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ELECTRONICS ENGINEERING DEPARTMENT

THRUST AREA REPORT FY 84

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Electronics Engineering Department Thrust Area Report FY'84

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Electronics Engineering Department Thrust Area Report FY'84

Abstract

This report describes the work of the Electronics Engineering Department Thrust Areas for FY'84: Diagnostics and Microelectronic Engineering; Signal and Control Engineering; Microwave and Pulsed Power Engineering; Computer-Aided Engineering; Engineering Modeling and Simulation; and Systems Engineering. For each Thrust Area, an overview and a description of the goals and achievements of each project is provided.

Acknowledgments

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Introduction

The Electronics Engineering Department's Thrust Areas combine research and development projects with state-of-the-art facilities to enhance staff productivity, to transfer technology within the Department and the Laboratory, and to exchange information with the outside scientific and engineering communities. The six Thrust Areas are:

- Diagnostic and Microelectronics Engineering
- Signal and Control Engineering
- Microwave and Pulse Power Engineering
- Computer-Aided Engineering
- Engineering Modeling and Simulation
- Systems Engineering

Thrust Areas ensure recognition of excellence in selected areas of importance to the Laboratory and are staffed at sufficient levels so that their effects are well focused and cost effective. The Thrust Area leaders are selected primarily on the basis of their technical expertise and are responsible for the Thrust Area's technical direction and accountability. Thrust Area leaders accomplish this goal, in part, by conducting frequent technical and resource reviews with the EE Department's program division leaders.

From the Thrust Areas, technology is transferred as capabilities and tools to our engineers and to Laboratory programs. This approach is proving to be cost effective, since a particular technology often has wide application. Furthermore, through our technology base, we continue to assist Laboratory programs in implementing unique capabilities, (e.g., image and signal processing systems).

Our Thrust Areas are highly interactive within the EE Department and with Laboratory programs. In addition, to stay at the forefront of technology, our personnel maintain contact with the outside scientific and engineering communities by sponsoring joint research projects with universities, by establishing relationships with leading industrial-technological centers, by hiring consultants, and by interacting with other research laboratories.

Exchange of information is a key function of the Thrust Areas. We have disseminated information by sponsoring technical working groups, by publishing journal articles, and by holding in-house workshops.

This Thrust Area Report gives several examples of how we have brought innovations and advanced technology to Laboratory programs and to the EE Department. We are dedicated to having a technology base that is responsive to present and future needs of the Laboratory.

E. A. LAFRANCHI
EE DEPARTMENT HEAD

I. Diagnostics and Microelectronics Engineering

Thrust Area Leader: J. W. Balch

Overview

The Diagnostics and Microelectronics Engineering Thrust Area conducts research and developmental work in several disciplines of microstructures that, generally, have applications for diagnostics of scientific experiments. The activities of the group involve work in silicon and gallium arsenide microelectronics, in silicon physical microstructures, and in integrated optics. Work in all these areas share a common tech-base in microfabrication technology--fabrication methods for producing structures with μm -sized features. Principal fabrication methods used include photolithography, chemical etching,

diffusion, and various thin-film deposition techniques. The demand for microfabrication research and custom components is growing rapidly at the Laboratory in R, Y, and Test Programs. These programs face an increasing number of diagnostic problems whose solutions involve custom components in the following areas: physical microstructures, high voltage semiconductor devices, very high speed microelectronics, custom VLSI, sensors and radiation detectors, and integrated optics (Fig. 1-1). One measure of the increased microfabrication activity at the Laboratory is the growth in the number of photomask designs used in the Microelectronics Facility to

Figure 1-1. The central tech base for the Diagnostics and Microelectronics Engineering Thrust Area is Microfabrication Technology.

develop new microcomponents for the Laboratory. For the past three years the number of photomask designs has increased at a 100% annual rate each year (Fig. 1-2). Along with this growth in the number of photomask designs, programmatic support to the Thrust Area has more than doubled to approximately 13 FTE and the staff has increased by about 50% to total 24. Of this total staff, thirteen have graduate degrees in EE or physics.

1984 Thrust Area Projects

The tech-base and Engineering Research projects whose reports are part of this final report have provided significant start-up support for many of the concepts and

technologies used in the programmatic applications of microfabrication technology. Several examples of programmatic applications have been included in the project reports. For 1984 the following projects were supported by tech-base and Engineering Research funds: (1) Gallium Arsenide Circuit Development, (2) High-Speed Solid-State Switches, (3) Gate Array IC Technology, (4) Microstructure Fabrication, and (5) Integrated Optics.

The Gallium Arsenide Circuit Development project conducted research on integrated-circuit linear amplifiers, hybrid-circuit linear amplifiers, and integrated-sample-and-hold circuits. An alternate structure for GaAs MESFETs was investigated for reduced sensitivity to parasitic back-gate biasing

Figure 1-2. One measure of the increased microfabrication activity at the Laboratory is the increase in the number of photomask designs used in the Microelectronics Facility to develop new microcomponents for the Laboratory. This figure shows that for the past three years the number of photomask designs has increased at more than a 100% annual rate.

effects that occur in GaAs ICs due to basic material defects in today's GaAs substrates. This new transistor structure, based on "p-ring" protections, showed encouraging preliminary results for transistors operated up to 40 V. This new transistor structure may provide significant improvements in the operation of GaAs linear circuits that must operate at much higher voltages than digital circuits. To complement the development of the integrated GaAs amplifier, we began a parallel development of a hybrid broadband amplifier. First versions of this amplifier demonstrated a gain of 10 and a 3 dB bandwidth of 1250 MHz. Also, a first design for a multi-gigasample/sec sample-hold circuit was completed and the preliminary performance of the first lot of circuits is reported.

The High-Speed Solid-State Switches project conducted research in both laser-triggered photoconductive switches and electrically triggered avalanche transistors. Using both analytical models and new fabrication methods, the dark current of photoconductive switches was greatly reduced. This led to the successful development of a 10-kV photoconductive switch presently used by Y Program for pulse-shaping applications. Also, improvements were made in pulse-generation circuits using avalanche transistors. By the end of the year a 1200-V, 200-ps risetime pulse generator was developed. Descriptions of both of these applications are included in the report.

The Gate Array IC Technology project completed the installation of CAD codes on the VAX computer network for automatic schematic capture and mask layout for a 5- μ m CMOS gate array IC technology. Most of these CAD tools and the CMOS gate array were exercised during an in-house training course offered during the spring of 1984 to Laboratory engineers. Several initial Laboratory designs for circuits to be built on gate arrays have exceeded the number of gates presently usable in a 5- μ m CMOS technology. Plans are underway to acquire a 1.25- μ m CMOS on sapphire technology (via RCA) that will have four times the density of the 5- μ m CMOS technology. This new CMOS technology should satisfy many of the Laboratory's circuit needs. Details of this work are described in the report.

The Integrated Optics project began its work to develop a wideband microwave to optical signal modulator built in lithium niobate substrate. A contract was issued for development of this device, and the first device delivered under this contract has been tested at low frequency. These test results are reported.

Microelectronics Facility

The Diagnostics and Microelectronics Engineering Thrust Area manages the Microelectronics Facility located on the second floor of Bldg. 131. This facility occupies approximately 6500 ft² of semiconductor processing and testing

labs. The facility contains photolithography equipment, diffusion furnaces, epitaxial reactors, plasma etchers, and an ion implantation system. For the design of photo-masks, staff personnel use a ComputerVision CADDs II layout system and a commercial CAD code (Silvar-Lisco) for automatic layout of gate array masks. The latter software runs on the EE Department VAX computer network. Design codes used by our staff include SPICE for circuit analysis, ILOGS for logic simulation, and SUPREM for process modeling. For the design of very high-speed GaAs MESFETs, an in-house developed 2D model code for gallium arsenide MESFETs is used.

Major additions to the facility this year included a new scanning electron microscope which provides routine pictures of the μm -sized structures developed in many projects. In line with the trend towards dry etching of semiconductor materials, we added two new plasma etchers to our equipment. Finally, the first of two clean rooms was delivered in the fourth quarter of 1984. The first one is a 250-ft² Class 100 modular clean room that will house our thin-film metallization stations. This room should be operational in early 1985. A second 500-ft² Class 10 clean room was delayed by the manufacturer and will not be delivered until the first quarter of 1985. This larger clean room will house our critical photolithography operations and should greatly enhance our ability to produce μm -sized features with

reasonable yield for our R&D and prototype production needs.

A serious effort was begun in 1984 to acquire a new facility to house our microfabrication laboratories. Working with an outside semiconductor facility consultant and Laboratory facility planners, we developed a set of preliminary building plans for a new building. Figure 1-3 shows a floor plan of the needed building. The total building occupies approximately 20 000 ft² and is divided into two sections--approximately 10 000 ft² will house the microfabrication laboratories and the other section, also approximately 10 000 ft², will house offices and light labs for a staff of 30. The plans will allow the building to be constructed and occupied in phases with most of the engineering staff remaining in Bldg. 131 offices until the last phase is complete. The first phase will be the critically needed microfabrication lab space. This part of the building will be outfitted with Class 100 modular clean rooms (approximately 3000 ft²) and has approximately 4000 ft² of floor space for locating the maintenance end of the microfabrication equipment in Service and Equipment (S&E) corridors. Locating the maintenance end of equipment outside the clean rooms is necessary for maintaining clean room conditions. The two new modular clean rooms presently being installed in Bldg. 131 and all of the microfabrication equipment in Bldg. 131 will be relocated in the new facility. A new building to

house our microfabrication labs is very important to the progress this Thrust Area will make in the coming years.

