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Energy and Technology Review

Lawrence Livermore National Laboratory

September 1981

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UCRL-52000-81-9
Distribution Category UC-2
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Optical Fibers in Nuclear Test Diagnostics

Our work on a wavelength multiplexer and new scintillator materials for use with optical fibers promises more efficient and sensitive nuclear diagnostic systems.

The Nuclear Test Program at LLNL conducts tests of new weapon designs in response to military needs defined by the Department of Defense. These tests provide information that researchers in LLNL's Nuclear Design and Military Applications programs can use in refining the designs and developing new ones. In addition, we carry out experiments in basic physics, using the nuclear devices as energy sources.

These tests require diagnostic instruments that are adequately designed to make very rapid and precise measurements and are durable enough to withstand hostile field conditions at the test site. The nuclear device tests take place in the Nevada desert, where aridity and extreme temperatures are common. A canister containing the shielded nuclear device and trailing communication lines is lowered into a shaft that may be as much as 700 m deep and 2 m across (Fig. 1). The hole is then filled with sand, gravel, and epoxy plugs to contain radioactive products. Detonation of the device creates extremely high radiation fields and heat, vaporizing the device and

everything in its vicinity within a few thousandths of a second.

The challenging environment in which the nuclear test takes place presents many difficulties to diagnosticians. They must collect data on events happening within the few thousandths of a second between detonation and the time the diagnostic instruments vaporize. These environmental and time constraints put rigorous demands on our diagnostic techniques.

We expect that the optical fiber techniques we are developing and incorporating into our diagnostic systems will help us meet these demands. Optical fibers, or light guides, are glass filaments that can transmit light over great distances.¹ They present an attractive alternative to the coaxial cables that are now used to transmit data from the detonating nuclear device at the bottom of the hole to protected receivers located on the surface. Optical fiber lines offer a 1:150 weight advantage over coaxial cables, an important factor when they must be suspended 300 m or more deep in test holes (Fig. 2). Since the fibers are glass, the signals they carry are immune

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Fig. 1

Preparing for a nuclear test at the Nevada Test Site. The silver-colored canister containing diagnostic instruments is being joined to the white canister containing the thermonuclear device. After the two are attached, the whole assembly, including the communication cables shown at the left of the picture, will be lowered into a deep shaft where the device will be detonated.

to the electromagnetic pulses that affect metal-cored cables.

The amount of data that can be transmitted by cables and optical fibers in a given time is limited by the bandwidth of the transmission medium. An optical fiber's bandwidth varies inversely with its length; a coaxial cable's bandwidth varies inversely with the square of its

length. The much greater bandwidth of the optical fiber allows it to carry more information per channel. In addition, the cost per information channel is less than for coaxial cables. We anticipate lower costs for field experiments in which we use the fiber systems.

Optical fibers maintain signal fidelity when transmitting data at short time intervals, whereas when data are crowded on a coaxial cable in order to transmit a large amount of information very rapidly, the signal often becomes blurred. Although signal fidelity deteriorates over distance in both media, it deteriorates much less in optical fibers. This advantage allows experimenters to station complicated and costly diagnostic equipment at a greater distance from the detonation point, that is, on the ground surface rather than at the bottom of the hole. This not only preserves the equipment from vaporization, allowing it to be used again, but also keeps it accessible for adjustments and repairs until just before detonation. When diagnostics are placed in the shaft (as some must be when coaxial cable is used) they are virtually inaccessible for up to a month before the test. (Table 1 compares selected fiber and coaxial cable characteristics, indicating the relative superiority of the fibers for prompt diagnostic instruments.)

The optical fiber systems now commercially available usually are not suited to weapon-testing diagnostics. This is, in part, because their bandwidths are inadequate in parts of the system other than optical fibers, their electronic components are vulnerable to radiation, or they lack passive radiation-to-light converters (RLCs). To develop the new capabilities and specialized tools and techniques necessary to exploit optical fiber systems, our fiber optics project is concentrating its research effort on developing RLCs, diagnostic systems for use in the field, and optical fiber technology. In the past year, we have made significant progress in these three endeavors.

Field Systems

To develop special optical fiber field systems for diagnosing nuclear tests, we combine the specialized knowledge, tools, and techniques derived from laboratory

Fig. 2

The small, orange, optical fiber cable has the same number of transmission channels (eight) as the eight coaxial cables behind it. Although each glass optical fiber is only 125 μm in diameter, it can transmit data at a rate up to 100 times that of a coaxial cable. Note the light signals being emitted at the ends of the fibers.

Table 1 Selected characteristics of optical fibers and coaxial cables.

	Bandpass, MHz ^a	EMP immunity	Approx. cost, ^b dollars	Weight, kg/km
Coaxial cables (2.2-cm-diam foam dielectric)	3.4 ^c 320 ^d	No	9.80	620
Optical fiber (graded index)	1300-1500	Yes	3.00	4.2

^a3-dB frequency for 1-km length.
^bPer meter channel.
^cBare cable.
^dCable equalized 10:1.

Fig. 3

Diagram of the diagnostic system containing the 20-MHz analog optical fiber line we used in a recent nuclear test. Information on radiation levels at the point of detonation was gathered by the PINEX camera and relayed to receivers above ground through both optical fibers and coaxial cables. The two signals from the PINEX were compared with each other and with control signals originating both at the bottom of the shaft and at ground level.

research on fiber technology with commercially available components.

The neutron spatial image of a detonated nuclear device is of great interest to weapon designers. For several years, LLNL diagnosticians have measured this image with an electronic camera called the PINEX (Pinhole Neutron Experiment). The PINEX measures the time-integrated image of the neutron output by using a plastic-based scintillator to convert the neutron barrage to an optical image, recording this image with a silicon-photodiode array camera, digitizing the information, and sending it

up the shaft via coaxial cable to be stored in a computer memory bank.

The silicon photodiode contained in the camera that records the optical image consists of a square array of discrete resolution elements, or pixels. In order to obtain better resolution, we recently replaced 50×50 -pixel arrays with 100×100 -pixel arrays and plan to use even larger arrays (possibly 256×256 pixels) in the future. As the size of the arrays increases, the data they deliver must be transmitted up the hole at higher rates to be recorded before the detonation shock arrives. Coaxial cable is inadequate for the expected future data-rate requirement of 200 Mbit/s over 1 km of cable.

A solution to this problem is to transmit the PINEX data over optical fibers, as we successfully did during a recent nuclear test. The optical fiber system we used contained the 20-MHz analog line shown in Figs. 3 and 4. A properly encoded video signal from the camera containing a 50×50 -pixel array drove a light-emitting-diode transmitter with a peak power output of 1.5 mW at a wavelength of 820 nm. The output from the transmitter was sent up the hole on 700 m of optical fiber that had a graded index of refraction and was designed to transmit at 400 MHz.

At ground level, the optical signal was converted into an electrical one by a receiver consisting of an avalanche diode and two additional signal amplifiers. The product was fed into a digitizing chassis and memory interface, where it was converted into a form suitable for computer storage.

We have concluded from this experiment and the results of subsequent systems analysis that future optical fiber systems with a 200-Mbit/s data rate will produce higher quality information if digital rather than analog data are transmitted over the optical fiber line. A digital system like that diagrammed in Fig. 5 would transmit 8-bit-quality data (with a noise level less than 1 part in 256), whereas a practical 100-MHz analog system would return only 6-bit-quality data (with a noise level less than 1 part in 64). We are now evaluating commercially available digital components and digital-transmitter/receiver pairs (designed for

optical fibers) with which we will construct a digital data link to be used in a forthcoming nuclear test. The greater information-carrying capacity of fibers will allow better resolved neutron pictures (256×256 pixels) to be taken during underground tests.

Radiation-to-Light Converters

Scintillators (materials that convert radiation to light by emitting optical photons when exposed to ionizing radiation) have long been used as reliable and convenient means of detecting nuclear radiation. The light given off by a scintillator in a radiation field is detected by a photoelectric device that emits an electrical signal.

Conventional plastic-based scintillators commonly used for detecting nuclear radiation are not suitable for use with very long optical fiber lines when the long fibers intervene between the scintillator and the photodetector. (Our diagnostic systems will require lines up to 1 km long.) The plastic scintillators emit most of their light in the blue region of the spectrum, a region of extremely high signal loss in optical fibers. High-bandwidth, multimode optical fibers with graded indexes of refraction generally are designed for minimum light dispersion in the near-infrared region of the spectrum. Furthermore, fibers designed for longer wavelengths near the infrared region have much less light dispersion and lower sensitivity to radiation interference.

These considerations point to the need for a scintillator with an emission peak in the near-infrared region of the spectrum if scintillators are to be used as the sole light source for long-distance transmissions over optical fibers. We need efficient radiation-to-infrared light converters.

Radiation-to-light converters that are to be used in diagnosing nuclear detonations should have the following characteristics, although exceptions may exist for special applications:

- An emission peak lying within the spectral range of 700 to 870 nm (near-infrared region).
- Fast time response (with a difference in the duration of radiation input pulse

and optical output pulse of less than 2 ns).

- Efficiency (ratio of light energy out to radiation energy in) comparable to that of conventional scintillators.
- Light output directly proportional to radiation input over at least a factor of 100 in dose.

