

To determine the crystal structure of the material, we pass an extremely well-collimated beam of x rays through the specimen (and through both diamonds) and record the diffraction pattern on x-ray film (Fig. 4). The collimator confines the x rays to the center third of the sample, minimizing stress gradients sampled even when the pressure becomes nonuniform. Interpretation of the resulting patterns, which consist of a complex series of concentric arcs (Fig. 5), is quite involved; however, we have efficient computer programs to assist in this part of the work.

The mechanism for applying the pressure is simplicity itself, merely a stout lever with a mechanical advantage of 10:1, actuated by a heavy screw and a Belleville spring at the long end. (A Belleville spring is a stack of cupped washers piled back-to-back around the screw so that they apply a balanced pressure all around the screw.) The pressure cell is compact and portable: it can be moved from the pressure calibration apparatus for the x-ray diffraction exposure without disturbing the pressure on the specimen.

Table 1 Pressure media and the limiting pressures below which they remain fluid and continue to exert hydrostatic pressure. Each of these media may be used in quasi-hydrostatic experiments at somewhat higher pressures. The quasi-hydrostatic range merges gradually into the nonhydrostatic range as fluids become more viscous without any definite line of demarcation.

Material	Hydrostatic pressure limit, GPa
1:4 ethanol/methanol	~11
Neon ^a	20
Argon ^a	12.5
Helium ^a	~60
Hydrogen ^a	>60

^aThe gases are injected into the diamond cell under high pressure (about 200 MPa); they liquefy when the applied pressure exceeds their vapor pressure.

Fig. 3 The laser pressure-calibration system. Blue light from the helium-cadmium laser (blue box at right) goes through the microscope into the diamond cell on the microscope stage (left). Fluorescent light from the ruby (red) goes up through the spectrometer to the photomultiplier detector (right). The x/y plotter in the foreground displays the output of the spectrometer that measures the wavelengths of the R_1 and R_2 fluorescence lines emitted by the ruby chip, taken at several different pressures.

Fig. 4 Equipment for making x-ray diffraction measurements of crystal structure under high pressure. X rays from the x-ray source (right) pass through the diamond-anvil cell (center) where some of them are diffracted at characteristic angles by the crystal planes in the specimen. Photographic film in the curved holder (left) records these diffracted x rays for subsequent crystallographic analysis.

... it was postulated that iridium, like iron, would undergo a phase transformation from a face-centered cubic ... to a close-packed hexagonal ... phase at higher pressures.

The customary working range of most diamond cells is 0 to 20 GPa. With our design, we can study material behavior under hydrostatic compression to 60 GPa (with helium as the pressure fluid). Pressures in the neighborhood of 120 GPa are attainable if we allow non-hydrostatic compression.

Diamond-anvil studies have many other uses beyond obtaining the crystal-structure data that is our primary concern. With the addition of a laser or resistance heater⁴ (or with cryogenic cooling⁵), we can explore the pressure-temperature phase diagram of a material. With appropriate modifications, the diamond-anvil technique can be used to make conductivity and resistance measurements.⁶ Infra-red spectroscopy and Raman spectroscopy are other possibilities.⁷ It is even possible to study the change in valence as a function of pressure in transition metals with Mossbauer spectroscopy.⁸

Experiment

We have recently investigated phase transformations in beryllium, gadolinium, scandium, and iridium. Iridium, in the platinum family, is the most corrosion-resistant metal known. It is useful in high-temperature applications and as a hardening agent for platinum. We have also investigated materials that are rare and quite toxic (e.g., certain actinide metals).

On the basis of the well-known regularities in the properties of the transition metals, it was postulated that iridium, like iron, would undergo a phase transformation from a face-centered cubic (α) to a close-packed hexagonal (ϵ) phase at higher pressures. Thermodynamic calculations predicted a transition pressure of about 9 GPa at room temperature (298 K).⁹ However, we could not see this phase transformation in our experiments using the diamond-anvil cell.

We measured x-ray diffraction patterns for iridium as a function of pressure between 7 and 30 GPa. Table 2 presents data regarding the pattern obtained at about 30 GPa which indicates that the crystal has a face-centered cubic structure with a lattice parameter

of 0.3737 nm. We observed only 111, 200, and 220 reflections, and the agreement between observed and calculated values is good.

Figure 6 displays the volume-compression data we obtained at room temperature, together with data from previous investigators.¹⁰⁻¹² We have been able to extend the measurements well beyond previous data, compiling a consistent set of data over the entire pressure range from 7 to 30 GPa. The agreement between the different sets of data is good. Iridium appears to be very stiff, showing only an 8% compression even at 30 GPa.

