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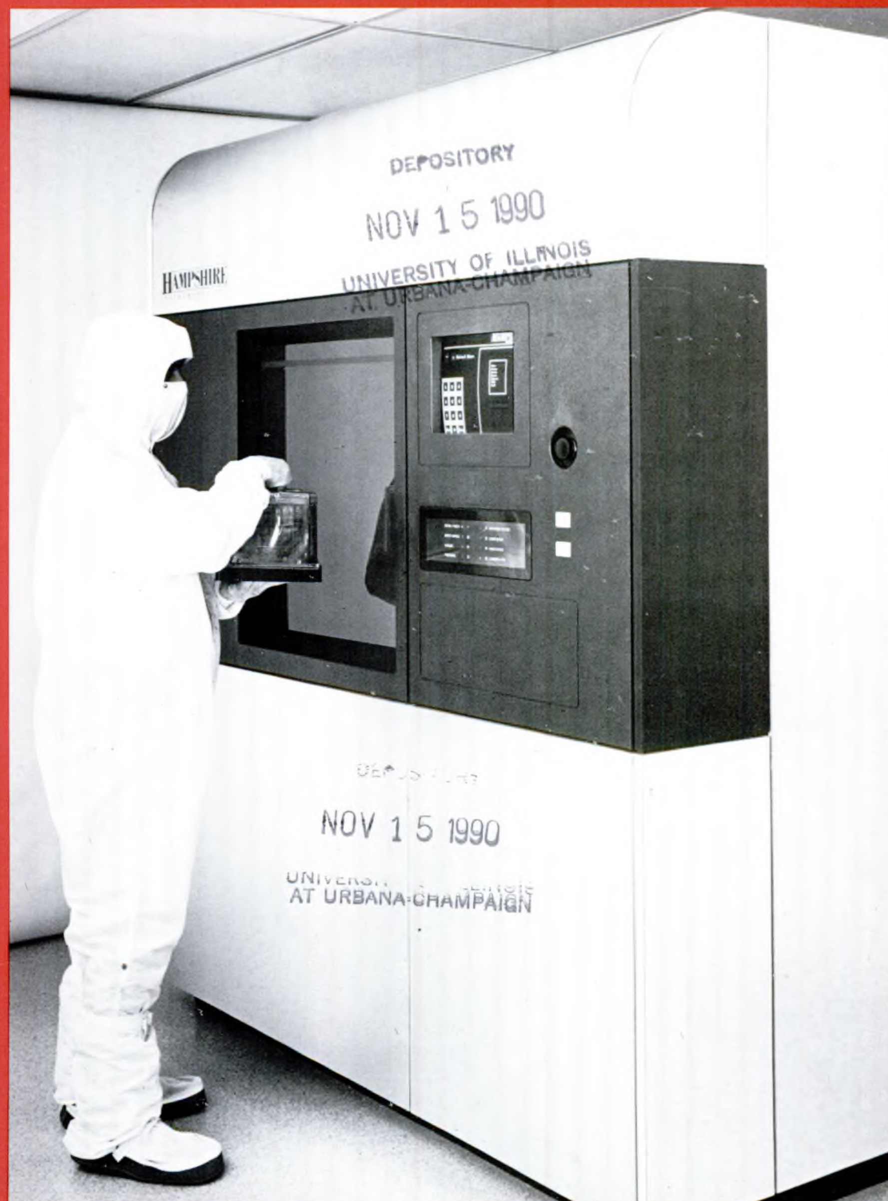

Plasma X-Ray Lithography

Rocket-Propelled Helicopters

Two significant early developments in the helicopter field were sponsored and funded by the Air Branch of the Office of Naval Research beginning in 1949. One was a new system of propulsion using tiny rocket engines on the blade tips of a midget helicopter. The other was a new system for the stability and control of helicopters. Both research projects were separate phases of helicopter development for the Navy.

The first U.S. rocket-powered helicopter, the RH-1, was developed for ONR by Gilbert Magill, president of Rotor-Craft Corporation, Glendale, California. The rocket system for the tiny, one-man, craft uses two thumb-size motors at the tip ends of the helicopter blades. Known as "Pinwheel," the RH-1 was under development for nearly four years, and first flew under tethered tests in 1953.

"Pinwheel," RH-1

"Stable Mable," KH-15

The Kellett KH-15, dubbed "Stable Mable," which was also rocket-powered, flew in 1953 after only eight minutes of tethered test. The KH-15 incorporated gyrostablizing controls designed to give helicopters greater stability in the air than heretofore possible. This project was developed by Kellett Aircraft Corporation at its Camden, New Jersey plant. The small Kellett craft gave the helicopter a high degree of stability and cut vibration considerably.

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Photograph of the lithography system produced by Hampshire Instuments, Inc. in which x-rays from laser-heated plasmas replicate patterns from masks into thin plastic (photoresist) layers. Scanning electron micrographs of exposed and developed photoresists exhibit sharply defined features, with widths less than 1% of the diameter of human hair, which are not degraded by the underlying surface topography. (See article on page 2.)

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Plasma X-ray Emission: Research, Development and Utilization

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Abstract

During the past three decades, x-ray emission from multi-million degree dense plasmas has been widely studied. From a scientific viewpoint, such x-ray emission provides detailed information on the atomic, collective and optical processes in plasmas. From a weapons viewpoint, plasma x-ray sources are of interest as simulators of nuclear weapons x-ray effects. From an energy viewpoint, inertial and magnetic confinement of plasmas is often studied by using their x-ray emission. With such work as a base, it was realized about 15 years ago that hot dense plasmas produced by electrical discharge heating or at laser foci could be useful sources for replication of man-made and natural structures. Applications to production of ultradense integrated circuits and to microscopy of live biologicals are envisioned. It is possible that, during the new decade, plasma x-ray sources will provide the basis for large scale commercial production of chips and for commercial supply of equipment to the medical community for histology. This paper reviews the physical, scientific, technological and potential commercial aspects of ultrabright x-ray sources for replication of micro- and nano-meter scale objects.

Introduction

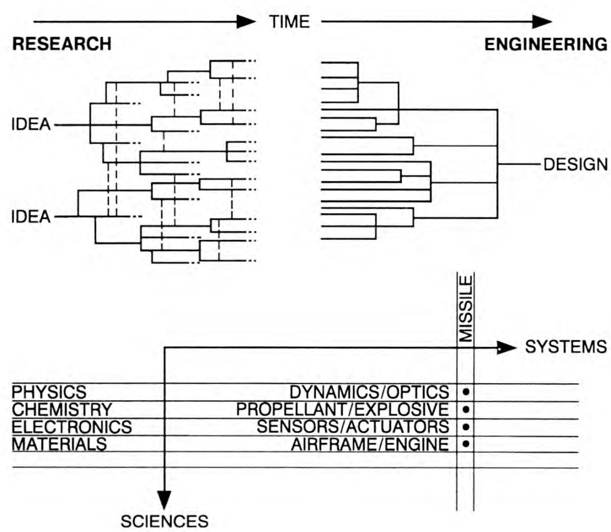
It is well known that the payoffs of research and development are not well known in advance. Pioneering work motivated by curiosity or by programs which agencies will fund often, maybe even usually, has impacts which are not foreseen at the time of the initial discoveries. Research and development in a given area produces an expanding pool of knowledge and capabilities. In contrast, the design of a device or system draws from many areas, down selecting from available options, to produce something which performs a desired function. Figure 1 indicates the temporal expansion of research and development, with its dead ends and diverse connections, and the focusing intrinsic to engineering. The topology of this sketch is indicative of the complexity of transitioning or transferring the results of R and D to either the military acquisition programs or to industry.

The Navy supports and performs research and development for several reasons, prime among them the generation of information useful to the DOD. Another major reason is to be able to exploit ideas and capabilities which originate elsewhere. Project HINDSIGHT showed that the inventions which enable most U. S. military hardware originate outside of the DOD (1). Indeed, they commonly predated the DOD and sometimes occurred abroad. Conversely, many of the advances made in Naval Research are having payoffs in commercial areas.

This paper is the story of how interest in x-rays from multi-million degree plasmas, initially motivated by the desire to understand such states of matter, and by weapons and energy programs, may lead to broadly important commercial capabilities for production of integrated circuits and other nanometer-scale structures, and for clinical study of live tissues with near-molecular resolution. To introduce the topic, some rudiments of plasma x-ray emission are reviewed briefly in the

Figure 1

Schematic representation of the growth and interconnections of ideas generated during research in various disciplines, some of which are listed, and the "down selection" of options during the engineering design of a system such as a missile (after suggestion of W. M. Tolles).



next section. The two following sections focus on early and continuing efforts in weapons and energy programs. Then x-ray lithography and microscopy are reviewed in another two sections. The concluding section contains some related material and summarizes current thrusts in each area. The current and potential importance of plasma soft x-ray emission for defense, energy, information and medical research, development and commerce is noteworthy. X-rays figure prominently in several plasma facilities which cost more than $100M to construct.

Plasma X-Ray Emission

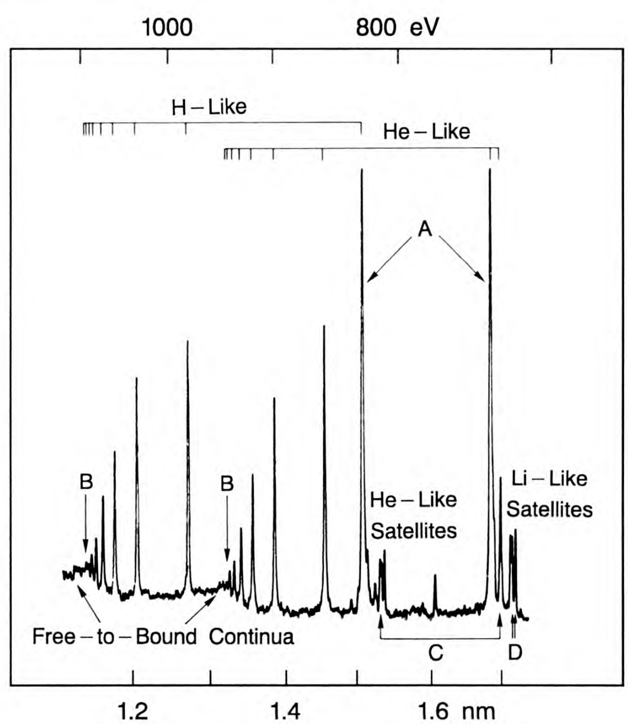
Plasmas consisting of electrons and ions constitute the fourth and highest temperature state of matter (2). They can form at temperatures as low as a few hundred degrees Kelvin, with maximum temperatures exceeding 10^9K. The densities of plasmas range from as low as 10^{-2} electrons per cm^3 to values as high as 10^{24} electrons per cm^3.

The formation of a plasma requires matter and energy. In nature, the matter may be in very tenuous cold interstellar regions with the plasmas maintained by collisional processes, or in extremely dense hot stellar interiors heated by nuclear fusion. Man-made plasmas heated by nuclear processes currently include fission devices (atomic bombs) and fusion devices (hydrogen bombs). Techniques to produce thermonuclear fusion within small (< mm diameter) pellets containing hydrogen isotopes, which are imploded to high densities using beams of laser light or ions, are currently receiving intense study. Great effort is also being expended to achieve efficient fusion, with net energy production, in very large (>m^3) low density plasmas confined by magnetic fields. Such plasmas are heated to multi-million degree temperatures by kinetic processes (electric current or atomic impact) or by absorption of microwave energy. Very hot, dense, small, short-lived plasmas are produced in the laboratory by high-current electrical discharges and by the absorption of submicrosecond laser pulses. Because of rapid cooling by x-ray emission and expansion, laboratory plasma x-ray sources are generally heated by discharge currents or lasers with peak powers exceeding 10^9 watts. Pulsed electrical and laser devices with power in excess of 10^{12}W are available and have been used for x-ray generation.

Like all states of matter, no matter how they are produced, plasmas are naturally luminous. Their spectrum depends dom-

Figure 2

Fluorine K soft x-ray spectra from a plasma produced by focusing a high power laser on a target of Lithium Fluoride. The lines labeled A permit determination of the plasma temperature, while those labeled B and C indicate the plasma electron density. The lines labeled D provide information on the state of equilibrium within the plasma (3).



inantly on their temperature and density, as well as their composition. Plasma temperatures in excess of 10^6K emit significant radiation in and above the soft x-ray spectral region (100 eV photon energy). Plasma temperatures are commonly expressed in electron volts, with 1 eV=11,600K according to eV=kT, where k is Boltzmann's constant. The shape and intensity of x-ray spectra from plasmas depend primarily on the density of the plasma. If the plasma has a low density and is optically "thin" then radiation emitted by the constituent ions can escape from within the plasma and the spectrum consists of line radiation superimposed on a thermal background. If the plasma is dense and large, it is partially or fully opaque, that is, optically "thick." Then the photon spectra is thermalized internally and the surface regions emit a black body continuum which may be modified by emission and absorption lines.

Whatever the spectral region, soft or hard, or the character and intensity of the emission from a million degree plasma,

Figure 3

Experimentally measured (bars) and computed (lines) efficiencies for the conversion of incident Nd laser radiation to soft x-ray emission in two energy ranges around 0.5 and 1 keV. For some atomic numbers over 30% of the laser radiation reappears as the softer x-rays and over 10% as the harder x-rays (4).

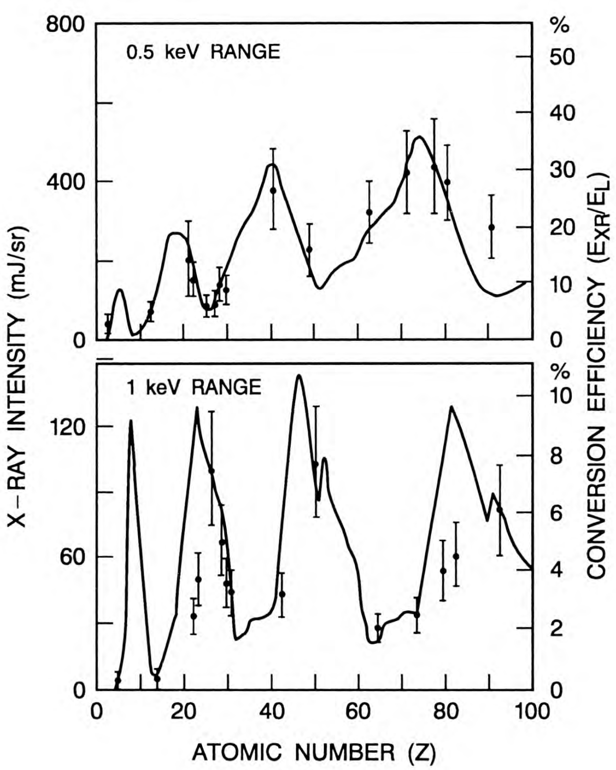
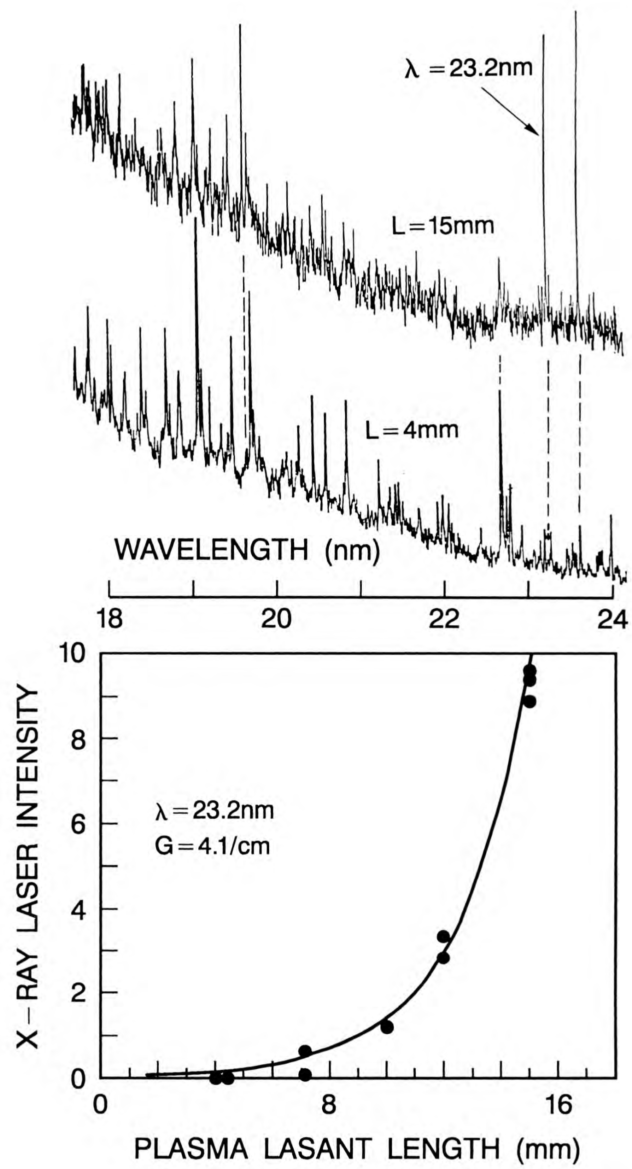


Figure 4

X-ray spectra from 10-electron Ne-like Germanium ions pumped by a Nd laser and variation in the lasing lines intensity with the length of the lasant plasma for one of the four laser lines indicated by dashes. The exponential intensity growth with length evidences laser action (5)..



x-ray measurements of emission from stars and laboratory plasmas are important. A wide variety of diagnostic devices is employed to obtain spectra, images and time histories from x-ray hot plasmas. Spectra can be measured with precision approaching one part per million, images obtained with angular resolutions near one microradian and temporal detail recorded with resolution approaching one picosecond. Plasmas heated by electrical discharges or laser beams commonly have temperatures above 100 eV and densities exceeding 10^{18} electrons per cm^3. Thus, they emit efficiently in the 0.5 to 5 keV range. They are usually less than one mm in at least one dimension, and stay hot and compact for times less than one microsecond.

