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Brief

New Cable Emplacement System Tested

Our new Cable Downhole System (CDS) for emplacing the cables used in the underground testing of nuclear devices is expected to shorten emplacement times by at least 80%, to improve our scheduling flexibility, and to save about \$2 million each year in labor and material costs. A 10-cable demonstration module of the CDS system received its first official field test the week of April 12 at the Nevada Test Site. The next system, a prototype, to be ordered upon successful completion of the current series of tests, is expected to cost about \$6 or \$7 million. According to present plans, the first operational use of the CDS will be scheduled in 1983.

The present system of cable emplacement evolved over many years of testing. It consists of supporting the cables by gathering them into compact bundles and attaching them to the emplacement pipe at frequent intervals to support them during the downhole operation and to help them survive the stresses that occur during the stemming

(backfilling) operation. As many as 150 to 200 diagnostic and control cables may be used in an event.

Unless we take steps to prevent it, the compact cable bundles can form channels through the stemming along which radioactive gases could travel. To prevent this, we fan the cables apart at several levels and pass them through a special fixture that keeps them separate during the stemming operation. Installing this fixture is extremely time-consuming and labor intensive. At least 8 out of every 10 days of emplacement time are spent attaching and fanning out the cables and only 2 days in actually lowering the nuclear device.

The new system will enable us to hang each cable straight down, independent of all the others and of the emplacement pipe. Computer-controlled tensioners informed by sensors of the length of cable already fed into the hole, adjust the tension in each cable to just support its weight as it descends. The cables we use are strong enough to support their own weight in holes shallower than 600 m. In deeper holes, additional support will be needed.

Because the cables are individually supported, they need not be attached

to the emplacement pipe. Because they are free to rearrange themselves randomly, fan-out fixtures are no longer required. Hence, the device may be lowered almost continuously, reaching its proper depth in 2 days instead of 2 weeks, with the use of much less manpower.

The addition of stemming can place severe stresses on a rigidly supported cable. The new system is flexible: the tensioners pay out cable as needed to relieve excess stress and keep the tension equal to the weight of the unsupported cable, as calculated from a variety of depth-of-hole measurements. By the time the stemming reaches the top of the hole, the cable tension is almost zero.

In addition to saving time and manpower, the new emplacement system

eventually will allow us to recover the emplacement pipe for use in subsequent tests. The emplacement pipe for a typical test costs about \$150 000; it is made of special steel, pull tested and carefully inspected to meet our nuclear safety standards. In previous tests, the pipe had to remain in the hole (and be destroyed in the test) because all the diagnostic and control cables were attached to it. Now, once the device is locked in place by the stemming, we will be able to pull the pipe out for reuse. ■

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Key Words: cable emplacement; Cable Downhole System (CDS); nuclear testing.

Measuring Microsphere for Fusion Experiments

Microsphere targets used in confinement fusion experiments require precise tolerances. We have the measurement techniques and the machinery to quickly and automatically fabricate microsphere targets.

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In inertial-confinement fusion (ICF) experiments, a high-power laser or particle beam is used to implode a tiny target containing deuterium-tritium (D-T) fuel, compressing and heating it until it ignites and burns (in the thermonuclear sense). A typical direct-drive ICF target consists of a fuel core surrounded by a spherical shell. The shell has two layers: an outer ablator of a material such as Teflon and an inner pusher of a higher density material such as glass. As the ablator is heated by a laser or a particle beam, it blows off, producing a rocket-like inward thrust that implodes the pusher, compressing and heating the fuel to the high densities and temperatures necessary to ignite it. For efficient thermonuclear burn, the fuel must stay together long enough to let a large fraction of the nuclei react.

It is crucial to this process that the implosion proceed symmetrically. A symmetric implosion is possible only with a target that has very smooth, uniformly thick walls, so the target must be fabricated to precise tolerances. We have developed several techniques that enable us to measure targets with the necessary precision.

Measurement Techniques

To permit trade-offs among speed, accuracy, and comprehensiveness, we need a variety of target-measuring techniques. Measurements to provide information about a fabrication process, for example, must be accurate but not necessarily rapid or nondestructive. Sorting the output of a low-yield production process requires high-speed, nondestructive measurements, but of only a few common kinds of defect. Final target measurements, to be used for correlating the results of implosion experiments, must be accurate, comprehensive, and nondestructive but need not be faster than an hour or so per target. Depending on the materials used, the various layers in a target may be either opaque or transparent. Each type demands a different measurement technique. As no single technique satisfies all of these requirements, we use several complementary approaches.

At present, our primary techniques of target measurement are optical interference microscopy, microradiography, and scanning electron microscopy. Each has unique assets and limitations.

Optical Interference

Microscopy

In interferometry, we deduce the amplitude (depth or thickness) of a defect by measuring an optical phase shift. This technique is highly sensitive to defects with a low aspect ratio (see box on p. 7). Optical interferometry has become the technique of choice for measuring transparent targets such as hollow glass and polymer microspheres. Measurements can be made quickly, sample preparation and handling are quite simple, and the technique is available in many variants.

To rapidly inspect a large number of target spheres, we use white-light interference microscopy. The interference pattern produced by light incident on a transparent microsphere of uniform thickness appears as a set of concentric rings perfectly centered on the sphere. Any deviation from uniformity shows up as a distortion of this pattern (Fig. 1). With this technique, we can rapidly measure the uniformity of microsphere thickness within $0.05\text{ }\mu\text{m}$, about 0.1 of the wavelength of visible light.

Initial inspection with interference microscopy tells us whether a batch of

Fig. 1

Pattern produced in a nonconcentric microsphere by optical interference. The mis-centering of the fringe pattern is a measure of nonconcentricity.

microspheres contains target-quality fuel capsules. If most have only a few isolated defects, we sort the batch for prospective capsules. Those with no immediately visible defects are then selected for detailed individual examination.

Full Surface Examination

To meet the exacting specifications for ICF targets, we must inspect the entire surface of the sphere for defects or contaminating layers and measure the uniformity of wall thickness. We have combined a modified interference microscope with a computer-controlled micromanipulator—the Topo I system—that enables us to systematically inspect the entire target. The microsphere is held in the field of view by two soft, flat, silicone-rubber pads, each fixed at the tip of a tiny stalk (Fig. 2). By moving the pads equal distances in opposite directions along either the *x* or the *y* axis, we roll the microsphere about its

center, which remains fixed. A programmed microcomputer controls the tip motion. With Topo I, we visually scan the target for defects through the interference microscope.

To make more accurate measurements than can be made by eye and to eliminate the need for an observer, we have automated the interferometric sphere-measuring process. The Automated Sphere Mapper (ASM), our most sophisticated optical measuring device, combines automated heterodyne interferometry with a computer-controlled manipulator to map the surface of targets. In the ASM (Fig. 3), a microcomputer controls the sphere-rotator system and coordinates rotation with interference phase measurement of the surface topography. The topographic data are stored on a disk and displayed in graphical form in real time. The graphics display can be permanently copied for comparison with other target spheres.

The ASM has several novel features: the optical system that performs heterodyne interferometry, the manipulator that positions the sphere during measurement, and provisions for computer control, data acquisition, and data display.