The other inference to be drawn from these data is that the theoretical description of iridium's compressibility will have to be revised. There may be a phase transformation in iridium at pressures higher than the 9 GPa predicted, but it will take further experiments to confirm this.

Future Work

Although our diamond-anvil apparatus has provided much valuable information about the high-pressure behavior of iridium and various minerals,

Table 2 X-ray data for iridium at 30.0 GPa. The parameter d is the spacing in Bragg diffraction, hkl refers to the indices of a plane in a crystal lattice, I is the intensity of a measured diffraction line, and the lattice parameter [the dimension of the crystallographic unit cell (cubic) under the conditions of the experiment] equals 0.3737 nm.

d (observed), nm	d (calculated), nm	hkl	I/I_0 (observed)
0.2157	0.2158	111	Strong
0.1867	0.1869	200	Medium
0.1323	0.1321	220	Medium

the accuracy of its measurements is seriously affected by background radiation from x rays scattered from the source. Also, there are certain materials of interest to the Laboratory's weapons programs that produce their own background radiation. One possible way to attack this limitation would be to replace the x-ray film with a detector system that suppresses the background. We are investigating one such system, the position-sensitive electronic detector, the shape of whose output signal depends on the location of the

Fig. 5

The powder diffraction pattern produced by passing x rays through a specimen of iridium under compression between two diamonds. The diamonds, being single crystals, yield a diffraction pattern consisting of an array of short radial streaks (they would be points if the diamonds were very thin); for the iridium, which is thin but consists of a

great many randomly oriented crystals, the point array is smeared into a set of short arcs. (Longer arcs come from a molybdenum foil inserted as a fiducial for determining the exact sample-to-film distance.) Variations in the number, spacing, and intensity of the shorter arcs provide clues to iridium's crystal structure at the particular pressure.

initiating event on the detector surface. Computer processing can decode this position information, producing a real-time map of the x-ray intensity.

The immediate advantage of such a system is the ability to suppress background statistically. The computer would record background (with the x rays, but without the sample) and then proportionately subtract this stored information from the data as they are being gathered. This should make it much easier to recognize and measure faint reflections.

Another advantage is that we will be able to monitor continuously the accumulation of diffraction data. Nothing can be learned from an x-ray film until it has been developed, and the proper exposure time must be determined by trial and error (generally, exposure times are greater than 120 hours). With continuous monitoring, it would be possible to observe the progress of the experiment and judge when we have collected enough data.

The position-sensitive detector would also make it possible to locate phase-change pressure thresholds much more quickly and accurately than is possible using photographic film. The computer could continuously compare the pattern being formed with the one recorded at the last previous pressure setting, and it would signal when it detects a shift that indicates a change in crystal structure.

Another possible modification of our present experimental arrangement would be to increase the x-ray

intensity. This would do nothing to improve the scattered-x-ray background, but it would shorten the exposure time required to obtain useful data. We are looking into the possibility of using more powerful x-ray sources such as the rotating-anode x-ray generator or synchrotron radiation from a charged-particle accelerator.

Incorporating both the high-intensity x-ray source and the position-sensitive detector system would greatly enhance our ability to investigate the high-pressure behavior of all kinds of materials. We are now beginning to investigate complex pressure-induced phase and density changes in various materials that we probably could not follow without such modifications.

In regard to geologic materials, we are contemplating a study of the role of transition elements in determining the phase equilibria relevant to the earth's deep mantle. It is known, but not understood on crystal chemical grounds,^{13,14} that ilmenite and perovskite, both important mineral phases, are destabilized by small amounts of iron and possibly other transition elements. Thus, determining the transition element chemistry of these high-pressure phases is crucial to an understanding of the possible conditions of stability for different mineral assemblages within the earth's transition zone and lower mantle.

All this is of more than academic interest, of course. Such a study could shed light on the way seismic velocities vary with changes in mineral structure as a function of depth in the earth. Precise data from such an investigation would be relevant to any system for monitoring and verifying test-ban treaty compliance through seismic detection.

Conclusion

Diamond-anvil high-pressure studies have progressed to the point where they complement shock-wave studies. Because they operate at static high pressure, they permit time-consuming procedures, such as x-ray diffraction measurements for determining crystal structure. The sample material is

Fig. 6

Volume compression data for iridium, derived from various sources. The combined data are complete enough to show that a phase transformation from a face-centered cubic crystal structure to a close-packed hexagonal form does not take place even at pressures up to 30 GPa. Such a transformation was predicted theoretically at about 9 GPa and would have been accompanied by a volume change (a break in the curve). Our measurements greatly extend the previous iridium data and form a consistent set of data over the entire pressure range from 7 to 30 GPa.

completely recoverable and the method is adaptable to minute specimens, a tremendous advantage when dealing with rare or hazardous materials.