Figure 1-3. Floor plan for a proposed Microfabrication Building. The total building occupies approximately 20,000 ft² and is divided into two sections. Approximately 10,000 ft² will house the microfabrication laboratories and the other 10,000 ft² will house offices and light labs for a staff of 30. The microfab part of the building will be outfitted with Class 100 modular clean rooms (approximately 3000 ft²). A new building is critically needed to house the expanding size of our microfabrication effort and to remove constraints on the work done in Bldg. 131 because of safety and environmental constraints.

1. Gallium Arsenide Circuit Development

*Principal Investigators: S. P. Swierkowski, C. F. McConaghy,
L. F. Jelsma, G. A. Cooper, and A. S. Blum*

Introduction and Objectives

As weapons researchers expand the range of information from their experiments, they incur needs for faster information rates. Because of its mature technology and its ability to be fabricated into a variety of circuit forms for most integrated circuit applications, silicon has been the preferred material. However, interest is growing in gallium arsenide (GaAs) because the basic physics of GaAs favors its use in those diagnostic applications in which speed is the primary issue. The technical challenge lies in the comparatively primitive state of the GaAs technology, a condition arising from its relative newness, its smaller industrial base, and its potential for very high speeds.

The complexity of the GaAs materials chemistry and physics and the complexity of the behavior of the GaAs transistors generates a large number of challenging problems. For example, in contrast to silicon technology, GaAs research concerns a crystal composed of two different atomic species; consequently, the number of defect types and possible dopant atom behaviors are larger than in the case of silicon. The presence of two active conduction band minima makes device modeling too complex for known

analytic methods. The material itself is less stable than silicon at elevated temperatures (400°C and up).

Work on GaAs has expanded rapidly in recent years. DOD sponsorship of work in support of various radar and ECM systems was the primary means of progress. Two instrument makers also have sizable efforts. A limited variety of traditional digital circuits has become available from "merchant houses" for GaAs digital chips.

The Laboratory has several special circuit requirements which are neither of interest to the market nor to manufacturers at large. Our circuits tend to involve relatively large voltages and large signal swings with linearity a major issue. We tend to need lower than usual frequency response, high impedance inputs, protection from high voltage transients, and integrated combinations of digital and analog circuits.

Our long-term goal is to build a technological base that will permit the gallium arsenide project to supply special purpose gallium arsenide integrated circuits to the Laboratory experimental programs. Our immediate goals involve a high-speed multichannel sample-and-hold and linear instrument amplifiers.

a) to allow fabricating 3-gate MESFETs with 1- μ m lines and gaps.

- b) to add on-chip capacitors with low leakage ($< 1 \text{ nA}$),
- c) to improve processing, especially the high temperature implant anneal, for better reproducibility, yield, and minimal backgating.

2. Extend the processing technology

-
- Figure 1 is a logic diagram of a 3-state sample and hold circuit. It features a 74139 3-to-8 decoder with inputs B, C, and D. Input B is labeled 'SAMPLE & HOLD', input C is 'EXT. C', and input D is 'READOUT TRIGGER'. The decoder's outputs S1, S2, S3, and S4 are connected to a 3-state buffer. The buffer's output is connected to the 'INPUT' of a 3-state sample and hold circuit. The circuit includes a 100pF capacitor, a 10k resistor, and a 100k resistor. The output is connected to 'OUTPUT'.

1-7

arranged for computer-automated probe testing.

Integrated Instrumentation Amplifiers

1. Redesign the AMP series to improve stability and increase bandwidth.
2. Demonstrate operation in a fieldable package with voltage protection.

Hybrid Instrument Amplifier

1. Demonstrate gains and bandwidths exceeding 25x and 1 kHz - 1 GHz respectively.
2. Operate in a fieldable package.

Progress

Digital Sample-and-Hold

Process Developments. The most significant processing improvement was to extend the contact lithography to allow us to fabricate 3-gate MESFETs with 1- μ m lines and 1- μ m gaps. The mask vendor improved its quality and has gone down to 3/4 μ m on passive test patterns. This key component serves as a digitally-strobed linear-sampling gate and is shown in Fig. 1-5 before the polyimide dielectric coating and 2nd-level metallization.

Another key sample-and-hold component is the analog signal holding capacitor fabricated with polyimide dielectric. We fabricated

30 chips with 1/4 to 3/4 pF capacitors and observed no pinholes. The leakage currents were < 1 nA which is required for the system readout. This acceptable leakage is probably dominated by an extraneous pathway in the semi-insulating GaAs and is suspected as being extremely small through the polyimide directly.

The high-temperature-implant annealing process was improved by adding an additional arsenic source (InAs) and raising the temperature from 800°C to 850°C. For the first time, our processing showed conventional or typical backgating characteristics on some of the chips; for conventional, unscreened MESFETs there was negligible backgating effect until a threshold of about 12-16 V was reached. On the remaining chips, the backgating was reduced by a factor of 2.4. The new anneal process appears to improve the annealing conversion by about 20%. It also has reduced the diode series resistance by a factor of 3. The FET and diode ohmic contact resistances are unchanged and are excellent ($R_c = 100 \Omega\text{-}\mu\text{m}$).

Testing. Both the TEST1 process-control chip and the SAM1 sample-and-hold chip were fabricated this year. Testing has begun but is incomplete.

The TEST1 chips have been spot-checked manually and appear very good. We are waiting for the probe card for the auto testor. The data reduction software for these measurements still needs to be done.

The preliminary testing of the individual sampler sub-circuits on the SAM1 chips is very encouraging. In summary,

1. The average propagation delay of three 13-stage ring oscillators is 87 ps.
2. The average propagation delay of inverters in the strobe pulse generator is 136 ps ($FO = 2$).
3. A one channel sampling circuit has sampled an analog signal

($T_p = 2$ ns) with an external strobe pulse of FWHM = 260 ps, which is the fastest pulser we currently have.

The logic circuits work very well, but the logic levels are at +2 and -2 instead of the design value of +1 and -3 V. The one volt shift resulted from the dramatically improved diodes as a consequence of process improvement. As a result of this shift in levels, the fast strobe pulse was not generated and integration of the digital with the

Figure 1-5. The 3-gate sampling MESFET and the readout buffer amplifier on the SAM1 GaAs chip before the polyimide dielectric and second-level interconnect metal deposition. The 3-gate FET has gates $1.0 \times 100 \mu\text{m}$. The buffer amplifier SEM picture has the input/feedback FET on the left and the 3-diode level shifter in the middle third of the picture.

analog parts of the circuit was not done. The trivial addition of one more diode in the logic level shifter should allow us to integrate the digital and analog circuits, but this will require another mask set.

These preliminary results were obtained on several chips with four different implant profiles and gate recesses from 200 to 1800 Å so the circuit is remarkably parameter tolerant. Figure 1-6 shows one of

the tested chips; the darker regions surrounding the LLNL logo and the dual gate NAND circuit is the 1- μ m-thick polyimide dielectric. The SEM beam and the secondary imaging signal are attenuated by the polyimide, thus darkening the image in this outer region. The LLNL logo and the gates were fabricated simultaneously and are 1.0- μ m line-width Cr-Au Schottky barrier metal 0.3- μ m high.

Figure 1-6. SEM photos of one of the complete SAM1 GaAs chips; the darker region surrounding the LLNL logo and the dual gate NAND circuit is the 1- μ m-thick polyimide dielectric. The SEM beam and the secondary imaging signal are attenuated by the polyimide, thus darkening the image in this outer region. The LLNL logo and the gates were fabricated simultaneously and are 1.0- μ m line-width Cr-Au Schottky barrier metal 0.3- μ m high. The photo on the right shows a single gate MESFET; the 1.0 wide gate lies inside the dark chemically recessed (0.13- μ m deep) etch trough. The rough-textured ohmic alloyed contacts for the drain and source on the upper left and right are within an n⁺ implanted region which does not show and which forms the true boundaries of the conduction channel.

Integrated Instrumentation Amplifier

Three major topics were addressed: the development of a fieldable package, design changes to resolve the remaining problems of the IC amplifier, and the search for an alternate technology in backgating resistant transistors.

Package. A compact, fieldable package prototype was developed in collaboration with FTSD. The circuit board is shown in Fig. 1-7. The package had an integral power supply with low-impedance-filtered-power-supply leads on a PC board to which the ceramic chip carrier could be electrically connected by an elastic polymer ring with conductive

metal strips on its surface. The amplifier performance in this package was comparable to prior results. Problems with heat from the power supplies and the inaccessibility of the supply voltage adjustment knobs led to the conclusion that it would be desirable to separate the power supplies from the amplifier housing.

Design. Although moderate gain and voltage swing had been attained in FY 83, bandwidth was inadequate, power supply settings were delicate, and stability was marginal. A program of changes to understand and fix the remaining problems was undertaken.

Design Synthesis. The design

Figure 1-7. The amplifier carrying ceramic is mounted in the square opening. This combination is enclosed in a case similar to that shown in Fig. 1-8.

equations were reviewed, then adapted to allow removal of a potentially unstable source follower and enhanced to allow a form of phase margin to be specified. The revised design equations were coded to yield component values for a set of performance and design constraints.

Design Analysis. The SPICE network analysis code was modified to replace an existing (JFET) subroutine with a modified subroutine that better modeled the dc and small signal ac behavior of a GaAs transistor (MESFET). The output of the design code is linked to the SPICE code to predict the performance.

Design Changes. To increase stability, four design changes were made:

1. A potentially unstable source-follower with a capacitive load was taken out of the design.
2. The phase margin in the feedback loop was increased at the cost of bandwidth.
3. A resistor was added to the source terminal of all MESFET current sources to increase output impedance.
4. Increased component-to-component spacing and a wrap-around "n-ring" drain transistor were used to increase isolation between components. The placement of parts was rearranged to increase isolation between stages.