In heterodyne interferometry, an optical phase shift in the measurement beam is converted to an electronic phase shift that can be measured very rapidly and accurately. The ASM embodies this principle in a novel design that measures the amplitude of surface features with an accuracy of 10 nm while requiring sphere position to be maintained only within a few micrometres. In an ordinary reflection interferometer, where the measuring beam is simply focused at one point on a sphere, any motion of the sphere along the beam axis has the same effect as a surface defect. A manipulator able to maintain sphere position with the required 10-nm accuracy would be extremely expensive.

To map the surface of an opaque target with the ASM, we first focus the measuring beam to a point on the front surface of the sphere (Fig. 4). The

Fig. 2

(a) In the Laboratory's Topo I and Automated Sphere Mapper (ASM) optical interference system, a microsphere target is held in the microscope's field of view by two soft, flat, silicone-rubber pads, each at the tip of a tiny stalk. (b) When the pads are moved equal distances in opposite directions along either the *x* or the *y* axis, the microsphere rolls about its center, which remains fixed. A programmed microcomputer controls the tip motion.

reflected beam is routed around the target to its rear surface and focused toward the center of the sphere so that it is again reflected, this time from a broad area of the rear surface. With this arrangement, any surface feature or irregularity in the diameter of the sphere causes a change in the path length of the measuring beam. The system measures local defects as they pass under the part of the beam focused on the surface. When these defects pass under the broadly focused beam on the rear surface, they are "averaged out" with a negligible effect on the beam.

The primary advantage of this interferometer lies in its relative insensitivity to changes in the position of the target sphere. Small motions of the sphere along the beam's axis cause no change in the path length, so that sphere position need be maintained only within 1 to 2 μm .

The manipulator we developed for the ASM is based on the same operating principle as the Topo I manipulator. In the Topo I, each tip is driven independently with a stepping motor, but this technique is neither fast nor accurate enough for the ASM. In the ASM, equal and opposite motion of the manipulator tips is achieved by a mechanical coupling that eliminates the need to simultaneously drive two stages at precisely the same rate.

As shown in Fig. 5, two flat plates are coupled by a set of three balls held in bearings that allow them to rotate but not to translate. The motion of the lower plate, which is driven by a set of x-y stages, drives the coupled plate an equal distance in the opposite direction. The motion of the plates is transmitted through holding arms to the manipulator tips, which then move in opposite directions to rotate the spherical target about its center.

The controlling microcomputer builds up a point-by-point map of the target sphere by driving the sphere rotator system while acquiring data from the interferometer. Figure 3 shows a micro-radiographic image of the target and a representative section of such a map. Map data are stored for subsequent

Fig. 3

In the ASM, a microcomputer controls the sphere-manipulator system and coordinates rotation with interference phase measurement of the surface topography. The topographic data are stored on a disk and displayed in graphical form in real time. The pull-out shows a three-dimensional target-surface map produced by heterodyne interferometry using the ASM system. The sphere is manipulated by the device shown in Fig. 5.

Fig. 4

The ASM uses optical interferometry to map the surface of an opaque target. The measuring beam is focused on a point on the front surface of the sphere and reflected and routed around the target to its rear surface; here, it is focused toward the center of the sphere and again reflected, this time from a broad area of the rear surface. An irregularity of the surface or change in diameter causes a change in the path length of the measuring beam.

Fig. 5

Target manipulator developed for the ASM. To rotate the target sphere for inspection without moving its center, the tips of the manipulator must move equal distances in opposite directions. Three balls rotating about their fixed self centers are used to mechanically couple the motion of two flat plates. When the drive plate (P_1) is moved in one of two orthogonal directions, the coupled plate (P_2) moves the same distance in the opposite direction. The motion of the drive plate is transmitted directly to the upper plate (P_2), which moves in the same direction. The net result is rotation of the target about its self center.

analysis. We can retrieve the stored data at random to display full or partial mappings in various formats.

The ASM embodies several substantial improvements over other sphere-measuring systems:

- 10-nm thickness resolution and 2- μ m spatial resolution.
- Total mapping time of less than 60 s for a sphere 150 μ m in diameter.
- Computerized data acquisition that eliminates human measurement errors and biases.
- Complete sphere mapping in a single data-acquisition scan, minimizing sphere handling.
- Interactive software that allows the operator to tailor a measurement to specific requirements.

- Real-time contour plots and pseudo-three-dimensional data plots plus hard copy of any display.
 - Data written on flexible computer disk for permanent, detailed, transportable storage.
 - Ability to enter scan data into LLNL's timesharing computer system for more extensive analysis and display.
- These features make the ASM the most advanced target-measuring device currently available.

Microradiography

For transparent targets, optical-interference measurements provide excellent thickness and uniformity data. For opaque targets, microradiography is the technique of choice. As almost all advanced target designs contain one or more opaque layers, accurate radiographic measurements are crucial to obtaining target-quality microspheres.

In microradiography, we illuminate a target with a small, very bright x-ray source. The unmagnified shadow of the target is cast onto a high-resolution photographic emulsion (Fig. 6). We obtain two views of the target by sandwiching it between two thin films, one of which is translated by a micro-manipulator to roll the target 90 deg between exposures. By examining the resulting x-ray images with a high-resolution microscope, we can measure target features to an accuracy of about 1 μ m.

Much more accurate information can be obtained by digitizing and computer processing the x-ray image. This process, when done conventionally with a flatbed densitometer, is very slow, requiring extremely careful alignment of the optics for each digitization. The result is a data tape that must be transferred to another computer for analysis.

To circumvent these problems, we developed the AXIAS (Automated X-ray Image Analysis System). In this system, the image is rapidly digitized by a microprocessor and then analyzed by a dedicated microcomputer. We use a television camera to examine, through a high-power optical microscope, a film plate containing x-ray images of an

array of targets. The video image of each target is digitized at high speed and stored in a special-purpose random-access memory from which it is computer processed.

We use a very bright xenon light to illuminate the x-ray image through the microscope. This enables us to set the camera to minimize the shading error and latent error of the vidicon tube. The microscope has several objectives of different powers to examine target images of various sizes with maximum resolution. At its lowest magnification, the system can view images up to $700\text{ }\mu\text{m}$ in diameter. At high magnification, the spatial resolution is less than $0.5\text{ }\mu\text{m}$.

The camera that records the image incorporates a logarithmic amplifier to detect optical densities in a linear fashion. Because of its very high signal-to-noise ratio, the camera can detect an optical density range of 3 (a light-transmission range of 1000). The video image is digitized in $1/30\text{ s}$ and stored directly in a random-access memory. To reduce electronic noise, the digitizer-processor sums and averages sequential frames of video images. Shading error from the xenon light source is subtracted directly from the image.

To provide fast and precise measurements of target thickness and uniformity, the digitized image is next transferred to computer memory. We have developed a very fast data channel for transmitting information from the digitizer's memory to the microcomputer. An entire image consisting of more than 250 000 points can be transferred in 1.4 s . The stored image is analyzed using noise-reduced scans, operator-controlled cursors, and least-squares fitting for maximum sensitivity.