One of our goals in investigating the high-pressure behavior of iridium was to test the theoretical prediction that iridium would exhibit a phase transformation from the face-centered cubic crystal structure at about 9 GPa. Our finding that no such transformation takes place even at pressures up to 30 GPa will need to be taken into account by physicists working to improve solid-state theory. ■

Key Words: crystal structure; diamond anvil; garnet; geochemistry; geophysics; ilmenite; iridium; olivine; perovskite; seismology; spinel; x-ray diffraction.

Notes and References

1. C. E. Wier, E. R. Lippincott, A. Van Valkenburg, and E. N. Bunting, *J. Res. Nat. Bur. Stand. (U.S.)* **A63**, 55 (1959).
2. W. A. Bassett, T. Takahashi, and P. W. Stook, *Rev. Sci. Instrum.* **38**, 37 (1967).
3. H. K. Mao and P. M. Bell, *Geophys. Lab. Yr. Book* **74**, 402 (1975).
4. Li-chung Ming and W. A. Bassett, *Rev. Sci. Instrum.* **45** (9), 1115 (1974).
5. H. K. Mao and P. M. Bell, *Geophys. Lab. Yr. Book* **78**, 659 (1979).
6. N. Sakai and T. Kajiwara, *Rev. Sci. Instrum.* **53** (4), 499 (1982).
7. H. J. Jodl and W. B. Holsapfel, *Rev. Sci. Instrum.* **50** (3), 340 (1979).
8. G. T. Zou, H. K. Mao, P. M. Bell, and D. Virgo, *Geophys. Lab. Yr. Book* **79**, 374 (1980).
9. W. A. Silberstein and E. I. Estrin, *Fiz. Metal. Metalloved.* **28**, 369 (1969).
10. R. N. Schock and Q. Johnson, *Fiz. Metal. Metalloved.* **31**, 1101 (1971).
11. R. G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz, and W. J. Carter, *High Velocity Impact Phenomena* R. Kinslow, Ed. (Academic Press, New York, 1970).
12. P. W. Bridgman, *Proc. Amer. Acad. Arts Sci.* **81**, 165 (1952).
13. R. Jeanloz and A. B. Thompson, *Rev. Geophys. Space Phys.* **21** (in press) 1983.
14. L. Liu, *Geochim. Cosmochim. Acta*, **41**, 1355 (1977).

Neutron Diagnostics for Magnetically Confined Plasmas

We have developed new instruments for measuring neutron fluxes and spectra, enabling us to study the fusion reactions and other processes in magnetically confined plasmas.

improved, however, fewer particles escape the plasma radially, thus weakening these diagnostic signals.

Future MFE tandem-mirror experiments will produce high-density, large-radius plasmas in which the dimensions of the plasma will grow in relation to the mean free path for processes such as charge exchange. Under these conditions, central plasma ions or charged reaction products that escape radially may do so only after undergoing many collisions in the outer plasma and cool gas regions, making it increasingly difficult to interpret diagnostic data. (In tokamak experiments, in which the plasma is confined in a toroidal device that has no "end," all losses are radial so that improved confinement also weakens their signals substantially.) Finally, the high central temperatures generated in fusion experiments can completely ionize many of the impurity species (such as hydrocarbons, air, titanium, and iron) in the central plasma, reducing the utility of their characteristic atomic line radiation as a diagnostic feature.

The higher fusion rates that result from improved confinement, however, also produce higher yields of neutrons and gamma rays. These uncharged reaction products readily escape the central plasma and thus can provide information about its parameters. As our MFE program approaches its goals of producing break-even power, we must rely increasingly on uncharged reaction products and on ions that escape the ends of the plasma to characterize its parameters and to measure its fusion

power output. We have recently developed several diagnostic techniques based on the measurement of neutron emission from a magnetically confined plasma. We are currently applying these techniques to LLNL's Tandem Mirror Experiment (TMX) Upgrade and they will soon be used on Princeton's Tokamak Fusion Test Reactor (TFTR).

Neutron Generation in Magnetically Confined Plasmas

Nuclear fusion occurs when two light nuclei combine to release energy in the form of energetic reaction products. In MFE experiments, the reactions of interest are typically those of the heavy isotopes of hydrogen: deuterium plus deuterium ($D + D$), deuterium plus tritium ($D + T$), and tritium plus tritium ($T + T$). Table 1 shows several such reactions and the kinetic energies of their products. (Some reactions may take alternate paths, indicated by the percentage composition of their products in the table.) All of the reactions generate fast neutrons which readily penetrate dense plasmas without significant interaction.