Process Changes. Three process changes were made. To enhance the durability of the IC, the MESFET gate metal was changed from Cr/Au to Ti/Pt/Au. To compact the design and eliminate any heating induced change after fabrication, the diode string anodes were formed with second level metal. This requires very accurate plasma etching of the opening dimensions of the dielectric layer. Finally, the sheet resistances of the MESFET channels were increased 20% to raise the drain-source breakdown voltage of the MESFETs.

The annealing temperature was raised and indium arsenide was added to the annealing capsule as a source of arsenic overpressure. The conversion efficiency increased by 20% and the resulting conversion was very uniform. There was some evidence of increased p-type surface conduction.

Chip Fabrication. During the fourth quarter we began the fabrication of the amplifier chip. Prior to starting, the required chip holders were modified to accommodate 2x GaAs pieces. This change allowed a larger number of amplifiers and process diagnostics on a waferette and allowed room for eventually adding voltage protection networks.

The initial run has been directed at learning to implement the new process. The measured sheet resistances were about 10% too low. Rather than correct this problem by restarting with a decreased implant dose, we decided to use this run to learn how to implement the remaining changes. After a

number of failures, we now believe that we can deposit the Ti/Pt/Au transistor gates reliably. In anticipation of the increased control of the plasma etch step that would be required, we allocated time during the third quarter to characterize our plasma etching. Etch rates on polyimide and photoresist were studied as a function of temperature. The variation of etch chamber temperature with time was measured at several power levels. A variation of etch rate with feature size was noted (bull's eye) and the amplifier mask layout was corrected for this. We are now beginning implementation of the final change, precise plasma etching, and anode deposition with second level metal.

Alternate Technology. Throughout this year, we have been examining alternatives to our present transistor design and fabrication.

The observed but not expected sensitivity of the amplifier performance (and in particular its stability) to certain power supply voltage settings suggests to us that backgate interactions (due to varying potential in the underlying "semi-insulating" GaAs) between components and between power supply buses and components are present. Based upon measurements of backgating test structures, we concluded that the model of undoped GaAs as an insulator was incomplete, and postulated the presence of a p-like surface layer, possibly processing induced. As a test of our theory, a modified transistor structure was designed and a test chip was prepared.

Figure 1-8 shows the new structure. Its major feature is a surrounding rectangular metal pattern which overlies and acts as a contact to a p-type implant.

Figure 1-8. The modified transistor has a surrounding rectangular ring of metal over either a p-type implant or an n-type implant. The surrounding structure also serves as the source electrode.

Figure 1-9. The drain to source currents (with $V_{GS} = 0$) is shown from 0 V, -10 V, -20 V, -30 V, and -39.2 V applied to the remote electrode. The surrounding n-type implant provides little isolation (a). The p-type implant provides much better protection (b) and only a very small change in the current is observed.

Hitherto unreported currents between the "p-ring" and nearby n-type areas of negative potentials prevented the planned tests, and more distant n- and p-type wells had to be used to evaluate changes in the back-gating. The protection afforded by a surrounding p-type structure was compared to that of an n-type surround. The change in the drain current vs drain-source voltage (with the gate-source voltage held at 0 V) as a remote electrode was biased to a negative voltage and was used as a test. The results were dramatically different as shown in Figs. 1-9(a) and 1-9(b). In the case of the n-type ring, Fig. 1-9(b), there is only a very small change in the current for the same applied voltages. The effect is similar for either n- or p-type remote electrodes. Clearly the surrounding p-ring result is excellent protection. Because of the limitations of this test chip design, more testing will be needed to fully evaluate the merits of this proposed structure. We are now revising the test chip design to correct the leakage current, to evaluate the modified transistor, and to provide the data required to implement an IC with the new transistor design.

We believe that if the outcome from these tests is favorable, this new structure will have commercial application in high-voltage, high-speed medium scale, commercial integrated circuits.

Hybrid Amplifier

To complement the development of the integrated GaAs amplifier work, we have been developing a parallel hybrid broadband amplifier. Recognizing the important need for this type of amplifier, we decided on a parallel approach to maximize the probability of success.

A broadband instrumentation amplifier with associated package and bias supply has been designed, built, and tested. Figures 1-10 and 1-11 depict the beryllium oxide substrate and completed package. The results of the test were impressive. As shown in Fig. 1-12, the gain is 3 dB down at 1250 MHz. At low frequencies the 3 dB point is 800 Hz. The output voltage swing was ± 6 V as shown in Fig. 1-13. The output voltage swing can approach 20 V and the offset voltage can be adjusted. The input impedance of the amplifier is 50 Ω and the output impedance can be changed to 50 Ω without appreciably affecting the output voltage swing or bandwidth. We had no stability problems with the amplifier. It is our opinion that the gain bandwidth can be considered improved.

We plan to incorporate in the design a voltage protection network. The objective will be to protect the amplifier from 1- μ s 500-V pulses.

Figure 1-10. The transistors, resistors, and capacitors are attached to a metalized, patterned ceramic; then, interconnected with wire bounds.

Figure 1-11. The fieldable package houses the hybrid ceramic, mounted on a PC board along with its power supply regulators and filters.

Figure 1-12. The gain function for the hybrid sampler is shown. Approximately 20 dB of attenuators is included.

Figure 1-13. The input and output waveforms for positive going (a) and negative going (b) pulses are shown. These waveforms are used for measuring amplifier linearity.

2. High-Speed Solid-State Switches

Principal Investigators: M. D. Pocha and J. C. Koo

Introduction and Objectives

There are many applications at the Laboratory and other DOE laboratories for fast electrical-switching devices. Most applications require devices capable of generating electrical pulses of several hundred to several thousand volts and tens of amperes with rise times in the range of 10 ps to 1 ns. Some examples of immediate applications in nuclear testing and laser fusion programs are in the following systems:

streak cameras, microchannel plates, electrical firesets, Pockels cells, optical pulse shaping, and general pulse and timing circuits.

Solid-state switches for these applications fall into two general categories: electrically triggered devices and optically triggered devices. Electrically triggered devices take advantage of fast avalanche breakdown mechanisms, which have time constants of less than 100 ps to several ns depending on the device structure. Optically triggered devices rely on the generation of electron-hole pairs due to optical stimulation, a very fast phenomenon occurring in femtosecond time intervals. Generally, optically triggered devices provide higher performance (higher voltage and speed) but require a relatively high power, fast laser to trigger, whereas electrically triggered devices are much easier to trigger

from low level electrical pulses. Both categories of devices are, therefore, of interest.

The overall goal of this project is to develop the capability to design and fabricate both electrically and optically triggered switches to meet the requirements of programmatic applications.

Specific goals during FY 84 were as follows:

1. To study pulse sharpening using avalanche diodes with the goal of generating greater than 1000 V pulses with sub-nanosecond rise time.
2. To study the dark leakage mechanisms in silicon photoconductive (Auston) switches with the goal of reducing the leakage current by about a factor of four at 10 kV pulse bias.

Progress

Avalanche Diodes

Our major accomplishments this year have been the development of a pulse-generating circuit which uses avalanche transistors and diodes to generate pulses of greater than 1000 V amplitude into a 50 Ω load, with rise times less than 300 ps, and the development of a one-

dimensional numerical model to enhance our understanding of the switching mechanisms. Considerable interest has been expressed in our 1000 V pulse generator by researchers within the Laboratory as well as

other laboratories. We expect to fabricate several more of these circuits for programmatic use.

Figure 1-14 shows a schematic diagram of the pulse generator which consists of two parts. The first

Figure 1-14. Schematic diagram of 1000 V - 300 ps pulse generator. The circuit consists of two parts. The first part (top) is a Marx-configured pulse generator using avalanche transistors to generate a relatively slow (~ 1 ns rise time) 1.5 kV pulse from a 400 V dc source. The second part (bottom) contains a pulse-sharpening diode and biasing components.

part is a Marx-configured pulse generator using avalanche transistors which essentially multiplies a 400 V dc source into a 1.5 kV pulse with relatively slow rise time (~1 ns). The second part is a circuit consisting of the pulse-sharpening diode and biasing components. A block diagram of the complete pulse

generator is shown in Fig. 1-15. The rise-time limiter is used to adjust the rise time of the pulse applied to the diode because we have found that a sharper, higher amplitude pulse can be obtained from the diode when the rise time of the incident pulse is lengthened to about 3 ns. Figure 1-16 shows a

Figure 1-15. Block diagram of 1000 V - 300 ps pulse generator. Note that between the two parts of the circuit (Fig. 1-14) is a commercial low-pass filter as a rise-time limiter. We find that a sharper, higher amplitude pulse can be obtained at the output of the diode if the rise time of the incident pulse is lengthened to about 3 ns.

Figure 1-16. Typical output pulse into a 50 Ω load from the pulse generator described in Figs. 1-14 and 1-15. Output swing is about 1.2 kV with a 10%-90% rise time of about 300 ps.

typical output pulse from this pulse generator into a 50 Ω load.

Development of this pulser has required very careful packaging. Much attention had to be paid to design of high-frequency stripline boards and to component mounting to prevent degradation of the pulse rise time.

The one-dimensional numerical modeling indicates that the fast-switching mechanism is basically a highly damped oscillation similar to that found in IMPATT diodes which have a physical structure close to that of these diodes. Our calculated results (Fig. 1-17) are re-

markably close in agreement with the measured waveform considering this is strictly a one-dimensional model. The magnitude of the waveforms match almost exactly. The primary discrepancy is in the frequency and amplitude of the oscillations. We plan to extend our model to two dimensions which will probably give us better agreement with experiment and also enhance our understanding of the mechanisms of the pulse-sharpening phenomenon. Once a good model is developed we will be in a position to vary parameters to determine the optimum structure for fabrication.