Fig. 4

The 20-MHz analog optical fiber line being calibrated in the laboratory. The reel in the foreground holds 1 km of optical fiber cable.

The greater information-carrying capacity of fibers will allow better resolved neutron pictures (256×256 pixels) to be taken during underground tests.

- Immunity to radiation damage for a time long enough to make the measurement.

In the past year, we have investigated several semiconducting compounds for suitability as RLCs: cadmium sulfide (CdS), cadmium sulfide with excess sulfur (CdS^+), cadmium selenide (CdSe), cadmium telluride (CdTe), and gallium arsenide (GaAs). At this stage of our research, we find that GaAs holds the most promise for fulfilling all the criteria listed above.² Its emission peak lies in a wavelength range very favorable for optical fiber systems (Fig. 6a). We found that GaAs has a very fast time response. An upper limit on the impulse response to low-energy electron excitation has been placed at 1.4 ns, and more recent measurements with a 10-ps laser pulse as the excitation source indicate that time response for GaAs may be even better, by up to a factor of 10 (Fig. 6b).

Light emission from GaAs is directly proportional to the radiation dose it receives up to a dose of about 2×10^4 rad, at which level its light output increases at a disproportionately positive rate (Fig. 6c). Gallium arsenide's absolute light output at lower radiation levels is difficult to measure because it is so low. Our tested samples have an efficiency of 2.29×10^{-13} J/cm² sr·rad (for a 1.4 ns radiation pulse), a level of efficiency that would limit the use of GaAs for systems requiring a photon-emission response time of about 2 ns and an accuracy of about 10%. In order to achieve RLC systems with a factor-of-10 more response time and accuracy, the output of the GaAs would have to be increased 10 to 100 times. Although this requirement

Fig. 5

Schematic drawing for a digital optical-fiber transmission line capable of a 200-Mbit/s data rate. This was designed for the large format camera arrays (up to 256×256 resolution points) we plan to use in future diagnostic systems.

may seem formidable, we believe there is a good probability of fulfilling it with more intrinsically efficient samples and improved sample geometry.

The data on GaAs we present here apply to samples at 77 K. We observed a radiation/light efficiency approximately 12.5 times better for the cooled samples than for ones at room temperature. Although field operation at low temperature would not be prohibitive, it would be inconvenient; one of our goals is to increase the efficiency of GaAs at room temperature.

Optical Fiber Technology

Our field experiments with optical fibers call for special techniques and tools. We are refining our techniques for the exacting and crucial procedures of polishing the ends of fibers and fusing them with electric arcs. We are also developing special connectors and terminals that will allow us to join fibers end to end under field conditions.

Optical fiber systems used in place of coaxial cable in nuclear diagnostics will be used most efficiently if more than one data stream is transmitted on each fiber at once. We can meet this condition and still obtain adequate resolution by multiplexing, or "stacking" data so that hundreds of data points can be transmitted simultaneously over a few fibers. The development of a multiplexing/demultiplexing system suited to our needs is a central task of our fiber-technology program.

The most important advances in fiber technology at the Laboratory are represented by a multiplexing/demultiplexing system capable of converting a two-dimensional ($N \times N$ pixel) image into a set of one-dimensional (N) signals and then back to two dimensions. This $N \times N$ to N spectral multiplexer³ can reduce the number of fibers required to transmit a given amount of data by up to a factor of 100. The multiplexer collects the light from an image source, selects a unique segment of the spectrum for each resolution element (pixel) in that source, transmits a number of these spectral segments over an optical fiber, and, finally, reconstructs a two-dimensional

Fig. 6

Data from our experiments with gallium arsenide (GaAs) indicate it has promise for use in future diagnostic systems. (a) The light emissions from GaAs under electron excitation peak in a wavelength range compatible with efficient transmission over optical fibers. (b) The optical pulse emitted by GaAs has a fast time response, that is, its light-emission curve rises to a peak and falls back rapidly. The graph shows the system-limited time response of GaAs under excitation by a laser operating at 850-nm wavelength. (c) The light output from GaAs varies directly with the amount of radiation the sample is exposed to (in a 1.4 ns pulse) up to a threshold at which light emission increases disproportionately. (All data here apply to samples cooled to 77 K.)

image of the original object viewed by "unstacking" (demultiplexing) the spectral segments.

Beginning with existing general concepts for spectral multiplexers⁴ (all of which had limitations in either transmission speed, energy efficiency, or image

Fig. 7

Schematic drawing of the optical-signal multiplexer/demultiplexer developed at LLNL. Optical signals from a light-emitting object (A) can be multiplexed (stacked) and transmitted through an optical fiber (D) to be demultiplexed and displayed as a coherent image of the original object on a cathode screen (F). The light spectra from many points on object A (points P_1 and P_2 in this example) are diffracted by grating (B) so they are displaced in relation to each other (C). The optical fiber (D) picks up a stack of spectral segments (each of which uniquely represents a single point on A) and transmits the stack to the demultiplexer. The spectral segments are unstacked by grating (E) in such a way that they are dispersed across a screen in the same relative positions they occupied in object A. Although each point on A is represented on the screen (F) by a segment of its emitted spectrum, the array of points on the screen collectively can constitute a full visual spectrum.

Fig. 8

Laboratory prototype of the optical-wavelength multiplexer/demultiplexer, which, by selecting segments from the spectrum emitted from an object and "stacking" the segments, enables optical fibers to carry as much as 100 times more bits of data than they were previously able to do.

resolution), we designed and built a successful multiplexer. In doing so, we performed numerous experiments to determine design parameters for the system and formulate them in engineering terms. We studied the size, shape, structure, spectral characteristics, and total radiant energy of the objects to be viewed, and the sensitivity, resolving ability, and configuration of the receptor of the final image. We also experimented with various types and arrangements of optical fibers, optical gratings, and lenses in order to determine their characteristics and optimal combination when used in a spectral multiplexer.

The Laboratory's prototype of a multiplexing/demultiplexing system is represented schematically in Fig. 7. The prototype itself is shown in Fig. 8. The multiplexing portion of the system consists of a lens that collects the light from the optically homogeneous image source, a plane grating that linearly disperses the spectra from many points on the image source, and a second lens that focuses the dispersed spectra on the receiving end of an optical fiber.

The development of a multiplexing/demultiplexing system suited to our needs is a central task of our fiber-technology program.

Fig. 9

This test pattern, consisting of 2500 resolution points (top of illustration), was transmitted over the prototype of the multiplexer/demultiplexer shown in Fig. 8. The 50 colored lines visible in the final image correspond to the 50 optical fibers over which it was transmitted. Note that, although the original pattern has a uniform color, the resolution elements in the transmitted image are dispersed across the visible spectrum according to the unique spectral segment the multiplexer selected for each of them. The white background pattern supplies the colors that are transmitted.

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The optical fiber, located at a fixed position at the focal point of the second lens, will intercept a different portion of each of these spectra. All points on the image source emit the same spectrum, but because they have different original spatial locations, the spectrum of each will be spatially shifted by the grating in proportion to its distance from the others. This shift will cause a unique portion of the spectrum for each point to fall on the same optical fiber.

A series of unique spectral segments collectively representing one row of the pixel array can be transmitted over one optical fiber. Other rows may be transmitted in the same manner on additional fibers. Figure 9 demonstrates the quality of a 50×50 -pixel image carried by 50 fibers. The arrangement and size of the optical fibers can affect the resolution quality of the final image. The number and distinctness of spectral segments carried by each fiber is limited by the width of the fiber's core, and the distance between the final, horizontal image lines is determined by the thickness of the cladding that surrounds each core and separates it from the others.

We are developing a diagnostic instrument incorporating our multiplexing system. Fifty spatial points will be

transmitted over each optical fiber. The data from the multiplexer will be focused, four lines at a time, across the face of a streak camera which will record spatial and temporal information about the image. The uses for this multiplexing system are not limited to diagnosing nuclear detonations; it has potential applications in relaying any image for which the number of resolution points is not extremely large and in data transmissions for which a higher data rate per cable would be a benefit.

Summary

We expect that incorporating optical fibers into our nuclear test diagnostic systems will enable us to obtain data of better quality than we now can gather and to obtain previously unavailable information. Our first field tests of optical fibers laid the groundwork for the more sophisticated optical fiber diagnostics we are now developing. Our research on radiation-to-light converters has yielded data that point to gallium arsenide as a promising scintillator for use in the diagnostic system. The functioning spectral multiplexer/demultiplexer we have designed and built has greatly increased the rate at which data can be transmitted by optical fibers, both in

diagnostic systems and in general applications. ■

Key Words: gallium arsenide; multiplexer; optical fiber; PINEX; scintillator.

Notes and References

1. Light propagation in optical fibers was the subject of an article in *Energy and Technology Review*, UCRL-52000-81-3 (March 1981), p. 1.
2. Related laboratory work on gallium arsenide in diagnostics was discussed in "Predicting Integrated-Circuit Performance," *Energy and Technology Review*, UCRL-52000-81-8 (August 1981), p. 1.
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Understand the Physics of Explosion Products

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Recent theoretical and experimental advances enable us to evaluate from first principles thermodynamic data on the detonation properties of various high explosives.