The rate of a fusion reaction (and thus the neutron generation rate) depends on both the collision rate of the fast ions and their subsequent probability of fusion. The collision rate is proportional to the product of the densities of the reacting species (or to the square of density in the case of $D + D$ and $T + T$ fusion). The neutron generation rate per unit volume in a thermonuclear plasma thus is very sensitive to its density. Even more important, the probability of fusion is a very sensitive function of ion energy, since this quantity determines the probability that the two nuclei will approach each other closely enough to overcome their mutual electrical repulsion and fuse. Figure 1 shows the effective fusion or reactivity of the neutron-producing reactions in Table 1 as a function of the mean energy of the reacting ions. The very steep slope at energies from about 5 to 15 keV occurs in the region where fusion reactors are expected to operate.

Table 1 Reactions between light nuclei of interest in current magnetic fusion research. Kinetic energies of reaction products (in MeV) are given in parentheses. Composition of reaction products is given in percentages: D = deuterium, T = tritium, p = proton, n = neutron, γ = gamma ray.

$D + D$	50%	$T (1.0) + p (3.0)$
	50%	$^3\text{He} (0.8) + n (2.5)$
$D + T$	~100%	$^3\text{He} (3.5) + n (14.1)$
	10^{-5}	$^3\text{He} + \gamma (16.7)$
$T + T$	100%	$^3\text{He} (1.3) + 2 \text{ neutrons } (\sim 5 \text{ each})$

Because reactivity, and thus neutron yield, increases roughly as the cube of the ion energy, neutron yield serves as a highly sensitive plasma thermometer. We have used an uncollimated detector to make accurate determinations of mean ion energy, a quantity closely related to the plasma temperature, by measuring both neutron yield and density in the end-plug plasmas of the TMX.³ Similar measurements are routinely made on plasmas confined in tokamak-like devices.

Determining Ion Energy Confinement Time

Hot ions in a magnetically confined plasma lose energy both by collisions with cooler ions and electrons and by charge-exchange reactions with cool gas. In many fusion experiments, ion energy loss is compensated by heating the plasma with neutral beams; that is, by injecting energetic neutral deuterium or hydrogen into the plasma. (Other techniques heat the plasma by inducing currents or by irradiating it with microwaves.) When plasma heating is terminated, the mean ion energy decays (cools) with a time constant τ_E . This time constant, which represents the energy confinement time, is an important plasma parameter. Because neutral deuterium beams used to heat a plasma also fuel it, termination of heating likewise causes the plasma density to decay according to a particle confinement time τ_p . Both decay processes reduce the fusion rate and hence the neutron yield. In a pure deuterium plasma, the time constant for decay of the neutron yield τ_N is related to τ_E and τ_p by

$$1/\tau_N = 2/\tau_p + \alpha/\tau_E,$$

where α is the logarithmic slope of the reactivity curve in Fig. 1. Since τ_p may be measured experimentally (by interferometry or neutral-beam attenuation methods) and α is already known, the decay of neutron yield τ_N (i.e., when plasma heating is stopped) provides a very sensitive measure of τ_E .

Figure 2 shows some typical neutron-yield data obtained in the east end plug of the TMX using a liquid

Fig. 1

Fusion reactivity, expressed as the effective fusion cross section times velocity, rises very rapidly with ion energy because the speed of the ions brings the light nuclei closer together to overcome their mutual electrical repulsion. The three reactions shown produce fast neutrons. Because neutron generation rates are very sensitive to the mean ion energy or temperature of a hot plasma, neutron yield is a correspondingly sensitive plasma thermometer.

hydrocarbon detector. (With this type of detector, neutron intensity is determined from the rate of recoil protons generated by neutron-proton elastic scattering.) The inferred energy confinement time τ_E of about 5 ms agrees well with that derived from estimates of the plasma energy content and the power loss.⁴ Moreover, the neutron measurement is less ambiguous than power-balance calculations, which rely on estimated losses and inputs that are difficult to determine experimentally.