Figure 1-17. Comparison of experiment with numerical model of diode. One-dimensional numerical modeling indicates that the fast-switching mechanism is basically a highly damped oscillation similar to that found in IMPATT diodes. Modeling will help us to optimize the diode and circuitry for best overall performance.

Photoconductive Switches

Again, our efforts have been twofold; first, we have fabricated photoconductive switches for use in programmatic applications, and second, we have conducted a study of the leakage current in these switches as it is the primary area in which improvement is needed.

Twelve fabrication runs have been performed during the year to try various different designs and electrode treatments. These experiments have provided data for modeling and understanding the mechanisms of dark current leakage. The current leakage mechanism has been

identified to be primarily a charge-injection phenomenon. Several different techniques have been developed to reduce the charge injection which has resulted in an order of magnitude reduction of this leakage current (Fig. 1-18).

An analytical model has been developed to improve our understanding of the leakage current mechanism and to provide some basis for the development of techniques to reduce it. The transient behavior during pulse bias cannot be modeled by steady-state equations (Ohm's law). The time varying current flow during pulse bias consists of a fairly complex set of waveforms.

Figure 1-18. Leakage (dark) current vs bias voltage for silicon photoconductive (Auston) switches. The current-leakage mechanism has been identified to be primarily due to charge injection at the contacts. Several techniques have been developed to reduce this charge injection which have resulted in an order of magnitude reduction of the leakage current at 10 kV bias (curve 1 vs curve 5).

Figure 1-19 shows a set of these waveforms for three different bias voltages applied to switches we have fabricated along with the theoretical waveforms expected. There are some discrepancies but the overall behavior is fairly accurately described by our model.

In the process of understanding and improving the leakage current, we have fabricated enough switches to provide Y Program with useful devices to incorporate into pulse-shaping circuits for NOVA (Fig. 1-20).

We have explored the fabrication of custom wide-band plastic

packages for these switches using the facilities of the Precision Shop and Plastics Shop at the Laboratory. This work should also benefit other projects in the Thrust Area which will require special packaging to get high frequency or fast rise-time signals in and out without degradation.

Publications and Presentations

1. Benzel, D. M. and M. D. Poeha, "A 1000 Volt 300 Picosecond Pulse Generation Circuit Using Silicon Avalanche Devices," submitted to Review of Science

Figure 1-19. Comparison of the leakage-current transient to our model. An analytical model has been developed to improve our understanding of the leakage-current mechanism. There are some discrepancies but the overall transient behavior is fairly accurately described by our model.

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2. Koo, J. C., G. M. McWright, M. D. Pocha, and R. B. Wilcox, "A Low Leakage 10000-V Silicon Photoconductive Switch," Applied Physics Letter **45**, 1130-1131; Lawrence Livermore National Laboratory, Livermore, CA, UCRL-90893 (1984).
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Figure 1-20. Typical electrical waveform from a charged line pulser using our silicon photoconductive switch. The pulse amplitude is approximately 5000 V (half the charge line bias voltage). These switches are currently used by Y Program in pulse-shaping circuits for NOVA.

3. Gate Arrays

Principal Investigators: W. G. Magnuson, Jr. and J. C. Davidson

Introduction and Objectives

The objective of the Gate Array Project of the Diagnostics and Microelectronics Thrust Area is to develop a capability for electrical engineers to design digital systems directly on silicon. Gate-array integrated-circuit technology focuses on the diversity of digital design projects and design approaches, the very low volumes of circuits needed, and the required fast turnaround.

For the past two-and-a-half years we have been developing a capability to support gate arrays from the design phase to the final tested and packaged stage. The project has developed several tools which range from logic simulation through layout to testing. We have introduced the technology to design engineers through seminars and two courses.

Figure 1-21 shows the major steps from a digital design to a finished, packaged integrated gate-array circuit. We have been working in all of these areas. In the sections below, we describe progress made in FY 84.

Progress

Figure 1-21 is used as an organizational guide in the following discussion. It represents the flow of operations in the design of integrated-circuit gate arrays.

Schematic Capture

At the Laboratory, digital designs almost always take form as a schematic. In the gate-array project we have been using the input to our digital logic simulator as a point of entry. This required a manual translation from a schematic to a text language input. Particularly for large designs, it was difficult to keep errors from creeping into this manual process. Because we were using an interactive graphics system connected to the VAX computer for the layout system (described below), we evaluated schematic entry software systems running on a Tektronix 4115B/VAX interconnection. However, we also considered personal computer schematic entry systems as they matured. Late in FY 84 we acquired a CASE Technology, Inc., IBM PC-based schematic capture system. Figure 1-22 shows a plot from this system. We are currently interfacing the output reports from the CASE schematic system to our other computer aids. We have developed interfaces to the RCA/Army VCAUA gate array, to the Silvar-Lisco GARDS system, and are working on the interface to the new SILOS logic simulator.

GARDS

We purchased and installed a Gate Array Design System package

Figure 1-21. Gate Array Design Flow shows the general sequence of operations from entering a design schematic through simulation, layout, fabrication, testing, and packaging. The entire process can be as short as one week.

Figure 1-22. Schematic diagram from CASE Schematic Capture System. The CASE Technology system runs on an IBM PC computer schematics. Drawings can extend over many pages with the system automatically keeping track of the signal connections. CASE information about the design is transferred automatically from the PC to the VAX computer for further processing.

developed by Silvar-Liscon to automate the layout placement and routing of the SPI7010B CMOS gate array. Installation of GARDS was an involved and exacting task because the explicit architecture of the SPI gate array had to be entered into the layout system's data base. Also, a library of components had to be encoded which matched an existing library on the ComputerVision (CV) system because GARDS, a VAX-based program, generates a tape output to the CV system for writing of the final PG-tape.

The input to GARDS is a netlist of the circuit to be realized. This netlist is currently generated as an output of our logic simulator, ILOGS. (We have recently installed SILOS, the updated rework of ILOGS.) The netlist generated by ILOGS (SILOS) is massaged into GARDS input format by a translating program written in-house. Once the netlist has been entered into GARDS, the circuit layout may be started by placement of its components. Placement can be performed manually, automatically, or a combination of both. (See Fig. 1-23 for an example placement plot.) Upon completion of placement, the circuit is ready for routing. Routing is done as a batch process. GARDS attempts to obtain a 100 percent completion of routing. If it is unable to completely route a design, it saves a list of nets to be routed. At this point an operator may interactively complete the routing. Currently, when a design has been routed, another GARDS subprogram is called to write a CALMA format tape containing the

design and is then read by the CV system. As noted earlier, the CV system is used to fracture the design file and to produce a PG-tape which is then sent out for mask making. The CV system is also used to generate plots of the completed designs. (See Fig. 1-24 for the final layout of the Davis Tester Chip.)

At present, our networking of ILOGS (SILOS), GARDS, and the CV system allows a circuit designer to construct a circuit comprised of basic logic gates such as inverters, ANDS, and NORS as well as larger building block components such as D-flip flops. The designer may construct any larger macros as long as it is composed of the components contained in our gate-array library.

Fabrication

We produce gate-array circuits in-house with the sole exception of the mask-generation step which is done by an outside vendor. Once we have the mask we fabricate the actual IC. Until recently we designed our gate arrays using a standard single-level 5- μ m line photolithography process. We discovered, however, that with the added edge and power of the gate-array layout tools, much larger and denser circuits are within the designer's reach. Two class design projects demonstrated the increase in complexity (discussed in the following section). These designs cannot be realized using a 5- μ m technology. To accommodate this increase in density, we developed

Figure 1-23. Placement plot from GARD5 Layout System showing the I/O pads around the periphery and blocks inside representing inverters, flip-flops, and logic gates. This drawing is from a Versatec plotter for quick checks and later reference.

the capability of a 3- μ m line technology. The development of this technology is an ongoing project. We are investigating and adapting the procedure for a lift-off technique used in GaAs circuit fabrication. The process behaves much differently in a silicon-based technology. The main problem is the development of a lip in the photoresist step. Four pictures illus-

trate the basic problem and the desired effect. Figure 1-25(a) shows how metal lines are missing and appear broken. Figure 1-25(b) demonstrates the "flagging" of the metal lines. These conditions are unacceptable for producing reliable if at all functional devices. These are the result of an insufficient "lip" definition in the photoresist step. Figures 1-25(c) and 1-25(d)

Figure 1-24. Final layout and routing from the ComputerVision shows the power and ground metal, the "internal" metal connections of the macros (building blocks), and the metal connecting the macros (routing). On intergraphics system, different colors are used to distinguish the different types of metal and other features.

(a) Sheared metal contact

(b) Metal with 'Flagging'

(c) Photoresist without 'lip'

(d) Photoresist with 'lip'

Figure 1-25. Scanning Electron Microscope (SEM) pictures of 3 μm metal and photoresist patterns. Because of greater routing densities on the design, we needed feature sizes of 3 μm place of earlier 5 μm . Consequently, the photolithography process needed to be refined. The SEM has proven invaluable in developing a new process. See the text for a description of the features shown in the above photos.

depict photoresist without a lip and with a lip, respectively. Research and development of this fabrication technology is continuing in our processing lab. As shown, a lip structure has been obtained but the processing steps involved have yet to be optimized. The investment in this necessary fabrication research will pay off when we obtain the new RCA CMOS/SOS 2700-gate array wafers which require 3- μ m line interconnect metal.