Detonation waves in high-density, solid explosives generate tremendous temperatures and pressures. One indication of these extreme conditions is the velocity of the detonation wave. In solid hexanitrobenzene (HNB), for example, it is more than 9 km/s, or more than 20 times the speed of sound in air.¹ A square detonation front 3.2 cm on a side in HNB converts energy at the rate of 400 GW (approximately equivalent, for the microseconds involved in the explosion, to the total electric generating capacity of the United States).

In research on explosives, we distinguish between initiation (the stimuli and processes by which a metastable explosive becomes a violently reacting system)² and detonation (the dynamic

steady-state energy-conversion process that propagates through the explosive).

A detonation wave propagates through an explosive medium by a complex interplay between the shock wave and the chemical reaction of the explosion. Energy from the shock wave breaks chemical bonds in explosive molecules. The recombination of these fragments into detonation products releases stored potential energy, which appears as kinetic energy of the product molecules and provides the pressure required to maintain the detonation front ahead of a rarefaction wave that follows behind.

Once the detonation wave has traversed the explosive, the hot gases left behind continue to exert pressure. Most of the work of an explosion is performed

by these gases; hence, our calculational effort is directed toward describing their behavior.

In this article, we are not concerned with the chemical reactions themselves. We will consider primarily the thermodynamic aspects of a steady detonation wave. This requires a detailed knowledge of the equation of state (EOS) of the complex mixture of explosion products.

Practical applications of explosives in nuclear devices require an exact knowledge of detonation waves and the forces they apply. We use hydrodynamic computer codes to predict these effects, but such codes are only as accurate as our knowledge of the impulse the detonation products can impart. The relationships among pressure, density, energy, and temperature in the detonation products are obtained from the explosive's EOS. The problem lies in determining accurately the EOS of the detonation products.

Detonation products generally are complex mixtures, the molecules of which can interact in many different ways and with different intermolecular potentials. Furthermore, the detonated explosive may consist of more than one mixture in more than one phase. It is difficult to handle such complex systems on a theoretical basis. However, nuclear-explosive technology has provided us with many experimental and theoretical tools for investigating the physical and chemical properties of materials under extremes of pressure and temperature. Experimental tools include the two-stage light-gas gun, particle-velocity gauges, detonation calorimeters, and fast infrared radiometers.^{2,3} Theoretical tools include quantum-mechanical codes (which we originally acquired for studying chemical lasers and isotope separation schemes) and several first-principles statistical mechanical methods useful for calculating EOS properties of reacting and nonreacting systems, both simple and complex. Using these tools, we have developed a theoretically derived model that enables us to calculate the EOS of detonation products from first principles.

We use shock waves to investigate the properties of matter at the temperatures and pressures present in the detonation

and implosion of a nuclear device, producing Hugoniot curves that relate pressure, density, energy, and temperature. We have also applied these experimental results outside the nuclear explosive programs, in studies such as the modeling of the giant planets.⁴

EOS of Simple Systems— Quantum-Mechanical Potentials

A reliable EOS model of a detonated explosive must give accurate shock-wave properties of each chemical species present among the detonation products, together with the thermodynamic properties of the complex mixture. As a first step in developing such a comprehensive model, we examined the EOS of individual chemical species.

Our first concern when calculating any EOS is to determine the rules governing how the individual molecules attract and repel each other. To do this, we use a quantum-mechanical potential, which we can calculate theoretically from the known mass, charge, and electronic structure of the molecule. Ideally, we could carry out such calculations for any cluster of molecules (two or more molecules in some specified geometrical relation), but in practice such calculations become unwieldy for all but the simplest molecules.

The hydrogen molecule, with only two electrons, comes very close to the ideal simple molecule, and we can compute accurate potentials for many hydrogen clusters. The nitrogen molecule, with 14 electrons, has much more complicated electronic interactions. However, in a detonation or shock-wave environment, only the strongest forces must be specified accurately, and we can tolerate approximations to the weaker forces. We can obtain a reasonably reliable calculation of the quantum-mechanical potential for nitrogen molecules by using the self-consistent-field (SCF) method.

To illustrate the difference between hydrogen and nitrogen, Fig. 1 compares SCF intermolecular potentials of two H_2 molecules⁵ and two N_2 molecules⁶ at four different molecular orientations. For hydrogen, each of the orientations gives

Fig. 1

Pair potentials at four different orientations for molecules of nitrogen and hydrogen, quantum mechanically computed using the self-consistent-field method. Of the two sets, the N_2 pair potentials are by far the more sensitive to orientation.

nearly the same curve, but for nitrogen, the curves are far apart. (The actual difference, indicated by the heavy black arrows, is much larger than it appears, owing to the logarithmic scale of the illustration.) At an intermolecular spacing of 2.9×10^{-8} cm (about that of the highest shock compression achieved in the experiments reported in Ref. 3), the difference in energy between the X and L geometries (defined in the illustration) is about 200 times larger for nitrogen than for hydrogen.

When we try to use these two-body potentials to calculate an EOS, however, the one for nitrogen agrees well with experiment to about 30 to 40 GPa, but the one for hydrogen does not. Hydrogen's electrons are loosely bound to nuclei and easily change their positions when we add a third (or fourth) molecule to the cluster. Most of nitrogen's electrons are tightly

bound, so that the repulsive potential provided by the core electrons is less subject to change. Thus, at fixed intermolecular spacings the presence of additional hydrogen molecules in a cluster changes the electron orbits drastically, but adding another nitrogen molecule has little effect. In order to bring our hydrogen EOS calculations into better agreement with experiment, we must include the effects of the additional molecules (the many-body effect).

Simplified Potentials

The *ab initio* quantum-mechanical potentials described above are cumbersome, and we must use simpler potentials (with the same physical features) in calculating complex post-detonation problems. Fortunately, because the high temperature in detonations (about 2000 to 5000 K) permits molecules to rotate

more easily, we can simplify the calculations by treating the molecules as spherical, including the average of their asymmetries (if significant) by means of a temperature-dependent factor in the potentials.

A further simplification is possible because compressions like those encountered in the detonation wave are intense enough to break up such orientational ordering as hydrogen bonding in water. The compression is still relatively low and the temperature is high enough, however, so that the repulsive force appears independent of orientation, even for a highly nonspherical molecule such as N_2 , so we need not complicate the expression by explicitly allowing for nonsphericity.

It is convenient to classify the intermolecular potentials of detonation products into three classes:

- Class 1. Potentials that obey the corresponding-states law.
- Class 2. Potentials that have a strong electrostatic attraction.
- Class 3. Potentials in which many-body interactions are important.

Each of these classes can be approximated by the exponential-6 (exp-6) potential, which consists of a repulsion that decreases exponentially with distance working against a van der Waals attraction proportional to the inverse sixth power of the distance. The exp-6 potential is characterized by three parameters: ϵ , the depth of the attraction; r^* , the magnitude of the repulsive core; and α , the slope of the exponential repulsion.

Class 1 Potentials

For most detonation-product species (O_2 , N_2 , CH_4 , CO , CO_2 , etc.), we have found that $\alpha = 13$ and that the parameters ϵ and r^* may be fixed by means of the corresponding-states scaling relation.⁷ The corresponding-states scaling relation requires us to express the reduced critical temperature and the reduced critical pressure in terms of universal constants identifiable with those of argon.

Figure 2 compares experimental pressure-density data for nitrogen, oxygen, and carbon dioxide with Hugoniot curves calculated by three different models. This evaluation was done with a new fast and

efficient statistical mechanical model⁸ using the exp-6 potential. This model provides EOS properties of fluids based on the first-principle fluid theories of statistical mechanics. Our statistical-mechanical EOS comes closest to the experimental points in each case. The other calculations shown are based on the Becker-Kistiakowsky-Wilson (BKW) EOS and the JGZ3 EOS developed by Jacobs, Cowperthwaite, and Zwisler.⁹ These EOSs and the LJD⁹ and the BKWR¹⁰ EOSs (not discussed here) have been used in the past by those investigating high explosives. They approximately describe the fluid-state properties of high explosives by an empirical gas-phase (BKW) or a solid-phase (LJD) EOS theory or a semi-empirical combination of gas- and solid-phase EOS theories (JGZ3).

Fig. 2

Experimental Hugoniot of nitrogen, carbon dioxide, and oxygen (see Ref. 3), compared with theoretical Hugoniot computed from the corresponding-states theory (see Ref. 7). BKW and JGZ3 are two widely used approximate EOS models; Hugoniot based on them are shown in red and orange, respectively, and that based on our statistical mechanical EOS model (Ross and Nellis) is shown in black. The oxygen Hugoniot has been shifted to the right by $+0.6 \text{ Mg/m}^3$ to distinguish them clearly from the carbon dioxide Hugoniot.

Fig. 3

Several theoretical Hugoniot of water are compared with experimental measurements (see Ref. 3). Only the Rowlinson potential with effective dipole, which includes a strong orientation-dependent electrostatic interaction in the pair potential, agrees well with the experimental data below about 30 GPa.

