AD-A250 569

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. ... ATE

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

University Research Initiative - Center for Ultrahigh Dynamic Performance Materials - Equipment

5. FUNDING NUMBERS

DAAL03-86-G-0195

6. AUTHOR(S)

S. Nemat-Nasser, Principal Investigator

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

ARO 24618.1-MS-UIE

11. SUPPLEMENTARY NOTES

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As part of UCSD's URI on Ultrahigh Dynamic Performance Materials, the ARO award included a $600,000 equipment grant for developing state-of-the-art high-strain-rate testing facilities at UCSD. Under this support, the following facilities have been developed:

1. Small broached gas gun, capable of both normal and oblique plate-impact testing, together with both displacement and velocity interferometric facilities.
2. Large gas gun for normal plate impact experiments.
3. Compression Hopkinson bar with dedicated data acquisition and analysis system.
4. Tension Hopkinson bar.
5. Torsion Hopkinson bar.
6. Miscellaneous data acquisition systems including a Le Croy and a flash X-ray unit.

These facilities were designed and constructed whenever possible, at UCSD. They include a number of innovative high-strain-rate testing techniques.

Included in this report is a brochure entitled "The Experimental Facilities of the Center of Excellence for Advanced Materials" which includes brief descriptions and photographs of many of the instruments reported herewith.

14. SUBJECT TERMS

compression, tension, torsion, ultrahigh dynamic

15. NUMBER OF PAGES

6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

92 4 27 435

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

92-11246

FINAL TECHNICAL REPORT

for the period

October 1, 1986 to December 31, 1989

on

University Research Initiative - Center for Ultrahigh Dynamic Performance Materials [Equipment]

Grant No. DAAL03-86-G-0195

Dr. S. Nemat-Nasser, Principal Investigator

University of California, San Diego, La Jolla, California 92093

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ABSTRACT

As part of UCSD's URI on Ultrahigh Dynamic Performance Materials, the ARO award included a $600,000 equipment grant for developing state-of-the-art high-strain-rate testing facilities at UCSD. Under this support, the following facilities have been developed:

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1.0 INTRODUCTION

As part of UCSD's URI on Ultrahigh Dynamic Performance Materials, ARO provided an equipment award to develop state-of-the-art high-strain-rate testing facilities. ARO grant No. DAAL-03-86-G-0195 was to specifically develop a gas gun for plate-impact experiments, and Hopkinson bars for compression, tension, and torsion dynamic testing of materials. Supplemented by the URI core contract, UCSD's contributions, funds from other sources and especially a large instrumentation grant from DOD'd BTI to ARO, unique state-of-the-art facilities involving a number of innovations now exist at UCSD. Attached to this report is a brochure entitled "The Experimental Facilities of The Center of Excellence for Advanced Materials", October 1990, which gives an overview of the existing capability in mechanical testing and other aspects of the study of advanced materials.

This final report specifically addresses instrumentation developed under ARO Grant No: DAAL-03-86-G-0195.

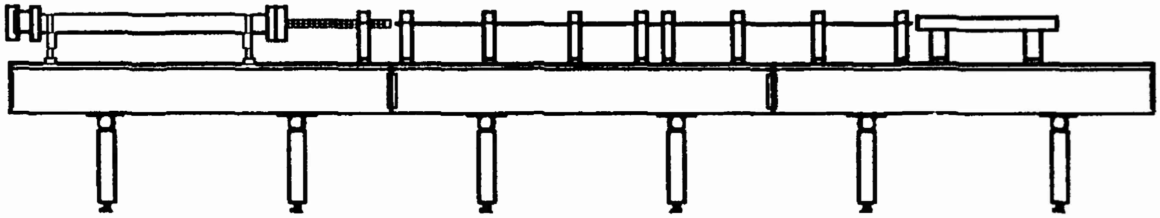
After a careful study of the availability of outside vendors for constructing the gas gun and the Hopkinson bars, examination of the existing capability at UCSD, and the basic requirement that our equipment must reflect state-of-the-art techniques for high-strain-rate testing which may demand innovative aspects, it was decided that it would be far more cost-effective and scientifically of greater potential to design and construct all necessary equipment -- as much as possible -- at UCSD. This would provide an opportunity for our students to receive hands-on experience, as also suggested by the ARO review panel. Upon this decision, and within six months, a compression Hopkinson bar and a small gas gun were operating in our laboratories. In addition, designs for a large gas gun and a compression, a tension, and a torsion Hopkinson bar, were in progress. At this writing and under this equipment award, the Center has the equipment listed in the following section.

One deviation from the original list of equipment, submitted under this equipment grant, had to be made. Since it was expected that the design and fabrication of the large gas gun would require considerable time so that the large gas gun would not be operational immediately, and since the small gas gun was operational at the early stages of our research, providing a powerful tool for ultrahigh-strain-rate testing, it was decided that instead of purchasing a VISAR, interferometry facilities should be developed for both displacement and velocity interferometry, applicable to both normal and oblique plate-impact experiments.

2.0 INSTRUMENTS ACQUIRED OR FABRICATED UNDER THIS AWARD

2.1. Hopkinson Bars with Dedicated Data Acquisition System

2.1.1 Compression Bar *



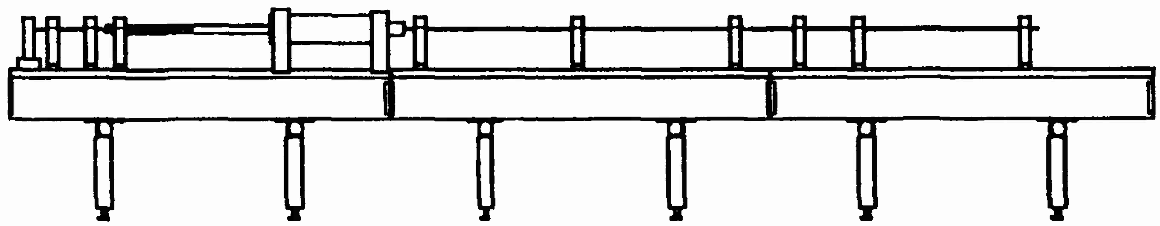
- Strain Rates up to 10,000/s
- Bar diameters: 3/8 to 1-1/2 inches
- Bar length, input and output, each: 48 inches
- Striker bars: 2 to 18 inches
- Tapered striker bars for pulse shaping
- Bar material: C350 maraging steel 350 ksi yield
- Ramp pulse modification
- Stress reversal capability:
  Compression followed by tension, and
  Tension followed by compression (with pulse trapping)
- Momentum trapping modification for single compression, or tension, or combined pulse

- *Data Acquisition System includes:*
  strain gage bridges, magnetic velocity system, Lambia low noise power supplies, separate channels for direct measurement of sample strains, 10 Mega sample 40995 Nicolet Digital Oscilloscope, and Datel Systems Turbo Deluxe Microcomputer.

*[refer to page 4 of the enclosed brochure for photograph]

2.1.2 Tension *

- Button end input bar, gas-gun-fired annular striker design
- 3/4-inch bar diameter
- Maraging steel and 17-7 stainless steel bar sets
- Momentum trapping modification for single tensile pulse
- Recovery of unfailed specimens loaded by a single pulse

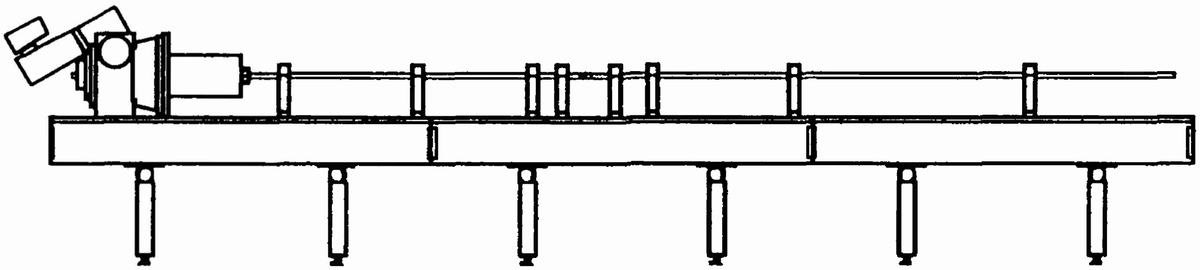


* [refer to page 5 of the enclosed brochure for photograph]

2.1.3 Compression-Tension

- Installed on either compression or tension bar platforms
- Single compression pulse followed by single tension pulse
- Recovery of specimens after a single load cycle
- Recovery of specimens after a single compression pulse

2.1.4 Torsion



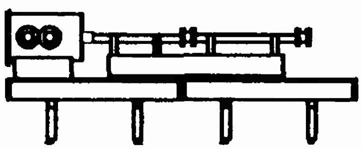
- Self-locking worm gear drive
- Precise, simple, pretorque and release mechanism
- Symmetric reaction torque
- Bending-free torsional waves
- Adaptable for multiaxial loading
- 1-inch diameter bar
- Variable pulse length

[refer to page 6 of enclosed brochure for photograph]

2.2. Gas Guns

Gas guns are precision instruments for flyer plate and other impact experiments. The flyer plate experiments produce extremely high rates in exceptionally clean states of homogeneous strain. The gas guns include a small, moderate-velocity instrument of 60-mm bore, and a large, high-velocity instrument of 56-mm bore.

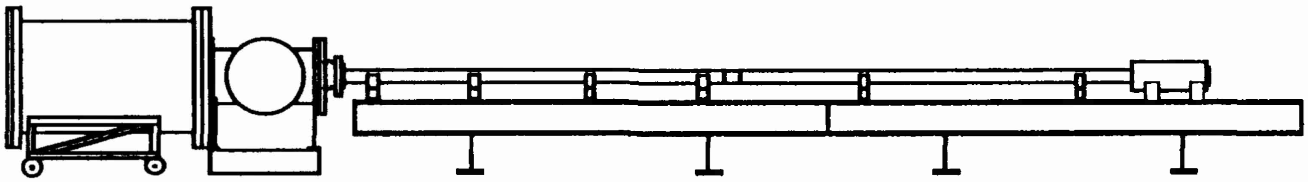
2.2.1 60-mm Gas Gun



- Up to 200 m/s impact velocities
- Micro-grooved barrel
- Normal impact and pressure-shear experiments
- Momentum trapped recovery experiments
- Normal and transverse displacement and velocity measurements by interferometry

[refer to page 8 of the enclosed brochure for photograph]

2.2.2 56-mm Gas Gun



- Over 1,000 m/s impact velocities
- Plate impact experiments
- Sphere and rod impact geometries
- Soft recovery system
- Complete interferometric measurement systems
- Flash X-ray radiographic capability

[refer to page 9 of enclosed brochure for photograph]

2.3 Flash X-Ray System

Function: This system provides visualization of internal structure of materials.