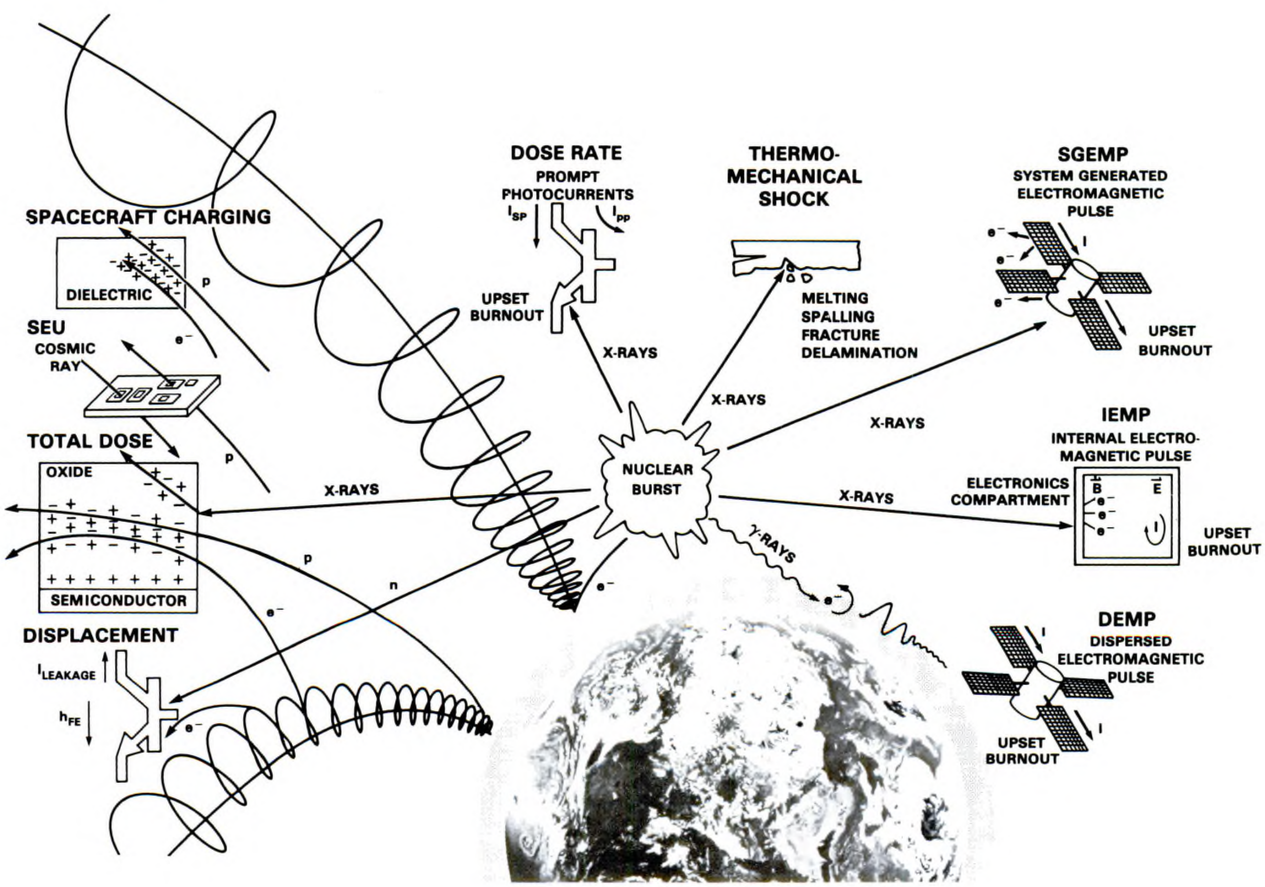
High resolution spectra are particularly rich in information on conditions within the interior of a plasma because they can contain numerous lines, each of which has a wavelength, shape and intensity. For example, the spectrum shown in Figure 2 was excited at the focus of a high intensity laser. It contains features which permit determination of numerical values for parameters describing the plasma. These can be compared with the results of supercomputer simulations of the kinetic, hydrodynamic and radiative behavior of laser-heated plasmas. The codes are employed to compute the results of laser-target interactions which are not accessible experimentally, as well as to guide experiments.

The overall loss of energy from a plasma into radiant energy can be obtained by integrating over absolute spectral, spatial and temporal data in the x-ray region. It is found, in some cases, that a substantial fraction of the entire energy budget for a plasma is lost to emission in the x-ray region. Figure 3 shows, for example, that a significant fraction of the energy incident on a target in a laser pulse will, after absorption and plasma production, expansion and cooling, have been emitted in the soft x-ray range. This remarkable "conversion" from laser radiation in or near the visible regime to the soft x-ray region occurs despite some of the incident laser radiation not being absorbed by the target and significant energy going into target heating and plasma expansion.

Line x-radiation from plasmas ordinarily occurs by uncorrelated processes in various ions, so-called spontaneous

Figure 5

Schematic indicating radiation effects on spacecraft, including prominently x-rays from nuclear bursts, which can produce a variety of electronic and physical effects on microelectronics and systems in space (7).



emission processes. Photons which encounter suitably excited ions can stimulate them to emit prematurely, that is, before their normal radiative lifetime. Stimulated emission on a limited scale is not observed distinct from the numerous ordinary spontaneous emission events. However, if steps are taken to preferentially deplete the population in the lower state or preferentially populate the upper state of a large number of some ion, then the condition of population inversion can exist. This is a necessary but not sufficient condition for observation of x-ray lasing. If the plasma is sufficiently large in one or more directions, spontaneous emission will be amplified in those directions and yield observable lasing, usually on a few lines. Because of the high energy densities required in x-ray hot plasmas and limits on laser and discharge powers and focusability, linear geometries are employed for x-ray lasants. A minimum volume of lasant with the proper conditions, and an adequate length for x-ray optical gain are both provided by this geometry. Figure 4 shows how the intensity of an ultrasoft x-ray laser line varies exponentially with the length of the lasant. Single pass lasing (amplified spontaneous emission) is the norm, although soft x-ray mirrors have been employed for production of two-pass lasing and rudimentary oscillators. Beam coherence is poor to date. X-ray lasing is very inefficient ($<10^{-6}$), so current research aims to increase efficiency as well as improving coherence and decreasing output wavelengths. Uses for x-ray lasers, notably three-dimensional holography on a molecular scale, probably follow the availability of convenient and reliable x-ray lasers (6).

In short, x-rays from plasmas are useful for studying the plasmas themselves, that is, to determine their internal conditions and energetics. If a plasma produced in a certain fashion, commonly by electrical discharge or laser heating, efficiently emits x-rays, then that plasma is available for use as an x-ray "light bulb." The conditions which must be achieved in order to have a useful plasma x-ray source are, firstly, a temperature in excess of 10^6K (100 eV). Secondly, high density favors intense x-ray emission, whether it be lines or continua. Next, since laboratory plasmas hot enough to emit x-rays are generally not sufficiently dense or large to approximate black bod-

Figure 6

Diagram showing methods by which high power electrical discharges can be employed to produce very hot, dense plasmas from, left to right, electrode materials, initially solid materials between the electrodes, low pressure gas-filled volumes, and initial vacua into which are puffed gases immediately prior to discharge. Different geometries are shown within each column (8).

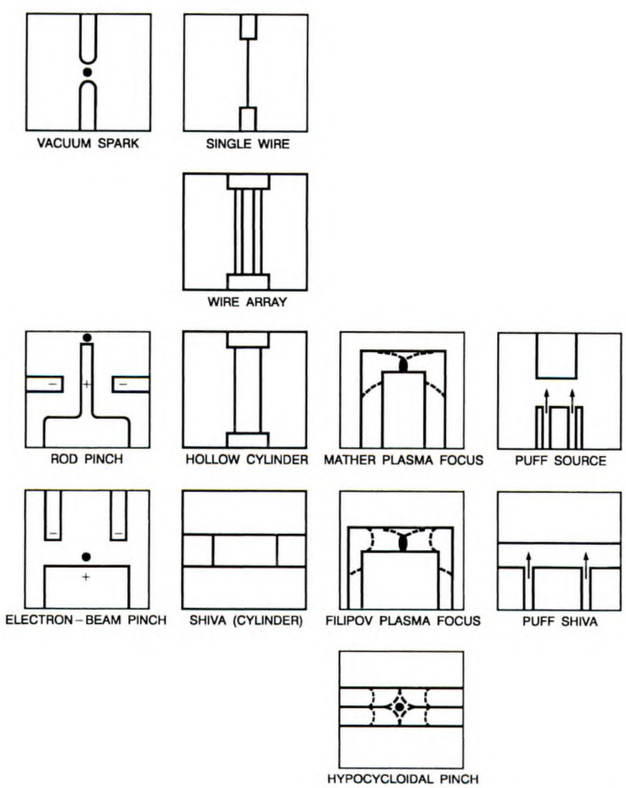
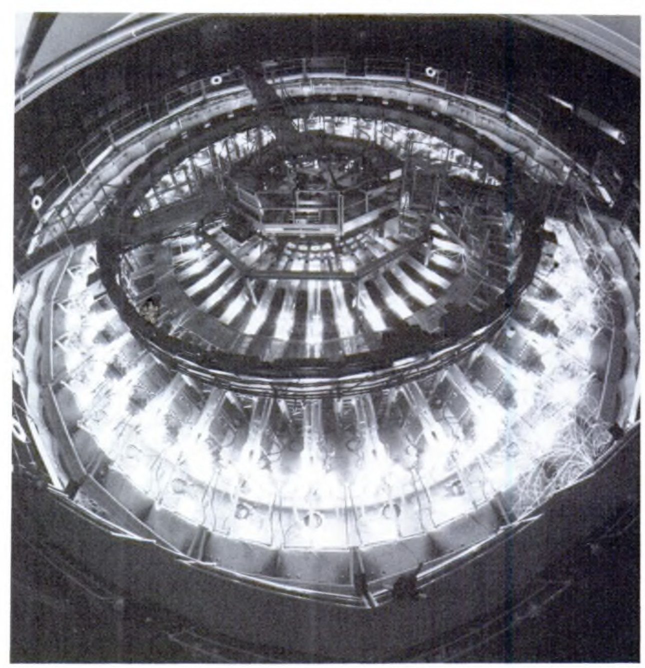


Figure 7

Photograph of the Saturn pulsed power generator at the Sandia National Laboratory (Albuquerque). The diameter of the device is about 30 meters. Optical radiation from the discharge of switches during a multi-terrawatt shot is evident (courtesy of K. Matzen).



ies, the choice of material for a plasma will dominantly determine its spectral character. Finally, the employment of linear geometries can result in soft x-ray lasers with output dominated by a few strong lines.

The study of x-rays from laboratory plasmas dates from the 1950's. It was initially motivated by the desire to diagnose the conditions existing within plasmas. Later, the overall energy partitioning in plasmas was studied. When it was realized in the late 1960's that hot, dense plasmas are bright x-ray sources, programs aimed at simulating nuclear weapons x-ray output were begun. In the same time frame, x-ray diagnostics emerged as a primary tool for study of plasmas produced in fusion energy programs. X-ray optical gain was demonstrated and x-ray lasers were developed in the 1980s.

Figure 8

Schematic of a Saturn load configuration showing the gas nozzle and the electrodes. The graph indicates the time history of the x-ray power emitted during a high power discharge (courtesy of K. Matzen and R. Spielman).

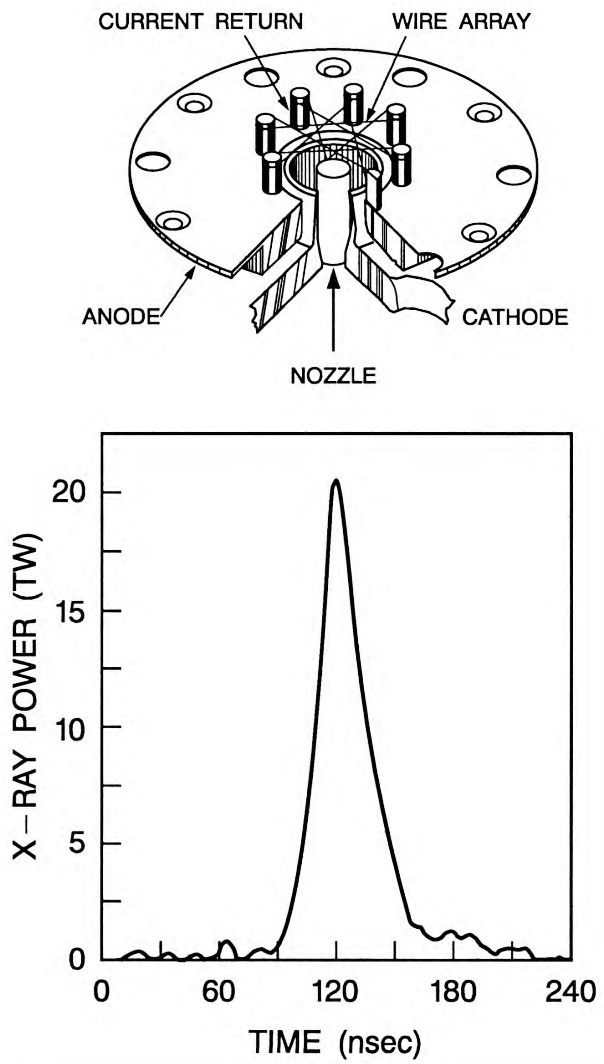
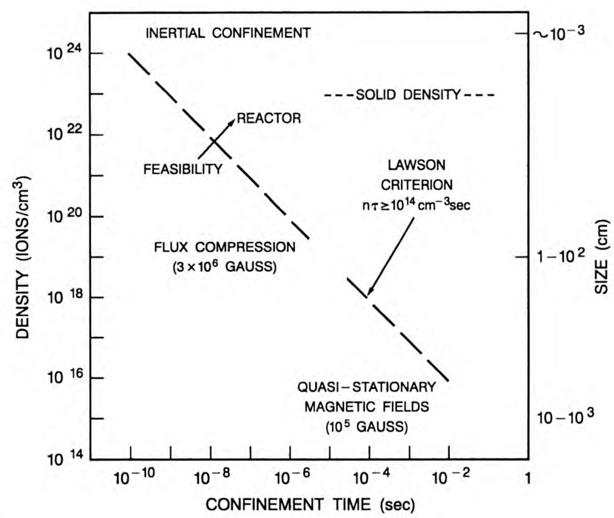


Figure 9

Diagram of the Lawson criteria plotted against ion density and confinement time. Regions explored for fusion energy production are indicated by shading (3).



Nuclear Weapon Simulation

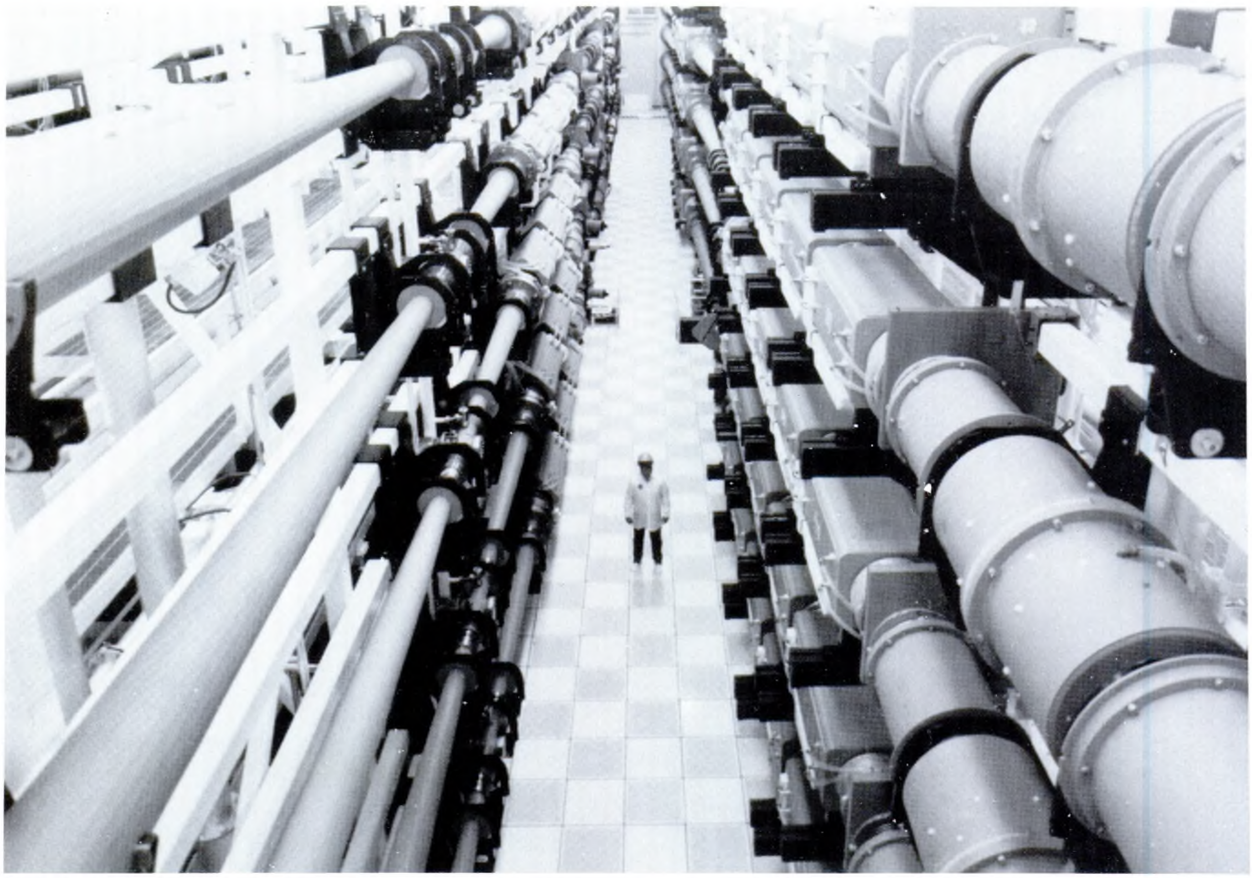
Nuclear weapons emit a significant fraction of their energy as x-rays. Potential employment of such devices high in the atmosphere or in space could have deleterious effects on space systems, as indicated in Figure 5. Since satellites can be employed for military communication, navigation and surveillance, and because commercial voice, data and video communications and weather forecasting depend heavily on satellites, x-ray and other radiation effects on space systems are important.

The response of materials, electronic and optical components and systems to x-rays can be studied underground using radiation from actual nuclear devices. While this approach provides realistic tests, it is expensive and may not be available in the event of some test ban treaties. The availability of laboratory (so called "above ground") x-ray sources enables x-ray testing at lower costs with higher repetition rates. Plasma sources, which produce soft x-ray pulses, and electron impact sources, which produce bursts of hard x-rays, are both employed.

Plasma x-ray simulation sources are usually heated by electrical discharges rather than by lasers. While both provide pulses near 10 nanoseconds in length, electrical sources can produce over ten times as much pulse energy as lasers. A

Figure 10

Nova laser bay at the Lawrence Livermore National Laboratory showing the beam transport tubes and components for the ten beams of the terrawatt Nova laser (courtesy of E. Storm).



pulsed power source has generated over 500 kJ of x-ray energy, compared to a few kJ for the largest laser.

Diverse geometries have been employed to confine and discharge heat plasmas to multi-million degree temperatures. These are shown schematically in Figure 6. Material in the plasma can come from or be placed between the electrodes, but these approaches lack reproduciblity and have slow repetition rates, respectively. Employment of low pressure fill gases, or immediate pre-shot gas injection, is favored. The "puff" devices, in which a gas which will emit the desired spectrum, is quickly admitted to the interelectrode volume to provide a conducting path for an immediately-following electrical pulse, are favored for x-ray simulation.