Our calculated EOS for nitrogen agrees well with experiment up to about 40 GPa. At higher pressures the experimental EOS "softens" (the material becomes easier to compress than would be expected from extrapolation of the low-pressure data). We are investigating the reason for this unexpected behavior (which might be explained, for example, by the formation of a monatomic metallic phase of nitrogen as a result of thermal dissociation), but it has little effect on our detonation-wave calculations because they mostly concern conditions below 50 GPa and the deviation is still tolerable at 60 GPa.

Class 2 Potentials

For H_2O , NH_3 , and HF (major chemical species with strong electrostatic attraction that are important for detonation problems), we define the attractive parameter ϵ in the $\exp(-\phi)$ potential to be temperature dependent. The temperature dependence takes into account an average

orientation-dependent electrostatic interaction that becomes appreciable at low temperatures (less than about 1800 K). We can determine ϵ either by a quantum-mechanical method or by fitting the Hugoniot data of individual detonation products.

Figure 3 compares experimental data for water with several theoretical EOS calculations. The Hugoniot calculated with temperature-dependent ϵ is in good agreement with the experimental data, even reproducing the ramped "toe" of the curve at low temperatures. The other calculations do not agree as well.

Class 3 Potentials

Only hydrogen, of all the chemical species exhibiting a class 3 potential, is of much importance in detonation problems. We have noted already how the many-body force softens the intermolecular pair potential for hydrogen and its isotopes. This softness may be accommodated in the $\exp(-\phi)$ potential by reducing α somewhat, to model many-body interactions.

EOS of Reacting Mixtures

The theoretical and experimental work we have discussed up to this point is a necessary preliminary to the description of detonation waves. The post-detonation products are never single elements or even pure compounds. Rather, they are hot reactive mixtures whose composition changes with temperature, pressure, and time.

To calculate anything about such mixtures, we must employ another simplifying assumption, in addition to sphericity. We use the van der Waals one-fluid mixture model, in which all molecules in the mixture are assumed to be identical and to interact by an "effective" $\exp(-\phi)$ potential. The ϵ and r^* of the mixture are really composites or weighted averages specified in terms of the concentrations and ϵ and r^* parameters of the constituents of the mixture. Since in this model every molecule interacts with the same potential as every other molecule, we can extend to mixtures the one-component EOS systems discussed earlier. The reliability of the one-fluid van der Waals

model has been tested and verified by extensive Monte Carlo and molecular dynamics computer simulations done elsewhere.

One complication associated with detonation problems is that because the detonation products are chemically reactive, their concentrations change with temperature and pressure. This makes it necessary to determine the concentration of all constituents (by minimizing the free energy) and to readjust the ϵ and r^* of the mixture at frequent intervals throughout the calculation.

Figure 4 illustrates a case (liquid carbon monoxide) in which the chemical reactions dominate the Hugoniot behavior.¹¹ Liquid carbon monoxide dissociates by reversible decomposition reactions into condensed phases (graphite or diamond) of carbon plus a fluid mixture of carbon dioxide, carbon monoxide, and oxygen. The mixture properties of carbon dioxide, carbon monoxide, and oxygen are well described by the van der Waals one-fluid model, but in what form would the condensed carbon appear—as graphite or diamond?

All previous chemical equilibrium models for post-detonation studies (including the BKW and the JCZ3 calculations in Fig. 4) have been based on the assumption that the condensed carbon will appear as graphite or "amorphous" carbon, which is difficult to define thermodynamically. None of these models is consistent with the experimental data. Only the Hugoniot calculated on the assumption that diamond-like carbon may also form follows the experimental points at high pressures.

At low pressures (between 3 and 25 GPa), however, none of the equilibrium or quasi-equilibrium models is satisfactory. This may well be due to a time-dependent effect in the experimental data. The time it takes to break the carbon-oxygen bond and recrystallize the dissociated carbon atoms may be longer at the low shock temperatures available in this pressure range than the typical shock-passage time (about 200 ns) in the experiment.

A study of hydrocarbon Hugoniot further supports the necessity of postulating a diamond-like phase of

carbon.¹² If we collect a large number of hydrocarbon Hugoniot into a single plot (Fig. 5), we find that they can be grouped, especially at high pressures, according to the proportions of carbon and hydrogen present. Our calculations indicate that at high shock pressures the replacement of carbon-hydrogen bonds with two different covalent bonds (H-H bonds to form molecular hydrogen and C-C bonds to form a diamond-like structure) is energetically favored. This simple model successfully reproduces the shock-wave data of hydrocarbons.

Fig. 4

A comparison of various attempts to calculate the Hugoniot of liquid carbon monoxide. The best fit to the experimental data (see Ref. 11) occurs when we admit the possibility that some of the free carbon formed may crystallize into a diamond-like phase.

Calculations of Post-Detonation Properties

To illustrate our calculation methods, we will consider three simple

Fig. 5

Experimental Hugoniot data of carbon and hydrocarbons. The Hugoniots of hydrocarbons having the same hydrogen-carbon ratio (H:C) tend to merge at high pressures and to separate from those of hydrocarbons with a different H:C ratio. This result can be predicted with a model that includes the formation of a diamond-like phase (see Ref. 12).

explosives—liquid nitric oxide (NO), RX-23-AB, and hexanitrobenzene (HNB)—as representative examples. Liquid nitric oxide is a highly sensitive explosive that dissociates into an equimolar mixture of nitrogen and oxygen.¹³ RX-23-AB, a specially formulated explosive consisting of hydrogen nitrate (70 mol%), hydrazine (5.9 mol%), and water (24.1 mol%), produces a stoichiometric mixture of water (73 mol%) and nitrogen (27 mol%).¹³ Since none of these reaction products is particularly reactive, either of these two explosives provides a simple test of the van der Waals one-fluid mixture model.

HNB, recently synthesized and tested at LLNL, is one of the most powerful chemical explosives available.¹ Its detonation products are mostly nitrogen and carbon dioxide, with small amounts of nitric oxide and carbon monoxide, and no significant amount of condensed carbon. Because these reaction products are more reactive, HNB provides a more complex test of the van der Waals one-fluid mixture model.

As a starting point for calculating post-detonation behavior, we select the Chapman-Jouguet (CJ) point, where the detonation products behind the detonation front reach chemical equilibrium. We

Table 1 The Chapman-Jouguet pressure (P), temperature (T), and detonation velocity (D) of three explosives, measured experimentally and calculated according to three different theoretical models.

Explosive	Unit	Experiment	Theory		
			Statistical mechanical model	JCZ3	BKW
Nitric oxide	P , GPa	10.0 ± 1.5^a	10.0	10.6	10.6
	T , K	—	3434	3136	2330
	D , km/s	5.62 ± 0.07^a	5.69	5.79	5.44
RX-23-AB	P , GPa	18.6^b	17.0	15.5	20.3
	T , K	(4000) ^c	2213	1966	925
	D , km/s	$7.48 (7.78)^c$	7.72	7.31	7.93
Hexanitrobenzene	P , GPa	42 ^e	36.9 (38.3) ^f	34.4	34.2
	T , K	—	4780 (5454) ^f	5121	3606
	D , km/s	9.34 ^e	9.11 (9.24) ^f	8.83	8.12

^aRef. 13.

^bRef. 10.

^cValues in parenthesis are by Urtie.v. given in Ref. 10.

^dThis C-J temperature may be unrealistically high; see Finger *et al.* in Ref. 10.

^eRef. 1.

^fValues in parentheses were obtained by neglecting formation of CO and NO.

use the C-J model⁹ (based on the hypothesis that the detonation wave travels with the same velocity as the following rarefaction wave) to compute the detonation pressure (P_{CJ}), energy (E_{CJ}), temperature (T_{CJ}), density (ρ_{CJ}), and velocity (D_{CJ}). On the assumption that the detonation products behind the detonation front are in chemical equilibrium, we should be able to use our model based on intermolecular potentials and the EOS of a detonated explosive described above to compute detonation properties at the C-J point.

Table 1 compares C-J calculations based on our statistical mechanical model, the BKW EOS, and the JCZ3 EOS with experimental C-J data of the three explosives. The detonation velocity can be measured directly and with little error. The calculation based on our model gives detonation velocities that lie within the range of experimental error for nitric oxide and HNB and between two experimental results for RX-23-AB. In each case, the values are superior to those obtained from the JCZ3 or the BKW model.

Because the experimental P_{CJ} values

are indirectly determined by various hydrodynamic methods, they contain larger uncertainties than those of P_{CJ} . Our model gives a P_{CJ} that is superior to those predicted by the JCZ3 or the BKW model.

In the cylinder test, a standardized test we have developed for comparing explosives,¹⁴ we detonate one end of a stick of explosive packed into a copper tube of specified dimensions and use streak cameras to record the adiabatic expansion of the tubing at various points along its length. The simplified geometry of this test makes it relatively easy to analyze the results and provides a good basis on which to construct a reliable EOS model for detonation products.