Major Equipment: 150 kV Hewlett-Packard Flash X-Ray

2.4 Interferometry Facilities

Function: In conjunction with the 60mm light gas gun, this facility measures both normal and and transverse displacements and normal velocity during plate impact experiments.

Major Equipment:

LeCroy 6880 1.3 GigaHertz Digitizer System
Oriel 10732 Optical Equipment
Spectra-Physics 2020-05 Argon-Ion Laser
Broomer 4700 Theodolite (micro) Alignment Telescope
Optical Components: compensated attenuator, beamsplitter, mirrors, lenses and mounts

[refer to page 8 of the enclosed brochure for photograph]

3.0 SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT

For the design and construction of instruments, namely Hopkinson bars, gas gun, and related facilities, which have all been designed and fabricated at UCSD, the following technical individuals have received partial support under this grant:

Principal Investigator: S. Nemat-Nasser (UCSD support only)

Research Engineers

Dr. John E. Starrett, Principal Development Engineer

Mr. Jon Isaacs, Development Technician III

Mr. Douglas Moore, Development Technician II

Engineering Aids (Undergraduate Students)

Mr. Brett Ellman, Engineering Aid I

Ms. Tammy Bui, Engineering Aid I

Mr. Jim Ledesma, Engineering Aid I

Mr. Chuck Wong, Engineering Aid I

ARO 24618.1-MS-UIE

A Part of the Final Report

The Experimental Facilities

of

The Center of Excellence for Advanced Materials

University of California, San Diego

La Jolla, California

The Experimental Facilities

of

The Center of Excellence for Advanced Materials

October 1990

Center of Excellence for Advanced Materials
4208 Engineering Building Unit I, 0411
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0411

619-534-5930
Fax: 619-534-7078

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I. Introduction

The Center of Excellence For Advanced Materials (CEAM) has grown from the Center for Dynamic Performance of Materials which was established at the University of California, San Diego (UCSD) by the U.S. Army Research Office in October 1986, and currently constitutes the major part of CEAM. The Center focuses on three interrelated scientific areas:

- **Materials**

  Includes microstructural characterization of undamaged and damaged materials, examination of the effects of metallurgical variables on the mechanical response, macromechanical characterization through quasi-static experiments in controlled environments, and materials development, including rapid solidification, chemical synthesis, and self-propagating high-temperature synthesis.

- **Modeling and Computation**

  Includes micromechanical modeling of nonlinear response and failure modes, constitutive characterization of the materials over a broad range of strain rates, including high and ultrahigh rates, the associated computer algorithms to be used in large-scale computer programs, and numerical prediction of material behavior over a broad range of strain rates.

- **Dynamic Tests**

  Includes quasi-static, and high- and ultrahigh-strain rate experiments on specific advanced materials with controlled microstructures using multi-axial testing machines, Hopkinson bar, flyer plate, and high-energy laser impact facilities. This has resulted in new developments of dynamic recovery testing techniques and in the time-resolved diagnostics of high-strain rate experiments through high-speed flash photography, X-ray photography, and innovative holography.

The remainder of this booklet summarizes the experimental facilities currently available at CEAM with special emphasis on the dynamic testing facilities.

II. Dynamic Testing Facilities

Dynamic testing facilities include Hopkinson bars, gas guns, electromagnetic loading facilities, and a unique laser impulse facility. These instruments have been designed and chosen to provide the range of experimental capability required to support the scientific focus of the Center. They include unique innovative features for **recovery** experiments.

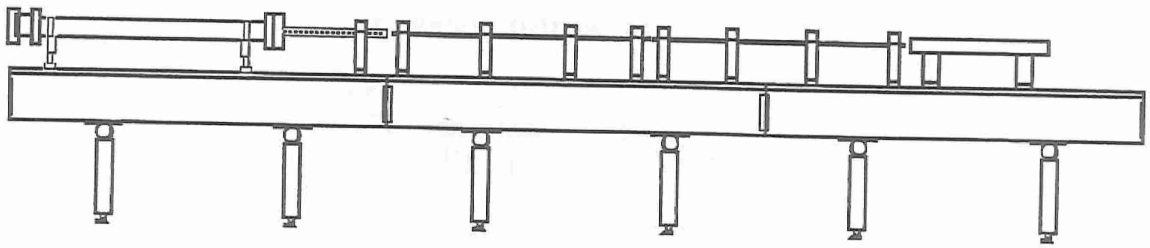
Hopkinson Bars

The split Hopkinson bar apparatus is used to conduct tests to obtain stress-strain data at high rates for materials in simple states of homogeneous stress. The flexible, modular designed bars include:

- Compression
- Tension
- Compression/Tension
- Tension/Compression
- Torsion

UCSD's Hopkinson bar techniques include several novel features for **recovery** experiments and dynamic Bauschinger studies.

Compression Bar



- Strain Rates up to 10,000/s
- Bar diameters: 3/8 to 1-1/2 inches
- Bar length, input and output, each: 48 inches
- Striker bars: 2 to 18 inches
- Tapered striker bars for pulse shaping
- Bar material:

  C350 maraging steel 350 ksi yield
- Ramp pulse modification
- Stress reversal capability:

  Compression followed by tension, and

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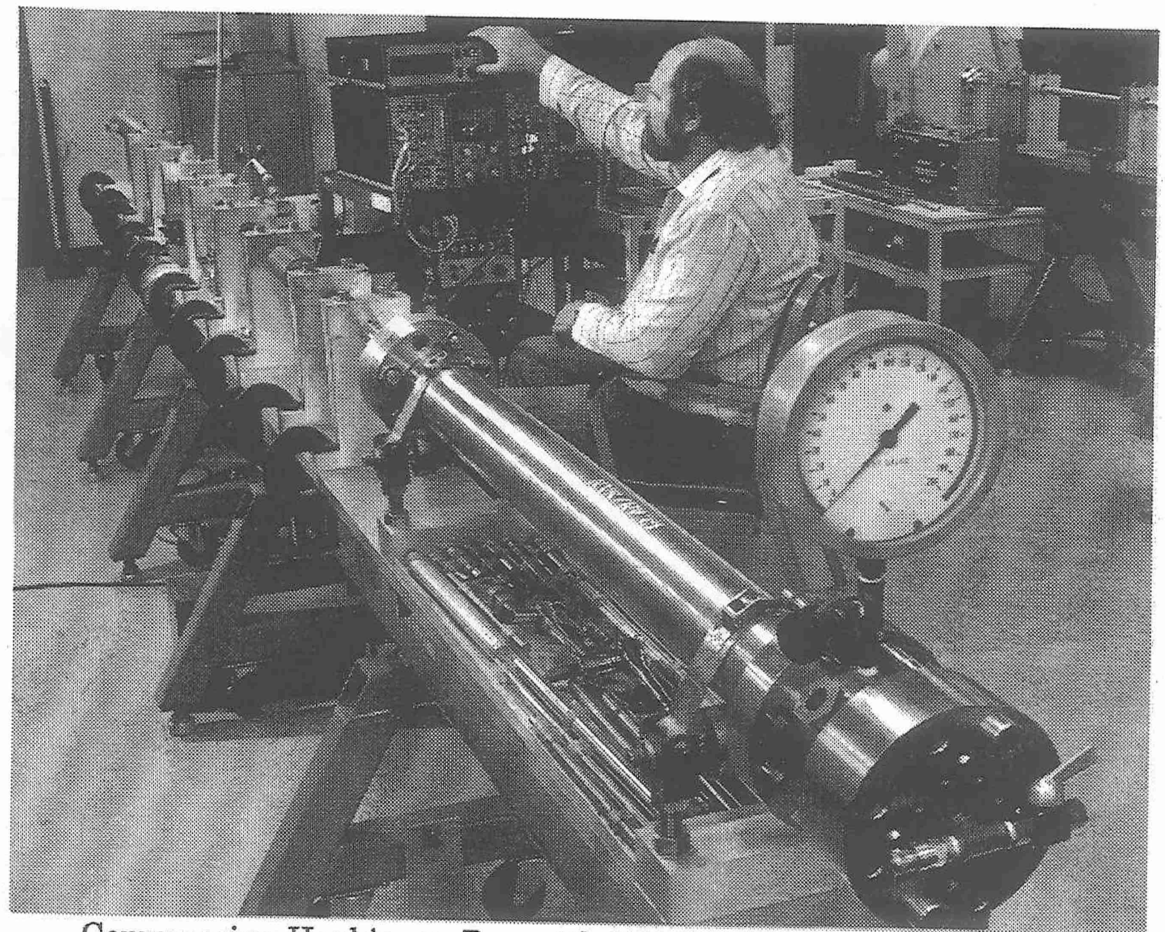


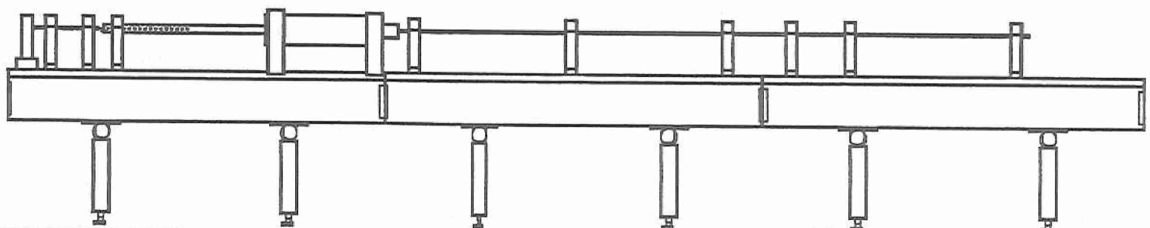
Compression Hopkinson Bar with Engineer Jon Isaacs Generating Stress-Strain Curve on Nicolet 4094B Digitizing Oscilloscope