Imaging Neutron Emission from a Plasma

Because many thermonuclear plasmas have complex shapes and nonuniform density profiles, the speed distribution of their ions varies significantly with location. The spatial profile of neutron generation is helpful in studying these effects. It is also needed to determine total neutron generation

Fig. 2

Decay of neutron yield (red), which gives τ_N , and plasma line density (green), which gives τ_p , in a cooling magnetically confined plasma. The line density decay was measured with a beam-attenuation detector. The plasma was heated by neutral-beam injection for 25 ms in a TMX end plug. When injection is terminated, the density and mean ion energy of the plasma immediately begin to decline because of particle losses and cooling processes. Both effects sharply reduce the neutron generation rate. Unfolding the effects of density decay from the observed decline in neutron yield provides a very sensitive measure of the time constant for ion cooling, τ_E .

Our collimated MFTF-B spectrometer is distinctive both in its mechanical design and in the shield material used.

Fig. 3

Typical neutron pinhole camera, consisting of a thick polyethylene shield with a small-diameter hole. Conical entrance and exit apertures approximate ideal pinhole geometry. The neutron image is formed on a position-sensitive detector behind the pinhole. Water absorbs scattered neutrons. The camera is normally used 2 to 8 m from the source whose image is to be formed.

(fusion power) over the whole plasma. Neutron pinhole cameras and collimated detector arrays have been used for many years to form images of neutron emission from plasmas.

Figure 3 shows a typical pinhole camera design. The ideal conventional pinhole camera consists of a small hole in a very thin shield of opaque material. Because fast neutrons are very penetrating in all materials, however, there are no thin opaque shields that achieve the desired total opacity. In Fig. 3, the ideal pinhole is replaced by an opaque material (polyethylene) of substantial thickness, and the hole itself is a cylinder of significant length.

Because a neutron's mean free path in the shield material is typically large compared to the diameter of the hole, neutron pinholes have diffuse edges. In addition, the significant thickness of the hole causes the off-axis image response to fall off more rapidly than predicted by the classical cosine law, since it is reduced to near zero at angles larger than d/l (diameter/length). Nevertheless, we have used a copper and epoxy pinhole similar to the design shown in Fig. 3 to obtain images of 14-MeV neutron emission with a spatial resolution of 1 mm.³ We have found that a copper and epoxy design is more suitable for D + T neutrons whereas the polyethylene design is better for the lower energy D + D neutrons.

A simpler design results when the pinhole is replaced with an array of several detectors, each having long cylindrical collimating optics (Fig. 4). Such a device samples fewer points at the object plane but is more efficient because its entrance aperture is larger in area. We have recently assembled a collimated array of neutron spectrometers designed to measure the 2.5-MeV neutron yield along several chords through a plasma in the Laboratory's Mirror Fusion Test Facility (MFTF-B) device, scheduled for completion in 1985.

Our collimated MFTF-B spectrometer is distinctive both in its mechanical design and in the shield material used. Attenuation of 2.5-MeV neutrons generated by D + D fusion is greatest in

materials with the highest hydrogen density. Although polyethylene or paraffin are the materials of choice for the shield because of their high hydrogen content, they are difficult to mold in large pieces without shrinkage and cracking. In addition, neutron capture by hydrogen generates very penetrating 2.2-MeV gamma rays which can generate an undesirable background signal in the neutron detectors.

These problems were solved by using a shield material of polyethylene particles mixed with a small amount of boron carbide and bound in paraffin. (Boron strongly absorbs slow neutrons and greatly reduces the number captured by hydrogen.) The mixture is mechanically strong, relatively easy to cast in large pieces, does not contract or crack after casting, and generates significant gamma rays only at about 500 keV. Gamma rays of this energy are sufficiently attenuated by the polyethylene to minimize their intensity behind the shield.

The shield contains four entrance holes that accommodate any of several interchangeable apertures having a variety of collimation diameters. Each aperture can be independently aligned. We determine the axis of the collimator by reflecting a laser beam from a thin mirror placed in front of the detector onto fiducial markings inscribed on the experiment's vacuum vessel (see Fig. 4). Because fast neutrons readily penetrate the mirror, it may be left in front of the detector during an experiment. Each aperture moves freely within a well that is sealed against neutron radiation by a collar of oil, enabling easy realignment.

Fig. 4

Our collimated neutron spectrometer designed for the MFTF-B experiment (the detector assembly is not drawn to the same scale as the vacuum vessel and plasma). (a) The system consists of four liquid-hydrocarbon scintillation detectors shielded with a mixture of polyethylene particles and boron carbide bound in paraffin. Four entrance holes in the shield accommodate interchangeable apertures having a variety of collimation diameters. Each aperture is mounted in a sealed, oil-filled well to permit independent alignment. (b) To find the axis of a collimator, we reflect a laser beam from a thin mirror in front of the detector onto markings on the vacuum vessel of MFTF-B.