Figure 6 shows how closely the three EOS models we have been examining follow the adiabatic expansion of RX-23-AB from the C-J point as calculated with the JWL EOS, an experimental EOS based entirely on cylinder-test data.¹⁵ Using the JWL as the norm and plotting it along the x axis, we then plot deviations from it for the other models. The portion of the graph that is

Fig. 6

Comparison of calculated cylinder-test adiabatic-expansion pressures with those derived from the JWL EOS, an EOS based directly on cylinder-test data. The significant portion of the data extends up to an expansion ratio (V/V_0) of about 3. Within this range, our statistical-mechanical-EOS calculation remains closest to that of the JWL EOS (plotted as the horizontal axis), never deviating by more than 7%.

significant for the present discussion extends to an expansion ratio (V/V_0) of about 3. Throughout this range, the disagreement between the pressure calculated with our statistical mechanical EOS model and the JWL EOS is 7% or less. The JCZ3 calculation is off by as much as 28%, and the BKW calculation deviates in places by more than 50%.

One of the important factors in evaluating the detonation performance of an explosive, and one of the most sensitive tests of the various EOS models, is the adiabatic gamma, a measure of the rate of pressure release along the C-J adiabatic expansion path. The adiabatic gamma is the partial derivative of the logarithm of the pressure with respect to the logarithm of the density at constant entropy.

Figure 7 shows how the adiabatic gamma for HNB, calculated according to various EOS models, behaves as a function of density. We plot two calculations using our statistical mechanical model. In

one of these, we neglect the formation of carbon monoxide and nitric oxide ("no side reactions"). Since these curves vary smoothly with density, we tentatively conclude that the peaks and valleys in the JWL and JCZ3 calculations have no thermodynamic significance, at least for the explosives examined here.

Because the adiabatic gamma is a second-order derivative of the free energy, it is extremely sensitive to slight deviations from the true EOS of the gases. This tends to magnify any slight imperfections in our hydrodynamic interpretations of cylinder-test data, for example. Hence we may be expecting too much of the JWL EOS in applying it to this calculation, even though it adequately fits the radius-vs-time histories of a large number of cylinder tests. A detailed examination of the adiabatic gammas for other explosives may pinpoint the exact cause of the structures seen in the JWL adiabatic gamma.

Conclusion

We have developed and tested an equation-of-state model that reliably predicts the detonation performance of high explosives. This development became possible after recent advances in chemistry, physics, and computing science, some of which took place at this laboratory. We plan to continue to refine ... extend this model.

Chemical-equilibrium calculations of exploding systems have sometimes been suspect, since time-dependent factors may be of overriding importance in determining post-detonation behavior. We believe that the good agreement between our unambiguous calculations and the experimental data for certain explosives should dispel such suspicions, at least for the three explosives investigated here. Application of our statistical mechanical model to other explosives and comparison with the corresponding experimental data will reveal whether time-dependent factors may be present in the post-detonation behavior of some explosives. ■

Key Words: detonation waves; equation of state—computations; explosives—computations; hexanitrobenzene; HNB; Hugoniot equations.

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Fig. 7

Adiabatic gamma, the rate of pressure release in the expansion of an explosive, calculated for HNB on the basis of the various equations of state described in the text. Our statistical mechanical calculations, with or without side reactions, are smooth and well-behaved in comparison with the others.

...the conference participants...
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...control questions. Third, with a...
...new administration developing its

...arms limitation talks...
...SALT), theater nuclear force...
...restraints in Europe, nuclear test...
...limitations, arms control in space,
...and nonproliferation policies. The...
...participants were urged to focus...
...on desirable long-term goals and...
...criteria for successful policy,

two speakers, chosen to represent different points of view. A three-person panel, also representing different points of view, commented on the presentations, and questions from the audience followed. Attendance was limited to about 200 to facilitate discussion.

Strategic Arms Limitation Talks (SALT)

In 1972, after several years of negotiation, the U.S. and the Soviet Union signed SALT I agreements limiting the number of land-based intercontinental ballistic missile (ICBM) launchers, modern ballistic missile submarines, and antiballistic missile launchers that each could deploy. A new phase of SALT began in that year and has continued ever since.

In Vladivostok in 1974, President Ford and General Secretary Brezhnev agreed in principle to strive for a SALT II agreement limiting each side to a total of 2400 nuclear delivery vehicles and to 1320 ICBMs and submarine-launched ballistic missiles (SLBMs) equipped with multiple warheads (MIRVs). In 1979, a SALT II agreement was reached, but it appears that this agreement will not be ratified by the U.S. Senate. Thus, it is not formally binding, although there are some indications that its provisions will be observed by both sides.

Two speakers addressed the issue of SALT at the LLNL Arms Control Conference: Paul Nitze, Chairman of the Policy Studies Committee on the Present Danger, and Walter Slocombe, Deputy Undersecretary of Defense for Policy Planning under President Carter.

Nitze outlined six criteria for an acceptable SALT agreement:

- The duration, review, and withdrawal provisions should be similar to those of the ABM treaty of 1972.

- The provisions of the agreement should be based on the principle of rough equivalence in strategic capabilities (i.e., advantages in certain types of capability on one side should be offset by advantages in other capabilities on the other side)

- The strategic nuclear deployments and capabilities allowed under such an agreement should be such that neither side can hope to gain in relative enduring capabilities by initiating a strike against the nuclear forces of the other side.

- The agreement should take into account not only large ICBMs and sea-based systems, but gray-area systems (i.e., theater nuclear forces).

- The agreement must embody precise definitions of and useful limitations on significant aspects of nuclear capabilities (e.g., it is not enough to limit the number of launchers, if they are not necessary for launch or if they are reloadable).

- The agreement should be verifiable.

Nitze explained that there are two

important dimensions to the SALT process: the substantive dimension, which has to do with the impact of agreements and discussions on the strategic nuclear capabilities of both sides, and the political-psychological dimension, which has to do with the impact of the postures and statements of the parties involved on public opinion in the U.S., in Europe, and in the world.

He discussed the important distinction between criteria for a desirable agreement and criteria for a negotiable agreement. It is easy enough to outline arrangements that would contribute to U.S. security and not too difficult to identify agreements that will contribute to the security of both sides, but the Soviets seem unwilling to accept such terms now. Thus, we are faced with the dilemma of having to choose between a SALT agreement that is somewhat one-sided in favor of the USSR, but still, on balance, advantageous to the U.S., and one that is so one-sided as not to be worth ratifying. The desirability of a SALT agreement from the U.S. point of view depends fundamentally on the nature of the nuclear threat that the Soviets will develop under it and whether the agreement permits us to have the programs we need to counter that threat.

Nitze had two recommendations for those now responsible for our SALT efforts. First, they should work out a framework of ideas to use as a guide in the treatment of the substantive and

political-psychological aspects of the SALT process. Second, they should work to reduce the vulnerability of the land-based component of U.S. deterrent forces and of our command, control, communication, and surveillance facilities. Without these steps, no meaningful SALT negotiations can take place.

Walter Slocombe, who had principal responsibility under President Carter to prepare policy plans for SALT and other arms control measures (from the Department of Defense point of view) responded to Nitze, terming the SALT process a "technical success but a political failure." SALT has established that an opportunity exists for meaningful agreements (and this is not self-evidently true in certain other areas). However, there has been a failure in the United States to agree among ourselves on the role of such agreements in our continuing confrontation with the USSR.

Slocombe contrasted three conflicting American views of the relationship between SALT and U.S.-Soviet relations generally. The first is that SALT is acceptable and desirable only to the extent that the Soviets are responsible people. This, Slocombe feels, is an unattainable condition that effectively cuts off the possibility of any negotiation. The second is that SALT is a way to make the Soviets into more responsible people. This so-called "web-of-relationships" theory is sure to be disappointing, he feels, if it is carried beyond the basic proposition that there is some level of restraint in Soviet international conduct that, if not followed, makes SALT impossible. The third is that SALT is part of our response to an unpleasant world in which our principal adversary is irresponsible, very powerful, firmly entrenched, aggressive in doctrine, opportunistic in practice, and yet able to act rationally in his own self-interest to avoid nuclear war. Slocombe subscribes to the latter view and believes that until we build political support for that view, we cannot expect much success in arms control.

Slocombe suggested that the maintenance of a dialogue with the Soviets is not particularly useful, except insofar as it is directed at achieving desirable agree-

The strategic nuclear deployments . . . allowed under [a SALT] agreement should be such that neither side can hope to gain . . . by initiating a strike against the nuclear forces of the other side. —Nitze.

ments: "The temptation to hold talks just to show that an agreement cannot be reached is risky politically and substantively unless the West has a position that can be publicly defended almost indefinitely. Playing games with gimmicky arms control proposals is not a competition in which the West has any comparative advantage."

Slocombe agreed with Nitze that a solution to the ICBM vulnerability problem must be devised and that adequate military capability is essential to any agreement, to leading the alliance, to rallying the public, and to our overall relationship with the Soviet Union.