Various electrical drivers, employing capacitive or inductive energy storage, can be used to heat plasmas. Figure 7 is a photograph of the azimuthally-symmetric Saturn facility at the Sandia National Laboratory (Albuquerque). It stores 5 MJ of energy in capacitors and generates electrical pulses containing 1.5 MJ in 30 nanosecond FWHM pulses (about 50 TW power). One "load" employed at the center of the Saturn generator for plasma x-ray production is shown schematically in Figure 8. Gas emerges form the nozzle near the cathode. Current flows through the ionized gas to a wire array on the anode. A megaampere current heats the plasmas. Strong magnetic fields produced by the current in the plasma pinches it to a size near 1 mm in diameter with a length of a few cm. The resulting high temperatures and densities produce intense x-ray emission. The time history of a 20 terawatt x-ray pulse is also given in Figure 8.

Simulation of nuclear weapons x-ray effects is dominantly a military interest pursued by a few nations. Fusion energy production, in which x-ray measurements figure prominently, has wider international interest.

Fusion Energy Production

For almost half a century, it has been realized that the production of energy based on fusion reactions might be possible. In order to obtain the fusion of light nuclei, it is necessary for those particles to collide with energy sufficient to overcome their mutual repulsion due to both having positive electrical charges. That is, a high plasma ion temperature, with its associated high ion velocities, is necessary in order to fuse pairs of particles. However, high temperatures are not enough for net energy production. Their spatial density and the time over which they exist must both be large enough if an adequate number of reactions is to occur, with a net positive energy release. The critical theoretical insight regarding net energy production, that is, the achievement of more energy out of a fusion reaction than is put in to start and maintain it, resulted from the work of Lawson. The Lawson criteria addresses the combined densities and confinement times which are necessary in order to gain energy from a fusion plasma. A statement of that criteria is given by the equation $n\tau > 10^{14} cm^{-3}$ sec, where n refers to the confined density and τ to the confinement time. For net fusion energy production, the product of confined density (cm^{-3}) and time (sec) must exceed 10^{14}, given a temperature which exceeds tens of millions of degrees.

The equation represented by the Lawson criterion shows that it is possible to trade density for confinement time in order to satisfy that criteria. Figure 9 is a plot of that criteria. It is evident that the Lawson criterion can be achieved in different regimes of density and confinement time. Research and development to date have concentrated on the extremes of this space, namely the very short-lived, extremely high density plasmas or very long-lived, low density plasmas. Significant attention was paid in past years to plasmas of intermediate densities (10^{19} ions per cm^3) and confinement times (10^{-5} sec), but flux compression is not now an active area of research.

The short-time, high-density approach to fusion is entitled inertial confinement fusion because the nuclear reactions occur over a time short compared to the explosive disassembly of the reacting plasma. That is, the inertia of the involved ions limits their acceleration and outward motion, resulting in reaction times of the order of picoseconds. The high densities required for ignition in inertial confinement fusion are obtained by the use of short pulse lasers or ion beams. Electrons at high energies have ranges too long for efficient compression

Figure 11

Theoretical calculation showing the four stages of heating, compression, thermonuclear burn and blowup of a pellet uniformly irradiated by high power laser (9) Stroboscopic x-radiographs of a microballoon initially one-quarter of a millimeter in diameter are shown as the laser pulse begins, and at 250 picosecond intervals, exhibiting compression and subsequent blowup (courtesy of L. Black).

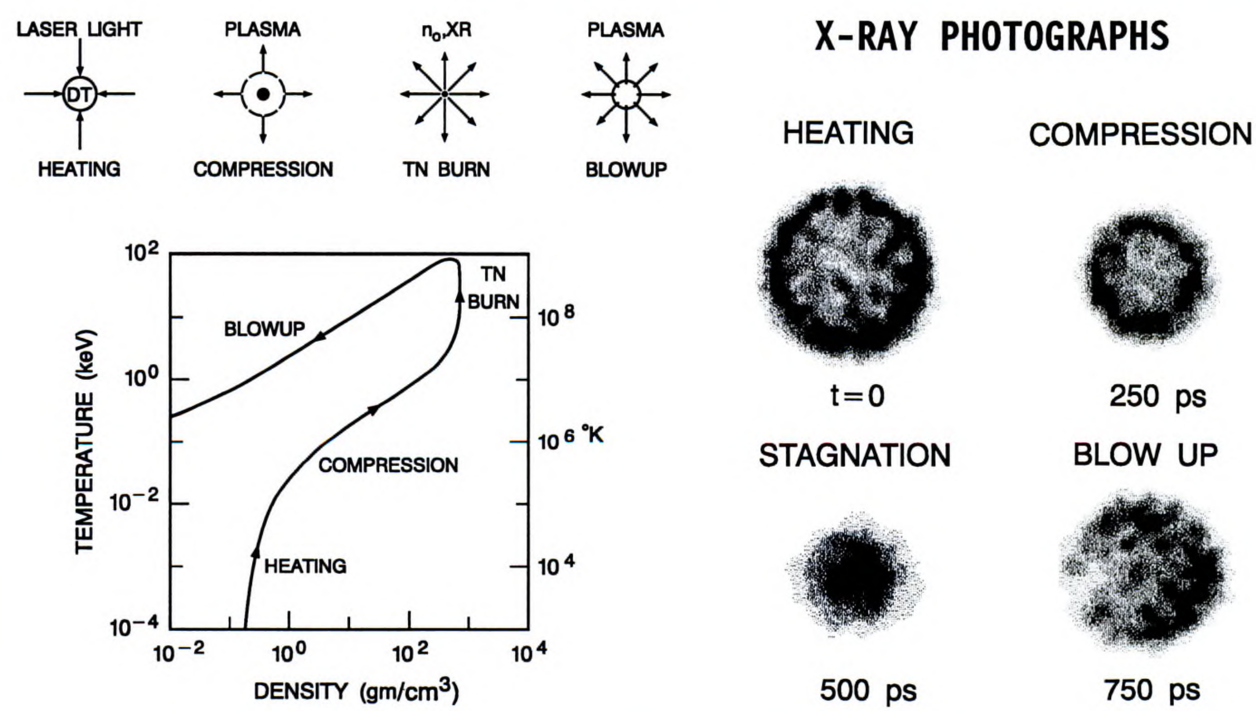
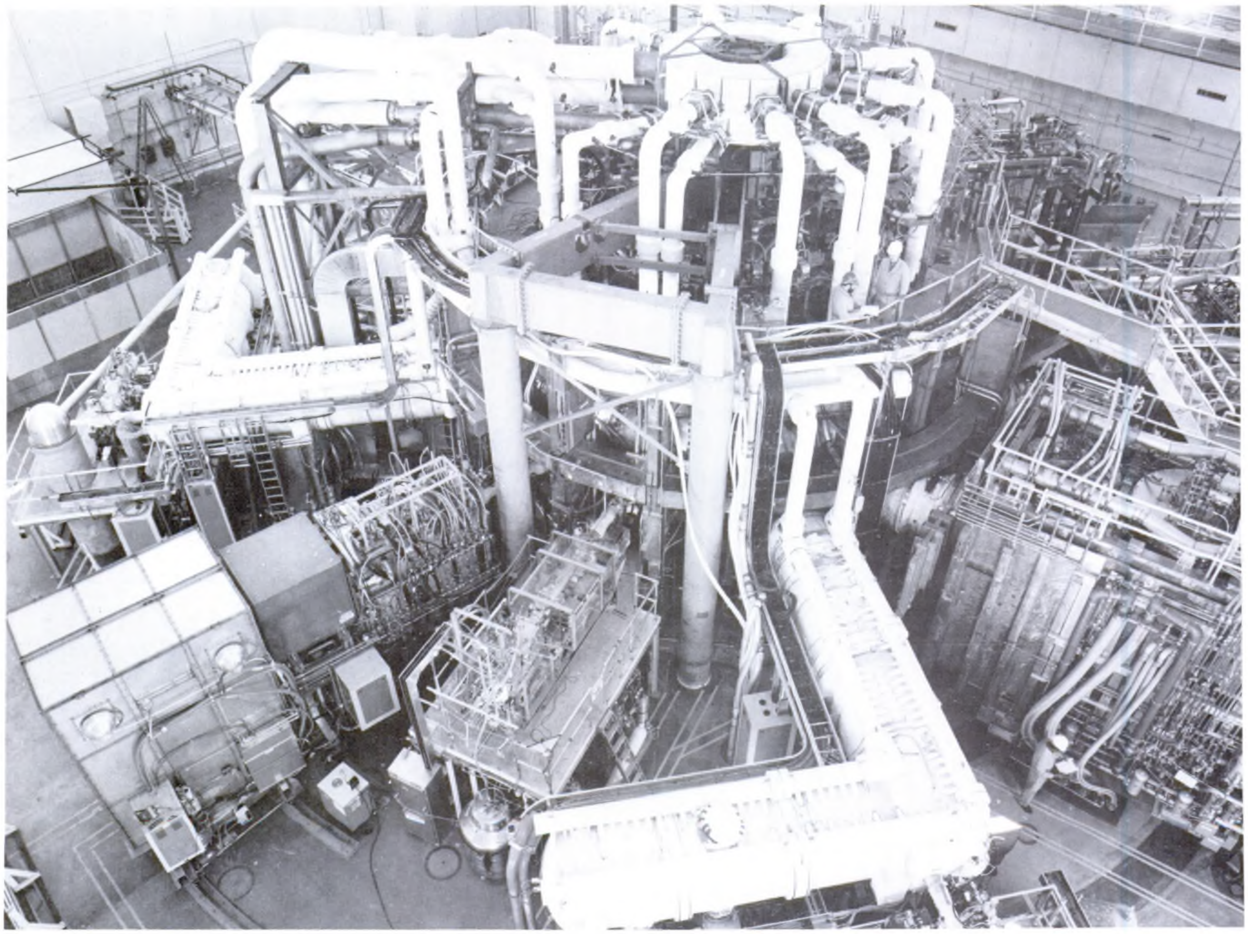


Figure 12

Photograph of the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory (courtesy of K. W. Hill).



of matter to the high densities necessary for inertial fusion. At the other extreme is magnetic fusion in which low-density, long-lived plasmas are contained within magnetic bottles of various configurations for times exceeding seconds. A variety of field configurations, both open ended and closed, has been studied. At present, interest is centered on toroidal magnetic configurations produced in devices called Tokamaks. The plasmas in the Tokamaks are heated by the electrical current that is induced to flow in the plasma by windings around the toroid, by the injection of neutral particles (which are unaffected by the magnetic fields) or by the absorption of radio frequency energy.

Many large laser systems have been built in the United States, Japan, the Soviet Union and Europe to drive small spherical pellets containing fusionable materials, namely isotopes of hydrogen, to the high densities necessary for inertial confinement fusion. Laser wavelengths ranging from CO_2 at 10.6 microns to KrF at 0.25 microns have been or are being employed. The shorter wavelengths, currently favored, are absorbed at higher densities in the exterior of the target pellet to be compressed and result in more efficient energy coupling and compression. Measurements of x-ray spectra, images and time variations are critically useful to all inertial confinement programs. In addition, total x-ray emission is heavily used in inertial confinement experiments. Direct irradiation of bare pellets is termed "direct drive." In this case, the integrated x-ray emission represents a significant energy loss. For the alternative approach, not surprisingly called "indirect drive," x-rays produced from laser irradiated targets or discharge heated plasmas are employed to bathe and implode the pellet. This process requires an additional step, namely the production of an intense plasma source of x-rays. The largest of the inertial confinement laser systems in the United States is the Nova laser at the Lawrence Livermore National Laboratory.

Figure 10 is a photograph of part of that laser. This facility cost approximately $175M, including the R&D, when it was completed in 1984. The Nova system can produce 125 kJ of radiation at the fundamental wavelength of 1.06 microns, 94 kJ, at the frequency doubled the wavelength 0.53 microns and 47 kJ at the third harmonic 0.35 microns. At present, more energetic laser systems are planned both by the Lawrence Livermore National Laboratory and by a consortium of European countries.

The sequence of events involved in the heating of hydrogen isotopes to very high temperatures at high densities is shown in the calculation given in Figure 11. The pellet consists of an exterior shell, which absorbs the incident laser or ion beams, or soft x-rays, and provides the matter which compresses the gaseous or frozen fusion fuel inside of the pellet. Initially, the absorption of radiation on the exterior of a pellet causes a Newton's third law reaction. That is, the jet-like blowoff of the exterior results in the motion of the shell towards its center, compressing the fuel within. As the contents of the pellet stagnate in the center, high temperatures and ignition are obtained rapidly. The released fusion energy results in a rapid rise in temperature at the high densities. Finally, the pellet disassembles, losing both temperature and density, after producing energy by fusion reactions. The sequence is shown schematically in that figure. Measured x-ray shadowgraphs of the compression of a pellet, taken on sequential shots, at the Laboratory for Laser Energetics (University of Rochester), are shown as well. It is seen that the pellet of initial 240 micron diameter is compressed to an x-ray hot diameter comparable to that of human hair, namely 75 microns. The conditions that exist inside a compressed pellet for a brief time are similar to those which exist inside a thermonuclear device or the interior of stars.

The situation for magnetic confinement fusion devices is similar to that for large fusion lasers. Major countries and regions have built Tokamak devices which are being employed currently for studies approaching and exceeding "scientific breakeven." That is the condition where the energy realized from the fusion reactions exceeds the amount of energy put into the plasma (but not the overall energy requirement, which includes that necessary to pump the toroid to the operating pressure, to set up magnetic fields, to provide cooling where necessary, etc.).

In the United States, the premier device is the Tokamak Fusion Test Reactor (TFTR) at Princeton University. Figure 12 is a photograph of that device. So far, the TFTR has been employed with deuterium. It is planned to perform experiments involving the heavier hydrogen isotope tritium, which is easier to fuse but which involves radioactive material handling problems, during 1993.

X-ray measurements are central to the diagnosis of the behavior of Tokamak plasmas such as produced in TFTR. High resolution spectra, images, time histories and total energy are all routinely measured. Figure 13 shows the time history of the ion temperature produced in the TFTR, a low value until the neutral particle beams are activated. In that figure is also shown the time variation of the x-ray emission, which is sensitive to the temperature of the electrons in the plasma. It is seen that a "sawtooth" variation in the x-ray emission reflects temperature variations due to instabilities in the plasma confined by the magnetic fields within the Tokamak.

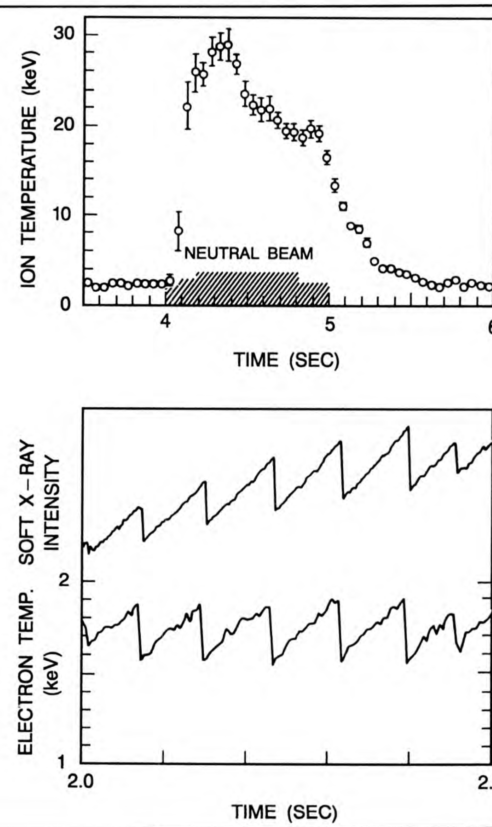
Many other instances could be given of x-ray data obtained from both the high density inertial and low density magnetic fusion energy plasmas. The central point is that x-ray measurements are indispensable to the assessment of the behavior of fusion energy plasmas, however they are produced and whatever their temperatures and densities.

X-Ray Lithography

Integrated circuits appear planar, but they are actually (and increasingly) three-dimensional structures. At present, a

Figure 13

Time history of the ion temperature obtained from x-ray data showing an approximate thirty fold increase in temperature when high power (20 MW) beams of neutral ions are employed to heat the plasma (10). Also shown is the time history of soft x-ray emission from the center of the plasma in this reactor, with "sawteeth" which reflect fluctuations in the plasma electron temperature (11).

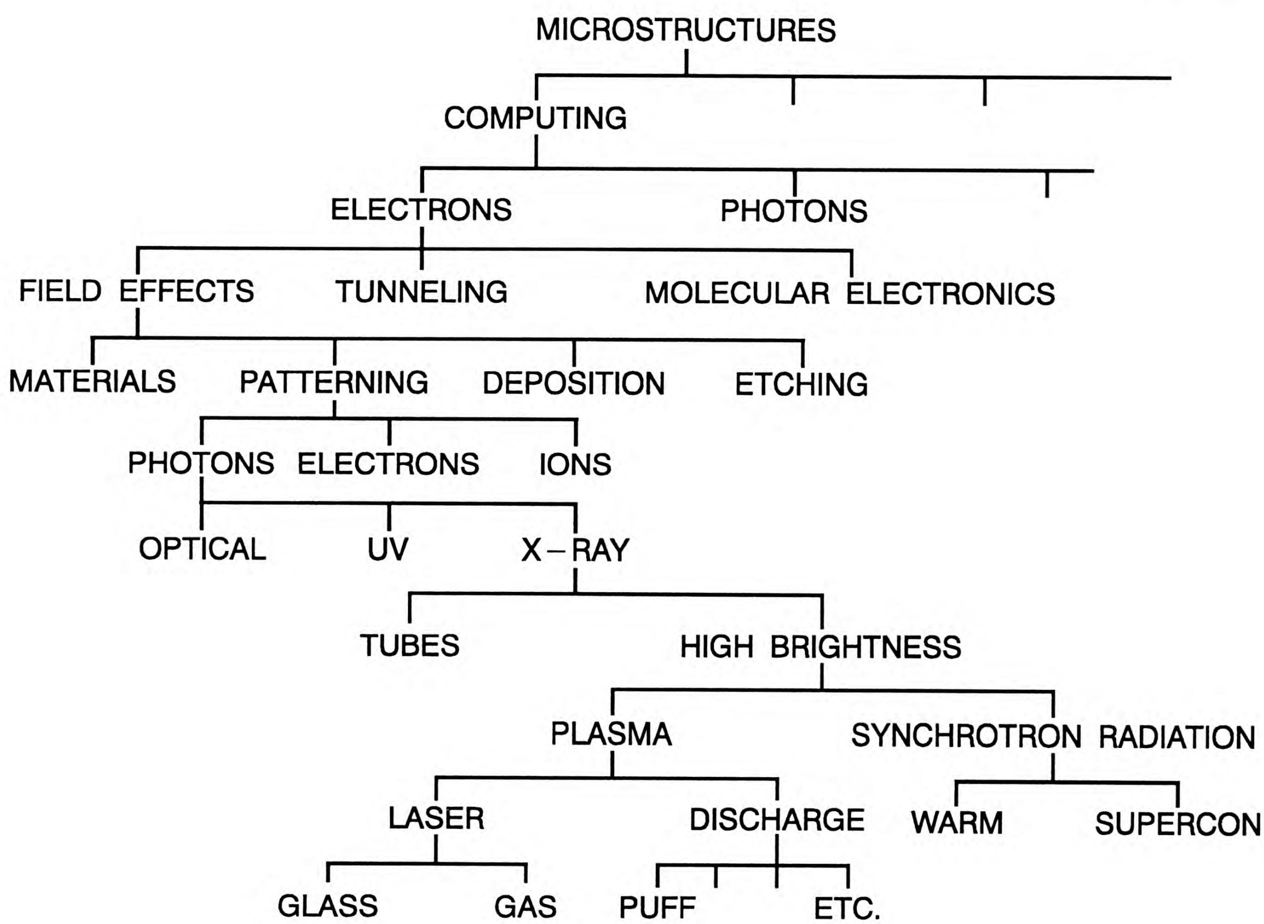


hierarchical competition exists among the goals and methods for production of integrated circuits and other small structures. Figure 14 shows that current conventional semiconductor devices may be supplanted by thin-film devices based on tunneling or by devices with electrically-active molecules. Four things are needed to produce current integrated circuits: starting semiconductor materials, methods to produce patterns, and techniques to controllably add or remove materials. Photons, electrons or ions can be used for patterning (hence, the "three beams" conference held annually in the U.S.). X-ray lithography is expected to replace ultraviolet lithography to produce devices with features below about 0.5 microns in width. X-ray tubes are too inefficient for exposure of resists, which are relatively insensitive. Hence, bright plasma or storage ring x-ray sources are being developed. Both laser and discharge heated plasma x-ray sources are attractive for lithography. Each of these sources may be produced with different drivers and configurations.