Figure 5 shows the spatial response of one of the collimating apertures measured using LLNL's Rotating Target Neutron Source I (RTNS-I). Because the field of view is ± 0.5 deg (full width half maximum), the plasma chord viewed from outside the vacuum vessel (6 m away) is only 10 cm in diameter. This gives a spatial resolution on the order of the Larmor radius of hot ions as they spiral about the magnetic field lines, which should prove to be adequate for experiments planned on MFTF-B. Resolutions of up to several Larmor radii will provide useful information. Although this instrument cannot be considered an imaging device, since it samples only a few points in the two-dimensional object plane, the sample points may be varied from shot to shot to generate a profile of the plasma.

Measuring Mean Ion Energy

The energies of neutrons generated by D + D and D + T fusion reactions depend on the initial energy of the reacting ions. (If the initial energy is essentially zero, the neutrons produced would be monoenergetic.) This dependence is the result of two distinct effects. The first and smaller effect is a direct transfer of kinetic energy from the reacting ions in the hot plasma to

the fusion-produced neutron. The second and larger effect results from the motion of the center of mass of the reacting ions relative to a fixed observer. The energy of a product neutron varies with its angle of emission relative to the motion of the center of mass of the reacting ion system as seen by the observer. For ions in thermal equilibrium, this angle is usually random, increasing the neutron's energy when it is emitted in the direction of the observer and decreasing it in the opposite direction. In consequence, the neutron energy spectrum seen by the observer is dispersed, a phenomenon called Doppler broadening. The Doppler width of the neutron spectrum is substantially larger than and increases with the mean ion energy of the plasma. For any isotropic Maxwellian plasma (that is, a plasma in thermal equilibrium), the Doppler width is given by

$$\Delta E_n = 67.4 \bar{E}_i^{1/2} \text{ (keV)}$$

for D + D neutrons, and

$$\Delta E_n = 144.5 \bar{E}_i^{1/2} \text{ (keV)}$$

for D + T neutrons, where $\bar{E}_i$ is the mean ion energy of the plasma, equal to $3/2$ of its temperature. These Doppler widths are much larger than those observed in atomic line radiation. Because of the large amount of energy released in the fusion reaction, the line widths are strongly amplified above the average energy of the plasma, a phenomenon that makes this type of measurement possible.

A High-Rate, Time-Resolved Neutron Spectrometer

The MFTF-B will provide a neutron yield more than adequate for time-resolved spectrum measurements. We have developed a neutron spectrometer system with sufficient energy resolution and high data-rate capability to observe the Doppler width in the neutron emission from MFTF-B plasmas, and its variation in time.^{6,7} The system, which will be located in the MFTF collimation assembly described earlier, uses liquid-

Fig. 5

To demonstrate the spatial resolution of the instrument, the collimated neutron spectrometer was swept past the RTNS-I line source of 2.5-MeV neutrons several times at different locations. The line source is obtained by viewing the edge of the RTNS-I target disk. The abscissa (θ) gives the angle between the source and the axis of the collimator. The data indicate that the collimated field of view was ± 0.5 deg (10 cm in diameter at the plasma) and that the out-of-field response fell to less than 0.1% of the on-axis response. Other scans indicate that the response falls off symmetrically on both sides of the peak.

hydrocarbon scintillation detectors similar to those used for neutron-yield measurements on TMX. A data unfolding program extracts the neutron energy spectrum from the observed energy distribution of the recoil protons.⁸

An important feature of the scintillator is that recoil protons generated by neutron interactions produce a slower fluorescence than do recoil electrons generated by gamma-ray or x-ray interactions. As a result, each type of radiation produces a characteristic pulse shape, enabling us to record simultaneously neutron and photon energy spectra in the same spectrometer.

We have developed a high-rate, time-resolved electronics system that analyzes the pulse height of scintillation-detector data and identifies the type of interaction at event rates up to 10 MHz, an improvement of two orders of magnitude over current data rates.⁸ Spectra are digitized with a resolution of 256 channels, readily upgradable to 512 channels. The system can record 50 neutron spectra per shot, the shortest accumulated over 50 to 100 ms. Spectra obtained during plasma build-up and decay can be reduced to Doppler width and mean ion energy after each shot. Data are reduced by a local microcomputer at a rate of about 10 s per spectrum. The system's neutron energy resolution remains adequate at the maximum data rate for making ion energy measurements in MFTF-B plasmas. Figure 6 shows a neutron spectrum unfolded from a 200-ms run at the RTNS-1.