To make a measurement, we extract a horizontal cross-sectional scan through the center of the target image. Sphere diameter and wall thickness are determined by locating the edges in the cross section. The accuracy of edge location is limited by film-grain noise. We can reduce grain noise by averaging several immediately adjacent cross-sectional scans (Fig. 7a.) This procedure

Fig. 6

(a) Microradiograph image of a hollow glass microsphere ICF target (hydrocarbon polymer coated). (b) Three-dimensional representation of the digitized image.

reduces resolution, however, as only one scan passes directly through the center of the sphere and thus represents a true cross section. We reduce grain noise without losing resolution by averaging along an arc (Fig. 7b). This method, which we call wedge-scan averaging, considerably reduces grain noise over that in an unaveraged cross section, providing much more accurate edge measurements.

To rapidly measure the diameter of a feature, we place operator-controlled cursors at its edges. The computer automatically reads out the distance between them. To make more accurate measurements, we use a least-squares fitting routine to analyze the x-ray image. This routine does a four-parameter fit to the data from the

wedge-averaged density scan. Running on the same microprocessor system that acquires the data, the fitting routine calculates values of diameter, thickness, and nonconcentricity in 2 to 3 min.

With this analysis, we can measure target diameter within 1%, wall thickness within 0.5 μm , and concentricity within 3% of the wall thickness. The entire process of image digitization, transfer, and analysis requires only a few minutes per image. We are developing a fully automated system that can rapidly scan and measure an array of target images.

Scanning Electron Microscopy

A scanning electron microscope (SEM) provides higher spatial resolution of ICF targets than either optical or radiographic methods. In an SEM, a highly focused electron beam generates an image of the surface with greater resolution than can be obtained with light. A good instrument can achieve a spatial resolution of less than 10 nm.

With an SEM, we can measure not only surface features but also the thickness and internal structure of fractured or cross-sectioned samples. High-resolution surface measurements are especially important because small surface defects can nucleate the growth of much larger defects in a coating. The SEM is also widely used in composition and microstructure analysis, a distinct but equally important area of ICF target measurement. Finally, SEM measurements are used to cross check and calibrate interferometry and radiography measurements.

SEM full surface mapping. We have developed several techniques to apply the SEM to the measurement of ICF targets. One technique uses a target manipulator, similar to that used with our Topo I and ASM systems, that enables us to systematically inspect an entire target under completely automatic control, recording the SEM images and storing them permanently on a video disk.

Fig. 7

(a) Left: the Laboratory's AXIAS x-ray microradiographic system extracts a horizontal cross-sectional scan through the center of a hollow glass sphere, coated with hydrocarbon (CH) polymers, shadowed on a photographic plate. Sphere diameter and wall thickness are determined by locating the edges in the cross section. Right: AXIAS-produced unaveraged cross section through a microsphere target. Grain noise is evident. (b) Left: Wedge-scan averaging along an arc eliminates noise while preserving resolution. Right: the same cross section analyzed by wedge-scan averaging. Grain noise is considerably reduced, providing much more accurate edge measurements. Least-squares fitting to these data provides very accurate measurements of thickness and diameter.

The target sphere is first coated with carbon to make it electrically conductive and then mounted between the manipulator tips. A microcomputer synchronizes stage motion, SEM scan, and the video-disk image recorder. The system records a series of partly overlapping images of the target surface, accumulating a montage that enables us to examine any point on the sphere. The recording time for an entire sequence (up to 1000 pictures) is as long as 36 h.

Once stored, however, the data can be almost instantly retrieved for examination.

The SEM system must be stable enough to need no readjustment during the entire mapping operation. This requires careful adjustment of the electronics, control of contamination in the electron-focusing column, and a stable electron emitter. Normal tungsten filaments have a 40-h life, during which their emission properties may change

The Character of Target Defects

Microsphere targets are subject to a variety of defects resulting from the fabrication process or subsequent contamination. A defect is characterized by its wavelength (width) and amplitude (depth or thickness).

Different kinds of defects affect the implosion process in different ways (left-hand figure). If one side of the pusher or ablator layer is thicker than the other, for example, the implosion will be nonsymmetric. An imploding target is subject to fluid instabilities. During implosion, the amplitude of small thickness variations or perturbations (pits, grooves, and protuberances) in the target surface or in the interface between layers grows exponentially. Such defects can cause the imploding shell to break up. Finally, the growth of small perturbations on the inner surface of the pusher can result in mixing of the pusher material with the fuel. This effect quenches the thermonuclear

burn and reduces target yield, even though the pusher remains intact and the implosion proceeds to high density.

These considerations have generated strict requirements for the initial smoothness and uniformity of each layer, surface, and interface in a target. As the growth rate of a perturbation depends on its wavelength, the requirements specify the maximum allowable initial amplitude for a defect of a given wavelength. The right-hand figure shows typical uniformity requirements for a target 600 μm in diameter with a wall 40 μm thick.

Because of the wavelength sensitivity of perturbation growth rates, we must be able to measure defects with a low aspect ratio (those with a small amplitude but a relatively long wavelength). In an extreme case (the minimum of the curve in the right-hand figure), we must detect defects with aspect ratios as low as 0.001. Such defects usually are invisible to measurements of surface contour. To effectively measure ICF targets, therefore, we need a set of techniques that resolves both wavelength and amplitude to cover the entire "defect space."

We have developed another SEM technique that uses the differential detection of backscattered electrons to measure surface topography.

greatly. We stabilize emission by using a lanthanum hexaboride emitter, which, when properly adjusted, is bright and stable for more than 100 h.

Our SEM system effectively complements full surface inspection with an interferometer. Whereas the optical interferometer is more sensitive to broad, low-amplitude defects, the SEM can detect surface defects smaller than the spatial resolution of an optical microscope. Our paper describing the SEM system received the Microbeam Analysis Society's award for the best instrumentation paper of 1979.¹

Backscattered electron mapping.

We have developed another SEM technique that uses the differential detection of backscattered electrons to measure surface topography. This technique is especially sensitive to low-aspect-ratio defects, improving the detection limit to about 1:50. Surface roughness can also be quantitatively measured by this method.

As backscattered electron flux is strongly dependent on the angle between the surface and the electron beam (the take-off angle), we can use the flux to measure local slope on a surface. Detectors on opposite sides of an electron beam incident on a sloping surface will see different signal levels. Our system consists of a conventional SEM with four backscattered-electron detectors placed radially around the primary electron beam at 90-deg intervals.

Because we use two detector sets, we can measure the slope in any direction. The computer controlling the SEM receives the slope data and calculates height differences, displaying them on a graphics terminal. By scanning a raster pattern over the sample, the computer builds up a topographic image of its surface (Fig. 8).

Future Work

Our present combination of measurement techniques is close to satisfying both resolution and speed requirements for transparent ICF targets. For opaque targets, much development work remains. For example, we still lack fast,

accurate techniques for scanning large numbers of opaque spheres, rapidly measuring the key parameters, and selecting acceptable targets. The prospect for developing such techniques is not promising. Future work on opaque-target selection, thus, may take a somewhat different direction. It may prove more feasible and economical to improve the fabrication process for opaque targets than to attempt to combine low-yield fabrication with rapid sorting. The availability of high-yield target-fabrication processes for a commercial ICF power reactor would permit more efficient use of production equipment and target materials and eliminate the need for fast, nondestructive sorting measurements. There are, of course, many intermediate possibilities. For example, sorting may be used at a point where it becomes neither feasible nor cost-effective to further improve the fabrication process.