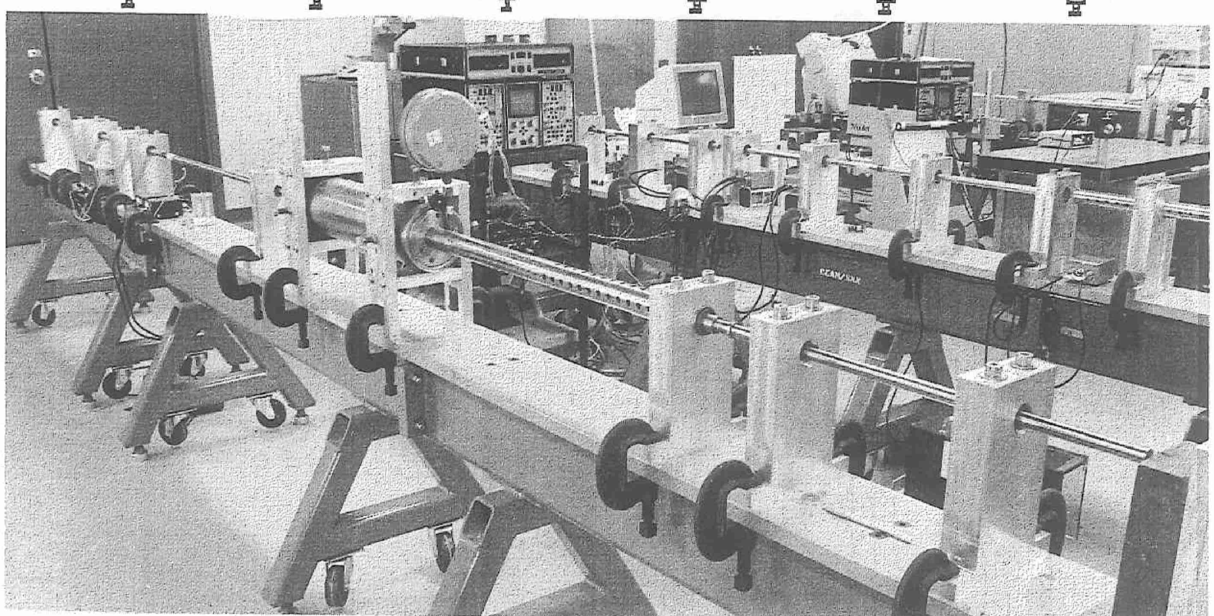
Tension

- Button end input bar, gas-gun-fired annular striker design
- 3/4-inch bar diameter
- Maraging steel and 17-7 stainless steel bar sets
- Momentum trapping modification for single tensile pulse
- Recovery of unfailed specimens loaded by a single pulse

Compression-Tension

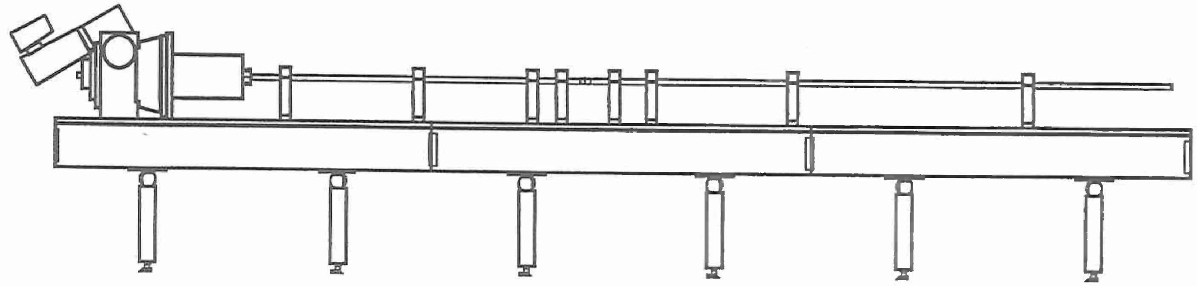
- Installed on either compression or tension bar platforms
- Single compression pulse followed by single tension pulse
- Recovery of specimens after a single load cycle
- Recovery of specimens after a single compression pulse



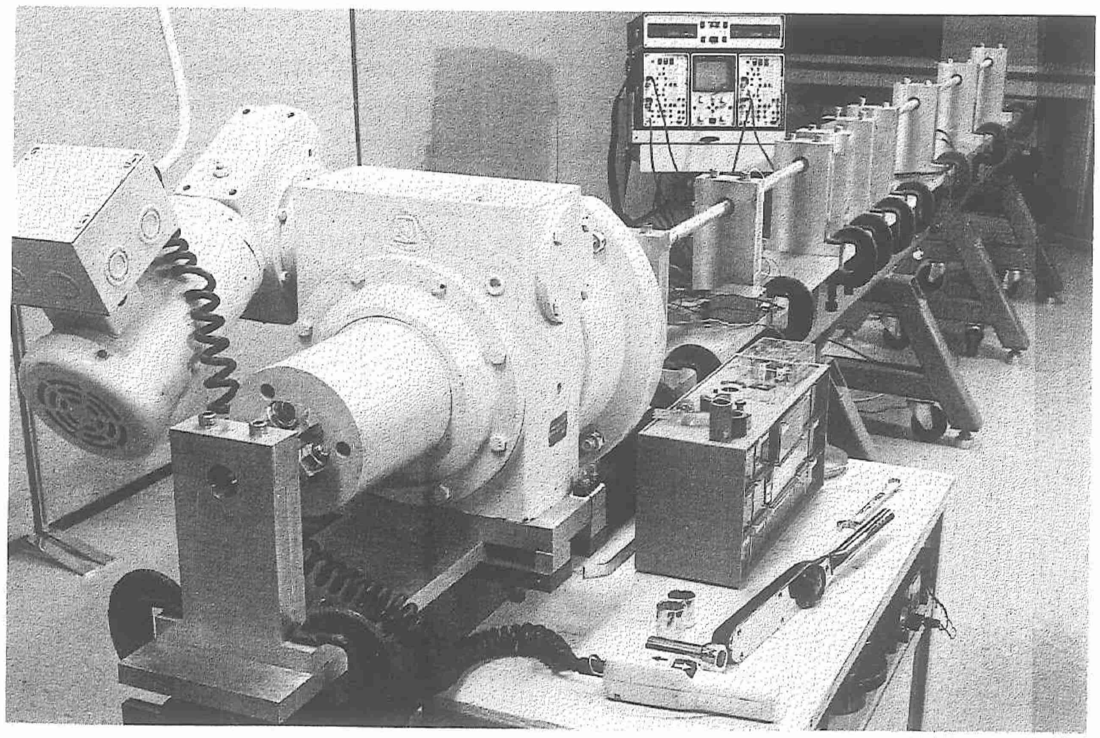


Tension Hopkinson Bar with Momentum Trap for Recovery Tests with a Single Tensile Pulse

Torsion



- Self-locking worm gear drive
- Precise, simple, pretorque and release mechanism
- Symmetric reaction torque
- Bending-free torsional waves
- Adaptable for multiaxial loading
- 1-inch diameter bar
- Variable pulse length



Torsion Hopkinson Bar with Pulse Width Modification

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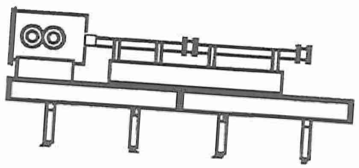
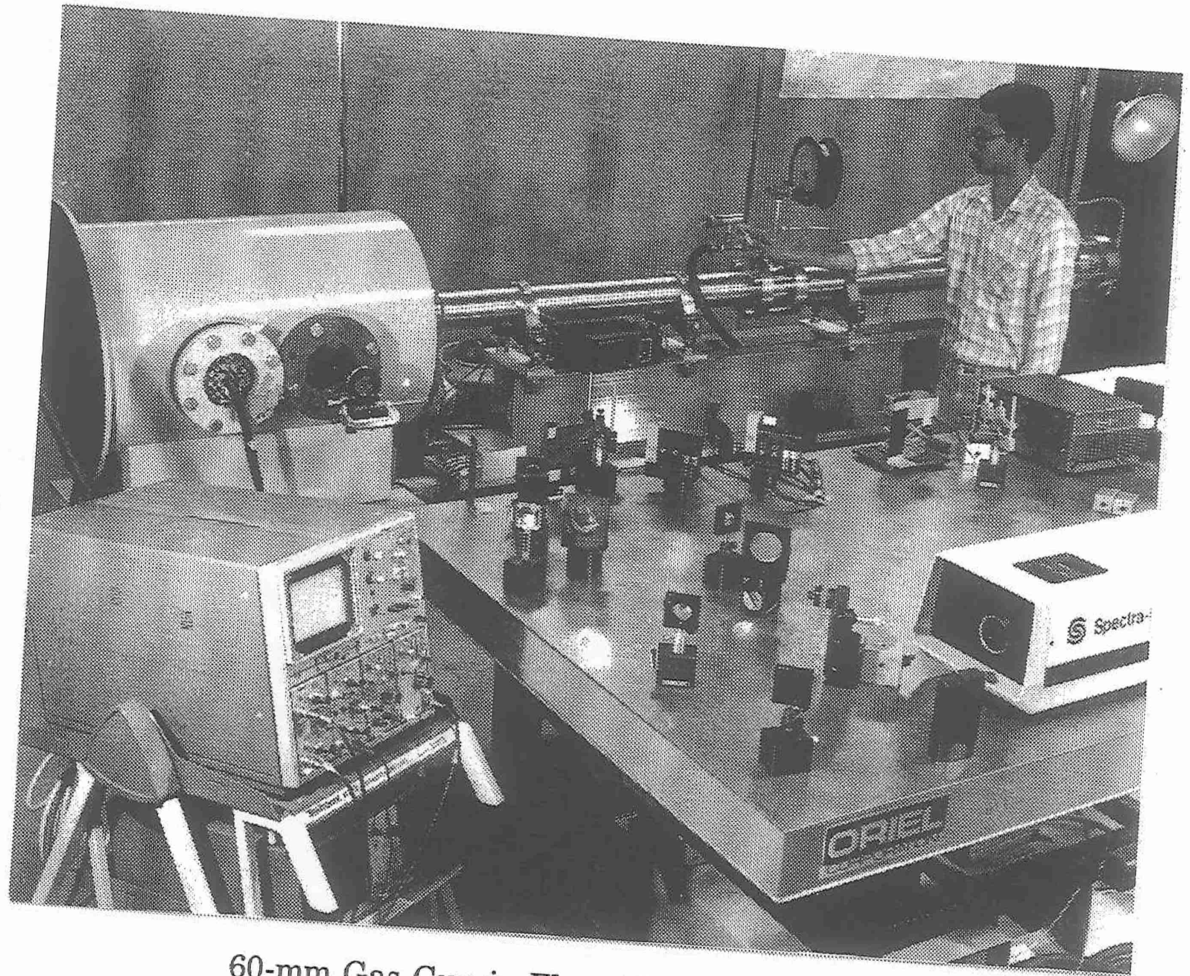
Gas guns are precision instruments for flyer plate and other impact experiments. The flyer plate experiments produce extremely high rates in exceptionally clean states of homogeneous strain. The Center's gas guns include a small, moderate-velocity instrument of 60-mm bore, and a large, high-velocity instrument of 56-mm bore.