Our data system is unique among nuclear spectroscopy instruments in providing digital control of all electronic adjustments. The local microcomputer sets all instrument parameters, which are recorded together with the data from each shot. In addition, digital control enables us to use fiber optics for data transmission, thereby isolating the system from the local environment (a requirement for high-power fusion experiments). The construction of this system is being funded by Princeton and will be implemented initially on their TFTR in 1983 to

Fig. 6

Neutron spectrum produced by D + D fusion, recorded with our high-data-rate spectrometer at the RTNS-1. The data were obtained in only 200 ms at a rate of 5 MHz. The energy resolution of the instrument was only slightly degraded at this high rate. The spectrometer will be used to make time-resolved neutron Doppler-width measurements on plasmas in the MFTF experiment, now under construction at LLNL.

measure neutrons generated by D + D and D + T reactions. We will be involved in bringing the system up at Princeton. Another such system will be used on the MFTF-B when that experiment is brought online.

Figure 7 shows some neutron energy spectra measured in the end-plug plasmas of the TMX with an early version of the MFTF-B spectrometer. The characteristic instrument line widths of the spectrometers varied from 160 to 200 keV at 2.5 MeV when unfolded from the experimental data. The spectrum on the west end-plug plasma showed a line width not significantly different from that of the instrument. The mean ion energy E_i had an upper bound of less than 4 keV, a value that agrees well with other types of plasma-energy measurements made on the same shots, including neutron yield.

The east end-plug neutron spectrum, however, showed a broad spectral line width that exceeded both that of the instrument and that observed on other shots when the plasma was known to be cool. Unfolding the instrument width from the data gave a Doppler broadening characteristic of a Maxwellian plasma with a mean ion energy of 14 to 17 keV. Because the TMX end-plug plasma is non-Maxwellian and anisotropic, with only about 5 to 7% of its ion energy in the axial direction, this value must be reduced slightly. The corrected energy is about 10 to 13 keV, in good agreement with other measurements.

Measurement of Doppler width enables us to determine directly the mean ion energy using a method that is independent of plasma density measurements. This is an important capability as the density profile of hot plasma is not always well known. The spectrometers are easily collimated, a feature

that enables us to use ion energy measurements to study the spatial profile of ion energy in various parts of the plasma.

Measuring Plasma Confinement and Heating

Neutron spectrum measurements also may be used to study the confinement time and slowing of particles in a plasma. Tritium is one of the reaction products of D + D fusion (see Table 1). Some of the tritium is briefly confined in the plasma, so that D + T fusion will occur even in a "pure" deuterium plasma. The relative rates of the two reactions provide important information about the confinement of charged reaction products such as tritium. Studies of D + T fusion rates in deuterium plasmas also indicate how much charged reaction products slow before escaping the plasma. (D + T reactivity is strongly peaked at about 100 keV, whereas the reaction product tritium is

Fig. 7

Neutron spectra measured on the east and west end plugs of the TMX, representing an accumulation of more than 30 shots. The spectral peak at 2.45 MeV results from D + D fusion in the hot plasma. Energy dispersion in the neutron spectrum of the east plug is substantially larger than the resolution of the diagnostic instrument, indicating a

Doppler broadening characteristic of a Maxwellian plasma at a mean ion energy of 14 to 17 keV (corrected to 10 to 13 keV for the anisotropic TMX plasma). As energy dispersion in the west-plug neutron spectrum is not significantly greater than instrument resolution, any Doppler broadening is less than that due to 4-keV ion motion.

generated at about 1 MeV.) Such information is important in determining the extent to which reaction products provide supplemental heating.

Neutron spectrum measurements may also enable us to study energy deposition in a plasma by neutral beams. Energetic deuterium injected tangent to the plasma current in a tokamak-like device reacts with deuterium or tritium ions to produce neutrons whose energies are substantially shifted up or down by the beam energy, depending on whether the beam current is directed toward or away from the detector. If the injected deuterium is slowed significantly by the plasma before causing fusion, the energy shift is reduced. We have calculated spectral data for beam-target reactions to examine the feasibility of using neutron measurements to study the slowing processes that allow the beams to heat the plasma.