Summary

Inertial-confinement fusion experiments require microsphere targets with walls that are extremely smooth and of a highly uniform thickness and concentricity. We have developed several new measurement devices and innovative techniques that enable us to measure such features quickly and precisely. These techniques lend themselves to a variety of applications, from rapid survey and sorting of large batches of fabricated targets to complete measurements of individual targets.

Although our techniques work well for transparent targets, much work remains to achieve the same results with opaque targets, for which the technical problems appear less tractable. Thus, for opaque targets, it may prove more feasible to improve fabrication processes. ■

Key Words: Automated Sphere Mapper (ASM); Automated X-ray Image Analysis System (AXIAS); inertial confinement fusion; micro-radiography; microsphere; optical interference microscopy; scanning electron microscopy; target analysis—ICF; Topo I.

Fig. 8

Topographic surface map produced with backscattered electrons. The computer scans a raster pattern over the sample and calculates the height differences, displaying them on a graphics terminal. The inset shows a scanning electron microscope image of the same area.

Notes and References

1. C. M. Ward, D. L. Willenborg, and K. L. Montgomery, "Full Surface Examination of Small Spheres with a Computer-Controlled Scanning Electron Microscope," *Microbeam Analysis*, 1979.

The Raman Spectroscopy Microprobe

Our Raman spectroscopy microprobe, the most sensitive of its kind in use anywhere, will provide us with new insights into the world of submicron-size particles.

For further information contact
Tomas Hirschfeld (415) 422-6364 or
Fred P. Milanovich (415) 422-6838.

The characterization of very small particles or of a microscopic region on a larger particle is an essential part of many research programs. We may wish, for example, to study a small defect, inclusion, or laser-damage track on or below the surface of an optical component, or a small particle of dust from stack emission, or fallout from an atmospheric nuclear test. The capability to analyze such small particles might be valuable also in the study of dirt, residues, and local imperfections in materials for the nuclear explosives program, for the analysis of inclusions in geologic samples, and for investigating microscopic biological subjects.

In such cases, it seldom is sufficient to know which elements are present. For all but the simplest compounds, there will be many different interpretations of the elemental analysis, and only with a molecular analysis can we decide which interpretation is correct. To determine molecular structure, we might use infrared spectroscopy or ultraviolet or fluorescence spectroscopy.

However, infrared lacks the required spatial resolution and sensitivity, and ultraviolet and fluorescence lack the universality and structural discrimination of infrared. We need a technique that combines the sensitivity and spatial resolution of ultraviolet spectroscopy with the universality and structural discrimination of infrared spectroscopy.

Raman spectroscopy, which determines molecular structure by scattering light from a sample and analyzing the characteristic frequency shifts of a very small fraction of the scattered light, is an obvious choice to fill this need. Being an inherently low-sensitivity method, however, it requires the use of new technology in order to deal with microscopic samples.

To view the stringent requirements of a micro-Raman spectrometer in the proper perspective, we must realize that the sample in a micro-Raman system is about ten million times smaller in volume than the smallest samples previously studied with conventional Raman

spectroscopy. Typical samples used with standard instruments have interaction lengths on the order of millimetres rather than fractions of a micrometre.

This great reduction in sample size has several consequences. It greatly decreases the amount of excitation energy that can be delivered to the sample. The 0.1- μm samples we are interested in measuring are smaller than the diffraction limit of the optics and, hence, are smaller than the smallest laser focus spot. As a result, much of the beam energy will miss the sample and go into the substrate. There is also a possibility that the enormous concentration of energy in a small spot will destroy the sample by vaporizing it or changing its composition. To avoid this, we must either reduce the beam power or effectively remove the energy absorbed by the sample.

In addition to dramatically decreasing the excitation energy we can put into the sample, the small sample size also shortens the interaction length. This, in turn, reduces by at least two orders of magnitude the fraction of the already-reduced excitation energy that can be transformed into Raman radiation.

Nor is this all. Because the smallest samples are smaller than the focus spot of the laser light, much light is scattered not from the sample but from the substrate holding the sample. This makes it necessary to collect more than ten times as many Raman photons as usual from the sample so as to distinguish between the Raman spectra of the sample and of the substrate.

From the foregoing, it is clear that, to obtain the spectrum required for analysis of a submicron-size sample in a reasonable time, a micro-Raman spectrometer must have a sensitivity or efficiency several million times greater than existing units that perform similar analyses on more typical samples. To obtain improvements of this magnitude, we had to do more than modify, adapt, or "clean up" existing instruments that have already been intensively optimized. Instead, we designed and constructed a microprobe-based Raman spectroscopy that applies

entirely new techniques and attains nearly optimum performance throughout a sophisticated system.

The Technical Approach

The technical problems we had to solve to make a practical Raman microprobe included getting enough light into the sample, enabling the sample to survive the energy being directed into it, and obtaining good Raman signals from a very small sample.

A laser is the obvious light source of choice to ensure supplying sufficient monochromatic light to the sample. To obtain the wide choice of wavelengths needed for the large range of potential samples, we selected a variety of lasers. The focusing requirements dictated the use of a highly stable optical bench (a 5000-kg granite slab) and a sample carriage of extreme precision.

To assure sample survival under illumination with concentrated laser light, even at minimum power (about 1 mW), is a significant challenge. We used high-conductivity substrates such as sapphire, lithium fluoride, even diamond, as well as a mirror to divert the transmitted beam. For delicate samples, it is possible to evacuate the sample chamber and cool the substrate, increasing both the thermal tolerance (allowable temperature rise before incurring sample damage) and the heat flow out of the sample.

The most difficult problem, however, is to obtain good Raman signals from such a small sample. For all our efforts to increase the amount of light reaching the sample, the corresponding Raman emission is still exceedingly weak.

First, we tried to collect as large a fraction of the emitted Raman light as possible. To do this, we had a deep-dish diffraction-limited ellipsoidal mirror machined on the LLNL diamond turning lathe. This mirror not only isolates a volume of submicron dimensions but also collects its emission several times more efficiently than do the lenses used in conventional Raman spectroscopy.

Second, we replaced the slit-and-photomultiplier system used for

detecting the Raman light in conventional systems with a vidicon (television camera tube). With this, we can detect light from a range of wavelengths simultaneously, instead of scanning slowly across the range and wasting all the light that falls on either side of the slit. We cooled the vidicon with dry ice (-56°C) and sequenced the computer scanning to minimize interference from electronic amplifier noise.

The final problem was to distinguish the resulting signal from various kinds of background. Part of this background comes from neighboring regions of the sample and from the substrate, but much more of it consists of elastically scattered light from the laser. Conventional Raman spectroscopy uses a double monochromator to eliminate the laser light, but this solution sacrifices the advantages of vidicon detection. Instead, we filtered the light with a double spectrograph of zero net

dispersion that was compatible with the television camera.

We used the data-manipulation capabilities of the computer data system to subtract residual background and to simplify the qualitative and quantitative interpretation of the data.

The Raman Microprobe

Figure 1 diagrams the layout of our optimally sensitive Raman microprobe, which includes a pair of lasers (argon ion and krypton ion) chosen for their ease of operation, stability reliability, and multiplicity of laser wavelengths.

A series of beam-directing mirrors guides the laser output into a spatial-filter beam expander. This is a pinhole/lens combination that strips away all but the best-aligned light rays and then enlarges these into a broad, well-collimated beam.