60-mm Gas Gun

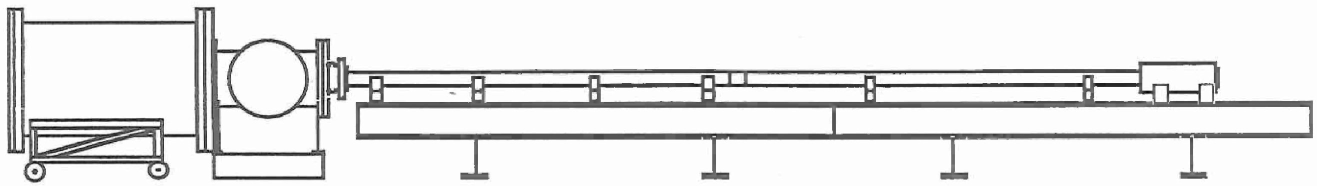


- Up to 200 m/s impact velocities
- Micro-grooved barrel
- Normal impact and pressure-shear experiments
- Momentum trapped recovery experiments
- Normal and transverse displacement and velocity measurements by interferometry



60-mm Gas Gun in Flyer Plate Configuration Operated by Graduate Student A. Machcha. Interferometry setup measures particle displacements and velocity of the back face of momentum trap, using Spectra-Physics 2020 argon ion laser.

56-mm Gas Gun



- Over 1,000 m/s impact velocities
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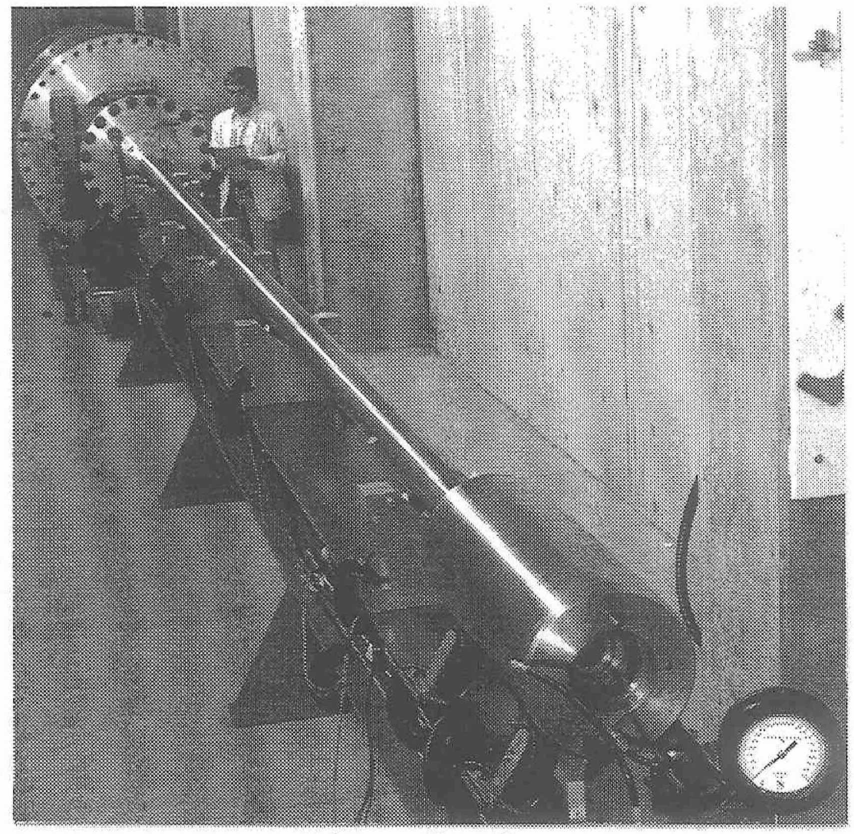
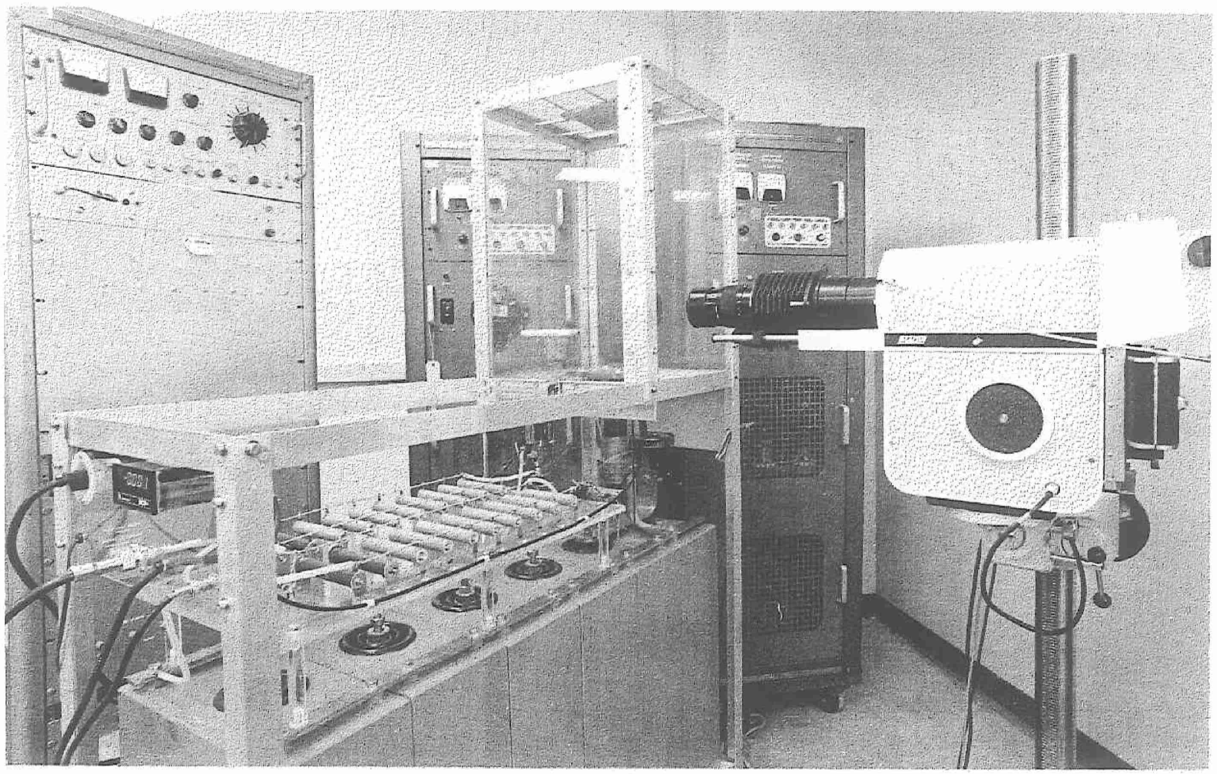


56-mm Gas Gun
Post-Doctorate M. Ahmadshahi checks data network at experimental end of the 56-mm gas gun

Electromagnetic Facility

Electromagnetic techniques provide an alternative to mechanical methods of generating high loads and loading rates. These techniques have the special advantage of precise timing, which allows carefully coordinated loading events to produce analytically tractable states of multi-axial loading. The present apparatus is operated as an electromagnetic flyer plate launcher or, for radial loading, by changing the coil and transmission line geometry.

- 20-gram, 50-mm diameter flyer plates
- Velocities of 150 m/s with less than 1 kJ input
- Fast recycling of apparatus
- Capacitor banks in excess of 20 kJ available
- Ignitron switching in excess of 100 kA available

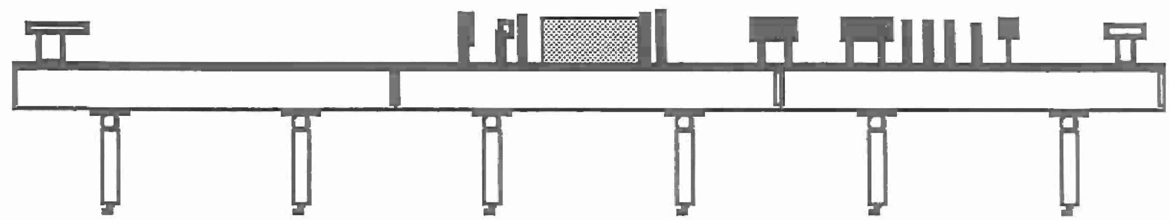


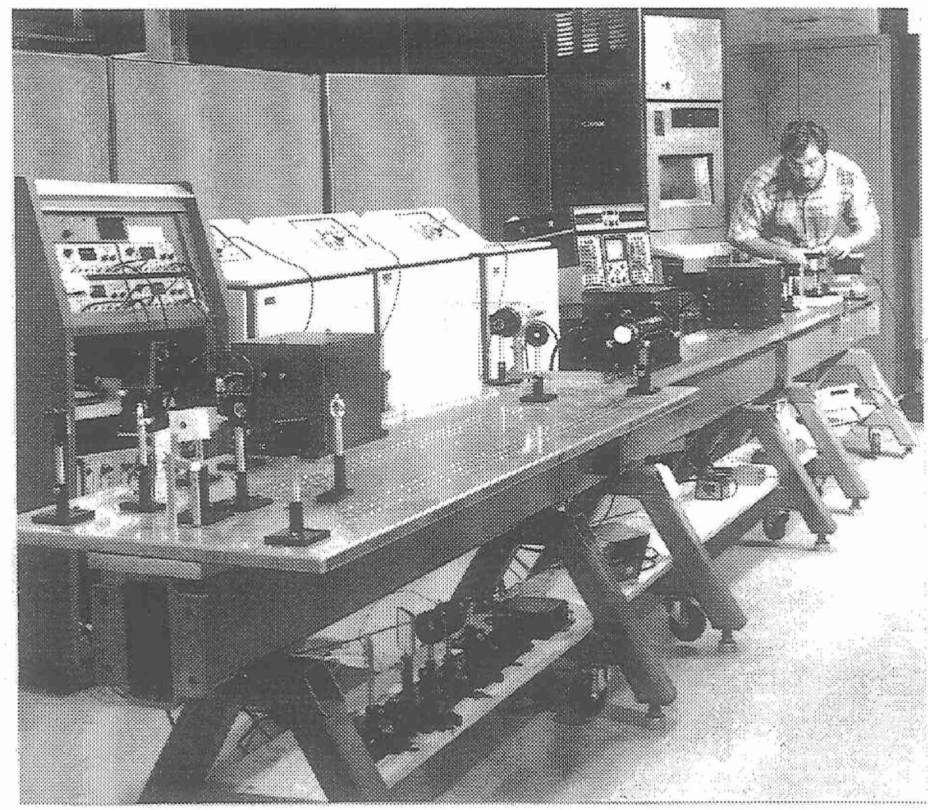
Electromagnetic Flyer Plate Launcher with Hadland Imacon 790 Camera (at right)