Restraints on Theater Nuclear Forces in Europe

Nuclear weapons play an important role in allied plans for the defense of Europe. NATO maintains conventional forces powerful enough to resist any but the most determined military effort on the part of Warsaw Pact nations, and plans call for the use of theater nuclear forces (TNF) on a small scale should a conventional attack be severe enough to warrant it. If this response does not deter the invasion, NATO will use larger numbers of nuclear weapons against military targets. If this fails, the ultimate deterrent, that of all-out strategic nuclear war, would have to be considered.¹

In recent years, there has been a steady build-up of Soviet nuclear forces designed for use in the European theater. This build-up is of considerable concern because it raises the spectre of a Soviet nuclear first strike. Of particular concern is a MIRVed Soviet missile (the SS-20) capable of reaching Europe from the Soviet Union. In 1979, President Carter responded to the SS-20 threat by proposing to deploy longer-range nuclear missiles in Germany—missiles capable of reaching the Soviet Union. He asked that Germany go on record publicly in favor of the deployment.

This placed Germany, which for many years had been delicately cultivating trade and other relationships with Eastern Europe and the Soviet Union, in an exceedingly awkward position. Chancellor Schmidt's solution was to announce two conditions for the acceptance of the new missiles: at least one other continental European nation must also accept the weapons on its territory, and TNF arms control negotiations between the U.S. and the Soviet Union must begin before deployment of the missiles. The missile issue is extremely controversial in Holland, Belgium, and Italy, one of which must accept the missiles if the German conditions are to be met. Thus, deployment is controversial. With regard to the second condition, the Carter administration did open TNF talks with the Soviet Union in Geneva, and the Reagan administration has announced its intention to continue those talks.

Two speakers addressed the problem of theater nuclear force (TNF) restraints: John Woodworth, currently of the Office of the Assistant Secretary of Defense, and David Aaron, Deputy Assistant to the President for National Security under President Carter.

Woodworth pointed out the complexity of TNF arms control. The policy choices are hard; the analytical foundations are more complicated than for strategic forces; and there is a thorny political and diplomatic dimension to every aspect of the problem. Extremely important relations with our NATO allies are at stake, and the issues are very sensitive.

He recommended two goals for TNF arms control negotiations: first, our defense programs and objectives must determine our positions; second, our positions and approach should strengthen and maintain the alliance. Obviously, the Soviet objective is to use the TNF issue to play upon public fears and thus "decouple" the defenses of Western Europe from those of the United States by diplomatic and political means.

On both sides there is a broad range of systems: long-range missiles, short-range missiles, battlefield systems, and a variety of aircraft. A key issue will be which systems to include in a TNF agreement. Counting the systems is difficult because

some (e.g., the Soviet SS-20 missile) are equipped with MIRVs, while others, notably the U.S. systems, are not. Also, some are reloadable, and some are not. Because many of the systems are mobile and others have a long range, there is some question as to whether regional restrictions are practical. Verification of a TNF agreement will pose exceptional challenges because of the newness and the mobility of the systems. It would be safe to say that fairly intrusive measures may be required, particularly in the closed environment of the Soviet Union and Eastern bloc countries.

Woodworth explained that the U.S. is planning to enter into TNF negotiations before the end of 1981 and that an intensive program of preparation is under way. It is expected that TNF will be negotiated in a SALT framework and that the talks will be bilateral.

David Aaron suggested that in attempting to negotiate TNF arms restraints, we should not be discouraged by the complex asymmetries in the strategy, deployments, political attitudes, and interests of the U.S. and the Soviet Union. In fact, it is precisely these asymmetries and differences that make it possible to reach agreements. Without them, it would not be reasonable to expect that both parties could walk away from the negotiating table with the feeling that they had gained something of value.

Aaron's thesis is that the basic purposes of the long-range theater nuclear force deployment program are political and that our arms control objectives in this area should be openly and clearly political as well: "Those objectives . . . should be first of all allied solidarity, second, some level of long-range theater-nuclear-force (LRTNF) deployment, and third, the establishment of a new framework both for the SALT negotiations and for their integration into the allied nuclear deterrent."

Aaron believes that discussions of LRTNF should be used to lead to a broader and deeper SALT negotiation. He is concerned that an independent or even quasi-independent TNF negotiation will reinforce the European notion that somehow detente there can be separated

... the basic purposes of the long-range theater nuclear force deployment program are political . . .

— Aaron.

from overall relationships with the Soviet Union. Moreover, forward-based systems (i.e., TNF) have always been of great concern to the Soviets, and our willingness to consider them as negotiable would provide a starting point for discussions of the more severe restrictions on strategic nuclear systems that the Reagan administration seems to seek.

Aaron suggests that we include British and French forces in the tally for purposes of a TNF agreement. This, he believes, would help us not just to avoid decoupling but actually to increase the coupling that exists between the British and French deterrents and NATO. Another advantage of such a move would be to emphasize the fact that British and French expenditures for strategic forces are part of the allied burden-sharing effort, a fact that is not always fully appreciated in Europe.

Aaron's final proposal is that we make the TNF negotiations multilateral. He feels that this would put maximum pressure on the Soviet Union and, most important, minimize its capacity to divide us from our allies. Strengthening the alliance is, in his view, the overriding objective of TNF negotiations.

Comprehensive Nuclear Test Ban

Limitations on nuclear testing have been among the more successful arms control measures over the years in terms of achieving actual treaties. The first such agreement, a test moratorium, began in 1958 and was terminated in 1961 when the Soviet Union unilaterally resumed testing in the atmosphere. The Limited Test Ban Treaty of 1963 prohibited testing in the atmosphere, in outer space, and underwater. The Threshold Test Ban Treaty (TTBT) of 1974 limited underground nuclear tests after March 1976 to a maximum yield of 150 kt, and a subsequent treaty limited peaceful nuclear explosions. (The latter two agreements were never ratified by the United States Senate. However, both the U.S. and the Soviet Union claim to have observed the provisions of the TTBT in their subsequent nuclear testing programs.) In recent years, efforts to reach agreement on a comprehensive ban on nuclear testing have been renewed, without success.

The first speaker in the forum on a comprehensive nuclear test ban was Herbert York, Professor of Physics at the University of California, San Diego, and former U.S. Ambassador to the comprehensive test ban negotiations. He was followed by Donald Kerr, Director of the Los Alamos National Laboratory.

York believes that the basic purpose of nuclear arms control and disarmament is "to provide the only sure means for avoiding a nuclear holocaust in the long run." The basic purpose of nuclear arms control is "to provide the necessary basis on which the process of nuclear disarmament can proceed." He regards nuclear arms control and disarmament as an independent objective, not simply as a means for achieving other objectives (e.g., international stability, national security, or financial savings). He supports other objectives (such as military preparedness and the nuclear component of preparedness) in the absence of relevant arms control agreements.

On the subject of a comprehensive ban on nuclear testing, York pointed out that the costs must be weighed against the benefits. The costs of a comprehensive test ban (CTB) are short-term and specific: a decline in stockpile reliability and foregone opportunities to design warheads specifically tailored to missiles already in the pipeline. The benefits of a CTB are long-term and general: "They are part of the whole process of trying to

avoid or avert or delimit a nuclear war in all of its aspects . . . way down the road . . ." The fundamental problem in weighing the costs and the benefits is that they are incommensurate with each other and can be evaluated only in terms of how they fit into some greater scheme. "When I apply my purposes to the question of whether the CTB is a good thing or not," said York, "I conclude and have for a long time that it is a good thing and that it ought to be accomplished."

York does not believe that a comprehensive test ban is a good thing as an isolated act. "A comprehensive test ban in a world in which all of the other aspects of the nuclear arms race are going forward in full gear seems to me to be obviously unstable . . . The appropriate time for a comprehensive test ban is when things in general are moving away from a dependence on nuclear weapons, when the process is the reverse of what it is today . . ." Also, a CTB is not his personal first priority. He would put SALT ahead of it and TNF negotiations, as well.

With this introduction, York presented recommendations for those who at some future date may resume negotiations on a comprehensive test ban. First, he proposed that the agreement on which such a ban is based must not be temporary (except in the sense that such agreements always have escape clauses). Second, he suggested that the negotiating team and the working group (an

intermediate body that makes recommendations to a cabinet-level group charged with responsibility for the negotiations) should be composed of people who believe in the process and who are seeking solutions. Debate is appropriate among the President and his immediate advisors on the advisability of negotiations. Once the decision to negotiate has been made, it is not only wrong but stupid to staff the working group with people who do not believe in the process. Negotiations tend to bog down when such people are involved, not because of recalcitrance on the part of the Soviets but because of obstructionist tactics on the part of members of the U.S. team.

York's final recommendation was that in preparing to enter into negotiations, we ask the right questions. Not, "Does a CTB interfere with the reliability of our stockpile of nuclear weapons?" but rather, "Given that it does interfere, how do we cope with that problem?" Not, "What is the threshold for identifying tests?" but rather, "Given all our intelligence resources, what can be said about verifying compliance with the treaty?"

Kerr agreed that a ban on nuclear testing is at this time not a proper priority for the U.S., pointing out that the base of knowledge and experience needed for developing weapons would dissipate as a result of such a ban, and the confidence in existing nuclear stockpiles would decline. He expressed the fear that, given our reliance on nuclear weapons since the end of World War II to offset substantial advantages by the Soviet bloc in the realm of conventional forces, such a decline in the reliability of our nuclear arsenal would have grave consequences for our security.

He noted that we no longer enjoy the kind of military superiority that would permit us to promote the highest and most disinterested aims (those associated with total nuclear disarmament). Thus, we must attend more narrowly to our own security interests, which include nuclear testing and the maintenance of a reliable nuclear stockpile.