The expanded beam is then turned at right angles by a Pellin-Broca prism and focused by a 400-mm achromatic lens to a $100\text{-}\mu\text{m}$ pinhole. (Between them, the pinhole and the spatial filter assure day-to-day reproducibility of the laser-beam location.) The expanding beam from the pinhole strikes an objective mirror in the illuminator, which focuses it tightly onto the sample stage.

In contrast to the laser light, which travels in a well-defined beam the wavelength-dispersed Raman signal leaves the sample in all directions. The ellipsoidal mirror collects a good portion of this scattered radiation and directs it through a prefilter into the input slit of the spectrograph. The prefilter, which rejects more than half of the signal light in order to reject almost all stray light, can be replaced by a high-transmission notch-filter assembly for applications in which stray light is less troublesome.

The spectrograph disperses the Raman-shifted light into its component frequencies, focusing an array of slit images onto the photocathode of an intensified vidicon camera. We cool the camera housing with dry ice to reduce thermal noise and improve its signal-to-noise ratio. The prefilter, spectrograph, and camera are mounted on an

Fig. 1

Our optimum-sensitivity Raman microprobe. A series of beam-directing mirrors guides the laser output into a spatial-filter beam expander. The expanded beam is turned at right angles by a Pellin-Broca prism and focused by a 400-mm achromatic lens to a $100\text{-}\mu\text{m}$ pinhole. The expanding beam from the pinhole strikes an objective mirror in the illuminator, which focuses it tightly onto the sample stage. The wavelength-dispersed Raman signal leaves the sample in all directions, but much of the scattered radiation is collected by the ellipsoidal mirror and directed through a prefilter into the input slit of the spectrograph, which disperses it into its component frequencies, focusing an array of slit images onto the photocathode of an intensified vidicon camera.

adjustable platform capable of moving in three dimensions. We support the platform at three points on air-cushioned legs that allow us to make microscopic adjustments in the position of the light-detecting assembly with respect to the illuminator.

Figure 2a shows the heart of our Raman microprobe—the illuminator—and the optical path. Laser light enters from the right, passing through the 400-mm achromatic lens (1) and the 100- μm pinhole (2) to a beam-splitting mirror (3). A small amount of the light goes straight through to a photodiode (6) that monitors input power. The remaining light reflects from the mirror down through a hole in a concave mirror onto a small convex mirror, back up to the concave mirror, and down again through a hole in the ellipsoidal collecting mirror (4) to a tight focus on the sample stage (5).

The sample stage is a conventional spider-like design with a coarse and a fine adjustment on each of the three

orthogonal motions. Some light from the sample retraces the folded path back up to the beam splitter, described above, and passes through to the microscope eyepiece. This makes it possible to see the effects of the focusing and alignment adjustments.

At (8), there is also a swing-away beam-splitter and penlight assembly (not shown) that is useful for back-lighting the sample in the collecting ellipsoid. This same system provides a calibration standard for the spectrograph (calibrated against a National Bureau of Standards intensity standard), using the other ray from the beam splitter. We operate the penlight under voltage for extended life and for stability of output.

The principal component of the illuminator is the ellipsoidal collection mirror (7), shown in more detail in Fig. 2b. The large numerical aperture of this mirror ($f/8$) yields an operational resolution of 0.7 μm at a wavelength of 500 nm and a paraxial magnification

Fig. 2

(a) Moderate-detail drawing of the illuminator section of our Raman microprobe. Numerals indicate (1) the focusing achromatic lens, (2) the entrance pinhole, (3) the beam splitter, (4) the focusing objectives, (5) the sample stage, (6) the photodiode, (7) the collection ellipsoidal mirror, and (8) the calibration and illumination lamp, not shown. The incident laser light is indicated in blue and the collected scattered radiation in pink. (b) Cross section of the ellipsoidal collector mirror. f_1 is 18 mm, f_2 is 322 mm, d is 50 mm, and the angle α is 60.9 deg.

(b)

of 18. This determines the image size at the entrance to the monochromator and ultimately determines the spectral resolution. The sample blocks part of the collected Raman light before it can reach the monochromator slit, making it necessary to use samples no larger than about 1 cm.

We first applied our Raman-spectroscopy microprobe to a problem concerning the explosive pentaerythritol tetranitrate (PETN).

The light-detecting element of our Raman microprobe's camera is the silicon-intensified target (SIT) of a computer-controlled charge-coupled diode detector, illustrated in Fig. 3. Light incident on the camera's photocathode ejects electrons, which are directed as an image onto a 500×500 array (12.5×12.3 mm) of photoconducting silicon targets. This charge is stored for

a programmable period of time and then is read by a scanning electron beam. For low light conditions, as in Raman spectroscopy, the collection interval may be several minutes long.

This detection system makes it advisable to calibrate both intensity and wavelength frequently, even from run to run in the same day. We have added a separate computer, driven by software we developed here, to perform these calibrations and to aid in data manipulation and storage. This computer, operating in series with yet another computer, also provides data basing and manipulation for a separate full-size Raman spectrometer.

In a typical operation, the camera's computer first acquires a spectrum. We then perform a wavelength and intensity calibration, if necessary, and transfer this information and the original spectrum to the second computer. In this way, the data are stored in two places, providing a convenient backup.

For routine wavelength calibrations, we obtain the spectrum of a macroscopic particle (about $100 \mu\text{m}$) of naphthalene, which is readily available, easy to handle, and has well-spaced narrow Raman lines of known wavelength. The data base of the calibration computer contains these known Raman shifts. The computer uses them to calibrate the 500-channel wavelength axis of the SIT.

Figure 4 shows two naphthalene spectra as examples of the instrument's capabilities. The spectrum shown in Fig. 4a is that obtained with a 12-s illumination of a $70\text{-}\mu\text{m}$ naphthalene particle with 2 mW of light at a wavelength of 514.5 nm. The spectrum shown in Fig. 4b is that of a micro-particle of naphthalene (about $10 \mu\text{m}$) under ambient conditions. This particle quickly sublimed under illumination. However, the light-gathering capabilities of the illuminator and the multi-channel nature of the detector made it possible to obtain a recognizable naphthalene spectrum.

Applications

We first applied our Raman-spectroscopy microprobe to a problem

Fig. 3

Schematic representation of the electronic camera used in our Raman microprobe. Principal components include the electron optical system, the silicon-intensified-target, and the scanning system for reading the stored image into the computer.

concerning the explosive pentaerythritol tetranitrate (PETN). We had noticed a significant decrease in the reliability of PETN that had been exposed to high temperatures. Various elemental analyses indicated that there had been no chemical change, and there were no major impurities or compositional variations other than the usual interbatch fluctuations typical of PETN preparations. This finding suggested that the change in properties might be the result of a change in crystal structure.

Below about 140°C, PETN is a nonhygroscopic crystalline solid (alpha-PETN). The crystals are uniaxial with a tetragonal unit cell of nominal dimensions $a = 93$ nm and $c = 67$ nm. The principal polymorph, beta-PETN, is observed on heating to 130–140°C but is presumed to revert completely to alpha-PETN on cooling.