Laser Impulse Facility

This unique facility provides a dynamic probe for investigating phenomena such as the evolution of microcracking in brittle materials under high loading rates. Because of the precisely limited mechanical energy, specimens can be taken above failure thresholds and recovered intact for post-test characterization. The extremely short duration of the pulse makes it an ideal instrument for probing other very fast phenomena, such as stress-induced phase transformations.

- 10J Q-switched ruby laser system
- Laser pulses as narrow as 20 ns
- Stress pulse width as narrow as 100 mm (0.004 inch)
- Multi-GPa stress levels
- Short time-scale, plane-wave stress cells





Laser Impulse Facility Includes 3-Stage Ruby Laser System, Pulse Slicer, Stress Cell, and LeCroy 6880 and Nicolet 4094C High-Speed Digitizing Oscilloscopes. Capable of one billion-watt output, the laser impulse system undergoes final alignment by Engineer D. Lischer.

III. Diagnostic Facilities

Image and data acquisition capabilities include cameras up to 20 million frames per second, X-ray flash photography, computer-generated holographic interferometry, and 1.7-GHz digital signal sampling.

High-Speed Photographic Facility

- Hadland Imacon 790

  20-million frame per second image intensifier camera

- Cordin 330A

  2-million frames per second, continuous access, 35-mm film high-speed camera

- Ellis Camera

  Million frame per second 35-mm film high-speed camera

- Ruby Laser System

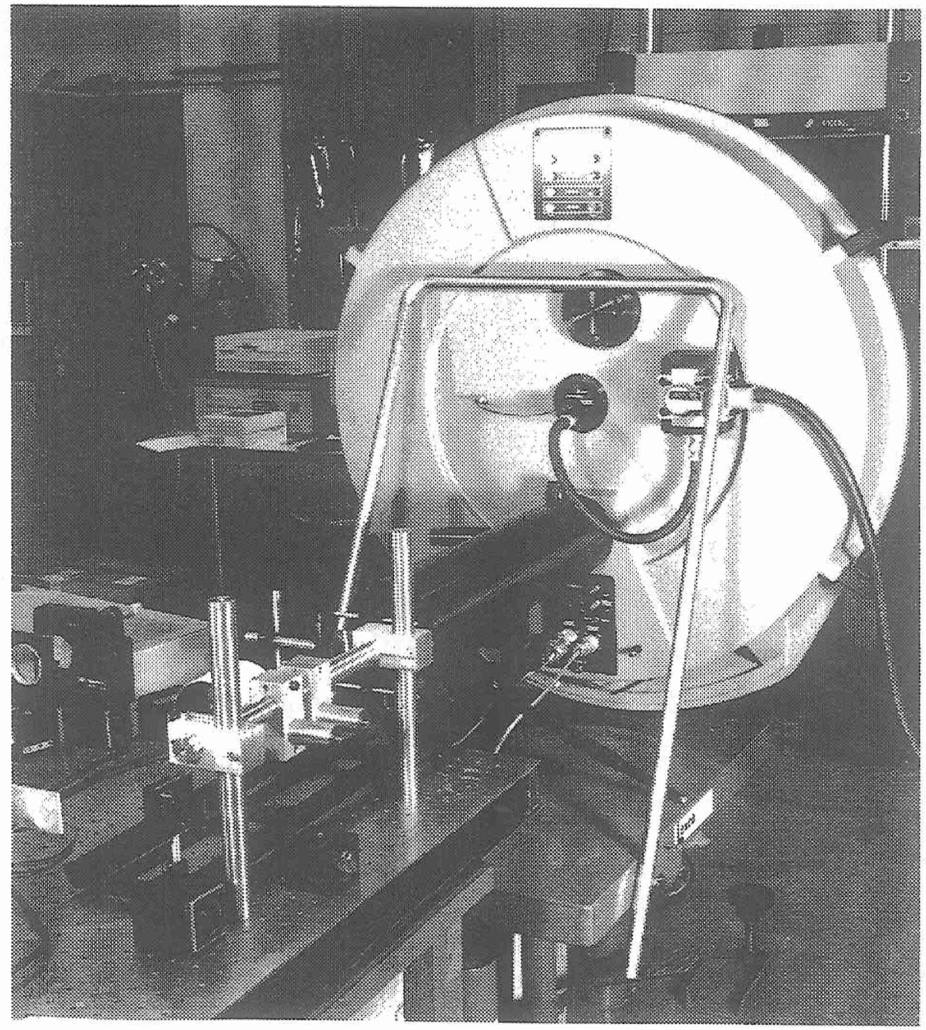
  Application specific pulsed laser light source

- Megawatt Flashlamp System

  Variable pulse duration, 4-megawatt xenon flashlamps

- Beckman and Whitley Drum Camera

  10,000-frame per second, rotating drum, 35-mm high-speed camera



Cordin 330A High-Speed Camera Configured for Holographic Interferometry

Holographic and Optical Measurement Facility

Four independent optical benches provide workstations for the two pulsed ruby laser systems and the two CW argon ion laser systems. These include:

Spectra-Physics 2020 Argon Ion Laser

Coherent Innova 70 Argon Ion Laser

1-Gigawatt Ruby Laser System

Application Specific Modulated Ruby Laser System

Real-Time Computed Speckle Holography

High Resolution Pulsed Laser Holography

Holographic Interferometery

Optical Interferometry Facility

Capabilities include normal and transverse displacement techniques and ultra-fast velocity measurements.

Displacement Interferometry

Velocity Interferometry

VISARS

Shearing Interferometry

Flash Radiography Facility

Two separate systems provide velocity measurements of gas guns and visualization of internal structure of materials.

150 kV Hewlett-Packard Flash X-Ray

450 kV Hewlett-Packard Flash X-Ray

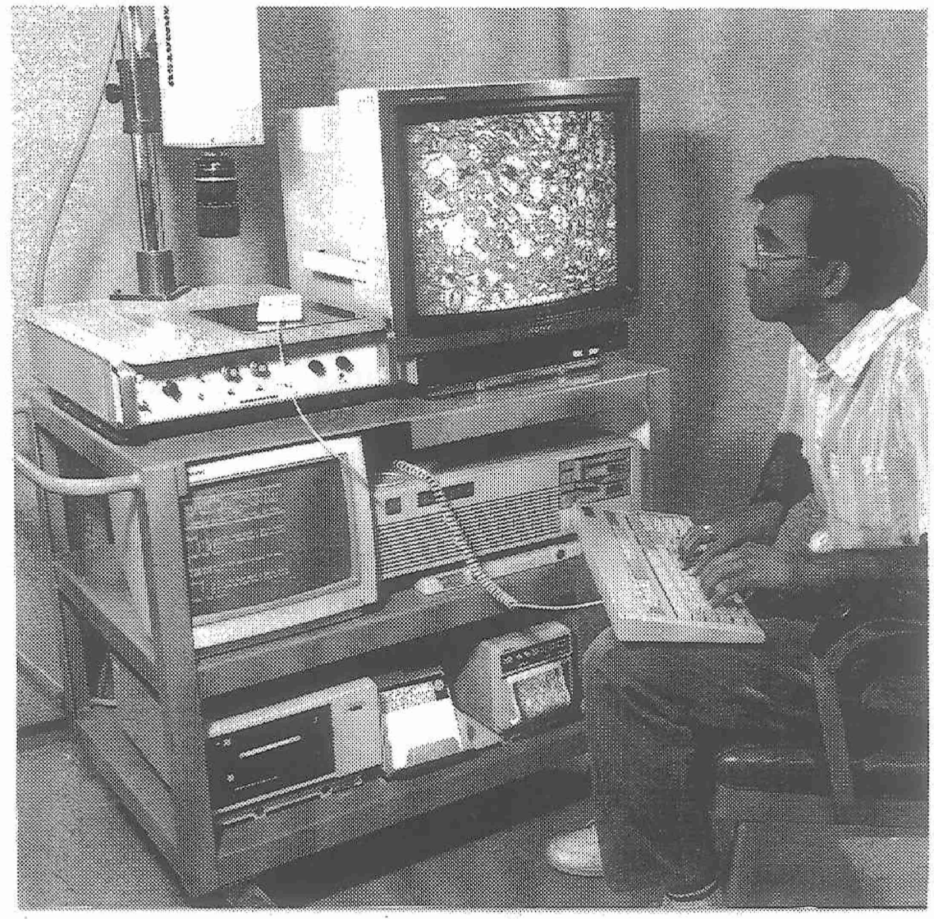
Image Processing Facility

- Imaging Technology Series 151 Image Processor

  Computer-generated holographic interferometry for measurement of very small displacements

- Werner Frei Image Lab

  Computer analysis of material microstructure before and after recovery experiments or *in situ* measurement and observation



Graduate Student G. Subhash analyzes granular flow data for photoelastic granules on the portable image lab

Digital Data Acquisition Facility

Ten independent mobile workstations provide for acquisition, storage, and computer analysis of data.