Kerr explained why the nuclear weapons test program is essential to the design, manufacture, maintenance, and

"A comprehensive test ban in a world in which all of the other aspects of the nuclear arms race are going forward in full gear [is] obviously unstable." —York.

certification of weapons. Since both warheads and their delivery systems are subject to technological obsolescence, we might be forced, under a complete test ban, to stockpile inadequately tested designs or to incorporate changes the full impact of which we could not predict with confidence. Furthermore, desirable changes to enhance safety and prevent unauthorized use could not securely be made without the opportunity to test: "I would be concerned, under a complete test ban, that given real life pressures and fallible human nature, we might on occasion stockpile inadequately tested designs or inadvisable changes; serious unreliability could result."

Nations with the potential to develop nuclear weapons are not driven to this end by the example of the major powers, but, rather, by their own security requirements.

—Kerr.

Beyond this fundamental difficulty is the problem of verifying compliance with a comprehensive test ban treaty. Verification is a crucial question because the military advantage that the Soviets might obtain by covert violations of a test ban treaty could be disastrous for us. Kerr spoke of the recent observation by a Vela test detection satellite of an event resembling a nuclear explosion in the South Atlantic as an example of how difficult verification can be. After careful analysis of the data, some scientists concluded that the event was in fact a nuclear explosion; the Director of one government laboratory even went on public record to that effect. The White House assembled a panel of independent scientists, who examined the same data and judged that the event was of natural origin. Given the strong disagreement in interpretation of the same data by presumably competent, technically trained Americans, it is clear that even more controversy would surround seismic verification data in an open international forum.

Kerr discounted the effect of a comprehensive test ban on the proliferation of nuclear weapons. Most, if not all, of the nations that have built nuclear explosives are believed to have been successful in detonating them on the first try. Thus, the only thing sacrificed by the signing of a comprehensive test ban would be the prestige or warning value associated with a public test, not the capability of developing nuclear weapons.

Nations with the potential to develop nuclear weapons are not driven to this end by the example of the major powers but, rather, by their own security requirements. "The causes of war and enmity which are responsible for the acquisition of weapons are deep and political. Failing a resolution of these differences, efforts at controlling the military hardware, which is but a symptom of that enmity, have been failures." Thus, in Kerr's view, it is very unlikely that a comprehensive test ban or even substantial nuclear disarmament by the major powers would materially affect the decision of other nations to build or not to build nuclear weapons.

Arms Control in Space

The U.S. has on the order of 100 active satellites of all types, civil and military, and the Soviet Union has about the same number. All other nations that own satellites have of the order of 10. Earth stations, capable of sending and receiving radio signals, are necessary elements of space communications systems. There are about 40 U.S. stations that track and command civil and military satellites.

The U.S. currently relies on satellites for warning of a missile attack within moments of launch, for reconnaissance information over areas of the world in which hostile forces are deployed, for reliable, high-capacity, worldwide communications, for meteorological information, and for accurate navigation and guidance information. This information is vital to our defense. Satellites might also some day be used as bases for weaponry of one kind or another aimed at earth targets, but at present this may not be an attractive option because of the cost involved in boosting masses into orbit.

The U.S. already has held three negotiating sessions with the Soviets on the subject of arms control in space.

Two speakers addressed this problem: LLNL Associate Director Michael M. May, and Robert W. Buchheim, former ambassador to the Joint Consultative Commission (established to review compliance with the SALT I agreements) and head of the U.S. delegation to the U.S.-USSR Antisatellite Negotiations.

May described three types of satellite representative of the wide range of defense satellite systems (Fig. 1):

- Low-altitude satellites such as those used for reconnaissance or verification of compliance with arms control agreements.
- Intermediate-altitude systems such as those used for very accurate navigation and guidance anywhere in the world.
- Satellites in very high (geosynchronous) orbits such as those used to sense the infrared emission of a missile's exhaust seconds after launch and those used for communication.

Land- or air-based missiles could be used against low-altitude satellites, and, with some considerable development, a land-based laser might be able to reach them directly overhead. Space-based missiles would be more expensive and no more advantageous than aircraft-based missiles against these satellites. A space-based laser might be effective, but it, too, would be an attractive,

would be an attractive, very expensive, and very vulnerable target.

A ground-launched antisatellite effort against intermediate-altitude satellites would require at least 16 to 24 launches of large missiles to destroy the system entirely, although destroying half of it or somewhat less might seriously degrade its guidance role. It would take the missiles about one hour to reach the satellites. Such an attack would be quite expensive (a billion dollars or more).

Air-launched missiles offer no comparative advantages over their ground-launched counterparts against intermediate-altitude satellites, and it is not clear whether a practical ground-based laser can be built to destroy such satellites. Space-based missiles or lasers could destroy them more rapidly than ground-based missiles, but the cost in development time and money would be very large (ten or more billions of dollars).

An antisatellite missile system effective against the very high-altitude geosynchronous satellites would require expensive rockets of the kinds used for lunar and planetary missions. If these targets were 'uncooperative' and did not radiate or broadcast, there could be significant difficulty in finding them. A ground-based laser system directed against such

Fig. 1

The inner orbit is for low-altitude (150 to 1000 km) satellites of the kind used for reconnaissance or verification of compliance with arms control agreements. Such satellites make one revolution around the earth every 90 to 105 min. In a day, a representative satellite would make 11 passes over the Soviet Union, spending *about one hour there altogether*. On a straight-up intercept, a Soviet antisatellite missile would take 1 or 2 min to reach the satellite. The satellite would have to be over the launch site at the time. If the antisatellite missile made at least one revolution before homing in on the target, the intercept time would be more like 2 h. The middle orbit is for intermediate-altitude satellites of the kind used for navigation and guidance. The Global Positioning System consists of 16 to 24 such satellites at altitudes of about 20 000 km, each one circling the earth every 12 h. To get a navigational fix, one must have four satellites

in view. The system provides three-dimensional accuracy to 10 m. A ground-launched antisatellite effort would require at least 16 to 24 launches of large missiles to destroy the system entirely. The minimum time to destroy one satellite would be about 1 h. To inactivate the system from a few ground locations would take about 1 day. The attack would be quite expensive—perhaps a billion dollars or more. The outer orbit is for high-altitude (36 000 km) satellites in geosynchronous orbits. Satellites of this type stay fixed over a selected point of the earth near the equator. Some are used to warn us promptly of missile launches from the Soviet Union and from the Atlantic and Pacific Oceans. An attack on these satellites would require ground-based missiles comparable to those used in lunar and planetary missions. They could reach the satellites in a minimum of about 1.5 h.

satellites probably is not feasible. A space-based laser system would be extraordinarily expensive, probably more so than the geosynchronous satellites themselves. Another approach to attacking high-altitude satellites would be to pre-position missiles near them. The cost of that approach would be comparable to the cost of emplacing the satellites.

May pointed out that a ban against arms in space would not really protect our satellite systems in a potential conflict because the ground stations upon which they depend are vulnerable and few in number. Also, as long as the critical satellites themselves are few in number, a small number of attacking antisatellite missiles could, in a short time, destroy all of them. If only a few antisatellite launchers are needed, verification of their presence or absence among the much larger number of Soviet launchers would be difficult or impossible. Thus, in the case of space systems as in the case of strategic weapons, the development of survivable systems not only is an essential requirement for strategic stability but probably also a prerequisite to meaningful arms control.

One area of negotiation that May sees as reasonable in the near future is that of defining "rules of the road" for space systems. Such rules would be comparable to those that have been accepted for centuries with regard to the use of the oceans by civil and military ships. Specific rules that might be negotiated would include: minimum separation distances for satellites in orbit or in transit to orbit (with measures to verify compliance) and the use of cooperative radio beacons (analogous to ships' running lights) on newly launched satellites to permit ready verification of orbit and general function. These rules could provide some assurance that antisatellite weapons were not being covertly pre-positioned close to critical satellites.

While May's analysis was primarily technical, Robert Buchheim's focused on the legal aspects of existing international commitments relevant to arms control in space and on the fine distinctions that must be made in framing new agreements. He pointed out that, in preparing

**"The development of survivable [space] systems is not only an essential requirement for strategic stability, it is probably also a prerequisite to meaningful arms control."
—May.**

to negotiate in this area, we must ask and find answers to questions such as these:

- What is an antisatellite system?
- Why might we want to put agreed limitations on antisatellite operations and/or the means for such operations?
- How can we define agreement coverage as concerns the dynamic classes of spaceborne objects to be dealt with?
- How can we define agreement coverage as concerns ownership of, control of, or other aspects of interest in and responsibility for a space object?
- What is the relationship of any new agreement on antisatellite matters to the Outer Space Treaty of 1967 to which we are already a party?
- Should an antisatellite agreement provide for limitations on what can be done to a space object, or should it also

... the core problem is that of devising practical and effective provisions through which to eliminate antisatellite means, prohibit their possession, or limit them quantitatively or qualitatively. — Buchheim

deal with operations to frustrate missions undertaken with systems in which space objects are components?

- What happens if an antisatellite agreement prohibits the damaging of a space object and some action of a party inadvertently damages a space object?