Testing and Packaging

The important area of IC testing is becoming increasingly complicated. Currently, when using the SP17010B gate array, it is necessary to be able to probe 76 I/O pads. (The coming RCA array has 132 I/O pads.) A probe station containing a probe card with a planar array of probes is positioned over the wafer containing several die (typically we design on quarter wafers containing 22 possibly functional die). The probes are connected to a Tektronix digital analyzer (DAS 9100) which generates and acquires signals with clock rates up to 25 MHz. The test vectors used are generated by a subprogram in our logic simulation. These vectors ensure some arbitrary percent of functional testing of the devices. Until recently these vectors had to be meticulously entered into the DAS 9100 via a rather complicated keystroke entry. As a means of further integrating our gate-array design capability, we purchased and

are currently installing a UNIX-based Tektronix software package which will allow the test vectors to be entered directly from VAX-based ILOGS (SILOS) files. This program also serves to store the acquired data on the VAX for further manipulation and output. As mentioned earlier, the increased I/O count which parallels the degree of integration in even larger gate arrays poses serious problems and difficulties in testing. In an effort to address the problem of increased I/O test wiring difficulties, we have worked with the University of California, Davis, in designing a gate-array circuit which will aid in assuring proper probe/pad contact. Dr. K. Wayne Current and graduate student Forrest Edwards designed a gate-array circuit which sends out a pulse to each of the I/O pads. This pulse, when acquired by the DAS 9100, ensures good contact has been made and serves to identify which test leads are attached to a particular pad. This chip, called the Davis Tester Chip, is used as the example design taken through our normal design process. Its placement and routing plots are shown in Figs. 1-23 and 1-24. A portion of the output seen on the DAS 9100, when this circuit is operating, is shown in Fig. 1-26. Note the pulses appear sequentially, indicating the relative pad position. The acquisition line/pad connection information is also contained in this output.

Once a design has passed wafer testing, the wafer is diced; the functional die are mounted and

bonded in one of a variety of packages in our process lab. Upon completion of packaging, parts are returned to the test set-up for final testing. After parts pass this test they are released to the original designer for use in the designer's system.

Communication

During FY 84, we taught a valuable ten-week course to twenty Laboratory design engineers. The course met three times per week for one hour, plus a 2-3 hour laboratory session. The course objectives were (1) to develop a familiarity with the capabilities and limitations of CMOS gate arrays and (2) to move designers toward designing on silicon.

The course introduced the advantages, disadvantages, and capabilities of gate arrays. To meet this

objective, we assigned team projects. Those projects required the development of our automatic layout and routing system described above. By the end of the course, each team member had been exposed to the critical stages in the actual gate-array implementation of a digital design.

Future Directions

There is continuing pressure to meet the needs of high speed and high levels of integration in digital (and analog) circuit design. We will be involved in bringing the new RCA CMOS/SOS 2700-gate array on-board in the coming months. As indicated above, we are working to have an optimized 3- μ m line process which will enable us to design on these wafers. With this new gate array, designs of up to 2160 gates will be automatically 100 percent

Figure 1-26. Tektronix DAS-9100 Tester Output. The "staircase" pattern are pulse inputs at each of the output pins and verifies that not only does the circuit work but shows that the tester probes are functioning correctly which is the primary purpose of this chip design.

routed. This array is capable of obtaining circuit speeds in the range of 40-400 MHz.

We plan to introduce the improvements to the gate-array project (CASE schematic entry, SILOS simulator, VGAUA layout system, RCA/Army VGAUA, etc.) by presenting several short courses to the forty participants of the two earlier gate-array courses. We will also actively solicit program designs applicable to gate-array implementation and assisting the design engineers.

We will be completing the interfacing of the CASE schematic entry system to our other computer programs. Our integrated system will include: 1) SILOS, 2) VGAUA, 3) Silvar-Lisco GARDS, 4) SCOAP, and 5) the SCALD Timing Analyzer.

The SCOAP program is a testability analysis program written at Sandia, then rewritten at Bell Laboratories. It will be used in conjunction with SILOS to develop effective test patterns for testing digital circuits. Test patterns will be automatically coupled to the Tektronix DAS-9100 tested through a VAX link.

The Timing Analyzer program will provide a very useful program in design verification. Together with SILOS, it should help the integrated-circuit program and general digital design.

The primary emphasis of FY 84 has been to complete the integration of a complete in-house gate-array design capability. Upon the introduction of the new RCA array, our efforts will turn toward facilitat-

ing the realization of several applications. We will also continue to maintain a close link with engineers/designers in terms of introducing gate-array technology and capabilities at the Laboratory through a series of seminars and courses.

Long-term activities in these areas may well encompass the investigation and acquisition of higher speed array technologies and perhaps even analog arrays. These activities will, of course, be derived from the needs of designers at the Laboratory. Not all designs need the advantages of size offered by gate arrays. To this end we have started the development of a Programmable Array Logic (PAL) capability. We have ordered a development system for 300-gate PALs which includes software and programmer. This system will be interfaced to the CASE schematic capture system.

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4. Microstructure Fabrication

Principal Investigator: D. R. Ciarlo

Introduction and Objectives

In our EE Microelectronics Facility, we fabricate microstructures (typically with dimensions measured in μm) using integrated circuit technology. During this past year, we continued to experience an increase in requests for microstructures from various programs throughout the Laboratory. They are used as targets or diagnostic devices in physics experiments.

The overall objective is to develop in-house microstructure fabrication capability to respond to the needs of the programs. We do this by working on current programmatic needs while simultaneously developing new and useful fabrication procedures. There is considerable motivation for an in-house fabrication capability since the microstructures requested are usually one of a kind and not commercially available. In most cases, the requesting physicist works closely with us to produce the final part. Since the Microelectronics Facility is run by the Engineering Research Division, we are not a captive organization and can easily respond to requests from any program. In addition, any process developed for one program becomes immediately available to all the others.

During FY 84, the objectives of the project were as follows:

1. To fabricate x-ray laser target components for R Program using the anisotropic etching of silicon.
2. To supply Laboratory programs with microstructures.
3. To develop our microstructure fabrication capability.

X-Ray Laser Targets

This was by far our most ambitious microstructure project to date. We worked closely with Target Assembly Group of Y Division to fabricate targets for a series of x-ray laser experiments on the Novette laser. Parts were produced by anisotropically etching thin silicon wafers using photolithography to pattern the wafers and silicon nitride to mask them during the etch. We took advantage of the preferential etch rate of certain etchants, such as potassium hydroxide (KOH), on the various silicon crystal planes in (100) oriented wafers. Figure 1-27 shows a cross section of the gas-type x-ray laser target. It consists of five parts: a center channel with thicknesses ranging from 40- to 100- μm ;

two vacuum windows with thicknesses of 50 μ m; and, two flashlamps with thicknesses of 200 μ m. Both the vacuum window and the flashlamp parts used thin free-standing silicon-nitride membranes, 1500-Å thick, as x-ray windows. These thicknesses were determined and given to us by the target designers.

Figure 1-28 shows a plain view of the five parts, along with a composite of all five. The small square holes were used as either vacuum holes, glue holes, or pump-

outs. The vacuum holes were used to hold the parts together during assembly. An adhesive was poured into the glue holes to hold the parts together after assembly. The pumpouts in the flashlamp parts were used to maintain a vacuum in the chamber between the vacuum window and the flashlamp. The thin vertical lines noticeable in the channel part were v-grooves etched into the silicon wafer. These were used to feed gas to the channel from one side and to measure the pressure of

Figure 1-27. Cross section of the gas-type x-ray laser target. Five thin silicon parts were used. One channel, two vacuum windows, and two flashlamps. Pump x-rays enter the laser cavity from left to right. Coherent x-rays exit into and out of the laser cavity shown in this figure.

the gas from the other. A scribe line was etched in the side wings of the channel so this wing could be snapped off after assembly and provide an exit hole for the laser x-rays. Many of the design features shown in Fig. 1-28 were driven by assembly considerations. We made a number of design changes during the project to increase the yield of fully assembled targets. Figure 1-29 is a photograph of the five finished parts. We eventually delivered enough parts to fabricate over 100 targets.

In this project, the benefits of using photolithography became obvious to us very early. First, it allowed us to etch the small features (few μm) required at the desired tolerances (sub- μm). Second, it allowed us to batch fabricate the parts. Figure 1-30 shows the outline of a 76-mm silicon wafer with 12 channel parts printed. Typically, we ran six wafers per run. It took two days to process these wafers. In two days, we were able to produce 6 x 12 or 72 channels, assuming a 100 percent yield. Toward the end of the proj-

Figure 1-28. Computer drawing of the five silicon parts used in the gas-type x-ray laser.

Figure 1-29. Photograph of the five parts used in the gas-type x-ray laser target. Each part is chemically etched from a thin silicon wafer.

ect, our yield was 90 percent for channels, 80 percent for vacuum windows, and 70 percent for flash-lamps. The somewhat lower yield for the vacuum windows and flashlamps was caused by breakage of the 1500-Å thin windows.

The most interesting benefit of the use of photolithography, and one we did not anticipate, was that it allowed rapid design changes. As mentioned earlier, much of the design was determined by assembly problems. When an assembly problem did occur, we were able to quickly change the design. Our photomasks, used to do the etching, were planned on a computer-aided design system. Typically, a design change could be drawn on the computer in 2 to 3 hours. It then took 3 to 4 days

to get a new photomask from our mask supplier at a cost of \$520.00.

Assuming a two-day wafer-process schedule, we implemented a design change and delivered new parts in 5 to 6 days after the design change was requested.