- LeCroy 6880

  Two 11-bit/8-bit, 3-channel, 1.3-GHz digitizing oscilloscopes

- Nicolet 4094C

  One 8-bit, 4-channel, 200-MHz digitizing oscilloscope

- Nicolet 4094B

  Three 12-bit, 4-channel, 10-MHz digitizing oscilloscopes

- Nicolet 310

  Two 12-bit, 2-channel, 1-MHz digitizing oscilloscopes

- Sony/Textronix RTD 710

  Two 10-bit, 2-channel, 200-MHZ digitizing oscilloscopes

IV. Quasi-Static Testing Facilities

Computer controlled hydraulics and multi-axial load frames provide state-of-the-art testing of materials under quasi-static loading. The large triaxial cell facility, fully computer controlled for the study of granular materials, is the only one of its kind.

- Axial-Torsional Testing

  110 kip Frame
  20 kip Frame
  Large Triaxial Cell

- Biaxial Testing

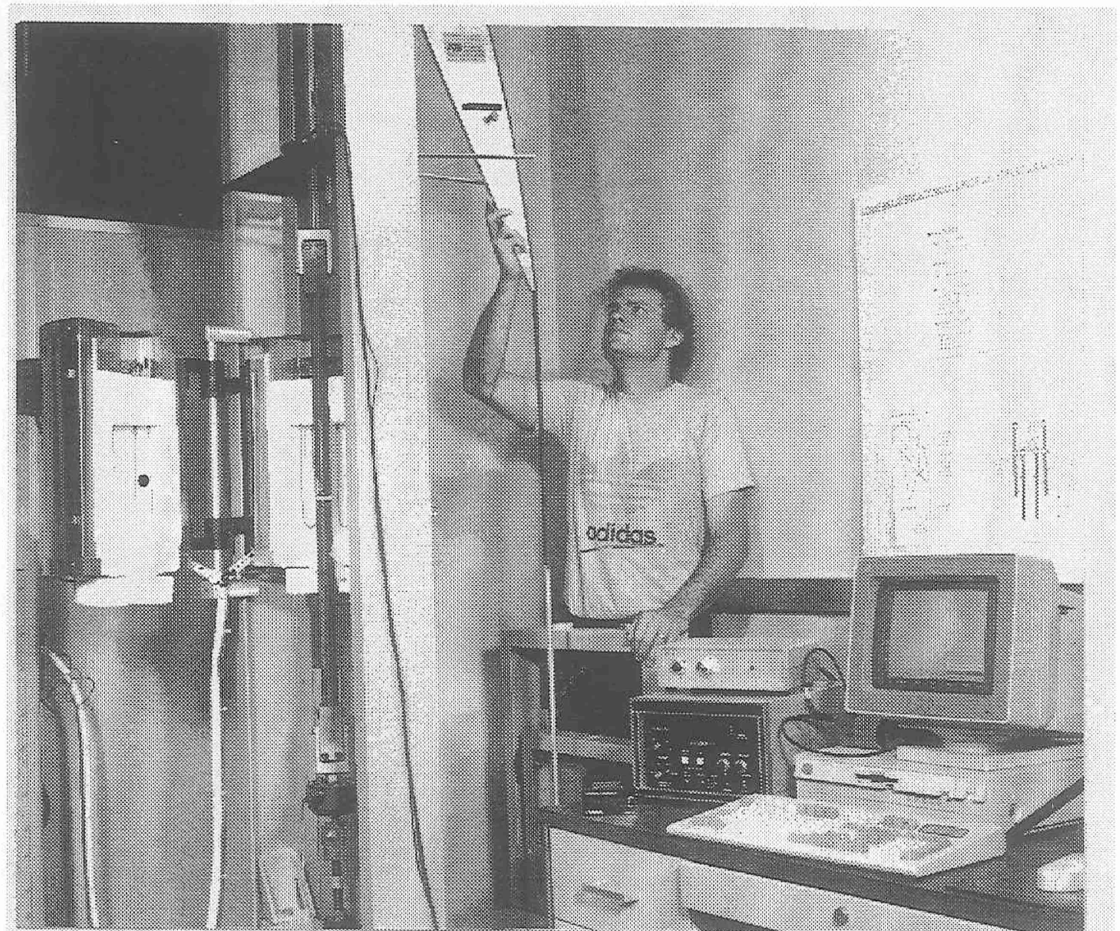
  Biaxial Frame
  Three 20 kip Frames

- High Temperature Testing

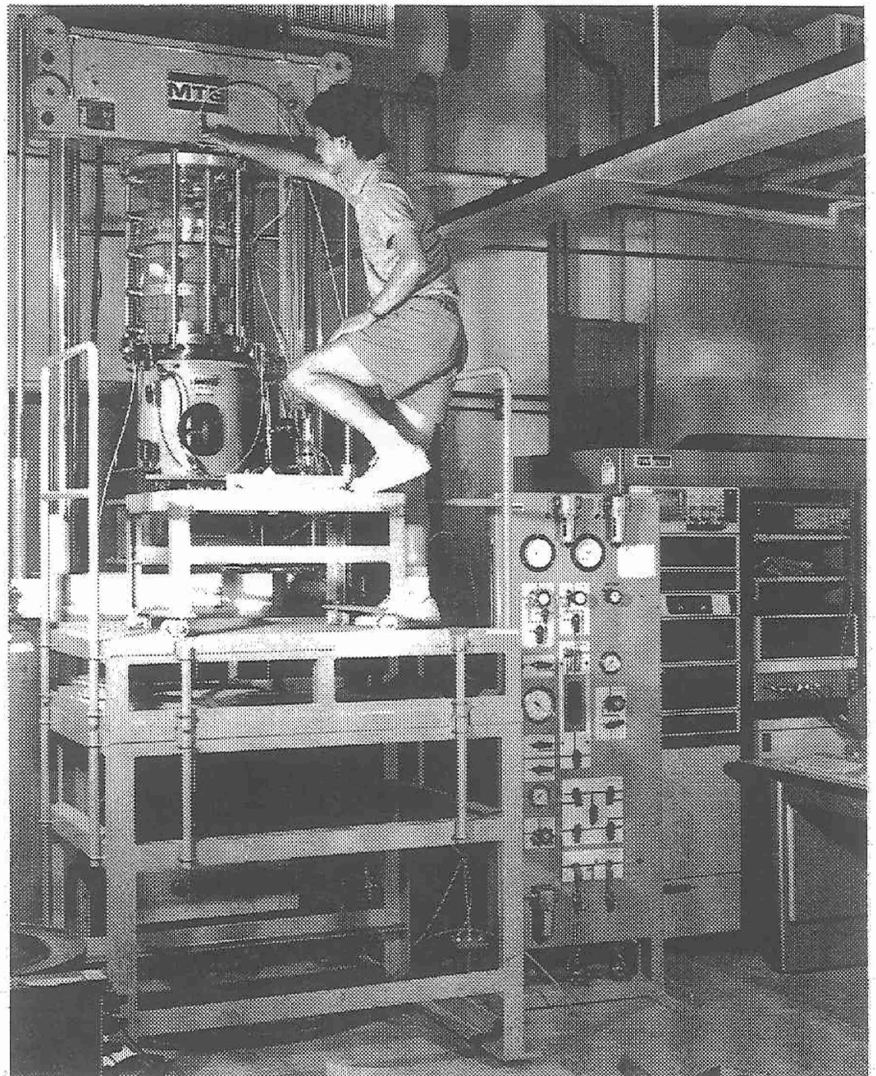
  Testing Furnaces
  Creep Machine

- Small Load Frames

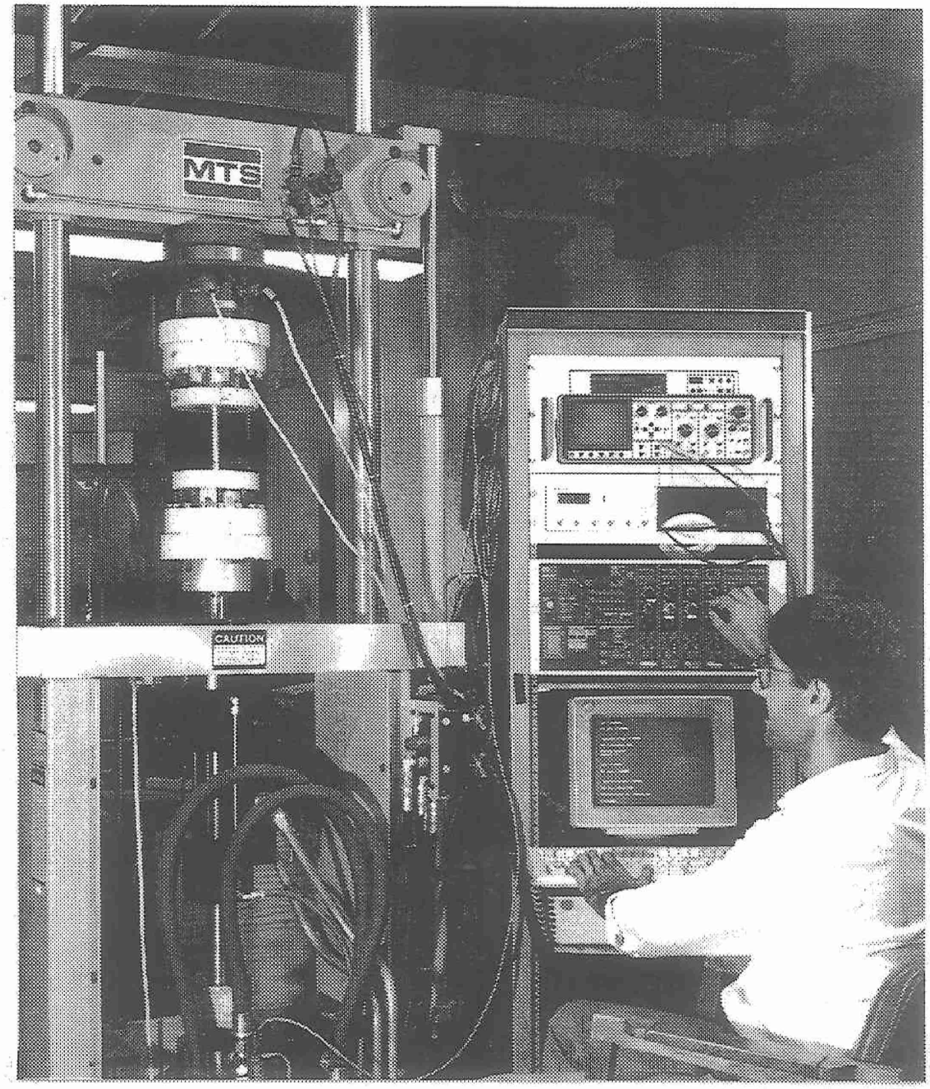
  Instron Screw Machines
  Fatigue Machine