Buchheim concluded that: (1) there are reasonable considerations for and against seeking further international agreements as to antisatellite activities; (2) such agreements could take a variety of forms, and each recognizable form should be examined as to its potential value to the U.S.; (3) examination of possible antisatellite agreements must take into account relevant existing agreements; (4) general agreement as to violence against space objects is a practical objective, while agreement as to measures to thwart the missions of space objects can proceed only on a case-by-case basis.

For Buchheim, the core problem is that of devising practical and effective provisions through which to eliminate antisatellite means, prohibit their possession, or limit them quantitatively or qualitatively. This is a very difficult task that is not made easier by the fact that an antisatellite system is quite likely to exploit facilities (for example, ground-based tracking and communications systems) that support other kinds of activities and the fact that some other systems (for example ABM systems) are likely to have some degree of antisatellite capability.

Nonproliferation Policies

Ever since the first nuclear weapons were developed in the 1940s, efforts have been made to minimize their proliferation. The current nonproliferation regime (i.e., the delicate framework of international agreements, policies, and attitudes upon which a presumption in favor of nonproliferation has been established) has its roots in the Atoms for Peace Program begun during the Eisenhower years. The chief fruit of this program was the establishment in 1957 of the International Atomic Energy Agency (IAEA), which today regulates and monitors the transfer of nuclear materials worldwide. The second foundation stone of the regime was the formulation of a Nonproliferation Treaty (NPT) in the 1960s. Parties to this treaty agree not to transfer nuclear weapons or to help other nonnuclear weapons states to develop them. Signatories also agree to put all their peaceful nuclear facilities under IAEA safeguards.

In the early 1970s, three events posed a threat to the nonproliferation regime: the Indian explosion of what was called a "peaceful" nuclear device; the Arab oil embargo and a fourfold increase in oil prices; and the proposed sale, without a clear economic justification and with obvious proliferation implications, of several facilities capable of producing weapons-related materials. In the late 1970s, several American initiatives were launched in response to deteriorating conditions.

The first initiative was the establishment of the Nuclear Suppliers Group in London to discuss guidelines for nuclear commerce. The second was a more cautious policy toward the use of plutonium in the U.S. nuclear program. The third was the promotion of an International Nuclear Fuel Cycle Evaluation (INFCE), in which 66 countries came together in Vienna to discuss the problems associated with the nuclear fuel cycle and ways of regulating usage to the benefit of all.

Two speakers addressed the problem of nonproliferation policy: Joseph Nye, Professor of Government at Harvard University and former Deputy to the Undersecretary of State for Security Assistance, Science, and Technology; and James Malone, Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs, Department of State.

Nye's purpose was to assess the gains and mistakes in the realm of nonproliferation policy over the last few years and to outline the major problems of maintaining a nonproliferation regime in the future. He feels that there are a few modest but important ways to strengthen the fuel cycle aspects of the international regime.

- Uncommitted states must be persuaded to join in the comprehensive

safeguards agreed upon by the INFCE working groups.

- Special procedures and safeguards must be developed for handling plutonium and highly enriched uranium.
- Provision must be made for internationally monitored spent fuel storage so that planned reprocessing that is driven by the excess supply of spent fuel (rather than by the demand for plutonium) can be minimized.
- We must reinforce national stockpile measures by an international institutional arrangement to ensure that supplies to vulnerable countries will not be interrupted.
- We must provide for the energy research and development needs of the smaller nations to obviate the need for weapons-usable fuels in their own programs.

... the credibility of deterrence ... permits allied states to forswear proliferation. — Nye

Nye suggested that first among the other problems to be faced in maintaining a nonproliferation regime in the 1980s is that of priorities. Nonproliferation is only one aspect of U.S. foreign policy, and some argue for a lowering of the priority traditionally assigned to it, on the ground that negative effects are exaggerated. Others maintain that proliferation would actually stabilize the international situation (as it has relations between the superpowers). Nye disagrees. The kind of prudence that has been demonstrated by the leaders of the U.S. and the Soviet Union over the past 20 years is not transferable to other potential nuclear powers unless one assumes stable command and control systems, the absence of serious civil wars, and the absence of strong destabilizing motivations. Nye believes that the first effects of acquiring new nuclear capability in many circumstances may actually be to increase a state's vulnerability and insecurity; the destabilizing aspects are further complicated if one thinks of possible roles of non-state actors (for example, terrorist groups).

Nye pointed out that even if a high priority is given to nonproliferation, difficult policy choices must be made in regulating the rate and degree. Proliferation is a staircase ascending to the first explosion and beyond. The rate of proliferation is measured in terms of the number of new first explosions; the degree of proliferation is measured in terms of the size, military quality, and deliverability of the nuclear arsenal. "Formulating sanctions that deter a quickening rate while creating firebreaks after a first explosion will require a delicate balancing act."

Nye believes that we must maintain the credibility of deterrence because it is precisely this factor that permits allied states to forswear proliferation. At the same time, we must move toward arms control so as not to provoke accusations that our nonproliferation policy is discriminatory. We must not be indifferent to the energy and economic concerns of poor countries because such indifference can weaken the nonproliferation regime. Also, we must be careful not to try to use

our nuclear status to threaten in other areas.

James Malone's presentation summarized in a general way the policy currently being developed by the Reagan administration on international nuclear cooperation and nonproliferation. He promised "realism, commitment, and flexibility" in this area, together with movement "back into the international mainstream."

He feels that nuclear energy must play an important role in the world's energy balance, and he is committed to effective use of nuclear power technology. By the same token, he supports nonproliferation as a component of our overall security efforts: "... we may not be able to cooperate widely in nuclear power in a situation of further proliferation." He asks the world to recognize that "... nuclear explosives, for whatever declared purposes, cannot be distinguished from nuclear weapons."

Respect for our international commitments (to the IAEA and the NPT) will be a keystone of the new policy. Also, we will consider evolutionary steps that can increase the durability of the international regime. Specific new policy directions will include the following:

- The U.S. will reassume its role as a major reliable partner in international nuclear commerce.
- The U.S. will take a practical approach to necessary fuel cycle operations for material subject to our agreements with other countries. The goal will be to ensure that planned programs go through without arbitrary interruption.
- The U.S. will strive to achieve and maintain effective and credible IAEA safeguards and will work to obtain agreement on full-scope safeguards by all suppliers and recipients of nuclear materials.
- The U.S. will seek a constructive evolution of the international framework, with emphasis on: (a) finding ways of dealing with the potential for subnational and terrorist sabotage or seizure of nuclear material; (b) implementing technical alternatives to avoid the presence of highly enriched uranium in research reactors; and (c) establishing an international plutonium storage system.

Summary

The purpose of the arms control conference held at LLNL on May 26-27, 1981, was to examine policies and negotiating goals in five major areas of nuclear arms control: strategic arms limitation talks (SALT), theater nuclear force (TNF) restraints in Europe, nuclear test limitations, arms control in space, and non-proliferation policies.

There seemed to be a near general agreement among participants that the new administration should prepare to resume SALT negotiations and that TNF restraints should be discussed in that context. Several speakers emphasized that military preparedness is a necessary prerequisite for meaningful SALT negotiations and that, specifically, we must reduce the vulnerability of the land-based component of U.S. deterrent forces and of our command, control, communication, and surveillance facilities.

The principal SALT issues were identified as: In seeking a new SALT agreement, should we count strategic systems in terms of launchers (without regard to actual warheads)?—In terms of actual warheads deliverable?—In terms of total payload? How should we deal with the possibility that launchers would be reloadable? How can compliance with an extended SALT agreement be verified?

Several speakers pointed to the extreme political sensitivity of the TNF question, urging the current administration to weigh very carefully the political as well as the substantive impact of their statements and negotiating positions. The main issues involved are: How can the solidarity of the NATO alliance be maintained, in view of the growing disparity between U.S. and European attitudes toward detente and arms control? What theater nuclear forces should be limited? What geographical area should be covered? How should we treat reloadable systems? How could compliance with an agreement be verified?

Widely differing attitudes were expressed on the question of a comprehensive test ban (CTB), but no one intimated that such a ban should be an immediate U.S. priority. Speakers and panel participants raised a number of questions that must be considered: Is such a ban in our national interest at the present time? If so, for how long? If not, what are the alternatives—a threshold lower than 150 kt? Limits on the number of tests? a mixed number/yield limitation? Is a CTB agreement verifiable? What impact does the lack of a CTB agreement have on the proliferation of nuclear weapons? How could we cope with weapon-stockpile reliability problems in the absence of testing?

With regard to arms control in space, the key issues are: Is it in the U.S. interest to prohibit antisatellite activities? How can we define which space objects are covered by an agreement and establish responsibility for them? Of what value is an antisatellite prohibition in the absence of survivable ground systems? How could a meaningful agreement be verified?

There was general agreement that a high priority should be given to non-proliferation efforts, particularly as they relate to dealing with subnational and terrorist sabotage or seizure of nuclear material and extending and refining the regime of safeguards now in effect. ■

Key Words: arms control; nuclear test ban; nuclear weapon proliferation; SALT; satellite vehicles—interception; satellite weapon systems; theater nuclear force.

Notes and References

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