Pattern production or replication, called microlithography although it is unlike the original lithographic methods employing oil and water on smooth stones, is accomplished in several ways. As indicated in Figure 15, the methods can be categorized according to the type of quanta employed and the method used to generate or replicate a pattern. In most cases, the radiation exposes a thin plastic layer (the photo resist) which, after development in a chemical bath (wet processing) or in a low temperature plasma (dry processing), serves as a stencil for addition or removal of materials. Ion beams can implant electrically-active elements, or sputter away material, but generally the goal of lithography is to produce the resist stencil for use in separate processes which add or subtract independently-chosen elements.

Figure 14

Diagram indicating alternatives and competitions on various levels regarding the use and production of microstructures by different means.



The most advanced and only commercial plasma system for x-ray lithography is based on plasmas heated with pulses from a glass laser system. A photograph of the system is shown in Figure 16. It is in the early stages of production, with a unit cost of over $2M. Cassette-to-cassette handling of 150 mm diameter wafers is employed. The masks have Au patterns on 2 micron thick membranes of single crystal silicon. X-rays in a band near 14A are emitted by iron-containing target plasmas. Conventional resists are used in this system in order to minimize the number of processing changes which have to be made to adopt x-ray lithography in production lines. The system uses proximity printing, with a mask-resist gap of 25 microns. Micrographs of exposed resists are shown in Figure 17. They exhibit the steep ("vertical") side walls and sharp corners which are among the main virtues of x-ray lithography, whatever the source.

Synchrotron x-radiation may prove to dominate plasma x-ray sources for lithography. Storage rings and associated aligners are roughly twenty times as expensive as the plasma-based aligner system. However, they offer radiation with a high degree of natural collimation and are known to be very reliable. A great deal of expensive development work on synchrotron radiation sources is presently underway in Japan.

X-ray lithography involves replication of man-made structures, namely masks. X-ray microscopy produces replicas of natural structures which can be magnified for study. The several types of x-ray microscopy are surveyed next.

X-Ray Microscopy

The production of magnified images of opaque materials, namely x-ray microscopy, is a small-scale variant of conventional radiography. It has a history which spans over four decades. Early work dealt primarily with images of biological samples, such as insects, and of metallurgical samples, especially multiphase alloys. That work declined in interest when better images of the biologicals and materials could be ob-

Figure 15

Matrix showing the quanta and techniques employed in lithography (8). Various combinations are used in production of integrated circuits and for research. Both projection and proximity methods for x-ray lithography are receiving intense study.

	FOCUSED BEAM (DIRECT – WRITE)	PATTERN PROJECTION	MASK (PROXIMITY OR CONTACT)
PHOTONS	LASER CHEMISTRY	SCANNING OR STEP & REPEAT	STEP & REPEAT
ELECTRONS	RASTER OR VECTOR SCAN	PATTERN ON CATHODE	OPEN MASK
IONS	FIELD – ION SOURCES	OPEN MASK	CHANNELING IN MASK

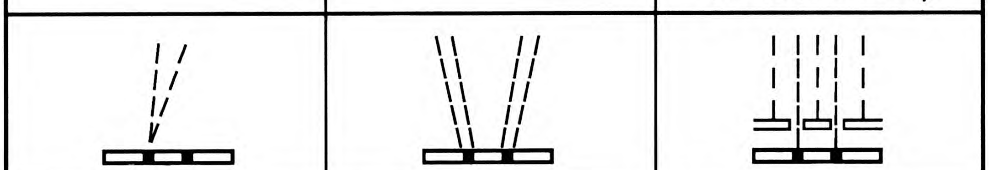


Figure 16

Photograph of the x-ray stepper produced by Hampshire Instruments, Inc. Wafers and masks are loaded in a clean room environment, automatically aligned, and exposed with x-rays from laser-heated plasmas (courtesy of C. M. Magin).

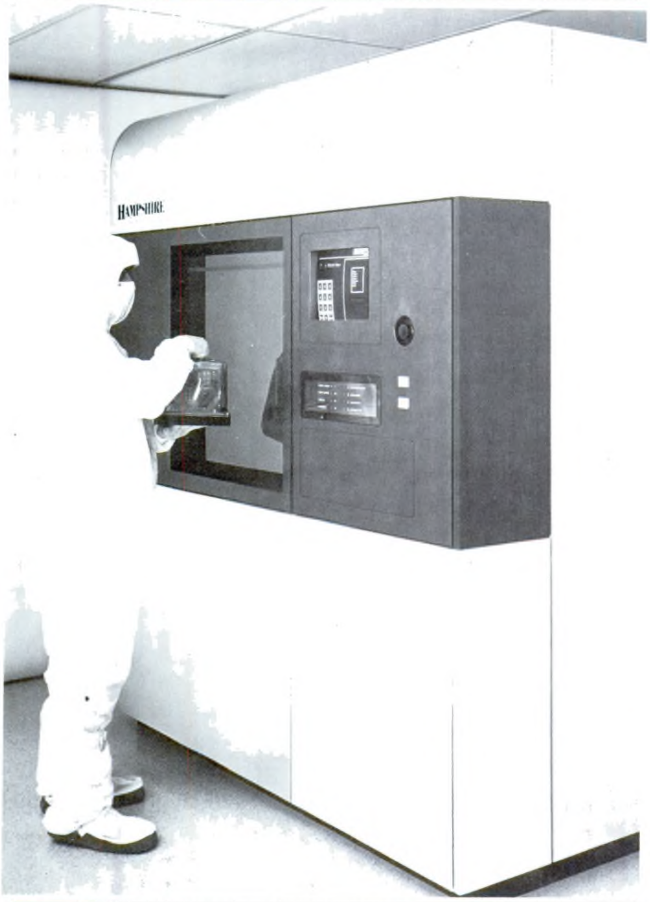
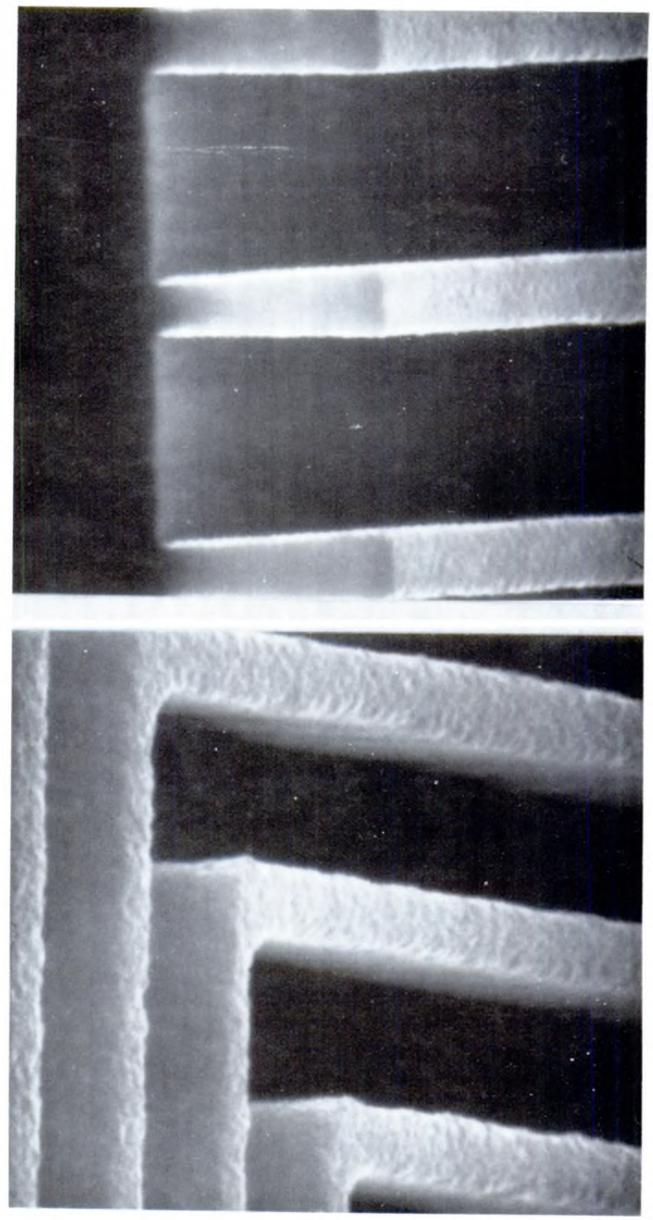


Figure 17

Scanning electron micrographs of photoresist patterns produced by x-ray lithography in the machine shown in the previous figure. Individual line widths are 250 nm wide, corresponding to roughly 1000 interatomic spacings. (courtesy of C. M. Magin).

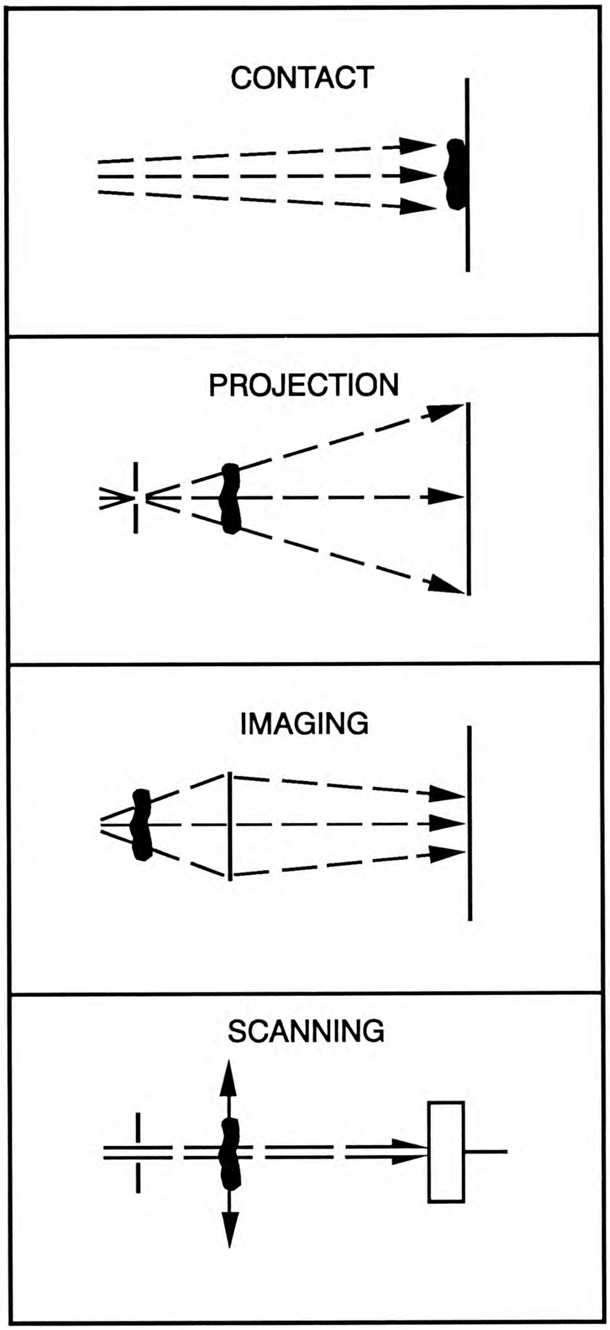


tained with commercially-available electron beam instruments. Such techniques, notably transmission and scanning electron microscopy, provide high resolution images, even to the scale of atoms. Further, they permitted obtaining structural information by analysis of diffraction patterns and compositional information by spectrochemical techniques. In short, x-ray microscopy held very little interest until bright sources of x-rays, especially storage rings and plasma sources, became available. Currently interest centers on the production of images with resolution below the cutoff of optical microscopes, approximately 200 nm, from live specimens for both biological research and clinical medicine.

X-ray microscopy techniques may be organized according to the sketches in figure 18. The technique most popular initially, which is now receiving much study, is very similar to proximity x-ray lithography. A "contact" print is made of the biological material of interest. Alternative methods include

Figure 18

Schematic of the four methods by which x-ray microscopy is performed (12).



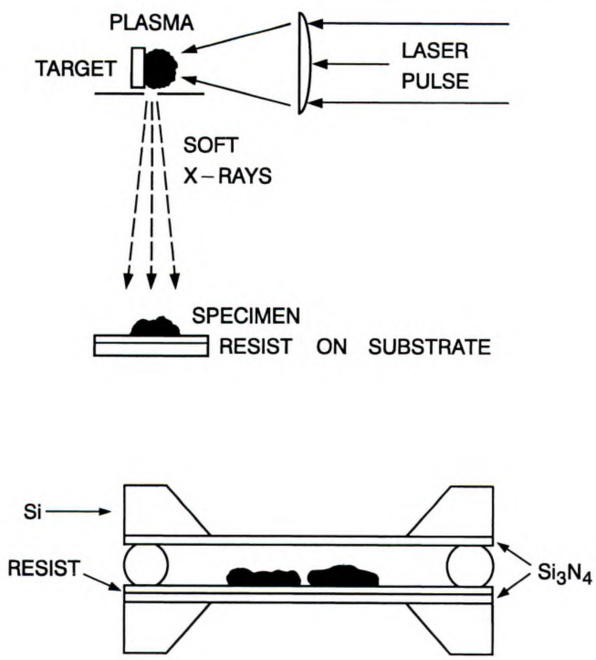
projection microscopy, in which a very small source or a source made small by a limiting aperture is used to project an image of the sample onto a recording medium. Its close relative is pinhole photography in which the limiting aperture is placed between the backlit specimen and the recording medium. The third approach to x-ray microscopy involves formation of an actual image of the backlit specimen. This approach is dependent on the availability of high resolution x-ray optics, notably Fresnel zone plate lenses. These were not available with interesting resolution until microlithographic techniques developed in the electronics industry were applied to the production of zone plates. The fourth approach to x-ray microscopy, unlike the others in which the entire image is obtained in parallel during simultaneous exposure, is the scanning technique. Here an image is built up pixel by pixel by scanning the fine beam relative to the specimen and recording the x-rays with a detector not offering spatial resolution.

In principle, all of the techniques for x-ray microscopy could be employed using pulsed plasma sources. However, the intensity requirements for projection microscopy are incompatible with plasma sources now. The imaging approach could be employed but does not seem to be studied with plasma sources at the moment. Of course, the scanning approach would require the use of a repetitively pulsed plasma source which would not be particularly convenient due to pulse-to-pulse variations in x-ray intensity.

The contact technique for x-ray microscopy is being employed with both incoherent and partially coherent plasma x-ray sources. Figure 19 shows a schematic of the manner in which plasma sources can be employed for contact microscopy. Details are shown for a thin-window cell which permits the incident x-rays to pass with little loss while at the same time maintaining the moist environment required to keep the biological specimen alive. Such cells can be employed either in the vacuum that is necessary for propagation of the soft x-rays relevant to x-ray microscopy, or in a low-pressure, low atomic number gas such as helium. Wavelengths of interest for microscopy of live biologicals fall in or near the "water window," namely between the oxygen absorption edge at 2.3 nm A and the carbon absorption at 4.4 nm. In this region, the x-rays efficiently penetrate the water but are preferentially absorbed by the carbon in the biological specimen. The photoresist which is exposed by the x-rays which penetrate the specimen has, after development, a surface topography related to the intensity of x-rays penetrating the sample. That is, thick or high absorbance sections in the specimen pass little radiation which produces little change and leads to little or no development in corresponding areas of photoresists. Unfortunately, contact x-ray microscopy requires the additional step of electron microscopy of the resulting resist topography. This usually involves increasing the contrast by coating the resist with a metal prior to electron microscopy.

Figure 19

Layout of components for contact microscopy using x-rays from a laser-heated plasma. The sample is in contact with the photoresist recording medium inside a moisture-retaining cell sketched at the bottom.



X-ray microscopy based on plasma sources is not as well developed as is x-ray lithography. In fact, no commercial equipment is available for x-ray microscopy using simple laser or discharge heated plasmas. Interestingly, a commercial device is available for x-ray microscopy using pulses from an x-ray laser. Figure 20 is a schematic and photograph of the COXRALM device offered for sale by Princeton X-Ray Laser, Inc. This instrument contains an optical microscope for selection of the area to be irradiated and imaged by the x-ray pulse. Although developed for use with x-ray laser pulses at 18.2 nm, such a device could be used with the incoherent radiation from simple plasmas. Figure 21 shows a false color image of a cell exposed with radiation from a Princeton soft x-ray laser. This photograph does not involve high resolution detail because it was a test exposure to determine the efficacy of the 18.2 nm laser radiation for contact microscopy.

It is expected that the employment by biological and medical researchers of both reliable plasma x-ray sources, whatever their origin, and "user friendly" imaging equipment will be necessary to assess the importance of x-ray microscopy in these fields. That is, the biologists and medical personnel involved should have at their disposal easy-to-operate x-ray microscopes which will permit them to concentrate on whether or not there are scientifically or clinically interesting structures in the range between approximately 200 nm and the limit of photoresist resolution near 20 nm.