In preparation for studying low-strain rates in materials at elevated temperatures, Graduate Student D. Owen checks the constant stress cam before starting a ceramic test in the Creep Facility



Studying properties of granular materials, Graduate Student N. Okada makes final preparations to the triaxial cell



Graduate Student A. Azhdari is calibrating the computer-controlled load cell on a 20-kip load frame with axial/torsional and biaxial capabilities

V. Materials Synthesis and Processing Facilities

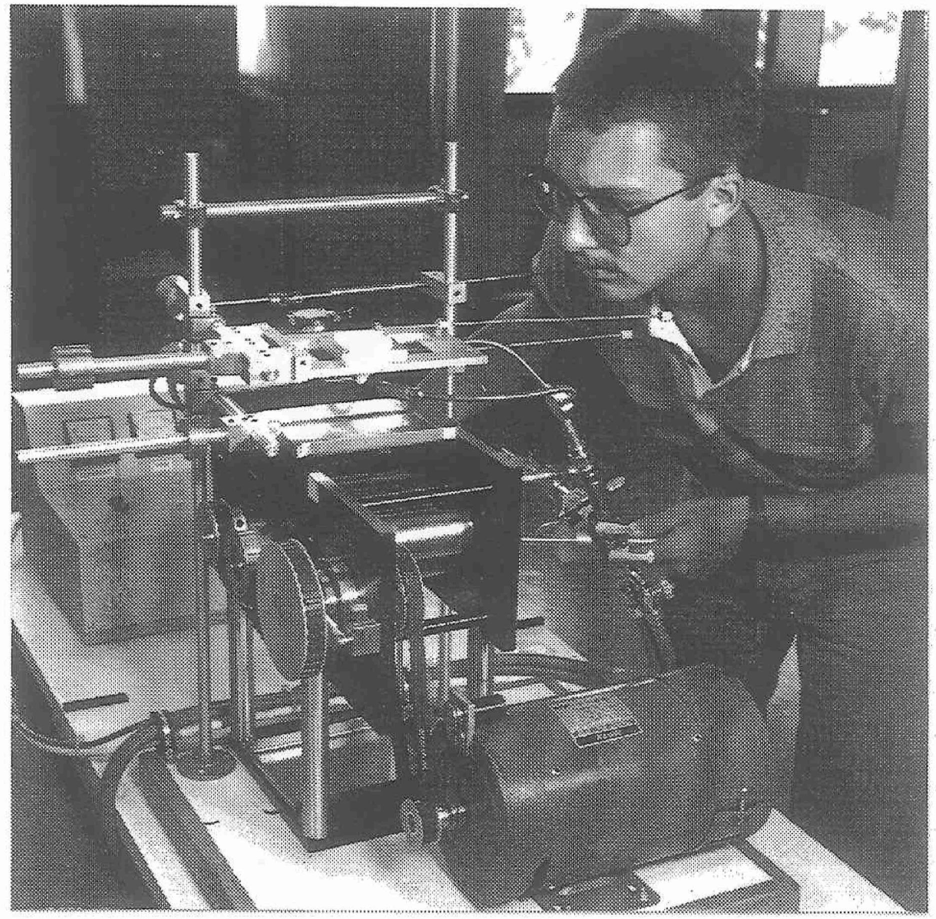
The CEAM facilities include equipment and machines for:

- rapid solidification
- chemical synthesis of oxide ceramics
- self-propagating high-temperature synthesis of non-oxides
- shock compaction
- high-impact forging

Rapid Solidification

Rods of metals or ceramics are melted through induction heating or gas torches. The molten material is ejected through dual rollers rotating at surface speeds exceeding 16 m/sec. The capabilities of this facility are:

- quench rates greater than 10^6 K/sec
- use of metals, ceramics, and particulate composite materials
- generation of metallic glass, oxide glass, and metastable crystalline phases
- generation of nanocrystalline materials



Undergraduate Student S. Emmenegger aligns a ceramic sample over the hydrogen torch before creating a novel material by rapid solidification

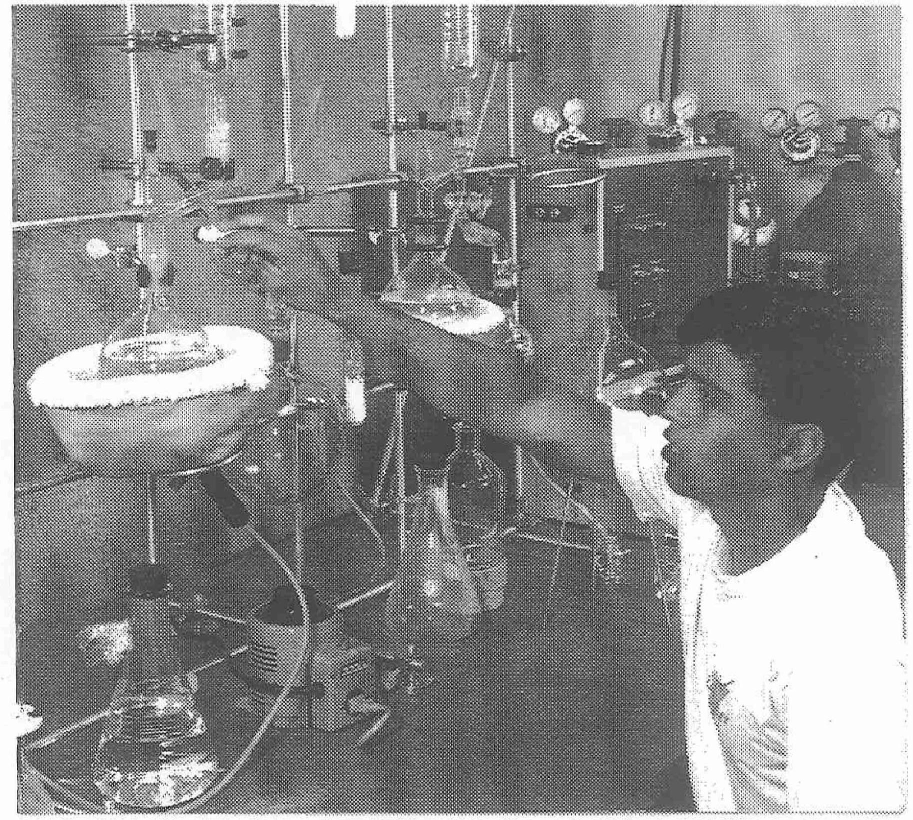
Chemical Synthesis of Oxide Ceramics

1. Alkoxide synthesis of amorphous powders

- Dissolve ultrahigh purity metal in alcohol
- Hydrolyze solution to precipitate hydroxide powders
- Results in:
    - ultrahigh purity powders
    - extremely fine particle sizes
    - reduced sintering temperature
    - co-precipitation of two metal hydroxides to form a two-phase or composite material

2. Synthesis of films of $YBa_2Cu_3O_{7-x}$

- Align thick (>10μm) films for optimal super-conducting properties by spin coating organic solutions
- Homogeneous, atomically mixed precursor gel
- Easily controlled
- Films can be spun on to complex shapes

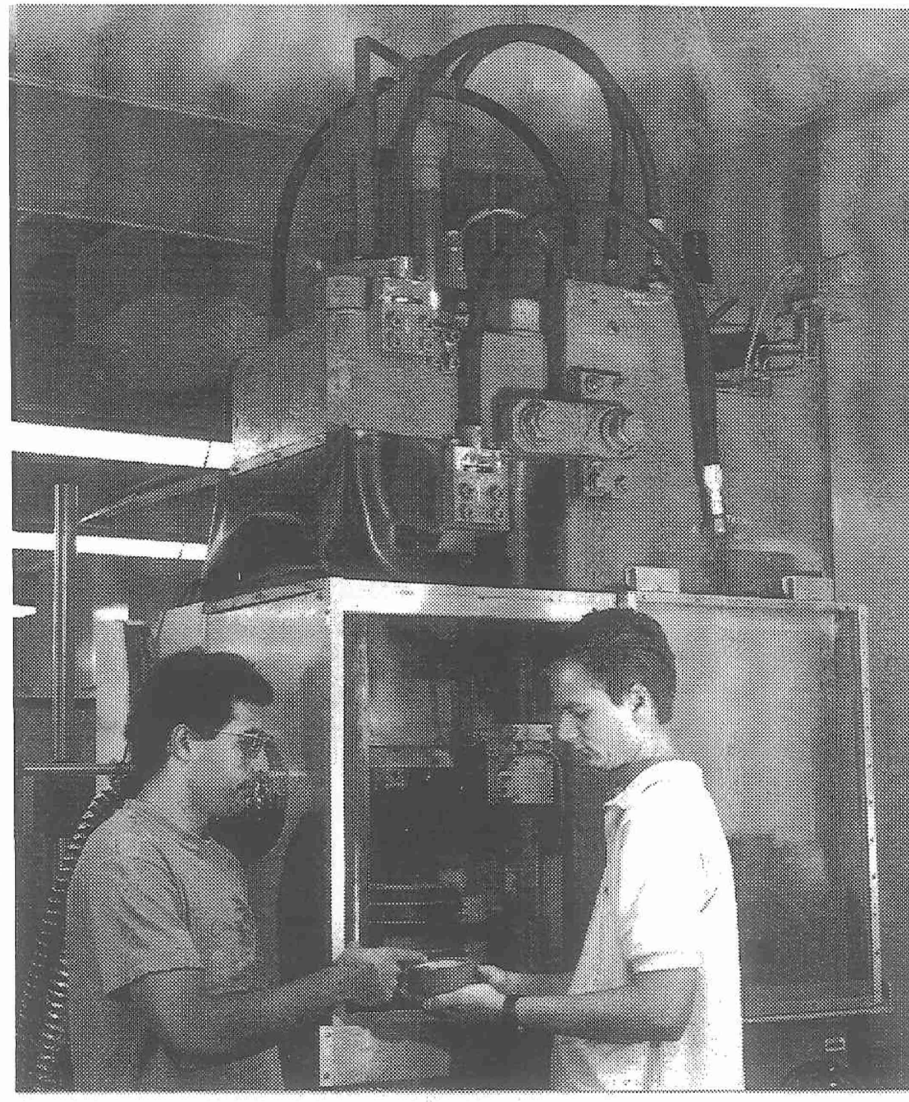


By adjusting flow rate, Undergraduate Student R. Contreras controls the process for synthesizing fine ceramic powders