The above discussion concerns primarily the five-part gas-type laser target. We also fabricated other components for the x-ray laser experiments. Figure 1-31 is a photograph of the parts used in the "ladder" target. This target consisted of two of the ladder parts separated by a spacer. The ladders were 100- μ m thick, while the spacers were either 50- or 75- μ m thick. Figure 1-32 shows an end cap with alignment cross hairs. This part was used on several types of targets

Figure 1-30. Computer diagram of how 12 channel parts were etched on a 76-mm diameter silicon wafer.

and was usually made from 100- μ m thick silicon. The size of the square center hole in these end caps could be easily changed to fit the experiment. They were easy to make since so many fit on a single 76-mm wafer. We eventually got it down to a "jelly bean" operation.

Figure 1-33 shows a scanning electron micrograph (SEM) of an end cap.

This project required the use of silicon wafers much thinner than those used for normal integrated circuit processing. Usually, 76-mm wafers, 380- μ m thick were used. These can be purchased quite readily for \$6.00 each. We had to backgrind these wafers to 130- μ m. Companies will do this for \$6.00 per wafer. These 130- μ m thick wafers were then back polished down to 50- μ m. Again, companies will do this for \$15.00 per wafer. The finished 76-mm

wafers, 50- μ m thick, were very fragile. We developed special equipment to handle them. This included rings to hold the wafers on their perimeter since use of the usual tweezers would break them. We also made very flat vacuum chucks to hold the wafers on the photoresist spinner. Some wafers as thin as 40 μ m were used, but these were only 50 mm in diameter since our polishing vendor experienced excessive breakage on the 76-mm wafers.

Most fabricated parts required that we pattern and etch the thin wafers from both sides. The flat vacuum chuck mentioned above allowed us to apply photoresist to one surface, bake it, then apply it to the second surface without damaging the first coat. We then had to print images on the two surfaces which were accurately aligned to

Figure 1-31. Photograph of the two silicon parts used in the "ladder" target. The parts were etched in 100 μ m thick silicon. Two ladder parts and one space were used in each target.

Figure 1-32. Photograph of an end cap with alignment cross-hairs.

each other. This was accomplished using the fixture shown in Fig. 1-34. With this perimeter of the 76-mm wafer, we were able to align the two images to within 1 μm . This alignment was especially critical for the channel part since a sharp-knife edge was required in the channel region. By careful alignment and by etching precisely half way through both sides of the wafer, we achieved a knife edge with a tip radius of less than 500 Å. Overetching would degrade this sharpness. Figures 1-35 and 1-36 show SEMs of the channel part. Figure 1-35 shows the knife edge and

the delta that was formed where the gas feed lines intersect the channel because the etching terminates on non-(111) crystal planes at this intersection. This delta could be tolerated in this target.

Figure 1-36 shows the scribe line at the end of and at right angles to the channel. As mentioned earlier, once the target was assembled, the wings of the channel were snapped off at this scribe line to open the two exits from the channel. The well-defined (111) crystal planes are clearly seen in Fig. 1-36.

Figure 1-33. SEM of the exit hole in an end cap. The alignment cross-hairs were separated from the square exit hole by 15 μm to preserve its shape.

Figure 1-34. Fixture used for double-sided lithography.

The free-standing silicon-nitride membranes in both the vacuum window and the flashlamp parts presented a special problem. These membranes had to be thin and transparent to pump x-rays, yet they had to withstand a 50-Torr pressure differential. In addition, their areas were fairly large, 300 μm by 1.2 cm for the vacuum window and 500 μm by 1.2 cm for the flashlamp. Initially, these membranes broke because of their intrinsic tensile stress. Eventually, we lowered this stress by increasing the silicon content of the silicon nitride. Tests indicated these membranes could withstand a differential pressure of 1 atm. Figures 1-37 and 1-38 are SEMs of some

flashlamp parts showing the location of the silicon-nitride membrane.

There was an excellent match between the requirements of this gas-type x-ray laser target and what can be achieved using silicon micro-fabrication technology. If one considers the size, tolerances, smoothness, and configuration required in the target, it is easy to understand the benefits of silicon technology. In addition, we were able to batch fabricate large numbers of parts. The plan for the next generation of targets is to refine the design to simplify the assembly procedure and to reduce the breakage. We have ideas on how to do this.

Figure 1-35. SEM of the channel knife edge showing the gas feed lines and the pressure transducer lines.

Figure 1-36. SEM of the channel scribe line. After assembly, the wings of the channel are snapped off at this scribe line.

Miscellaneous Microstructures

In addition to the more extensive projects discussed above, we also worked on a number of smaller microstructure projects.

We fabricated x-ray calibration targets for Test Program by electroplating gold on a beryllium substrate using photoresist as a mold. Figure 1-39 is a SEM of such a target. The smallest lines are 12 μm , center to center, and the gold is 18- μm thick.

We continued to fabricate B-dot microprobes for Test Program where they are used to measure transient magnetic fields. Figure 1-40 is a

photograph of the smallest microprobe we have made. It has a loop radius of 235- μm . Photomasks are now available to fabricate B-dot microprobes with the following dimensions:

<u>Loop Radius</u> (μm)	<u>Conductor Width</u> (μm)
130	50
160	50
235	50
710	50
2600	250
2800	50

Figure 1-37. SEM of an early flashlamp design. The narrow vertical slit was used to support a 1500- $\text{\AA}$ thick silicon nitride film. The flashlamp material was evaporated onto this film.

Figure 1-38. SEM of the central part of a flashlamp. The center hole was used to maintain a vacuum between the flashlamp and the vacuum window.

The sensitivity of these microprobes varies from 1.4×10^{-7} V/T/s to 3.4×10^{-5} V/T/s.

We continued to make target mandrels for Y Program. These mandrels are made by plasma etching silicon using silicon dioxide and photoresist as a mask. The resulting pattern is coated with a metal which is subsequently peeled off. Because of the undercut etch pattern, many individual parts are formed depending on the shape of the pattern.

We developed a process for coating copper discs with plastic coatings such as polystyrene and polyvinyl chloride for Y Program.

The thicknesses were as high as 40 μm . These coatings are used to replicate the grooves on the copper substrate. They are used in laser targets.

We fabricated thin silicon membranes for use in transition radiation experiments by the Physics Division. The membranes were made by diffusing boron into one surface of a silicon wafer to a depth of the desired membrane. The silicon was then etched from the opposite surface using a concentration dependent etch such as ethylenediamine-pyrocatechol-water (EPW) or potassium hydroxide (KOH). The etch stops when it reaches the boron-doped silicon. A border was used to hold the individual membranes.

Figure 1-39. SEM of a gold on beryllium resolution target. The gold is 18- μm thick.

Figure 1-40. B-Dot microprobe with a 235- μm loop radius. These are used to measure transient magnetic fields.

Figure 1-41. Silicon wafer with several $4\text{ }\mu\text{m}$ thick membranes. They are made using a concentration dependent etchant.

Figure 1-41 shows a wafer with many individual membranes still attached to one another. For this project, we stacked the membranes so that they were separated by 3 μm . We did this by making parts that would nest inside each other. Figure 1-42 shows the three membrane sizes we used which ranged from 5-mm square to 10-mm square. All three membranes were 4- μm thick. Three- μm aluminum dots were evaporated in the corners of the parts for use as spacers. Figure 1-43 shows all three membranes properly stacked.

Microstructure Development

As time permitted, we worked on new processes because of their potential usefulness for microstructure fabrication. The following describes some of this work.

The concentration-dependent etching described above was studied. We found that the EPW etchant was far more selective for boron-doped silicon vs undoped silicon than was KOH. We also found it possible to selectively dope a silicon surface with boron to etch a pattern all the way through a wafer. Figure 1-44 shows how thin silicon fibers can be formed by selective boron diffusion. We are now studying the cross-sectional shape of these fibers as a function of the diffusion schedule and etch procedure. We are using the process simulation program SUPREME in these studies. During this work, we also found that EPW will etch a silicon-nitride mask slowly, but will not

touch a silicon-dioxide mask. On the other hand, KOH will etch a silicon-dioxide mask slowly, but will not touch silicon nitride.

Often it is desirable to fabricate a thin silicon membrane without resorting to the boron-doping technique mentioned above. We developed Teflon fixtures which uses a system of Viton O-rings to expose only one surface of a silicon wafer to a chemical etchant. With this fixture, we were able to etch a 5-mm circular section of a 500- μm wafer down to 25 μm . Attempts to go thinner caused the membrane to crack, probably because of mechanical stresses. We are continuing to work on thinning procedures that do not involve a heavy boron diffusion of one surface.

We continued to develop our plasma etching capability. Our goal here is to establish a reactive ion etch process using an oxygen plasma to etch plastic materials such as polyimide with straight sidewalls. Such structures are extremely useful as molds for electroplating. Recently, we purchased a small turbomolecular vacuum pump which should allow us to achieve the 10 millitorr pressure required for this work.

The orientation dependent etching of KOH was compared to EPW. The etch rate ratios for KOH for the three silicon crystal planes, (100), (110), (111), is 300:600:1; the etch rate ratios for EPW are 50:30:1. Thus, the KOH is more anisotropic or directional. We used this difference in anisotropy to etch pyramid-shaped structures on a silicon surface with EPW as the etchant.

Figure 1-42. Three membrane sizes fabricated for use in transition radiation experiments.

Figure 1-43. Three membrane assembly. Each membrane is separated from the other by 3 μm aluminum spacer.

Figure 1-44. SEM of thin silicon fibers fabricated using a concentration dependent etch.

Figure 1-45. SEM of pyramid-shaped microstructures etched on the surface of a (100) oriented silicon surface. Center-to-center spacing of the pyramids is 20 μm .