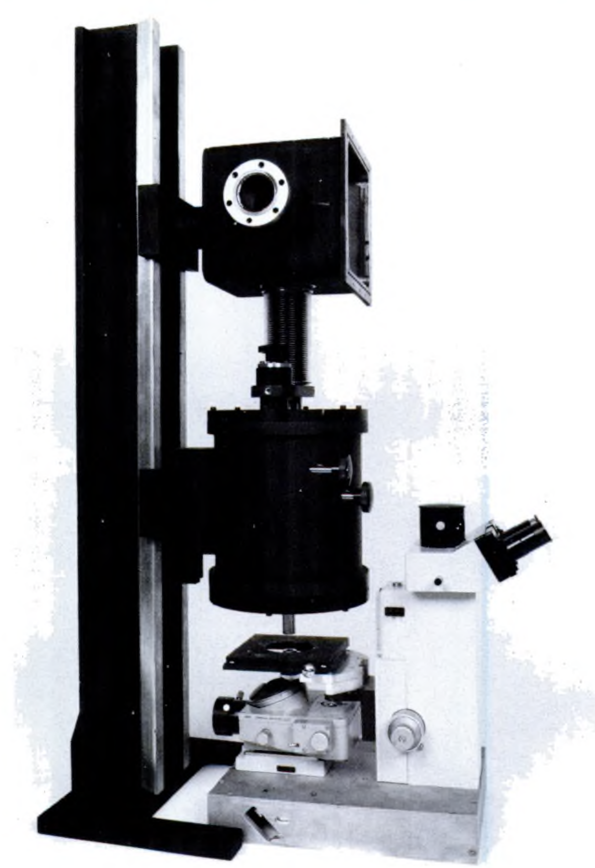
While x-ray microscopy is not as advanced as x-ray lithography at the current time, it offers significant promise. It is entirely possible that, if interesting structures are found in the supercoiled DNA or other features within cells, such as microtubials, then x-ray microscopy will be an important routine tool in biology and medicine after the turn of the millennium.

Conclusion

In the past three decades, x-ray emission from plasmas has been widely employed to study conditions within and energetics of multimillion degree plasmas. In the past two

Figure 20

Photograph of the Composite Optical and X-ray Laser Microscope (COXRALM) developed for contact x-ray microscopy with pulses from a soft x-ray laser (courtesy of S. Suckewer).



decades, hot and dense plasmas have served as sources, first, for x-ray lithography and, later, for x-ray microscopy. Figure 22 is a plot of the number of publications annually in the indicated areas regarding x-rays from plasmas. Interest in x-ray lasers clearly increased in the mid 1980s due to earlier reports of significant gain. Measurement of x-rays from laser-heated plasmas became popular with the initiation of inertial confinement fusion programs in the early 1970s. It was pre-dated by a strong interest in x-ray emission from any plasma source. The long and high level of interest in astrophysical plasma x-ray sources is interesting given that x-ray astronomy is dominantly of academic interest.

Research and development continues in each of the areas reviewed above. Currently active thrusts involving plasma x-ray emissions include:

Plasma X-ray Sources	Parametric Studies
Plasma Heating	Capillary Discharges Femtosecond Laser Plasmas
Plasma X-Ray Emission	X-ray Lasers: Efficiency, Coherence and Short Wavelengths Picosecond X-Ray Pulses
Plasma X-ray Diagnostics	High Resolution Optics Multichannel Detectors Streak Cameras
Nuclear Weapon Simulation	Higher Intensities Greater Spectral Fidelity
Fusion Energy Production	Inertial Confinement: Short Wavelength Lasers and Higher Powers Magnetic Confinement: Larger Tokamaks and Heating Methods
X-ray Lithography	Brighter Sources Projection Techniques Production Systems
X-ray Microscopy	Brighter Sources X-Ray Optics Research Systems

Characterization of incoherent emission from plasma x-ray sources continues to be an active area. Numerous x-ray characteristics (spectral, spatial and temporal) must be quantified for various applications as a function of the diverse parameters involved in generating hot, dense plasmas. Detailed numerical calculations of plasma x-ray output requires large codes on supercomputers, and are usually not adequately accurate for applications.

Electrical discharge heating of plasmas in capillaries is attracting attention as an alternative to the more studied magnetic confinement due to fields from the discharge currents. Heating of solid targets by recently available femtosecond lasers produces hot plasmas with particle densities near those of solids ($\approx 10^{23}$ electrons per cm^3) and very high energy densities. Soft x-ray emission from such plasmas has short ($\approx$ picosecond) pulse lengths, and may prove useful for stroboscopy of very fast events.

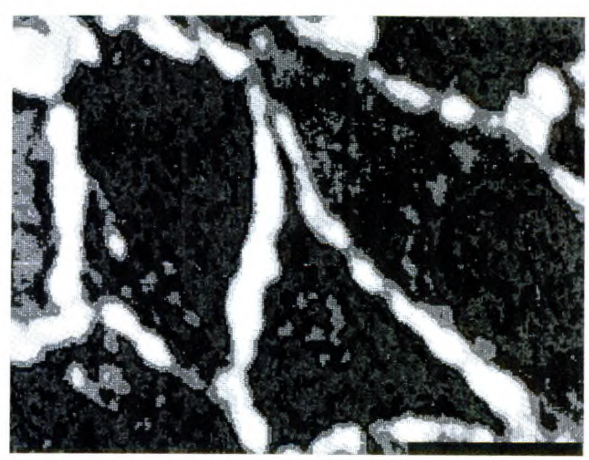
X-ray lasers represent a major research area for plasma emission now. Experimentally, production of x-ray lasers requires powers generally exceeding 10^{11}W and nanosecond-scale pump laser rise or fall times. Electrical discharge sources, with time scales near 10 nanoseconds, have not yet proven successful as pumps for x-ray lasers despite the large energies which they produce. If x-ray laser pulses with adequate coherence are developed, x-ray holographic imaging with resolution approaching 10 nm may be attainable. X-ray laser calculations are challenging because plasma ray optics, in addition to atomic, kinetic and hydrodynamic theories, are necessary components of comprehensive codes.

Plasma diagnostics instrumentation continues to evolve. X-ray optics for spectroscopy and imagining of plasmas based on flat field gratings or on multilayers and crystals are available or under development. Area x-ray detectors for spectral and spatial resolution, notably solid state arrays, and streak cameras and sampling oscilloscopes for near picosecond time resolution, are commercially available.

Simulation of the energetic x-ray output of nuclear weapons using discharge-heated plasmas remains an active area. Total or partial test ban treaties, which are increasingly possible, would preclude underground testing of military components and systems. The availability of plasma and other x-ray pulsed x-ray sources would then be even more important.

Figure 21

Scanning electron micrograph of the photoresist exposed while in contact with viral infected cervical cancer cells exposed with soft x-rays. The black bar corresponds to a length of 10 microns (courtesy of S. Suckewer).



Hence, the development of increasingly capable plasma sources for simulation of nuclear weapon effects continues.

Plasma x-ray measurements remain fundamental tools in both inertial and magnetic confinement programs. Currently, large gas excimer KrF lasers are being constructed, while work with large solid state Nd systems continues. X-ray spectroscopy and imaging are used in virtually all inertial fusion research. Ever larger Tokamaks are planned, with the International Thermonuclear Experimental Reactor now being discussed. X-ray spectral and temporal diagnostics will continue to be an integral part of all research Tokamaks.

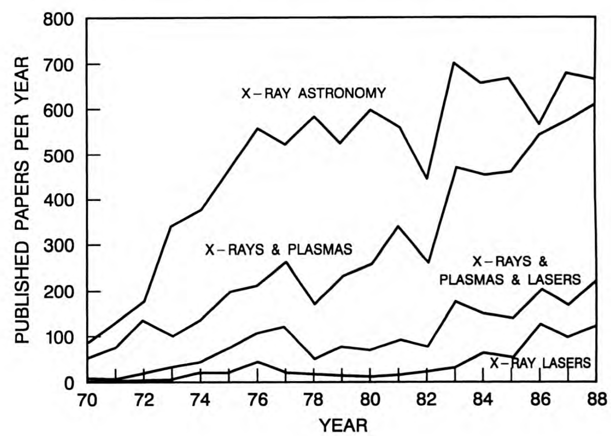
Plasma x-ray lithography is competing now with storage ring sources of synchrotron x-radiation. The commercial system employing laser-heated plasmas will receive extensive use in the coming years which should demonstrate its performance and reliability. Meanwhile, development of discharge-heated plasma x-ray sources for lithography continues in the U.S. and Japan. Which plasma sources prove best, and how they compare with synchrotron radiation for routine commercial production of integrated circuit with submicron features, should be known within the next ten years. The viability of projection x-ray lithography will be known over the same time scale. Whatever sources and methods prove best, the availability of production-worthy hardware, especially masks, will determine the commercial importance and impact of x-ray lithography.

Microscopes employing x-rays from plasmas are under development now. Their brightness and the availability of high resolution x-ray optics for direct imaging will be central to x-ray microscopy. If reliable and convenient sources of incoherent or coherent plasma x-radiation are available to biologists and clinicians, they can perform research on structures in living tissues with sizes in the range of 20 to 200 nm. It remains to be learned whether or not structures exist which are useful for biological research or clinical diagnoses. If so, major bio research laboratories and hospitals may be equipped, possibly by the year 2000, with plasma x-ray microscopes.

Competition amongst x-ray sources, notably plasma and synchrotron radiation, has been noted. It is probable that all bright x-ray sources will find use in research, development or commercial efforts. Large, expensive (>$100M) storage ring facilities will remain research oriented. Compact synchrotron radiation sources, still costly (>$10M), may be heavily used for x-ray lithography, but probably not microscopy. Plasma sources (>$1M) may prove adequate for lithography as well as microscopy. Plasma x-ray sources might, and probably will, prove useful for research in areas such as surface science now done at storage rings or with weaker laboratory sources. Commercial development of discharge or laser heated plasma systems, complete with beam lines to collect, monochromatize and focus x-radiation onto samples, is expected during this decade. Such systems would provide a alternative to synchrotron radiation, especially for work requiring high peak powers.

Figure 22

Plot for the last two decades of the number of papers published in Physics Abstracts having to do with x-ray lasers, x-rays from the plasmas involving lasers, and x-rays from plasmas heated by any means. The publication rate for studies in x-ray astronomy is also shown for comparison (courtesy of R. W. Peacock).



It is noted that long-standing commercial x-ray work generally involves hard x-ray with energies exceeding 5 keV, above which air will transmit x-rays over useful distances. Non-destructive testing, and medical radiography and therapy, usually require x-ray energies in the 10-100 keV region. The analysis of materials involves lower energies, usually 10-20 keV for diffraction structural analysis and 5-20 keV for spectroscopic chemical analysis. Emerging x-ray lithography and microscopy both involve soft x-rays (0.2-2 keV), well below the air cutoff. Commercial employment of the entire x-ray spectrum seems appropriate as we approach the centennial of the discovery of x-rays by Roentgen in 1895.

Acknowledgemnets

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Biography

Dr. David Nagel is Superintendent of the Condensed Matter and Radiation Services Division at the Naval Research Laboratory, where he has worked since 1962. His research has centered on x-ray measurements in plasma, atomic and solid state physics with over 100 publications in journals, books and encyclopedias.

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Rear Admiral William C. Miller, USN
Chief Of Naval Research

RADM Miller became the 17th Chief of Naval Research June 15, 1990. He returns to OCNR where he has had three previous assignments. In 1975, LCDR Miller came to ONR as a scientific officer for the Vehicle Systems Program. From 1984 to 1986, CAPT Miller was Director of the Low Observables Directorate for ONT. CAPT Miller, from 1986 to 1987 was the commanding officer of the Naval Research Laboratory. A native of Los Angeles, California, RADM Miller is a 1962 graduate of the U.S. Naval Academy. He was promoted to the rank of Rear Admiral in 1990.

After his first tour of duty aboard the destroyer USS DUPONT, he attended graduate school at Stanford University where he earned Master of Science and Ph.D degrees in electrical engineering in 1967.

Subsequently, he served on the guided missile cruiser USS GRIDLEY and the guided missile destroyer USS SAMPSON, and commanded two ships: the frigate USS McCLOY and the destroyer USS CUSHING.

His assignments ashore have included: service on the personal staff of the Chief of Naval Operations; member of the Electrical Engineering Faculty and later Executive Assistant to the Superintendent of the U.S. Naval Academy; and Executive Assistant to Assistant Secretary of the Navy (Shipbuilding and Logistics).

He assumed duties as Director, Undersea and Strategic Warfare and Nuclear Energy Development Division in the Office of the Chief of Naval Operations in August 1987. Subsequently, he served as the Deputy Director for Research and Development Requirements, Test and Evaluation with the Office of the Chief of Naval Operations before becoming Chief of Naval Research.

As Chief of Naval Research, RADM Miller manages the R&D organization responsible for the conduct of the basic research, exploratory development, and advanced technology development programs of the Navy. He also exercises policy oversight for the Navy's laboratories and R&D centers. The organization's annual budget, over $1 billion, is allocated for research and development work conducted in universities, Navy laboratories and industry.

RADM Miller reports directly to the Secretary of the Navy via the Assistant Secretary of the Navy for Research, Development and Acquisition. He is the Navy's Science and Technology Executive and ranks organizationally with Deputy Assistant Secretaries of the Navy. Organizational entities reporting to the Chief of Naval Research include the Office of Naval Research (the first federal research agency), the Office of Naval Technology, and the Office of Advanced Technology, all located in Arlington, Virginia, and associated laboratories and field offices: the Naval Research Laboratory in Washington, D.C.; the Naval Oceanographic and Atmospheric Research Laboratory at the Stennis Space Center, Mississippi; and overseas offices in Tokyo and London.

RADM Miller's personal awards include the Legion of Merit, two gold stars in lieu of the second and third Legion of Merit, the Meritorious Service Medal, the Navy Achievement Medal and several campaign and service medals. He is a twenty-year member of the Institute of Electrical and Electronics Engineering.

RADM Miller is married to the former Barbara Jean Leach of Burbank, California. They have five Children: Linda, William, Julie, James, and Marianne.

Computational Mechanics of Material Behavior

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Alan Needleman
Brown University

Solid mechanics research in recent years has become more closely coupled to materials science research and advances in the science and technology of designing and processing of materials. In addition, as nontraditional materials such as composites and nontraditional applications as microelectronics devices become technically more sophisticated, significant new challenges for solid mechanics are developing. This article highlights some recent advances in the understanding of how continuum behavior of materials and structures is controlled by the interaction of microstructural material characteristics and distributions with macroscale stress and strain fields. It will be demonstrated that computational approaches, specifically finite element analyses are critical to the research.

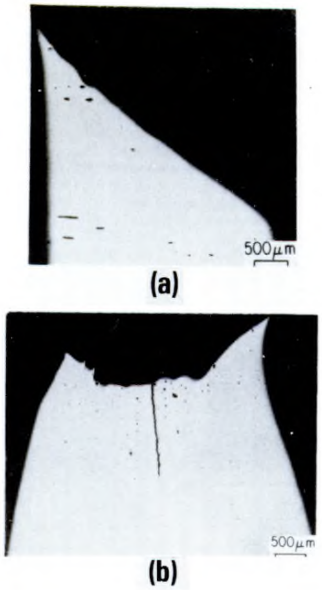
Introduction

As an engineering design and analysis tool, the finite element method (FEM) has its roots in the extensions of classical matrix force methods of structural analysis to study more complex shapes and loading conditions associated with advanced aircraft developments begun in the 1940's. The fundamental concept for the FEM, the approximation of solution fields on geometric subspaces, is inherent to the foundational work of ancient geometry. Early Egyptian and Chinese mathematicians and engineers used the method of circumscribed and inscribed triangles and rectangles to calculate the value of π to seven significant figures by A.D. 480. It is important to appreciate that the early stages of FEM evolution in the civil and aeronautical engineering applications were built around sound physical insight into the behavior of these systems. Over the last four decades, significant progress has been made towards establishing a very rigorous mathematical foundation for the FEM. It has been this blending of mathematical rigor and physically sound foundations which has allowed the accurate computation of some of the most complex problems in the mechanics of material behavior.

Computational studies have become essential in both the exploration of microstructural behavior modes and in the evolution of macroscale constitutive and damage laws for modern materials. A characteristic of modern material systems is that they often have been engineered for optimum performance. One of the most obvious historical examples of this is in the development of high strength, ductile metal alloys. Distributions of large and small particles and grain sizes are utilized to both raise yield strength and allow for plastic flow around stress concentrators such as voids and cracks. Examples of how computational studies have helped to quantify the nature of ductility and strength evolution will be presented. Contemporary structural applications are emphasizing the replacement of metallic alloys with fiber reinforced composite materials. In typical composite structures applications, the domain of damage at the material level often progresses to a size scale equal to a significant fraction of the minimum structural dimensions. Thus, it often becomes necessary to directly model the interaction of deformation and failure modes over length scales quite large in comparison to the microstructural dimensions of the material constituents. In such cases, large scale scientific supercomputing is often the

Figure 1

Ductile Failure Modes in Flat (a) and Round (b) Tensile Bars.



only approach capable of providing insight into the coupled scales of material behavior. As an example of this class of coupled micromechanics and macromechanics problems, the combined panel buckling and delamination growth observed in compressively loaded composite panels will be shown.

The evolution of computational solid mechanics research into nontraditional areas can be seen in recent advances for understanding the phenomena associated with the generation of defects in thin films and the influence of mechanical and/or thermal stress on the performance characteristics of microelectronic devices. To illustrate this, recent work which simulated the piezoelectrically induced threshold voltage shift in GaAs MESFET's will be discussed. This last example is indicative of the types of interdisciplinary research impact that the utilization of large scale scientific computing facilitates within the solid mechanics field.

Solid mechanics research has traditionally evolved from supportive roles to other technologies such as structural engineering, metallurgy, and manufacturing. Trends in modern technology are leading to technologies that are multidisciplinary and often based on forefront scientific research. The solid mechanics research community, and the ONR Solid Mechanics Program, have responded to this trend by extending the scope of phenomena and characterization scales encompassed in its research. Large scale computing is proving to be a critical component in providing the "data base" essential to developing an understanding of the dominant processes and parameters in such highly coupled and multidisciplinary technologies.

Micromechanics of Ductility

Modern engineering alloys generally have microstructures which have been 'engineered' for desired ductility, strength, and toughness. Much of the science for designing such materials is based on qualitative analysis and empirical data. The ability to quantitatively predict the influence of variations in microstructural composition on the material properties used in engineering design would have a major impact on the material design and application disciplines. Experimental studies of ductile fracture have shown that microvoid nucleation and rupture play a central role in the failure process. The voids nucleate mainly at second phase particles by decohesion of the particle-matrix interface or by particle fracture. Final failure involves the growth of neighboring voids to coalescence into crack-like fracture surfaces.

A comprehensive review of progress on computationally modeling of ductile rupture processes has been given by Needleman[1]. A framework for studying progressively rupturing solids within a continuum framework has been established by Gurson[2]. Gurson solved the problem of the growth of an initially spherical void in a cell of perfectly plastic material

Figure 2

Computations of Crack Development Caused by Local Material Loss of Strength in Round Tensile Bar.