Dynapak Facility

The Dynapak is a high-energy rate machine for processing materials. The hammer derives the kinetic energy from compressed nitrogen gas (3,000 psi maximum pressure) and is propelled at velocities ranging between 10 and 20 m/s. The machine has the capacity of 20 strokes per minute. The maximum energy rating of the machine is 17 kJ. The ancillary equipment includes an environmental chamber, and heating and cooling furnaces. The machine has the following processing applications:

- dynamic forging
- dynamic compaction of porous ceramics
- dynamic extrusion of solids and powders

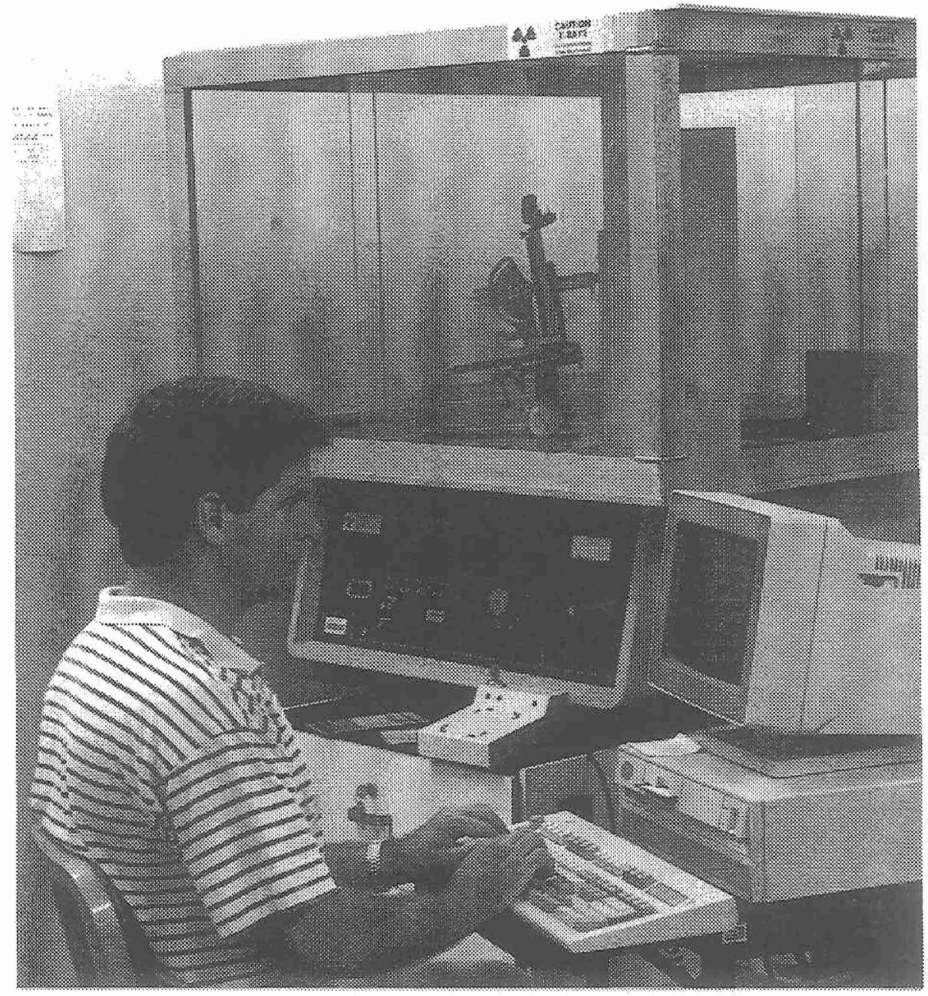


High-Velocity Forging System
A new ceramic material formed by dynamic compaction in the Dynapak Facility is being studied by Graduate Students J. LaSalvia and D. Hoke

VI. Material Characterization Facilities

Analysis of materials is performed before and after subjection to a known loading history. Characterization studies are dependent on reproducible sample preparation and analyzing equipment quality.

- Philips Analytical X-Ray System
    - Computer-Controlled Diffractometer
    - Laue Camera
- Ultrasonic Sound Velocity Measurement Facility
    - MATEC MBS 8000 Measurement System
    - Marconi 10-kHz to 1-GHz Signal Generator
    - Fully Computer-Based with Digital Sampling
- Nikon Metallographic Microscope
- Olympus Binocular Microscope
- Leco Microhardness Tester
- Quantasorb BET Surface Analyzer
- Perkin Elmer Differential Thermal Analyzer
- Sample Preparation Equipment



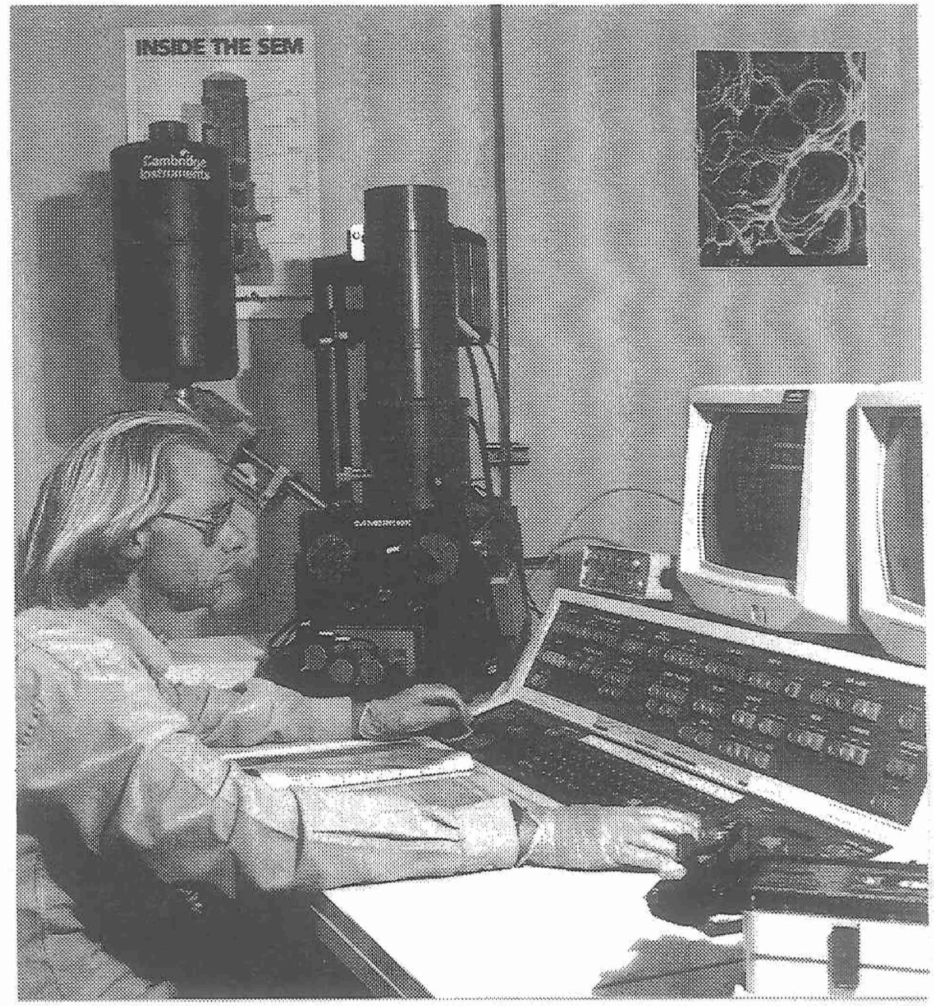
Post-Doctorate M. Rashid programs the computer-controlled x-ray diffractometer. (Laue camera shown mounted behind leaded windows by x-ray system.)

Division of Engineering Electron Optics and Microanalysis Facility

- Cambridge Stereoscan 360 Scanning Electron Microscope with an integrated Link AN10000 X-Ray Analysis System
  - Fully computer-controllable
  - Point-to-point resolution of 2.5 nm
  - Quantitative, semi-quantitative, or fully-quantitative compositional analysis on 1-micron scale range
  - Secondary and backscattered electron detectors
  - Accelerating voltages between 200 to 40,000 volts

- Philips CM30 300kV Transmission Electron Microscope with a Link AN10000 X-Ray Analysis System.
  - Fully computer-controllable, high-resolution, intermediate voltage instrument for high-spatial resolution X-ray microanalysis
  - Accelerating voltages between 50 kV and 300 kV
  - Ultimate resolution: 0.18 nm line-to-line
0.23 nm point-to-point
  - High-spatial resolution X-ray microanalysis on elements down to beryllium on periodic table

- Special TEM specimen holders include:
  - low-background single-tilt holder for microanalysis
  - double-tilt low-background holder for diffraction and microanalysis
  - liquid nitrogen low-background double-tilt holder with controllable temperatures from 100°C to -170°C
  - single-tilt furnace holder capable of 1,300°C



Students are trained in system operation to facilitate the time-consuming search for material attributes. Shown here, Graduate Student/Fellow B. Altman follows the start-up procedures of the scanning electron microscope in preparation for specimen viewing.

VII. Specimen/Equipment Fabrication Facilities

- Powder Facilities
  - Glove Boxes
  - Mixers
  - Ball Mills
  - Presses
- Furnaces
  - Tube Furnaces
  - Muffle Furnaces
  - Vacuum Oven
- Materials Science Machine Shop
- Division of Engineering Machine Shop
- Upper Campus Machine Shop
- Glassblowing Shop