To investigate the possibility of permanent temperature-induced crystal-structure changes, we used x-ray diffraction and Fourier-transform infrared spectroscopy (FTIR) to examine bulk PETN specimens. The x-ray diffraction studies showed a barely discernible line narrowing, but the FTIR was more successful. Although the spectral peaks kept the same locations, several peaks showed significant intensity differences, depending on whether the sample had been temperature cycled. Such intensity changes in peaks that remain constant in wavelength could be caused by a variety of local changes in crystal symmetry, defect levels, stress, strain, etc.

For a better understanding of these postulated structural differences, we turned to microanalysis of individual PETN crystals, using the Raman microprobe. Figure 5a shows the Raman spectrum of the heated PETN from a bulk sample, taken with a conventional Raman system. Figure 5b shows the Raman spectrum of an individual PETN crystallite taken with our Raman microprobe.

Figure 5c shows one recurring major spectral difference observed during particle-by-particle analyses, a strong enhancement of the 594-cm⁻¹ line (and the fluorescence background). This difference is well in excess of reproducibility differences for a given particle and indicates that, although all the particles have the same composition (each shows all the same peaks), they

Fig. 4

Raman spectra of naphthalene particles taken with our Raman microprobe. Measurement parameters: (a) particle size, 70 μ m; laser power, 2 mW; laser wavelength, 514.5 nm; prefilter bandpass, 40 nm; slit width, 167 μ m. (b) Particle size, 10 μ m; laser power, 500 μ W; all other parameters identical to (a).

Fig. 5

Raman spectra from an investigation of temperature-caused changes in the sensitivity of PETN explosive. (a) Spectrum from a bulk sample of PETN taken with a conventional Raman spectroscopy. (b) Spectrum of an individual crystallite of PETN taken with our Raman microprobe. (c) Spectrum illustrating the variation in the intensity of the 594-cm^{-1} line.

must differ in crystal structure on a microscopic scale.

Attempts to produce this spectral change by methodical increases in laser intensity on native particles were unsuccessful. This, together with the spectral differences and the FTIR data, indicates that the degradation mechanism cannot be a simple bulk one but must

reflect either a macroscale stochastic mechanism or the influence of a much smaller initial sample heterogeneity on a crystal-by-crystal basis.

Other work in progress on the Raman microprobe includes:

- Measurement of the dependence on temperature of microscopic ruby crystal fluorescence. Once we have calibrated the fluorescence of such particles, it may be possible to use them as sensors to measure local temperature variations in flowing gases.
- Characterization of preexisting defects (bubbles) in laser glass. Preliminary results not only show that these bubbles are filled with air (not some other gas) but also enable us to calculate their formation temperature.
- Characterization of laser damage in KDP (potassium diphosphate) crystals used in laser-frequency multiplication. Preliminary results indicate that the final step before visible damage occurs is thermal rather than photochemical.
- Investigation of the microstructure of fiber-composite materials—the embedded polymer fibers, the surrounding matrix, and the interface between them.

Future Work

As with most instruments in the course of development, the microprobe has seen service in research even before being completed to design specifications. We expect to continue to make refinements and improvements over the next few years, chief among which would be cooling the sample stage with liquid nitrogen.

Meanwhile, we are applying the microprobe to several problems in the LLNL explosives program. In the near future, we expect to extend our applications to biological problems, with emphasis on the study of sub-cellular structures, and to environmental problems, with emphasis on power plant particulate emissions. ■

Key Words: argon-ion laser; infrared absorption spectroscopy; krypton-ion laser; molecular structure; Raman spectroscopy.

Thirty Years Ago: Controlled Thermonuclear Reactions

The Laboratory's first progress report, covering September 1952, began with a description of the Controlled Thermonuclear Reactions Program (now known as magnetic fusion energy). In this article, we combine excerpts from early progress reports with anecdotes and reminiscences of staff members to follow this program through its first year.

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The possibility of using controlled thermonuclear reactions (CTR) for power production came to the fore in the early 1950s. In late February 1952,¹ less than two months after Ernest Lawrence had asked Herb York, "Should there be a second laboratory?" Herb reported on the "jobs now underway on new weapons work" and the people working on them. One entry in this truly first Project Whitney progress report noted: "[Joe] Lepore - part time. Studying available information concerning Thermonuclear Power; preparing joint report with me on same."

Later that spring, Herb delivered three lectures in Berkeley on "considerations pertinent to the problem of utilizing controlled thermonuclear reactions for the production of power."

Art Hudgins remembers that "Herb's lectures were given in the Bldg 50 auditorium on the Hill. Not only was the concept of controlled thermonuclear reactions classified in those days but even the name itself. The auditorium had been cleared and a guard at the door checked your badge against his list. If you weren't on the list, you didn't get in."²

Dick Post recalls: "I had just come to Berkeley to do an experiment on the synchrotron with my first graduate student, Chuck McDonald. When Herb gave his three lectures on Controlled Thermonuclear Reactions, I caught an

* * *

Dick Post on Project Sherwood

We found out much later that the name "Project Sherwood" had been invented by Paul McDaniel; one of its ingredients was a reference to "Friar" Tuck, the English physicist Jim Tuck who headed the Los Alamos CTR program. Since we at Livermore didn't know at the time where the term had come from, we created a different etymology which made the rounds:

Question: Wouldn't it be great if we could make CTR work?

Answer: Sure would!

My first meeting with Jim Tuck occurred during [this] meeting in Denver. As Herb and I were walking in downtown Denver, there loomed up in the distance a tall figure, draped in a large Navajo blanket and smoking an enormous meerschaum pipe. That was Jim Tuck. He may not have been impressed with me, but I certainly was impressed with him!

incurable case of the fusion bug. A few days later Herb suggested that I look into plugging the end of a solenoid field with microwave radiation. I did the calculations: the numbers came out on the low side for that idea, but I found several offshoots which offered more promise at the time. On the spot, almost, Herb invited me to come to Livermore and gather a team to work on the problem. I started off running; Jack Steller and I did a quick experiment to show that a magnetic mirror could confine a low-temperature rf plasma. In June, I reported on our work at the Classified Conference on Thermonuclear Reactors in Denver, Colorado, which Herb York and I attended. This meeting addressed the desirability and feasibility of starting a national program, which would later be known as Project Sherwood."

As Herb recalls: "That summer [1952], before coming out to Livermore, I remember a number of meetings . . . The one I remember best is Sherwood and getting the mirror machine program going. There was a national meeting in Denver . . . on the subject of whether or not there should be a national controlled thermonuclear program. I came back with the feeling that yes, there ought to be a national program, and with the additional feeling that boy, that really would be a good adjunct to the program at Livermore. We'd been thinking about it before, but it probably wasn't until then that it became sort of an official element of the program."

Project Whitney was outlined in considerable detail in Herb York's prospectus³ for the Livermore site, in which provision had been made for a small Controlled Thermonuclear Reactions Group: "It is proposed to set up a small group of about seven physicists (junior and senior) and/or engineers . . . Their initial goal will probably not be to try to get a reaction going, but to reach some sort of halfway point by, say, setting up a plasma with a temperature of 100 eV (1,200,000°K) and then investigating various points of interest such as particle mobility across and along

field lines, heat conductivity, plasma oscillations, etc."