Starting with small nitride squares as a mask on a (100) silicon surface, the KOH etchant resulted in small irregular-shaped islands. However, when the same material was etched using EPW, small uniform pyramid shapes were obtained. This happened because of the relative rates with which these etchants etch the three primary crystal planes. Figure 1-45 shows small pyramids etched using EPW. Each pyramid has

a base that is 10- μ m high. They are separated by 20- μ m, center to center. The base is 15 x 15 μ m. Such structures could be used as high-current field emitters if they were coated with the appropriate material.

5. Integrated Optics

Principal Investigator: J. C. Koo

Introduction and Objectives

The long-term goal of this project is to establish in-house design, production, and testing capabilities for the development of integrated optics to satisfy the future experimental needs of the Laboratory.

To achieve the goal of transmitting more and more information, broadband optical fiber systems along with optical detectors or sensors must be introduced in place of customarily used coaxial cable systems with direct electrical detectors or sensors. Optical fibers are primarily developed by the Bell Telephone System for use in telecommunication systems. In developed optical telecommunication systems, the signals are transmitted through digitized, pulsed-injection semiconductor lasers. In recent years the integrated optics of broadband electrical optical modulators and detectors offered vast applications in our future experimental measurements due to their extremely broad bandwidth and fast response.

The Laboratory needs to develop its own in-house fabrication, research, and development capabilities because of the wide variety of experiments conducted. Integrated optics will certainly offer us vast possibilities for developing engineering and scientific capabilities.

We started this project during FY 84. To increase speed, we contracted the development of a Mach-Zehnder Interferometric Microwave Detector to an outside firm. Concurrently, with outside cooperation, we began developing in-house production capabilities. The objectives of FY 84 were as follows:

1. Obtain a contract with Battelle Columbus Research Laboratories (BCRL) for assistance in the fabrication of the Mach-Zehnder Interferometric Microwave Detector. Details of this contract require:
 - a) delivery at the end of year of several completed prism-coupled, functional devices,
 - b) training of one of our technicians in the basic fabrication procedures.
2. Design and fabricate a mask set for a Mach-Zehnder Interferometric Microwave Detector to be used for fabrication by BCRL.
3. Begin developing fabrication capabilities and testing facilities at the Laboratory.

Progress

At the end of March 1984, our contract with BCRL was approved. The contract period was from April to December, 1984. We contracted to provide BCRL with a set of production masks and the necessary lithium niobate wafers. BCRL agreed to try to produce several devices on a best effort basis. They also agreed to train one of our technicians at their production laboratories.

In April and May, we tried to redesign our mask set to fit the requirement of the production procedures of BCRL. Even though the mask set was CAD, it took several tries for the mask house to make these masks because of the long and narrow structure of the optical waveguides. By the end of May, we delivered the mask set to BCRL so they could fabricate the device. The basic device in three dimensions is shown in Fig. 1-46.

In September we visited BCRL. Mr. James R. Busch, a research scientist at BCRL, demonstrated the low-frequency electrical-field

Figure 1-46. Mach-Zehnder Interferometric Microwave Sensor. A Mach-Zehnder Interferometer is formed by optical waveguides on the LiNbO_3 substrate. The microwave signal is fed into the sensor through the coaxial cable onto the microwave stripline. As the laser light passes through the Mach-Zehnder Interferometer, the electrical field of the microwave signal modulates the phases of the two laser beams in the two arms in opposite directions. Because of optical interference between the two laser lights at the output, the amplitude of the laser light will be modulated to reflect the microwave signal.

modification effect present in the packaged device. The low-frequency response of this device is shown in Fig. 1-47.

After returning to the Laboratory with this device, we set up our own optical testing equipment as shown in Fig. 1-48. The brass box, tilted at an angle in the setup second from the right, is the optoelectronic device. Figure 1-49 shows a piece of lithium niobate wafer after in-diffusion of the optical waveguides (not visible in the photo) and with microwave strip-line lying directly on top of these

waveguides just before electroplating. The optical waveguide on this device has been tested by BCRL to be of good quality.

In conclusion, during the past nine months with the assistance of BCRL, we successfully established in-house fabrication capabilities and in-house testing setup. The present device available to us is less than desirable because (1) its low frequency data indicate there must be a severe mismatch in its structure, and (2) optical coupling through prisms is not practical for our experimental usage.

Figure 1-47. Frequency response of the first device produced by BCRL. The top trace is the electrical input signal—a square wave with a frequency of 5 MHz and amplitude of about 1.4 V. The bottom line shows the response of the optical signal at the wavelength of 6328 Å.

Figure 1-48. The Laboratory's in-house optical test setup. A Helium-Neon laser is shown at the extreme left side of the photo. A detection photodiode is located at the extreme right side. The Mach-Zehnder interferometric microwave device is enclosed in a copper box located immediately before the detection photodiode.

Figure 1-49. Photograph of Mach-Zehnder interferometric microwave device fabricated in-house. A gold-plated microwave stripline is shown fabricated on the top of optical waveguides (not visible in the photo) on a LiNbO_3 substrate. A scale in mm is shown at the bottom: each division represents 1 mm.

II. Signal and Control Engineering

Thrust Area Leader: J. V. Candy

Overview

Research Objectives and Developmental Projects

The Signal and Control Engineering (SCE) Thrust Area is engaged in a wide variety of research and development activities in signal processing, image processing, and control. Its primary goal is to develop and disseminate technology in signal and image processing and control throughout the Laboratory as well as to external governmental, university, and industrial agencies. In the long range, research effort is currently devoted to solving large-scale problems in signal and control, while developmental effort strives to bridge the gap between research results and project application.

To satisfy these goals during FY 84, research efforts were devoted to the study of large-scale control systems and the development of model-based signal processing algorithms. The major accomplishments for FY 84 include: (1) the development of tracking analysis software for advanced weapons systems, and the completion (Phase I) of the Signal Processing Software Development Package (SIG) and Signal Acquisition and Processing Station (SAPS) software and hardware development projects in signal processing; (2) the development of new algorithms in

image processing; and (3) multivariable control software development (DELIGHT) in control. The result of these efforts has provided the Laboratory with the capability to solve varied problems in these technical areas.

The programmatic impact has been extensive during FY 84. For instance, the interactive signal processing package, SIG, has been widely applied to weapons and energy projects alike (e.g., the applications to electromagnetic analysis and magnetic fusion). Image processing techniques are applied directly to the advanced weapons projects as well as to governmental studies (e.g., the applications to atmospheric environmental projects). Control engineering currently impacts large-scale platform design as well as isotope-separation projects.

This report will discuss the following research and development projects for FY 84:

- Signal Processing: Research in tracking algorithm performance and model-based signal processing (articles 1 and 2) with development activities in SIG

software and SAPS hardware (articles 3 and 4) as well as applications to electromagnetic analysis and magnetic fusion (articles 5 and 6).

- Image Processing: Research in change detection algorithms, microwave tomography (see Modeling Thrust Area), and diagnostics with software developments and applications in advanced weapons and analysis (article 7).
- Control Engineering: Research in large-scale systems and multivariable control algorithms (article 8) with development projects in control and frequency domain system identification and applications in machine control and advanced weapons systems (articles 9 and 10).

Facilities

The facilities of the SCE Thrust Area have been improved during FY 84. Interactive signal processing facilities have grown substantially over the past few years, especially with the inclusion of a VAX 11-750. The SIG laboratory, located in Bldg. 131, has developed around a 32-bit, VAX 11-780 minicomputer--a machine commonly used in governmental, university, and industrial settings. This facility is the focal point of signal processing and control activities for software distribution as well as for development. The peripheral equipment currently available (Fig. 2-1) consists of input/output devices, graphics, and standard terminals as well as color capability, including screen hard copy. Through the interactive computer-aided engineering network (ICAEn), signal process-

Figure 2-1. Signal and control facility.

ing algorithms may be accessed by network users. In this way current algorithms are readily available for Laboratory use. The signal processing development systems also communicate directly with this facility. The SAPS, the SIG development workstation, the LSI-11/23 workstation, and the 68000-based SUN workstation are all interfaced to the central VAX for data transfers and software updates.

A large amount of the digital image processing research and development at the Laboratory is performed using the Image Processing Research Facility (IPRF). The principal components of this facility currently include a VAX-11/750, an AP-120B high-speed array processor, an IIS Model 70/E image processor, an IIS Model 70/E image

display system, and a VICOM image processing system. Figure 2-2 illustrates the configuration of the system together with some of the peripheral components. The VAX-11/750 has replaced our former computer, a PDP-11/70, and is now fully integrated into the facility. We have implemented a device-to-device transfer capability that allows the array processor to communicate directly with the VAX disks without the usual time-consuming use of the VAX CPU. The VICOM image processing system, originally supported by its manufacturer only as a stand-alone system, has also been integrated into the IPRF so that images can now be transferred between the VAX and the VICOM system.

Figure 2-2. Block diagram of the LLNL Image Processing Research Facility. The host processor, a DEC VAX-11/750, is connected to a large assortment of peripherals and image display systems. In addition to the 9-track tapes and large disks, the system has two image display systems: an International Imaging Systems (IIS) Model 70/E and a 68000-based VICOM system. An Eikonix CCD image digitizing system provides a high-quality on-line image digitization capability. A data link (OCTOPORT) is under development to provide communication with the LLNL OCTOPUS computing facility. The array processor (AP), which handles virtually all of the image processing computational burden, is connected to both the VAX and the disks to provide a direct-transfer capability between the AP and disk, thus avoiding the traditional I/O overhead associated with configurations that require all data to pass through the host to reach the AP.