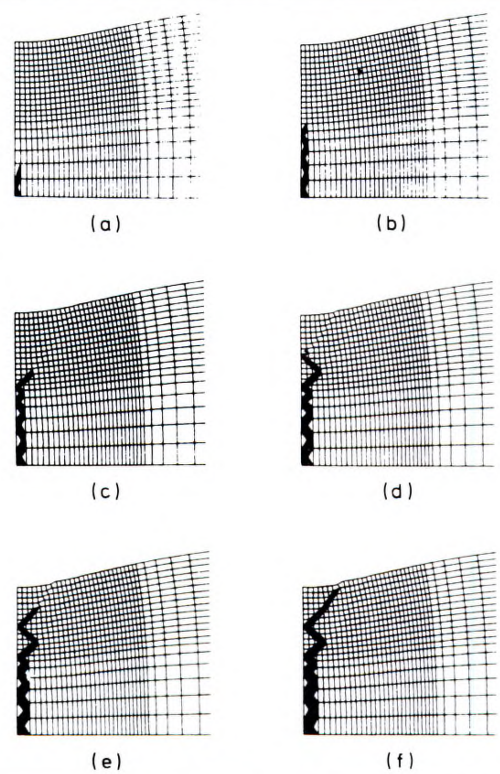


Figure 3

(a) Typical Random Distribution of Voids in a Unit Cell. (b) Comparison of Average Stress-Strain Behavior for Various Void Distributions. Curve 2e corresponds to Distribution in (a).

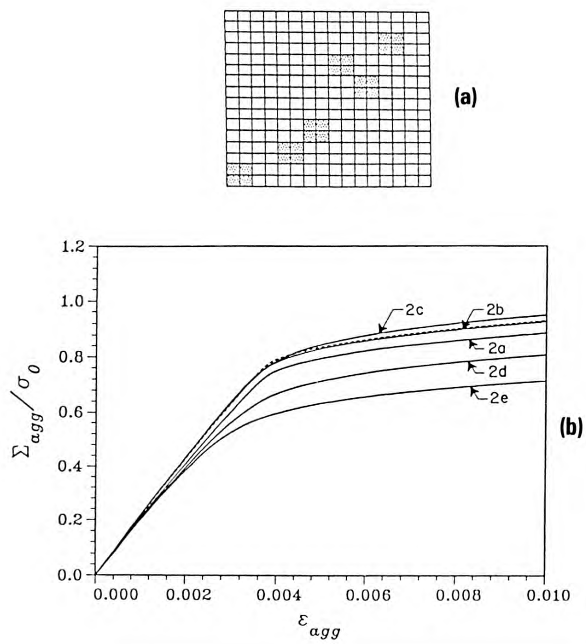
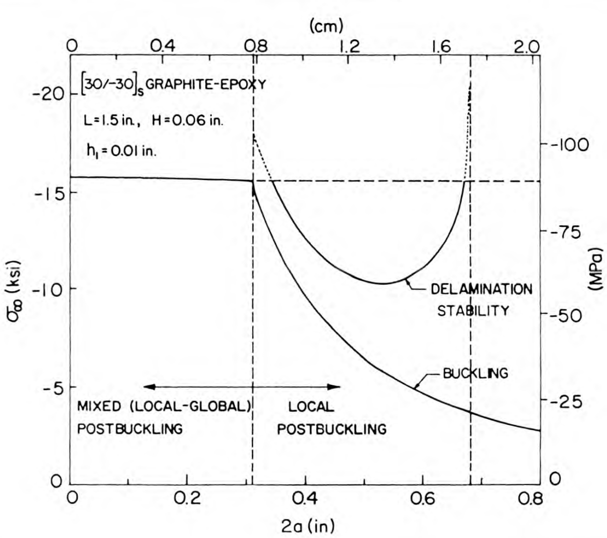


Figure 4

Complete Map of Various Failure Modes (e.g., Local or Coupled Global-Local Buckling and Postbuckling Stability, and Delamination Stability) in Delaminated [30/-30]s Granite-Epoxy Composite Laminate.

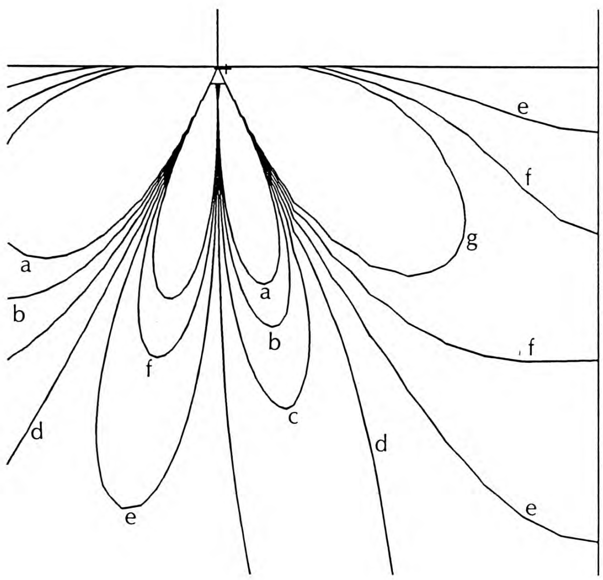


subjected to varying degrees of triaxiality in applied stress. The resulting solution formed a constitutive law for a two phase material consisting of a void and a plastic material. The evolution of porosity is described thus in terms of the general properties of the matrix material and a scalar parameter, f, the void volume fraction.

The original form of the Gurson model has been modified by Tvergaard and Needleman to more accurately model the evolution of porosity observed both experimentally and in refined unit cell computations in which the actual void geometry was modeled. Detailed FEM computations using extensions of Gurson's original model have provided significant insight into failure mode dependency on three dimensionality of the stress state and on distribution and volume fraction effects of void nucleating second phase particles. Figure 1. compares the ductile fracture modes observed in round and flat tensile bar specimens of a typical ductile steel alloy. For the round specimen subjected to an axisymmetric tension, diffuse necking down of the bar cross section is followed by a cup-cone type of fracture. For the plain strain tension test on the identical material, failure occurs in a localized shearing mode along the 45 degree principle shear plane, with very little necking of the cross section. Finite element studies of necking and failure in the round bar tensile test using a form of the Gurson model have properly identified the role the specimen geometry plays in determining the material failure mode. A crack forms in the center of the neck and propagates outward towards the free surface as is shown in Figure 2a, where the shaded region indicates material which has undergone a complete loss of stress carrying capacity. The tendency of the crack to zig-zag, in both experiment and computation, is a consequence of the shear localization being inhibited by the additional plastic work associated with the hoop strains that accompany shearing in the axisymmetric geometry. As the free surface is approached, this axisymmetric constraint is relaxed. This allows the shear localization mode to dominate and the cone failure surface to propagate to the outer surface. For the flat, plane strain specimen, the geometrical constraint associated with the axisymmetric stress state in the round bar does not exist. For this specimen, once a shearing failure initiates, it can propagate across the entire specimen as is shown in Figure 2b. A critical point is that the steel matrix material modeled in Figure 2 is continuously strain hardening and thus never sees a reduction of stress carrying capability. Failure and localization associated with decreasing stress capacity (strain softening) is solely a manifestation of the reduced area of material available to carry load due to the increasing porosity of the material. The results shown in Figures 1 and 2 clearly illustrate the important concept that material failure at the macroscopic scale is not simply a simple parameterization of material properties which can be defined and measured locally. Failure is by definition a propagating phenomena in materials when defined over a macroscopic domain. Detailed

Figure 5a

Regularly spaced contours of piezoelectric charge density, obtained from line load analysis. Contour a corresponds to a level of $-1.21 \times 10^{16} cm^{-3}$. The portion of the gate and substrate shown in this diagram extends 0.5um in the vertical direction and 0.8um in the horizontal direction.



computational studies are often the only route available to identify the interaction between geometric and material characteristics of failure.

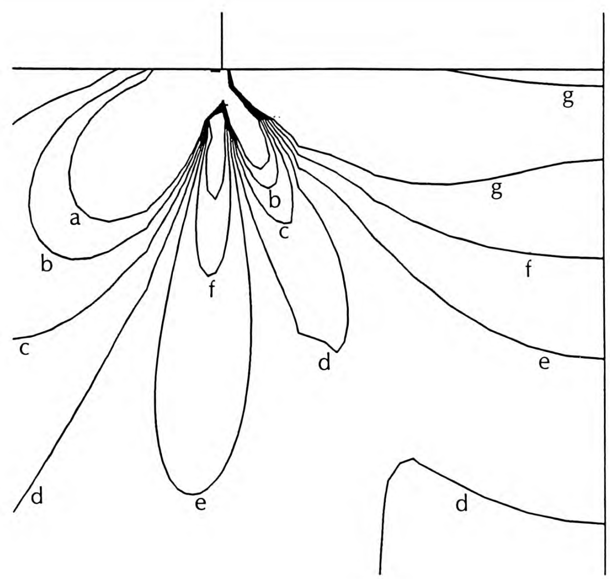
Void distribution effects were shown to play a significant role in the ductile fracture process in experiments by Dubensky and Koss[3]. Becker analyzed void growth and coalescence in a small volume element using a modified Gurson constitutive law, but with a nonuniform distribution of void volume fraction.[4] He found a significantly smaller fracture strain for a solid with a nonuniform porosity distribution than for a solid with a uniform porosity distribution and the same volume average porosity. The work of Becker, while modeling nonuniform porosity distributions, utilized the Gurson law locally. Since the Gurson law was derived assuming periodic arrays, Needleman and Kushner studied a porous plastic solid subjected to plane strain tension and containing a doubly periodic array of clusters of voids[5]. The void distribution within each cluster is random. Figure 3 shows one such distribution (cluster) and the predicted macroscopic stress-strain response for three distributions and a cell containing a single void giving the same total porosity. The directionality of the clustering distribution has its main effect on the aggregate flow strength. An increased density of voids along the 45 degree shear planes as shown in Figure 3a, gives a significant reduction in strength for the aggregate material. The magnitude of the strength reduction is also found to decrease with decreasing initial porosity. A clear understanding of the role of clustering of failure initiating sites in ductile materials is critical if quantitative constraints are to evolve for microstructure distribution control in modern 'engineered' materials. While materials are designed assuming uniform microstructural distributions, inspections always identify regions of highly non-uniform microstructure distribution. Computations such as just discussed can serve to set bounds on the limits of deviation from assumed microstructure which can be accepted as a function of the actual three dimensional stress state the material will see in service.

Failure In Composite Structures

Delamination growth is a common failure mode in structures composed of fiber reinforced composite materials. Delamination is associated with the propagation of crack like failure surfaces which develop between layers of fibers with different orientations. While delaminations have many char-

Figure 5b

Regularly spaced contours of piezoelectric charge density, obtained from FEM analysis for vertical gate sidewalls. Contour a corresponds to a level of $-1.41 \times 10^{15} cm^{-3}$. The portion of the gate and substrate shown in this diagram extends 0.5um in the vertical direction and 0.8um in the horizontal direction.



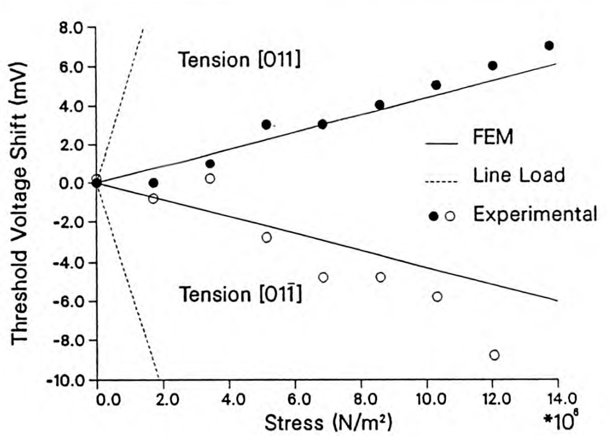
acteristics similar to cracks in homogeneous materials, they generally have far more complex stress states associated with the region of large stress concentration ahead of the 'crack' tip. Delaminations can often grow to lengths significantly greater than the material thickness before initiating unstable growth leading to structural failure. In the case of compressively loaded composite structures, the failure process is far more complex. The structural cross section at a plane containing the delamination actually appears as two uncoupled sections. If we consider a flat plate of thickness h loaded in its plane, with a delamination a distance b from its center plane, the plate would appear locally as two plates with thicknesses h/2+b and h/2-b. For compressively loaded structures, buckling is often a critical failure mode. The critical buckling load in a plate is inversely proportional to the thickness cubed. Thus, while the uncracked plate may not buckle, the delaminated plate and its two ligaments formed by the delamination might buckle under design stress levels.

Yuan considered the fully coupled problem of combined delamination growth, ligament buckling, and full panel buckling in a flat laminate with a small initial delamination[6]. It is important to recognize that the delamination growth is determined by singular asymptotic fields while buckling is a function of the global structural geometry. Thus, the calculations of Yuan must accurately couple processes whose characteristic length scales are orders of magnitude different. To accomplish this, he embedded local singular fields into laminate plate finite elements which account for the very large geometric rotations associated with buckling. In this way he was able to delineate the interaction of the failure processes and develop failure maps as shown in Figure 4. The overall failure behavior can be separated into several distinct regions. Figure 4 represents a failure map for a symmetric [+30/-30] laminate of thickness 0.06 inches and with outer ply thickness equal to 0.01 inches and inner ply thickness 0.02 inches. the delamination is assumed to exist between the at the interface between an outer and inner ply. As a function of the initial delamination length, 2a, different failure processes can be identified. If $0a<2a<0.31$ inches, the laminate buckles globally and collapse occurs when the buckling load for the unflawed plate is reached. When $0.31<2a<0.348$ inches, the ligament buckles locally and continues until collapse is reached with no delamination growth. For $2a>0.348$ inches, coupled buckling and delamination growth occurs. In the region $0.348<2a<0.5333$ inches, the laminate buckles locally. As load is increased in the postbuckled region, the curve of unstable delamination growth is reached. The large delamination opening stresses generated by the buckling deformation then cause the delamination to grow rapidly until it meets the stable portion of the delamination growth curve. As the load is further increased, the structure fails by a continuous growth of the delamination. For $0.533<2a<0.667$ inches, the failure is similar to the previous regime except that the local buckling proceeds directly to the stable delamination growth regime. Above 2a=0.667 inches, failure occurs directly by unstable buckling of the ligament.

The example just given illustrates again the complex interactions which occur between material and geometric (structural) characteristics when studying the macroscopic failure processes in structural materials. It should be clear that optimized materials can not be designed based solely on simple material characterizations if failure is to be considered as a design variable. Thus, as the demands on the structural design engineer become more refined, both in terms of strength and life cycle prediction, mechanics and materials engineering considerations become tightly coupled.

Figure 6

Plot of the relation between the threshold voltage shift and remote substrate stress, including experimental data. The gate length is 1um.



Mechanics Of Microelectronic Devices

Computational approaches are extremely important in areas of solid mechanics where nontraditional applications of mechanics often involve coupled processes between mechanical, chemical, thermal, and electronic phenomena. An interesting example of this can be seen in the work of Ramirez, et al on the prediction of piezoelectrically induced threshold voltage shifts in gallium arsenide, GaAs, metal-semiconductor field effect transistors, MESFET's[7]. They give a concise history of work since the early 1980's on the nature of short channel effects in GaAs MESFET's that depend on the orientation of the gate with respect to the substrate. Because it is piezoelectric, stresses caused by thermal processing or mechanical load will lead to residual charge fields in the GaAs which must be overcome in order to operate electronically.

Ramirez et al report a comparison of experiments and computations of the effects of mechanical stress on the dc electrical parameters such as threshold voltage for a specific MESFET. By utilizing a finite element model of the actual device, the could simulate in detail the interaction between the bonded semiconductor and metallic conductor. Previous studies had utilized approximate analytical solutions in which the load on the semiconductor due to mismatch between the metal and semiconductor was idealized as a point load normal to the semiconductor surface. Figure 5 compares the charge contours in the GaAs computed from the finite element analysis and those from the approximate analytical solution . It can be seen that throughout the entire region under the gate the FEM model predicts significantly smaller charge densities than the line load approximation. The FEM model also shows the secondary charge density lobes located closer to the center of the gate and the primary lobe confined to a region much closer to the surface than those predicted by the line load. Ramirez,et al also compared predictions and experiments on threshold voltage shift as a function of applied mechanical stress to a printed circuit board containing a chip. Their results are shown in Figure 6. Their results show the significant potential of computational analyses of coupled phenomena for designing optimal and reliable microelectronic devices.

While interactions of mechanics researchers and materials scientists involved in alloy and composite material development has a long and productive history, the opportunities for solid mechanics research to contribute in areas such as microelectronic device and material development is relatively new. The opportunities for scientific payoff are extremely great and represent one of the most exciting opportunities for researchers in solid mechanics.

Summary

In this article we attempted to give a very brief overview of contributions being made by the utilization of FEM analysis and large scale scientific computing in solid mechanics research which are outside the historically traditional areas associated with FEM applications. No attempt was made to be rigorous and complete on citation of references. The references included contain more complete citations and discussions. The work cited is representative of the research in the newer initiatives within the ONR Solid Mechanics Program. The work of Needleman, Becker, and Kushner was part of the micromechanics thrust, while the work of Yuan was done as part of the composite materials program. The cited work by Ramirez, et al is one of the first accomplishments to come out of the Micromechanics of Thin Films Program initiated by ONR in 1986. Ramirez' work at Brown University was performed as part of his Ph.D. thesis done under the supervision of Professor L.B. Freund. That of Becker was also done at Brown under the supervision of Professor A. Needleman and the work of Yuan was done at the University of Illinois under the direction of Professor S.S. Wang.

Solid Mechanics has historically been a field in which mathematical analysis was used to gain rigorous insight into experimentally observed physical phenomena. As technology progresses, the need to understand observed phenomena at more refined scales has made the class of problems for which purely analytical solutions are sufficient extremely small. FEM analyses will continue to grow in usage as a tool for fundamental research in solid mechanics.

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Authors

Alan S. Kushner is Professor of Mechanical Engineering at the State University of New York at Stony Brook. Prior to joining the faculty at Stony Brook, he was the Manager of the Solid Mechanics Program at ONR from 1983 to 1988. During his time at ONR, Professor Kushner initiated new program thrusts in the areas highlighted in this article. Alan Needleman is Professor of Engineering and Dean of the Division of Engineering at Brown University. Professor Needleman has been an ONR contractor since 1984 and his ONR supported research has contributed to the joint materials and mechanics composite interfaces thrust in addition to the micromechanics effort.

Active Control of Turbomachinery Surge and Stall

Robert J. Hansen
Office of Naval Research

The article below describes results obtained in an Office of Naval Research (ONR) program on active adaptive control of complex physical systems, formulated and conducted in close collaboration with the Air Force Office of Scientific Research. The results have far reaching implications for the design and operation of aircraft and shipboard gas turbines.

The world's largest jet transport plane is speeding down the runway for takeoff at the 1989 Farnborough Air Show. The left inboard engine begins emitting flames from its exhaust. The takeoff is aborted, and the engine is so seriously damaged that it must be replaced. A few months later at the Paris Air Show, an advanced fighter is executing near-ground maneuvers. At a critical point flame is observed at the engine exhaust. The engine loses power and the plane crashes. In the same time frame a Navy helicopter carrying a 4,000 lb. bomb load looses power in one of its two engines while hovering off the fantail of an ammunition ship at night. The bomb load must be jettisoned for the pilot to sucessfully land under the power of the remaining engine.