Jim Carothers has commented on being recruited for this program: "Along with a lot of other people on the Hill, I finished my thesis work in June of '52. I had been working on both the synchrotron and the 184-inch cyclotron, and had gotten to know Herb York in a casual way. Well, when you finally get done being a student, there's this problem of finding a job... One evening, at the cyclotron, Herb mentioned casually that he was starting a small program that needed people: would I like to work with him? He wasn't very explicit. I got the impression it had something to do with controlled fusion, which I had never heard of. I read some stuff about it, it seemed interesting. A few days later I said, 'Sure, I'd like to do that.' He said, 'Good. Come to our meeting this afternoon.' So a few days later, Al Kirschbaum, Harmon Hubbard, and I were working together wondering what this fusion stuff was all about. Somehow, weapons and moving to Livermore, or even the word Livermore for that matter, hadn't been mentioned. But it was an easy way to solve the job hunting problem."

The first official monthly progress report from the Livermore site (see box on this page) suggests this group's early thoughts and plans and gives perhaps the first formal statement of the Lab's CTR program.

Dick Post, author of most of the early CTR progress reports, remembers some of the thinking on "one of our earliest ideas, a radiofrequency confinement scheme. Ed McMillan was especially critical of the idea, and (with considerable prescience) took a somewhat jaundiced view of the prospects for an early solution to the fusion problem. He based his feelings on the 'thermodynamic' argument that what we were trying to do went so far against the tendency for a hot gas to reach thermodynamic equilibrium with its surroundings that the gas would find myriad ways to foil our attempts to confine it. As to the rf scheme, he pointed out that a high-intensity rf

UNIVERSITY OF CALIFORNIA, RADIATION LABORATORY - LIVERMORE SITE

Period to September 30, 1952

MONTHLY PROGRESS REPORT NO. 1

November 24, 1952

1. CONTROLLED THERMONUCLEAR REACTIONS

Aimed toward a better understanding of the problems arising in attempting to produce a controlled thermonuclear reaction, a program of experiments and theoretical calculations was broadly outlined during the period ending September 30. A start was also made in assembling and designing equipment to be used in the program, and some simple preliminary experiments were carried out.

The program consists of two parts. The first part is to be a study of fundamental processes in a plasma and the development of means for measuring the temperature, density and diffusion rates in a hot plasma. The second part of the program is directed toward trying to solve the primary problem — containment, i.e., keeping a plasma from being cooled by heat convection to the boundary walls.

Several promising ideas which may point the way toward the solution of the containment problem were under consideration. Almost without exception these ideas propose the use of some type of dynamic focusing by intense rf fields, in some cases used in conjunction with steady d.c. magnetic fields. One of the most promising attacks which has been suggested is the use of the new (Brookhaven) strong-focusing principle to effect confinement. A simple way to use a cavity resonator in a mode which satisfies the formal requirements for strong-focusing has been proposed, and some calculations leading to a test model machine of this type have been made.

The following experiments have been essayed up to September 30:

1. The propagation of a microwave signal through a low-density plasma in a magnetic field has been measured. The measurements have been compared with theory and used to estimate the diffusion of the plasma across a magnetic field.
2. The "magnetic mirror" effect has been studied in a preliminary way. This study is for the purpose of finding ways to enhance the effect by the use of rf fields.
3. The ion temperature in a heavy "P.I.O." discharge has been measured by spectroscopic (Doppler shift) methods.

Future work may be expected to continue on these and other experiments. It will be accelerated when the group reaches its full complement and when the facilities for its operation at Livermore are finished.

radiation field had an enormous equivalent 'temperature' toward which the trapped particles would aspire, thus giving them the impetus (and the thermodynamic excuse) to boost themselves rapidly out of the confining fields."

The November 1952 progress report noted that "a dynamic rubber sheet

*Fig. 1
Rubber sheet model
of the strong-
focusing method
of confining
plasma.*

model of the strong-focusing method of confinement had been built (Fig. 1); many qualitative features of the expected particle trajectories and the effect of collisions on particle motion could be directly observed." According to Dick Post, "we hoped that the oscillating electric fields excited in a large cavity resonator might confine a hot plasma. The physics involved was similar to that of the strong-focusing accelerator. To provide a visual demonstration that an oscillating field would hold in a 'particle,' we built a rubber sheet model where the combination of gravity and the (variable) curvature of the rubber sheet mocked up the rf fields. Thus, even though it was always 'downhill' outward on some part of the surface, the oscillation of curvature involved kept the ball centered. Even two balls, hitting each other randomly, could be kept in (sometimes). The model was an attempt to lend plausibility to an idea which appeared implausible to disbelievers."

Post continues: "In 1952, hardly anyone understood even the simplest aspects of the confinement of plasma by mirrors: there just wasn't any prior work to go on. To illustrate this point: an idea called 'cornucopia' came up during our first month or two. It involved the

thought that perhaps mirror leakage could be prevented by bending the constricting bundle of flux lines in the mirror region so they would curve sideways, resembling a horn of plenty. In this way, the argument went, the leaking end would be 'out of the line of sight' of the particles approaching the mirror, and they 'wouldn't find the hole.' As we later discovered, the particles are 'smarter' than that: they simply would be guided around the corner and leak out, or else drift across the bent field lines and be lost anyway."

The November 1952 progress report announced a second major line of attack on the confinement problem, an investigation of the enhanced magnetic mirror. (The existence of the mirror effect itself had already been observed through cosmic-ray research.) To this end, the report states, "a small magnet assembly has been constructed to test additional features of the idea. In this device an axially symmetric magnetic field with a large field gradient at each end is maintained. Provision is made for exciting the discharge by a transverse rf field at a frequency close to the gyroresonant frequency of the ions in the center of the field. If the ions are contained by the enhanced mirror effect, this will be made evident by the lengthened persistence of the density of ionization after the excitation is turned off. Plans are underway for a somewhat larger assembly which will incorporate a longer region of uniform magnetic field and better means for producing the resonant acceleration. Thus far the enhanced magnetic mirror has continued to appear as one of the most promising ways of containing a high density discharge."

Dick Post makes this comment on early CTR diagnostics: "It should be remembered that an understanding of the basic physics of magnetic confinement was not the only thing we were lacking back in 1952-1953. While we were trying to gain understanding through experiments, we also had to feel our way along by inventing our own diagnostic techniques to measure the plasma properties. One of our early ideas in

this area involved radiochemical tracers."

The January 1953 progress report describes this "experiment to test the feasibility of measuring ion density distributions in a discharge by radioactive tracer methods. The tracer gas (Iodine 131) was successfully distilled from a sample of irradiated tellurium and passed into a discharge tube to the extent of about one percent of the initial activity. With easily attainable initial activities a transfer of approximately one percent of the tracer gas is sufficient to make feasible the measurement of density distributions to a reasonable accuracy. Some rather involved problems in surface chemistry were encountered in the course of the experiment since it is apparent that the iodine which is used as the tracer gas is chemically active and, when hot, reacts with the surroundings. The possibility of using xenon gas obtained from a fission slug from a pile is also being investigated; furthermore, xenon is an inert gas in which the chemical problems will be considerably simpler."

In February 1953, the progress report gave the program name—Controlled Thermonuclear Reactions—a parenthetical explanation (Arc Research). One reason for this was that the program name had become more highly classified. The term "Arc Research" referred only to the work at Livermore; the national program also received a new name, Project Sherwood.