Impurities in a plasma, particularly those with a high atomic number (Z), scatter injected energetic ions away from the beam axis. When neutral deuterium is injected into a tokamak-like device tangent to the plasma current, beam scattering by impurities should cause observable changes in the beam-target neutron spectrum. (This effect results from the dependence, previously noted, of observed neutron energies on the angle between the detector and the motion of the center of mass of the ions.) Our computer simulations show that the energy resolution of existing spectrometers is adequate to measure the extent of pitch angle of scattering and thus to estimate the effective atomic number of the plasma, which indicates its impurity content.⁹

Summary

The improved magnetic confinement of hot plasmas is expected to result in substantial generation of fusion energy. As confinement improves, however, fewer energetic charged particles escape the central plasma, and diagnostic measurements must rely more heavily on uncharged reaction products (neutrons and gamma rays). We have developed neutron spectrometers with sufficient

energy resolution to measure the mean ion energy of magnetically confined plasmas at temperatures and densities characteristic of magnetic fusion experiments now and in the future. Such measurements may be highly resolved in time and space. Because spectrometer efficiency is absolutely calibrated, spectral measurements also implicitly contain fusion-rate data. Thus, it should be possible both to measure the fusion power of a machine and to study the buildup and decay of mean ion energy, the confinement of reaction products, the relative density of impurities, and the slowing of reaction products and of injected species. □

Key Words: Doppler width; Magnetic Fusion Test Facility (MFTF); neutron spectroscopy; neutron imaging; thermonuclear fusion; Tandem Mirror Experiment (TMX).

Notes and References

1. The Laboratory's tandem-mirror MFE program was reviewed in the October 1982 *Energy and Technology Review* (UCRL-52000-82-10), p. 1.
2. Conventional diagnostic techniques for magnetically confined plasmas were described in the August 1979 *Energy and Technology Review* (UCRL-52000-79-8), p. 17.
3. D. R. Slaughter, *Neutron Yield Measurements on a TMX End Plug*, Lawrence Livermore National Laboratory, Rept. UCRL-52923 (1980).
4. D. P. Grubb et al., *Energy Confinement Studies in TMX: Power Balance*, Lawrence Livermore National Laboratory, Rept. UCRL-86482 (1982).
5. V. W. Slivinsky et al., *Appl. Phys. Lett.* **30**, 555 (1977); R. W. Bauer and R. C. Weingart, *A Time-Resolved Fast-Neutron Pinhole Camera for Studying Thermonuclear Plasmas*, Lawrence Livermore National Laboratory, Rept. UCRL-77527 (1976).
6. D. R. Slaughter, *IEEE Trans. Nucl. Sci.* **NS-26**, 802 (1979).
7. H. P. Spracklen, *IEEE Trans. Nucl. Sci.* **NS-29**, 896 (1982).
8. D. R. Slaughter and R. Strout, II, *Nucl. Inst. Meth.* **198**, 349 (1982).
9. D. R. Slaughter, *A Neutron Diagnostic that Measures Z_{eff} in a Neutral Beam Heated Tokamak*, Lawrence Livermore National Laboratory, Rept. UCRL-82158 (1979).

Past Titles

Articles published in recent issues of the *Energy and Technology Review* are grouped below mainly according to their chief sponsors, the Assistant Secretaries of the U.S. Department of Energy. Research funded by other Federal agencies is listed under Work for Others.

ENERGY RESEARCH

Predicting Hazards from Large Spills of Liquefied Gases (January 1983)
Understanding Tandem Mirror Devices (November 1982)

DEFENSE PROGRAMS

Inertial Fusion

Laser Fusion X-Ray Measurements (January 1983)
Laser-Heated Flashlamps: a Step Toward a Soft X-Ray Laser (January 1983)
Neutral-Solution Processing of Large Antireflective Surfaces for High-Power Lasers (Brief—January 1983)
The Feasibility of Inertial-Confinement Fusion (December 1982)
Laser Fusion with Green and Blue Light (August 1982)

Military Application

How Old is the Universe? (December 1982)
Measuring Equations of State with the Electric Gun (December 1982)
The Regional Seismic Test Network (November 1982)
A Universal Sensor for Potentiometric Titrations (Brief—August 1982)
Electrosynthesis of N_2O_x : the Key to Inexpensive HMX (August 1982)
The Compuron: How Round is Round? (August 1982)

FOSSIL ENERGY

Large-Block Experiments in Underground Coal Gasification (November 1982)

LABORATORY HISTORY

Energy and Resource Programs (October 1982)
Inertial Confinement Fusion (October 1982)
The Tandem Mirror MFE Program (October 1982)
Chemistry and Materials Science in Retrospect (September 1982)
Computing at LLNL (September 1982)
Project Plowshare: A Brief History (September 1982)
The LLNL-Nevada Organization (September 1982)

NUCLEAR ENERGY

Successful Demonstration of the AVLIS Process (Brief—August 1982)

WORK FOR OTHERS

Defense Advanced Research Projects Agency

ATA Injector Meets Design Goals (Brief—January 1983)

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government thereof, and shall not be used for advertising or product endorsement purposes.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$4.50, Microfiche \$3.00