These are but three recent examples of a phenomenon called surge, a large-amplitude, low-frequency instability which limits the performance of all turbomachines as well as individual compressors. It can be thought of as an unstable, axisymmetric resonance in the engine or compressor, which occurs when the rotational speed exceeds a critical value or the distortion to the inlet flow becomes severe. To avoid surge and its attendant consequences all aircraft and shipboard turbines used by the Navy are operated in a suboptimal state, with attendant penalties in performance and fuel efficiency. This operating penalty is shown schematically in Figure 1, which is a plot of compressor pressure rise as a function of flow rate through the machine.

During the past year ONR sponsored research conducted at laboratory scale has shown the potential utility of active control concepts for attenuating surge. (Active control involves the use of one or more actuators which are driven with amplitude and phase to attenuate the unwanted phenomenon.) At Topexpress, Ltd. experiments have employed a 60hp Rover turbine engine with a centrifugal flow compressor and axial flow turbine. This engine was selected because it is sufficiently rugged to take into and out of surge without permanent damage. Pressure sensors were located just downstream of the compressor. Their output was supplied to a master controller which drove a valve regulating the compressed air supply to the combustion chamber. A schematic of this active feedback

Figure 1

Constant speed line for a compressor showing suboptimal operating point to avoid surge.

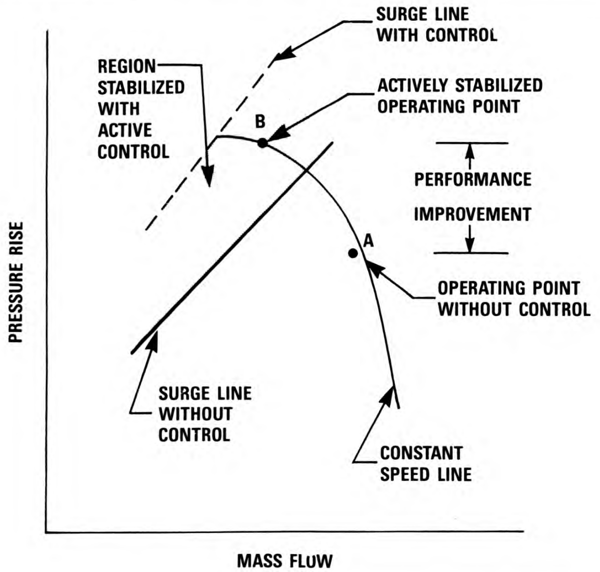
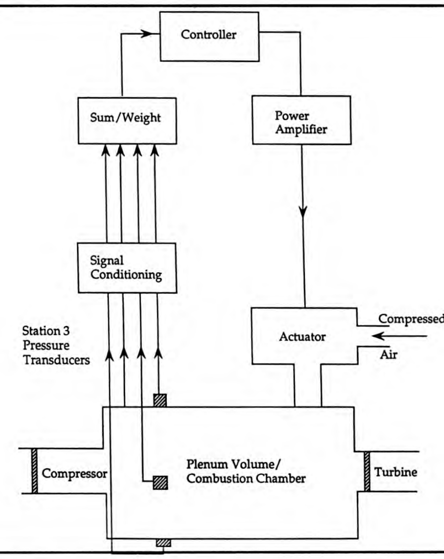


Figure 2

Control system schematic for active control of surge experiment.



control system is shown in Figure 2. Figure 3 shows the operation with active control off and on when the conditions for surge in this engine occur. With active control off the large low-frequency pressure oscillations (in this case measured just upstream of the combustion chamber) persist until such time as the engine is slowed to a small fraction of the speed at which surge began. In other words, surge is a highly hysteretic effect.

The exercise of active control, in contrast, is observed to pull the engine out of surge in a single surge cycle. Clearly the risk of engine damage is greatly reduced by confining surge to a single cycle; and reduction in thrust is momentary. With such safeguards the engine may be operated much closer to the surge line than would be othrwise possible. Moreover, the surge line may actually be moved to a favorable location, as shown schematically in Figure 1.

Figure 3

Pressure excursions in the engine caused by surge without and with active control.

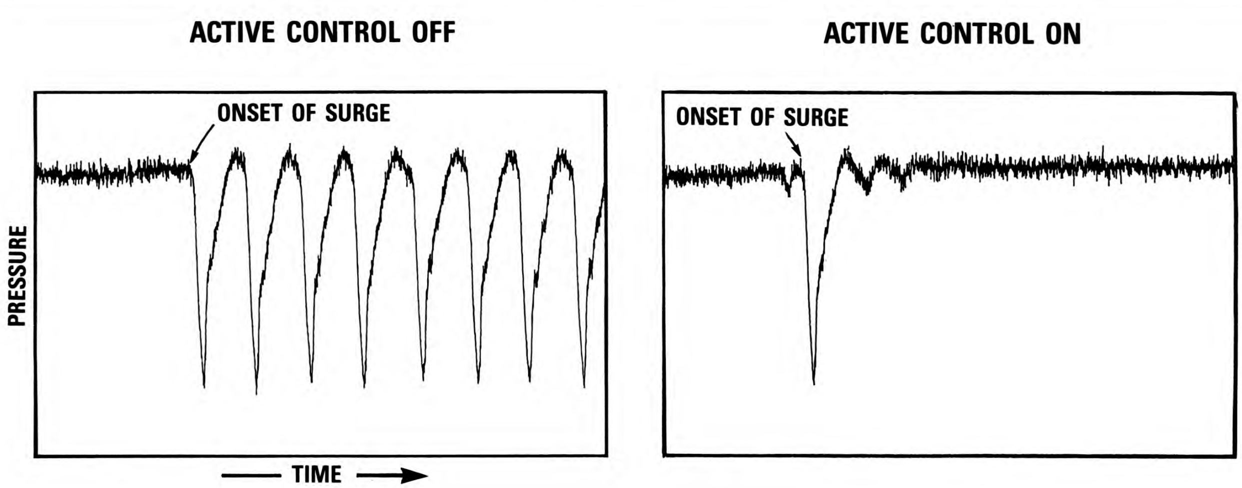
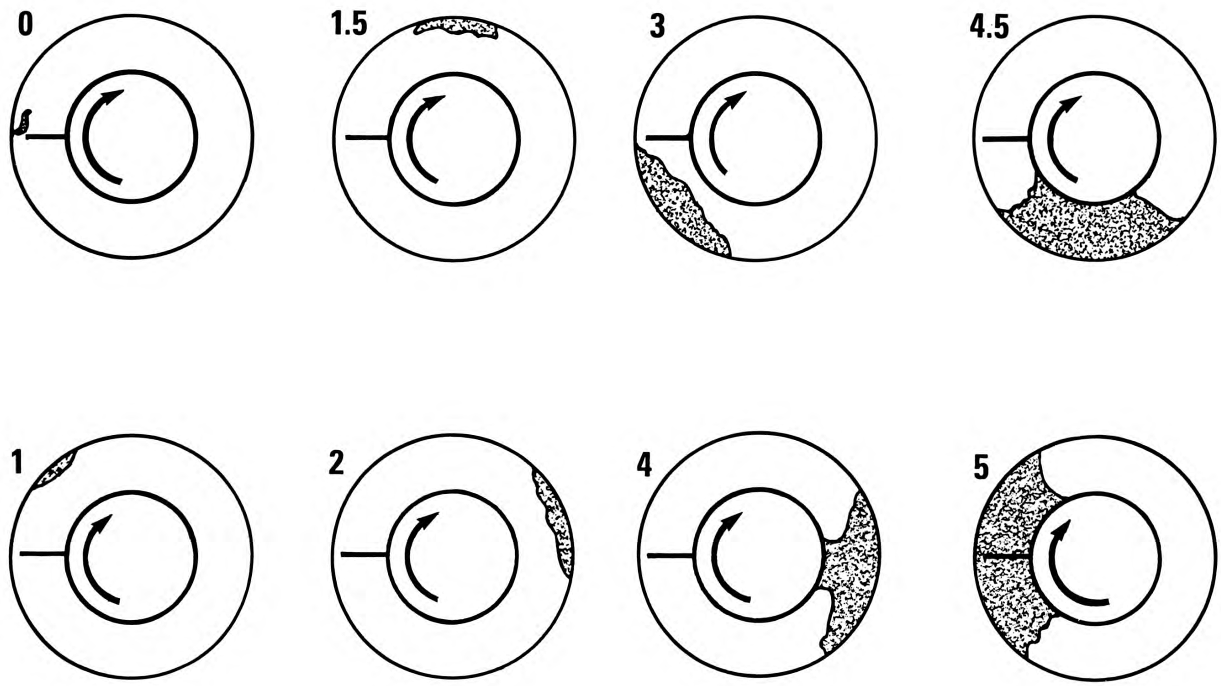


Figure 4

Growth of a rotating stall cell in an axial flow compressor (numbers refer to number of revolutions of the machine from the time that the rotating stall condition is exceeded).



A complementary investigation at the Gas Turbine Laboratory of MIT has focused on active control of rotating stall in an axial flow compressor. In this geometry the first instability observed takes the form of a small region where the flow on the rotor blades is stalled (lift is lost). This small region quickly grows and, if allowed to persist, triggers surge. Measurements of the stalled region are shown in Figure 4, showing its rapid growth from inception in five revolutions of the rotor. Rotating stall is a more spatially and temporally complex phenomenon than surge, and its control requires the use of many active elements. In the MIT experiments twelve independently moveable inlet guide vanes, distributed around the azimuthal extent of the machine as shown in Figure 5, are the actuators which operate under the control of a feedback control system. The control system utilizes the inputs from fluid velocity sensors near the compressor inlet to optimize the motions of the actuators for rotating stall attenuation. Results obtained to date are shown in Figure 6. The range of stable operations of the compressor is increased by 10% when only the first azimuthal mode of instability is controlled actively. Active control of the first two azimuthal modes increases the range of stable operation by a full 20%.

These experimental studies are accompanied by a range of analytical and numerical investigations to develop improved fault tolerant, adaptive feedback control strategies. For example, the utility of fuzzy logic for identifying faults in the control system/physical system combination is being investigated at Georgia Tech. Barron Associates is studying neural network architectures that are particularly well suited to feedback control of systems whose characteristics are either unknown or only partially known. The Naval Research Laboratory is examining how genetic algorithms might be used to provide fault tolerant feedback control. Cal Tech is investigating improved methods for system identification of open loop unstable systems (i.e., systems such as a turbomachinery component in the surge or stall domain). In all eight teams of investigators are studying the feedback control aspects of active control in close collaboration with Topexpress, MIT, and others who are doing experimental studies of physical systems for which active control offers the promise of significantly improved performance.

The potential payoff of active control of turbomachinery surge and stall is enormous to both the military and civilian sectors, offering the possibility of increased thrust to weight

Figure 5

Schematic of experimental setup to study active control of rotating stall in a laboratory scale axial flow compressor (front view – shows azimuthal actuator locations).

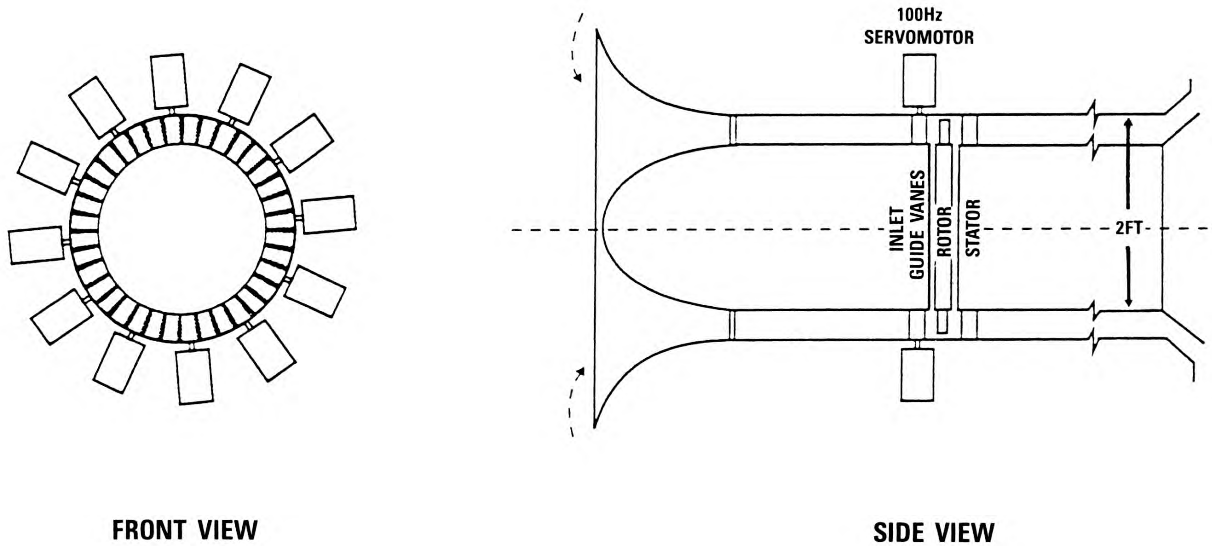
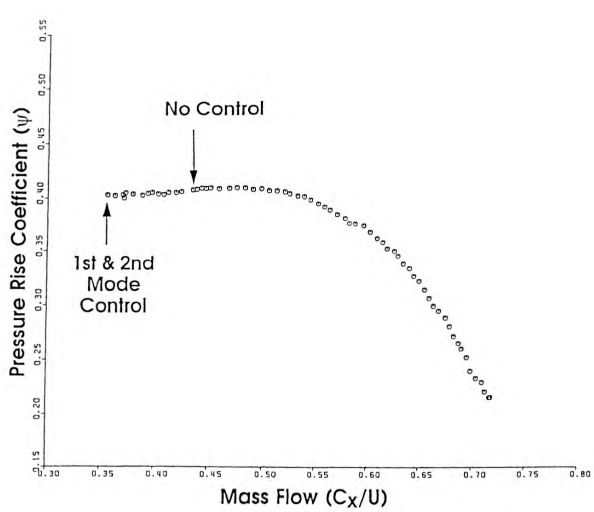


Figure 6

Constant speed line when active control is exercised, showing the extension of the stable operating range for control of first azimuthal mode and first two azimuthal modes of rotating stall.



The potential payoff of active control of turbomachinery surge and stall is enormous to both the military and civilian sectors, offering the possibility of increased thrust to weight ratio and reduced fuel consumption. To realize these benefits continued applied research and development will be required to (a) investigate a range of actuation approaches and identify those which are most promising for a given machine geometry; (b) scale up the results obtained to date to full sized, multistage machines; (c) optimize the combination of actuators, sensors, and control algorithms for fault tolerant control of surge and stall at these larger scales.

Biography

Dr. Robert J. Hansen has been the Director of the Defense Sciences Division of the Office of Naval Research since 1987. He came to ONR from the Naval Research Laboratory, where he conducted and supervised research in computational and experimental fluid mechanics, acoustics, and related areas. He received his undergraduate education at Stanford University and did his graduate work at the Massachusetts Institute of Technology.

Technology Transfer and Cooperative Research & Development Agreements

Joseph T. Bolos, Director of Acquisition
Office of Naval Research

If you are a Government scientist or engineer, imagine increasing your income by $100,000 per year! If you are a commander or technical director of a Government laboratory, envision potentially bringing millions of dollars in non-appropriated funds into your activity which can be spent in a myriad of ways! If you are a commercial company and know of an invention in a Government lab that can be commercialized, imagine going to that lab and, on an exclusive basis, entering into an agreement allowing you to commercialize and market the invention in exchange for payment of royalties! These are not hypothetical concepts but current events taking place in Government laboratories and organizations supporting research.

Many people believe that research under Government contracts is conducted for the sole purpose of satisfying the Government's needs. But is has long been a Government practice that in carrying out its research it will support the academic mission of American educational institutions. These institutions use the contract or grant funds in their laboratories, which also are usually paid for with Government funds, to provide a place for their students to practice what they learn. An additional goal for use of this research, which has recently been emphasized, is to commercialize it as much as possible. This supports the public good and keeps the United States competitive with other countries through results such as creating new products, new jobs and new ways to compete in world markets. This goal for commercialization of Government inventions is one of many activities under the umbrella of "technology transfer."

Most Government agencies, however, are not in the business of commercializing products. They don't have the people or the facilities to make and sell these commercial products. Those who are in the commercial business however have always been encouraged to look for Government inventions that have commercial potential. Success in interesting these companies to commercialize has been limited. So in 1980 commercialization of research supported by the Government was encouraged by Congress through passage of PL 96-480 and PL 96-517. This latter law is known as the Stevenson-Wydler Act of 1980. Further encouragement and coverage was provided by a later presidential Executive Order (EO). A change in 1989 by PL 101-189 added Government Owned Contractor Operated (GOCO) laboratories to the coverage under the law.

The PL's allowed small business and non-profits to retain title to inventions under government contracts or grants. The EO allowed all other commercial organizations to retain title. Now for the first time intellectual property rights in inventions made by the contractor's personnel could be retained under Government contracts even though the Government paid for the work. It also allowed the commercial organizations to patent and license those inventions. To obtain these exclusive reports, contractors had to agree to pursue patents. Of course the Government retained rights to use the inventions for Government purposes.

In 1986, an amendment to PL 96-480 extended similar rights to Government personnel in Government laboratories who had made inventions, owned by the Government, which had commercial potential. The law broadly defines laboratories as any government organization whose main purpose is research, development, or engineering. This 1986 change was named the Technology Transfer Act (PL 99-502) which amended the earlier PL 96-480. The intent of this later law was to assure that the results of appropriate Government technological inventions made in Government laboratories became available to states, local entities and the private sector for commercialization. The concept was similar to that under contracts; commercialize Government inventions through perusal of patents and/or government know how to assist the patent effort. But now the 1986 law was addressing inventions in Government laboratories made by Government employees. Specifically, the Act allowed Government laboratories and commercial partners to enter into Cooperative Research & Development Agreements (CRDAs). These CRDAs allowed arrangements for both the Government inventors and their laboratories to receive royalty payments on any commercial product that was developed and sold using their invention. It also allowed arrangements to be negotiated on any future inventions or patents as a result of an original idea or patent. This was a very strong incentive for both the inventor and the laboratory technical director to agree on commercialization of inventions or transfer of ideas and know how. These agreements allowed commercial partners to obtain rights to commercialize Government ideas on an exclusive, non-interference basis.

In 1989 as part of the Defense Authorization Act (PL 101-189) further changes were made to allow GOCO's to enter CRDA's. In order to do so the GOCO's director must obtain the approval of the sponsoring agency on the specific CRDA arrangement. This addition also provided protection from release of information under the Freedom of Information Act for five years after the information was developed pursuant to activities under the Act.

What are some of the inventions in Government laboratories that can be commercialized? How about new ideas like a better anti-fouling paint for ship bottoms, fire retardant material for Government fire fighters, personal communication devices for troops in the field, and new brakes for military aircraft? Can you see where these concepts that would support new Government products could also have potential for new commercial products? Commercial development and Government development can often be conducted in parallel.