In early 1953, construction began on a small model CTR "reactor" that used the principle of enhanced magnetic-mirror confinement. The February 1953 progress report continues: "This machine consists of an 11-foot stainless steel tube, surrounded by a solenoid capable of producing an axial field of 3000 gauss, with increasing gradients at the ends. Rf accelerating electrodes, specially shaped, will run almost the entire length of the device to provide a rotating accelerating field. A pulsed ion gun which can inject protons at an energy of a few kilovolts is to be connected to one end of the device. Care had been taken to provide for

Dick Post on serendipity

In one of our early Table Top [reactor] experiments, we tried to temporarily "gate" out one of the mirror fields by inserting a copper cylinder inside the coil. The idea was that the pulsed field would be temporarily excluded, allowing plasma to get in, after which the field would penetrate the shell and build up the mirror. But when we tried it at high field, we crushed the shell. We looked at our collapsed shell as just a problem to be solved. Someone else observed this effect and went on to invent "magnaforming," a presently used industrial technique for forming metals by using pulsed magnetic fields.

* * *

outgassing of the entire structure, so that a vacuum better than 10 mm Hg should be obtainable.

"The significance of this device is that it may offer a relatively simple way to generate a very hot plasma of moderate density. The initial condition for the discharge, that of a very low neutral particle density within the reactor volume, is most important because of the existence of charge transfer collisions. For example, if the initial neutral pressure in a device in which it is hoped to contain a hot plasma is 10 mm Hg (i.e., a moderately good vacuum), then calculations show that a one kilovolt proton could only survive under these conditions for about 10 microseconds before it would be lost to the wall through charge capture from a cold neutral particle. This lifetime is much less than the expected time of containment by the fields. Thus, in this hypothetical case, transfer collisions would mask the control of diffusion by the magnetic field.

"The ways out of this difficulty appear to be several. The simplest is to improve the vacuum. Another is to operate at much higher ion energies, in which case the charge transfer cross section becomes much smaller."

The next few months were devoted to building and testing the magnetic-mirror model reactor. In April, the main vacuum chamber was assembled and the rf accelerating system completed; in May, the ion gun and focusing system tests were begun. In June, the first experiments were performed. "Injected hydrogen ions from an ion source have been reflected with near-zero loss at

the far end of the machine. This was accomplished by imparting angular momentum to the injected ions as they move into the machine (by means of rf excitation at the ion gyroresonant frequency) and then allowing these particles to move into a region of increasing axial magnetic field. As both H^+ and H_2^+ ions were emergent from the ion source, it was found that there were two resonant frequencies at which ions were reflected, each corresponding to the reflection of one type of ion only, in its proper proportion."

Also in June 1952, construction began on an electron model of the magnetic mirror (Fig. 2). Dick Post comments on

* * *

Dick Post on early growth in the mirror program:

The Chairman of the Atomic Energy Commission in those days was Admiral Lewis L. Strauss. He took an intense personal interest in controlled fusion research, including visits to the laboratories. In late 1953, he and I were standing in the largely empty area of the old Drill Hall [Fig. 3] as the Table Top facilities were being set up. His question to me was: "Is there anything I can do to help speed up your program? Just name it." He was sincere in his question and his promise—our budget doubled in 1954, and more than doubled again in 1955.

the purpose of this new model: "Since the idea of mirror reflection of charged particles was only loosely understood at the time, we wanted to make a direct demonstration of the idea to help convince ourselves (and others) that it could work. The electron-beam model [Fig. 2a] had an electron source on the left, a 'regular' magnetic field created by the loosely spaced windings in the center, and a 'mirror' field (the tightly wound coil on the right). A pencil electron beam was shot obliquely into the 'mirror,' producing the helix motion [shown in Fig. 2b]. The electrons' path is made visible by their passage through a low-density gas. We were delighted to see that reflection really did occur, and that it could be controlled."

August saw the coalescence of several ideas into a specific plan for the construction of a magnetic-mirror device with improved characteristics. The specifications for the Table Top Reactor, as it was later named, were: "A long evacuated vacuum chamber, surrounded by magnetic coils which can produce a large pulsed magnetic field in the axial direction. At one end of the

*Fig. 2
The electron-beam
model of the mag-
netic mirror (a).
A pencil electron
beam shot obliquely
into the 'mirror'
produced the helix
motion seen in (b).*

*Fig. 3
The Drill Hall,
Bldg. 53, where the
Table Top Reactor
was set up and
operated.*

chamber is to be located an array of pulsed ion sources capable of injecting, at an angle, many amperes of space-charge neutralized ions at energies of a few kilovolts. By steadily increasing the magnetic field from an initial value of, say, a few thousand gauss, it is possible to trap the injected ions (and electrons) between 'bumps' or 'magnetic mirrors' consisting of regions at the ends of the tube where the axial field is increased relative to its value in the central section.

"Continued increase of the axial fields (up to 10,000 gauss or more) results in adiabatic heating and radial compression of the plasma. In addition, the plasma may be further compressed and heated in the axial direction by programming the magnet coil currents to move the location of the mirrors inward. At the end of this compression and heating cycle, occurring perhaps 1/100 to 1/10 second, it is contemplated that the plasma could have reached a density of perhaps 10^{14} ions/cm³ and an effective ion kinetic temperature of perhaps 100 keV. Should this point be reached, the reaction rate per unit volume would become large. Although randomizing processes in the plasma would lead to a finite containment time, it appears possible that these times could be long enough to permit a reasonable percentage burn of the reacting (deuterium) plasma. Reversal of the adiabatic compression would lead to the recovery of part of the particle kinetic energies by conversion to electrical current in the magnet coils.

"To be sure, the complete lack of experimental knowledge of the behavior of a super heated plasma contained by a magnetic field precludes any positive assurance that such a scheme will work, but at least as far as present knowledge will carry us, the proposal looks attractive."

The Table Top Reactor was completed in June 1954 in the Drill Hall and was tested that summer (Fig. 4). Dick Post recalls that "it was designed to create a hot, mirror-confined, plasma through the pulsed magnetic compression of a plasma shot through one mir-

ror into the confinement chamber. Almost immediately, as we turned up the power, our first pulsed coil failed. We had not accurately calculated the stability of the magnet coil windings. Under the magnetic forces the windings compressed axially and bunched up. This was our introduction to the magnitude of the forces we had to deal with. It led, soon, to the development of fiberglass-reinforced pulsed coils that solved the problem beautifully."

Key Words: Arc Research; controlled thermonuclear reaction (CTR); magnetic fusion energy; magnetic-mirror confinement; Project Sherwood; Project Whitney; Table Top Reactor.

Notes and References

1. An article describing the establishment of the Livermore site of the U.C. Radiation Laboratory appeared in the February 1982 issue of *Energy and Technology Review* (UCRL-52000-82-2), p. 19.
2. Some of the anecdotes quoted in this article are taken from oral history interviews between Jim Carothers, Archivist, and the persons quoted. The interviews themselves can be consulted in the Laboratory's archives.
3. The "prospectus," Herb York's original (1952) written plan for activities at the Livermore site, is reproduced in the article cited in Reference 1.

Fig. 4
The completed
Table Top Reactor
(a); (b) the pulsed
coil before the
test and (c) after
power was applied.

Past Titles

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