Now let's look at these CRDAs a little closer. They are legal instruments authorized by the Technology Transfer Act which allow Federal laboratories to enter into agreements with other partners, including but not limited to, industrial partners. They contain provisions addressing the plan for commercialization and may include future payment of royalties. The laboratory inventor will receive a minimum of 15% of whatever royalty arrangements are negotiated, up to $100,000 per year, and more with presidential approval. The laboratory may retain most or all of the remainder of the royalties and can use the funds for a variety of purposes. The laboratories can use them to pay for expenses incidental to the administration and licensing of inventions; reward scientific engineering and technical employees; educate in mission R&D disciplines; or support activities related to licensing potential.

The Act allows each Federal agency to delegate authority to enter into CRDAs down to the directors of laboratories and provides that special attention be paid to small businesses when entering into a CRDA. Preference is given to collaborators who do most of their manufacturing in the United States.

The CRDA is not a contract nor a grant as they are defined in Federal procurement and assistance statutes. Therefore, it is not necessary to meet the conditions required by the Federal Acquisition Regulation (FAR) or the policies issued by the Office of Management and Budget for grants and cooperative agreements. Competition is not required. There are no dollar thresholds, and no minimum number of offerors or cost analysis requirements. There is no regulatory need to include any of the clauses required by the FAR, but some provisions may be required by other laws. However these CRDAs are contracts in every sense of the word. Some are more complex than Government contracts. There should be provisions to control a variety of issues such as data rights, property ownership, facilities sharing and usage, and rights to future inventions. The CRDA does create a legally binding and enforceable agreement so basic contract legal principles do apply although all the provisions of FAR are not applicable.

What is typically shared? Technology can be data or hardware. The Federal laboratories or their commercial partners may provide and share personnel, facilities, equipment and other resources. The Government laboratory and inventor can share the "know how" of the inventor and can collaborate on development of the potential of the invention. The Federal laboratory can not provide funds however. It can receive funds from one or more of its collaborating partners but can not provide funds.

Is anyone really doing this? Yes. Many agencies are taking advantage of this provision of law. Even before its passage, agencies like the National Aeronautics & Space Administration (NASA), the Department of Energy (DOE), and the National Institutes of Health (NIH) all had in their missions transfer of technology to the commercial sector. But since the passage of the Technology Transfer Act many other agencies have joined in becoming active in technology transfer to the commercial sector. They have issued policy statements and directives to their technical personnel and management and have created model CRDAs and patent license agreements. They have created, as the Act requires, offices who act as advisors for technology transfer. These are called Offices of Research and Technology Advancement or ORTAs. Their laboratories and inventors are already receiving income and royalties stemming from their CRDAs and patent licensing agreements.

How many agreements are there? Over 200 agreements are now in place since the 1986 law. Many (over a thousand) CRDA type agreements were placed prior to the Act. Since 1986 to 1989 over $4.6 million has been paid in royalties and about $1 million went to individual inventors. But this is only the tip of the iceberg since, typically, three to four years are required to generate royalties. So many of the royalty payments under the agreements since the 1986 Act are yet due.

How is the issue of patents covered under CRDAs? The Technology Transfer Act reaffirms the licensing to a contractor of Government developed technology through a patent license. It also permits the transfer of rights for future anticipated patentable inventions developed through the cooperative efforts covered under a CRDA. Thus, patents are the basis for technology transfer under Cooperative Research and Development Agreements. Under CRDAs the U. S. Government shall obtain at least a non-exclusive, irrevocable, paid up license to practice any invention or have the invention practiced throughout the world by or in behalf of the U. S. Government.

When developing a CRDA what are the typical concerns? There are many issues to consider. Some are who is providing facilities and/or equipment and who can use them. There are concerns for how will information, technology, or know how be shared, and who will perform what R&D activities. Also what are the funding arrangements (remember the Government cannot provide funds) to non-federal partners. Who has title to the property and who is responsible for damages? A major concern always is what are the exact intellectual property rights arrangements.

Now let's look at some current issues related to CRDAs. A common problem is the intellectual property rights related to software. It is probably one of the most difficult issues. While Federal laboratories can patent their hardware inventions (including related software in some instances) and exclusively license others to rights for commercial development, they cannot copyright stand-alone software. Under current law Government employee developed software is not protected. Since the economic success of so many projects depend on software exclusivity, or in fact are software projects that have commercial potential, companies are reluctant to take on these types of projects when substantial investment is necessary.

Further, there are slow procedures and complex CRDAs to contend with. Some agencies are having difficulty determining a "fairness" standard in notifying companies of available opportunities. While normal Government acquisition standards for competition do not apply, some open forum for disclosure of commercialization opportunities may be necessary. There also is a need for the government to announce this intent to grant exclusive rights to someone after an arrangement is negotiated but before it's awarded. In addition because these CRDAs are not standard contract arrangements, the clauses and procedures are something new and whenever the Government system deals initially with new things there are bound to be problems.

Finally, there are conflict of interest concerns to contend with. Occasionally, commercialization of an agency product with one commercial partner to the exclusion of others may be a particular problem to an agency who has a regulatory mission or whose mission requires open dissemination of information in equal manner to all of its constituents. Also personal financial interest in a CRDA can cause the Government inventor problems in dealing with the contractor partner on other projects. The sharing of royalties under a patent license under a CRDA by itself is not a conflict of interest but dealing with the same contractor on other project may be.

All of the above problems are being examined and possible solutions identified. Remember that technology transfer and commercial development of an agency's product have been practiced for some time by agencies having authority in their basic mission. The 1980 and 1986 laws gave emphasis to this practice and provided incentives for all Government agencies to enhance their technology transfer efforts. They also allowed contractors to retain rights to inventions under contracts if they pursued commercialization and also created institutions in the Federal Government to be advocates for technology transfer. The 1986 law allowed Government laboratories to enter into CRDAs to commercially develop their inventions or bring ideas to the point of patent. It also allowed them to grant in advance exclusive rights for commercialization of inventions developed under a CRDA.

The level of accomplishment of the Federal Government under the 1986 law varies but it is still relatively new. Some royalty arrangements so far have been substantial for both the inventors and their laboratories. While CRDAs are not easy to write, agencies using them have found the challenge to be small when considering the potential pay-off.

Author

Mr. Bolos has been the Director of Acquisition at the Office of Naval Research since 1983. He has authored several papers on contracting issues. He presented a paper on Technology Transfer at the 1989 Acquisition Research Symposium in Washington, D.C., sponsored by the National Contract Management Association (NCMA) and the Defense Systems Management College. This article is based on that paper.

Mr. Bolos is Editor of the Washington Chapter NCMA Newsletter, an associate instructor with the Florida Institute of Technology in their Masters program, an NCMA Fellow, and a frequent lecturer on contracting and personal improvement topics. He has worked part time for over five years with the Director of Defense Research and Engineering (Research and Technology) in streamlining the DoD contracting system for Science and Technology. He is currently a group leader under a Deputy Secretary of Defense Task Force for Laboratory Demonstration leading an effort to reform the small purchase and procurement systems of the Federal Laboratories and R&D Centers.

Research Notes

The Journal of Defense Research

Some members of the scientific and technical community of Government laboratories may not be aware that there exists a secret level quarterly technical journal that publishes important research contributions that cannot be published in the open technical literature. The *Journal of Defense Research (JDR)* is published by the Defense Advanced Research Projects Agency and is the only refereed journal for classified papers at the secret level. Papers in the Journal must conform to the highest professional standards and constitute significant studies that are likely to be of permanent value to defense, research, engineering, and technology.

In addition, the Journal serves as a permanent record of achievement on defense problems and allows proper credit and priorities to authors of classified research. The Journal also publishes comprehensive and authoritative reviews on specific subjects which bring together the results of research from diverse groups.

The Journal includes papers involving fundamental technical and conceptual analyses in which present and proposed systems, equipment, hardware, environment, and tactics are examined. It includes research results dealing with air, ground, or sea warfare. The Journal distributes about 1300 copies to cleared members of the DoD and to DoD contractors with appropriate need to know; surveys have shown that the readership numbers 15,000 to 20,000.

In the past few years, the JDR has published secret papers on a number of technical issues dealing with land, air, or naval systems, for example: monopulse radar countermeasures, submarine laser communications, fiber optic guided missile programs, neutral particle beam phenomenology, and others. In addition, some special issues have surveyed such subjects as high energy lasers and the Strategic Defense Initiative.

If you want to be added to the JDR distribution list, requests should be submitted to the Director, DARPA, 1400 Wilson Boulevard, Arlington, VA 22209-2308, Attention: JDR Program Manager, or telephone (202) 694-5919 or Autovon 224-5919. Application forms can be obtained from the same source.

The Journal is also interested in receiving classified papers in defense research. If you are interested in submitting a paper to the Journal, please contact the Managing Editor, Journal of Defense Research, Battelle, 1300 North 17th Street, Suite 1520, Arlington, VA 22209-3817 (phone 703-875-3340).

The Navy's Senior Scientific Advisors

The Navy's principal advisors in planning research and development programs is a small group of civilians collectively known as the Naval Research Advisory Committee (NRAC). NRAC consists of 15 persons preeminent in the fields of science and technology, university professors, heads of scientific laboratories, executives of high-tech companies, and at least one medical specialist.

NRAC has been in existence since 1946. Reliance by the Navy on the civilian scientific talent dates much earlier. The first advisory committee, called the Permanent Commission, was founded in 1863. Subsequent advisory committees utilizing civilian experience and skills to solve major technical problems followed. The best known of these was the Naval Consulting board, organized in 1915 under the chairmanship of innovative Thomas Edison. This board was established at the request of Secretary of the Navy Josephus Daniels to consider major problems of naval research and development, including not only such questions as new weapons and devices for submarine warfare but also the establishment of a naval research laboratory. Its membership consisted of Edison, and two members from each of 11 national technical societies. It functioned through its many subcommittees, such as those for submarines, transportation, production, organization, manufacture, and standardization. Its chief contributions were the screening of some 40,000 inventions submitted to the Navy during World War II and assisting the Navy in obtaining counsel from civilian scientists and engineers.

Out of more than 100,000 suggestions submitted to the government during the war, only 110 had sufficient merit to warrant detailed examination by the subcommittees and *only one* invention went into actual production. No clearer proof was needed than, in the development of new technologies, random ingenuity is no substitute for a systematic and scientific approach to the needs of the Navy.

During World War II, the scientific and technological talent of the nation was pressed to the war effort through the Office of Scientific Research and Development (OSRD), created by President Roosevelt in 1941. OSRD served as a center for mobilization of the scientific personnel and resources of the nation to "maximum utilization of such personnel in development and applying the results of scientific research to defense purposes." World War II was, in Winston Churchill's words, "The Wizard War," a conflict that was won largely by scientific and technological advances. The major weapons of the Wizard included radar, sonar, the proximity fuse, atomic energy, and data handling machines – the precursors of computers – for code breaking efforts. OSRD, however, was a wartime agency, destined to be disestablished as soon as the war was over. Its civilian scientists and engineers would then return to their peacetime pursuits in the universities and industry.

Near the end of the war a group of naval officers, with the support of eminent scientists, succeeded in persuading the Navy to respond to the expected postwar loss of technical and scientific expertise by establishment of a permanent naval research organization that would supervise Navy-side research and support civilian research and development. By supporting on a long-term basis civilian scientists at universities and in industry, the Navy would benefit from a constant flow of new knowledge. The Navy would not have to depend on mobilization of scientists in time of war when it would be too late to exploit new technology.

A proposal for the establishment of the present Office of Naval Research (ONR) was submitted to Congress. Greatly aided by the impact of the publication of "Science, the Endless Frontier," a report by the head of OSRD, that proposed a centralized federal research agency, the bill became Public Law 588 on August 1, 1946. ONR was to "plan, foster, and encourage scientific research in recognition of its paramount importance as related to the maintenance of future naval power and the preservation of national security."

The law creating the Office of Naval Research also authorized the Secretary of the Navy to establish a Naval Research Advisory Committee consisting of not more than 15 preeminent civilian scientists to advise the Chief of Naval Research on matters related to research. The Committee members were to meet at such times as specified by the Secretary of the Navy. The initial NRAC membership consisted of ten men who met for the first time on October 14, 1946. The initial members included such well known figures in science as Karl Compton, President of Massachusetts Institute of Technology; his brother Arthur Compton, a physicist at the University of Chicago; Detlev Bronk, President of the National Academy of Sciences; and Warren Weaver, Director for Science at the Rockefeller Foundation. These members and their successors represented three important sectors of the scientific and technological community of the nation: industry; government laboratories; and the academic community.

From 1946 through 1956 NRAC served principally as advisor to the Chief of Naval Research in developing the role and mission of the newly established Office of Naval Research. In 1956, the Chief of Naval Operations requested the Committee to intensify its activities on his behalf. Subsequently the Secretary o the Navy restated the mission of the Committee so that it now acts as advisor not only to the Chief of Naval Research but to the Secretary of the Navy, the Chief of Naval Operations, and the Commandant of the Marine Corps.

While the other services and the Department of Defense each have scientific research boards, NRAC, the smallest of these and the only one founded by statute, takes pride in being in many respects the most influential. Indeed, several major decisions of the Secretary of the Navy and the Secretary of Defense on major U.S. weapon systems can be traced directly to the recommendations of this small but important group of forward-looking Americans.

Improved Boiler Water Treatment To Save Navy $1 Billion

Navy researchers and engineers have developed a boiler water treatment system that is expected to save the Navy $1 billion in maintenance and man-hour service costs over the next 15 years.

The automated system is being implemented in all conventionally powered naval vessels that use steam propulsion. The savings was announced in a recent Quarterly Status Report of the Surface Ships Propulsion Systems Program.

The Navy started investigations into new water treatments to clean, in situ, the high pressure boilers aboard naval vessels in the late 1960s. Chemical research studies were performed at the Naval Research Laboratory (NRL), using tetrasodium ethylenediaminetetraacetate (Na_4EDTA), in water environments under extreme conditions of high temperatures and pressures.

Scientist in charge of the investigation at NRL, Dr. David Venezky, worked with Robert Dausuel of the Naval Ship System Engineering Station (NAVSSES), Philadelphia, Pa., to apply the chemical understanding developed in the laboratory to a successful application in shipboard high-pressure (1200 pounds-per-square-inch) Navy boilers.

After considerable research, tests, evaluations, and excellent results from four trial ships, the Chief Engineer of the Naval Sea Systems Command (CHENG-P), directed the implementation of a boiler water treatment based on an Na_4EDTA and hydrazine process. According to a recent CHENG-P Status Report, the USS *Constellation* (CV64), the USS *El Paso* (LKA), the USS *Forrestal* (CV59) and USS *William V. Pratt* (DDG44) are continuing to accumulate uninterrupted steaming hours using the new in situ treatment system. After up to 15,500 hours of operation, inspections of these ships to date show corrosion-free and deposit-free watersides without the need for further in-port cleaning. Prior to the introduction of the improved treatment, boiler cleaning was necessary after 1,800 hours of normal operation.

CHENG-P reports that 1989 inspections of the USS *Forrestal* and USS *Constellation* have found that the new treatment is effective in eliminating corrosion and deposits throughout the steam system; and deaerating feed tanks, boiler watersides, superheaters, main engines, main condensers, and catapult receivers. In addition, all surfaces were treated with the chemical.

Shipchecks for all conventionally-powered steam ships were accomplished last year with ship alteration materials being issued the first quarter of 1990. The introduction of the new treatment Fleet-wide began in the second quarter of 1990.

Dr. Venezky notes that, in 1967, NRL was requested to assist in the examination of Na_4EDTA as an improved boiler treatment process under operating conditions in a ship propulsion high-pressure boiler. NRL's study of Na_4EDTA, and its reactions in aqueous solution at high temperatures and pressures, resulted in the first report of the "thermal decomposition" of Na_4EDTA and its rates of "decomposition" in aqueous solutions. This report, notes Dr. Venezky, was encouraging and resulted in NRL assisting in testing, evaluating and developing the Na_4EDTA water treatment in collaboration with NAVSSES, Philadelphia, and in the early stages, with the Naval Ship Research and Development Center (NSRDC), Annapolis (now the David Taylor Research Center).

Dr. Venezky points out that the cooperation between three Navy facilities was instrumental in the achievement of a new Navy boiler water treatment. Basic research was accomplished at NRL and in the early stages laboratory results were tested on a developmental scale at NSRDC, Annapolis. Later, the boiler test facilities located at NAVSSES, Philadelphia, were used to study the treatment thoroughly and its control in an operational environment prior to conducting actual shipboard tests.

The success of the Philadelphia tests, which were substantiated by NRL-developed analytical methods, were followed by extensive tests of the Na_4EDTA treatment aboard the USS *Harry E. Yarnell* (DDG17). The results of this shipboard testing demonstrated that the use of Na_4EDTA to clean, in situ, high-pressure steam boilers could extend the normal 1,800 hours of operation between cleanings to 15,000 to 20,000 hours. In addition, the passivated surfaces within the steam systems treated with Na_4EDTA would be beneficial when boilers were shutdown for long periods of time.

Dr. Venezky says that earlier investigators, using organic chelating agents like Na_4EDTA for treating boiler water, failed to take into account the chemical reactions taking place under the extreme conditions within a boiler. Therefore, they were unable to control the in situ treatment. The inclusion of hydrazine by request of CHENG-P in current water treatment reduces the oxygen content in the boiler water and preserves the Na_4EDTA that keeps metal ions in solution rather than precipitating to form sludge deposits on the walls of the boiler.

Tech Base Notes

Described below is a synopsis of recent technology accomplishments sponsored by the Office of Naval Technology, which is the Navy research and development (R&D) organization responsible for conducting the exploratory development (6.2) category for the Navy. Exploratory development programs are conducted in industry, academia and in the Navy's own R&D centers.

Microchip Tagging of Maintenance Records

Under sponsorship of the Office of Naval Technology, the David Taylor Research Center has demonstrated the feasibility of using microchips to keep maintenance records of aircraft components right on the component itself rather than on paper files located in some remote location. Under the ONT project, microchip tags containing maintenance and configuration records were attached to key components of a CH-46 helicopter during an eight month period of operation. The data on each tag was periodically downloaded via a portable scanner. Application of this technology in the future is expected to reduce maintenance costs, improve inventory control and preclude the loss of certification data.

Expandable External Fuel Tanks

A project sponsored by the Office of Naval Technology has determined the feasibility of a process for rapid, at sea assembly of external fuel tanks by aircraft carrier crews. The process, developed by the David Taylor Research Center, involves welding of three stackable tank components and a pressure test of the finished tank. The combined time of welding and testing takes less than ten minutes. The disposable tank will require far less storage space than the current non-disposable wing tanks and the process can be easily mastered by the ship's crew.

PC-Based Map Generator

Existing shipboard tactical displays are capable of presenting limited skeletal outline versions of maps and charts showing only shorelines and country boundaries. Under Office of Naval Technology (ONT) sponsorship, the Naval Ocean Systems Center has developed a rapid (one-second) personal-computer-based, high resolution multicolored-map/chart display of range-scale or target offset following an operator's request. To date, a substantial subset of the World Vector Shoreline data base, approximately 40% of the estimated 40 Megabytes, has been converted from a vector to a compressed runlength coded raster form. Samples of the converted database and software have been distributed to approved contractors for further development. This data base is being used to demonstrate map presentations for the AEGIS Program.

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