1. Tracking Algorithm Performance Analysis

Principal Investigator: S. G. Azevedo

Introduction and Objectives

Target tracking is an estimation problem for which many different computer algorithms may be designed. To choose the algorithm best suited for a particular problem, one must trade off tracking performance for computational price (memory size and speed, CPU speed, numerical accuracy required, etc.). The performance of target-tracking algorithms has become increasingly important at the Lawrence Livermore National Laboratory (LLNL). Several Laboratory programs involved with advanced weapons systems require very sensitive acquisition, pointing, and tracking (APT) equipment for the project to succeed. The Laboratory is taking a lead role in some of these projects, with contractors providing their expertise to the APT problem. To evaluate the work done by these contractors, LLNL must have an understanding of the tracking problem.

We present here a software tool to analyze and compare the performance of various target-tracking algorithms, both to one another and to an "optimal" solution, using high-quality graphics displays. The purpose of this project is to develop an analysis capability in the tracking area. The eventual goal is to provide those organizations involved with these types of algorithms (R Program, Navy, etc.) a

means of visualizing the effects of many target-tracking designs in noisy environments.

The Tracking Algorithm Performance Analysis Program, called TRAPP, accepts input in a standard format from simulation and estimation codes. It then displays the trajectories of the data in one of a variety of formats--overhead, relative, bore-sight, and earth reference frame. The simulated (true) values of target locations may be overlaid with optimal and several suboptimal estimates in any combination. The trajectories of a separate observer platform may be plotted or used as a display viewing position. Several analysis techniques are also used to compare the relative merits of algorithms; these techniques include a covariance analysis, tracking-error ellipsoids, a suboptimality index, and an innovations analysis.

The software design and partial implementation for TRAPP have been completed and described in "Tracking Algorithm Performance Analysis Program (TRAPP)" by S. Azevedo. The design will allow the program to handle increasingly complex problems as the project matures. The most important and immediate problems are the interface issues: on input, how to store and retrieve large amounts of data as efficiently as possible; and on output, how to display the

information so it will make sense to users.

Progress

The overall goal of the TRAPP project is to create a program to analyze the performance of various target-tracking algorithms using the following techniques:

1. Graphical displays. We have access to several high-quality color graphics display devices to plot the information in a variety of styles.
2. Covariance analysis. The TRAPP project will use the standard covariance analysis used by navigation specialists to observe their algorithm performance.

3. Special-purpose information. Some knowledge of the actual tracking system studied is incorporated to provide a user with information peculiar to his or her problem (unit conversions, different viewing angles, special labeling, etc.).

For potential users to make effective use of this tool, some information must be known about the tracking system and data must be available. Figure 2-3 shows a block diagram of inputs to a covariance analysis system. The blocks are described as follows:

1. A Truth Model (simulator, or "true" target). This is a highly accurate model of a

Figure 2-3. TRAPP input/output block diagram.

tracking scenario that closely matches the physical system. This model, which may be refined as more information becomes available, may be nonlinear and of a very high order. The model is likely to be stochastic because known randomness in the system is included. The output of a simulation using this model will be time histories of any known (deterministic) forcing functions, the noisy measurements acquired by the tracking system, and the "true" values of the system states. In some cases, Monte Carlo runs will be needed to obtain ensemble averages of those quantities.

2. An Optimal Estimator (optimal tracker, or "best" estimate). Using the truth model, an optimal estimator algorithm can be constructed to provide the best (least squares sense) estimate of the state values over time. The estimator algorithm should incorporate the knowledge of the truth model and produce estimates of the states and of the state error covariances. Here again, ensemble averages of Monte Carlo runs may be necessary. This estimator represents the best example of what any estimator can hope to perform and can therefore be used for comparison purposes.
3. Suboptimal Estimators (suboptimal trackers 1-n). Many

candidate schemes to implement suboptimal estimators (e.g., fewer states, linear relationships) may now be used and compared to the optimal estimator.

In addition, scenarios for other suboptimality (e.g., missing measurements, reduced word-length) may be incorporated. These estimators would produce time histories of gain sequences and state estimates.

Given these inputs, covariance analysis involves propagating a model using the suboptimal gains to find the error covariances for each suboptimal estimator. Mean and steady-state estimates can then be compared to the optimal estimate.

Any number of display options to view the outputs of this type of analysis are possible, such as the following:

1. True-target track overlayed with the estimates for each target and/or the observer. Several possible coordinate transformations may be required to view the track from the proper reference frame. In all of these possible views, error bounds (ellipsoids) can be overlayed to give a measure of the confidence surrounding each estimate. The requests for views of this kind involve the following considerations:
 - Coordinate Systems. Rectangular, polar, modified-polar, and bore-sight.

Figure 2-4. Tracker estimates from noisy measurements: (a) aircraft location using the optimal estimator track, (b) track of the suboptimal estimator.

- Reference Frames. Earth frame, flat-earth frame, and observer reference frame.
 - Dimensionality. Two- or three-dimensional coordinate systems.
2. Error covariance plots for many runs displayed in three-dimensional, or pseudo three-dimensional systems.
 3. State and state error estimate plots for many runs displayed in three-dimensional, or pseudo three-dimensional systems.

Other nongraphical values such as the performance indices of the optimal versus suboptimal estimators may also be used to provide effective performance measures.

Several programs have been developed at LLNL to model state space systems, such as programs called SEASIM, SEAS, SSIMNL, and SEEK. These programs accept modeling information, noise parameters, and other data (e.g., forcing functions, measurements) to produce time histories of simulated and estimated quantities. A common output file format has been specified for all of these programs so that a single graphical post-processor program called SEPLOT, can display the data. SEPLOT can display the time history of each element in a state space system as well as other diag-

nostic information. The very general design of SEPLOT allows it to be used for many applications involving state space systems.

TRAPP can be viewed as an additional post-processor program for target-tracking applications. It has been designed to accept data from both the simulation and estimation runs. If the states of the system represent position and velocity data for a target or observer, then TRAPP can be used to view the data in a different, more natural, way. Actual target locations over time can be displayed from several viewing angles and several runs can be displayed on the same graph (e.g., the true and estimated target trajectories). Example displays in Fig. 2-4 show overhead plots of the estimated trajectory of an aircraft flying with constant velocity from left to right given noisy measurements. Figure 2-4a shows the aircraft location using the optimal estimator track, and Fig. 2-4b shows the track of the suboptimal estimator. The triangle marks on the curves are equal-time fiducials used to locate errors at fixed time points. Figure 2-5 displays the same data as shown in Fig. 2-4 with the addition of error ellipsoids drawn at each sample point to show the 2-sigma (95% confidence) interval around each point.

Figure 2-5. Tracker estimates with error ellipsoids: (a) aircraft location using the optimal estimator track, (b) track of the suboptimal estimator.

Suboptimality index = 0.3564 (1 = optimal)

Tracking errors:

State	RMS error (optimal)	(suboptimal)	Ratio (1 = optimal)	% out of bound	
	(optimal)	(suboptimal)		(optimal)	(suboptimal)
Range	1.075	1.783	0.603	3.13	1.79
Bearing	0.913	1.547	0.590	3.13	8.04
Range rate	0.0108	0.0611	0.0177	4.02	0.00
Bearing rate	0.00642	0.0363	0.177	2.23	0.00

Innovations analysis:

Innovation number	Mean value [bound]		Whiteness (% out)	
	(optimal)	(suboptimal)	(optimal)	(suboptimal)
1	0.6239 [0.4058]	0.0493 [0.4411]	3.60	1.80
2	-0.0424 [0.4411]	0.0599 [0.4802]	5.41	3.60

Table 2-1. TRAPP performance indices.

Another type of output of TRAPP is shown in Table 2-1. Here we obtain a measure of suboptimality that can be presented in single numerical values. The plot and table outputs presented here give us much more insight into the actual tracking problem than do simple time histories of the states or errors. In addition, a quantitative performance indicator can be used to compare algorithms effectively.

Summary and Future Enhancements

TRAPP is a program used to analyze the performance of target-tracking algorithms; it is capable of displaying the outputs of trackers/estimators in physical coordinates. TRAPP can be used to compare the results of candidate suboptimal trackers with each other and with the optimal solution.

Other design features are still to be added to TRAPP. Following are some advanced features we have marked as important:

1. Easy ways to customize the displays to other applications.
2. Other analysis techniques (e.g., actual tracking error).
3. Port to a graphics workstation.
4. Vectors to show velocity.
5. Object sizes to represent target distances on three-dimensional plots.
6. Ability to show multiple displays from different viewing positions simultaneously on the same plot.

7. More flexible displays (e.g., varied sizes and colors, a timing feature).

8. Ability to make movies.

Acquisition-pointing tracking is an important problem in modern weapons systems design. Navigation and fire control depend on the most accurate estimation schemes available. The proper tools are equally important factors in evaluating candidate tracking algorithms developed by LLNL and other organizations. TRAPP is a tool used to compare these algorithms effectively and easily using standard analysis techniques and advanced graphical displays. The comparisons are done objectively by comparing them to one another and to the optimal solution.

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2. Model-Based Signal Processing

Principal Investigator: J. V. Candy

Introduction and Objectives

Most Laboratory projects involve the phenomenology of various processes for weapons- or energy-related applications. Instrumentation, cabling, or propagation mediums often inhibit the capability to extract the desired signal because of limited bandwidth and inherent noise characteristics that contaminate the measured response data. This phenomenon is especially prevalent in transient-type measurements. In this paper, we discuss the investigation of model-based signal processing techniques, which can be applied to extract the desired signal contaminated by the channel characteristics and noise.

Most instruments are selected to be fast or wideband relative to the process currently measured; however, in many instances (e.g., transient measurements) this is not possible. Thus, the effect of the instrument, as well as of the noise, must be removed from the data to decrease the amount of overall uncertainty. A typical example is the removal of measurement probe effects at the Transient Electromagnetic Facility (ERF Program). In underground testing (NEP, FTSD, L, NESD programs), the equalization or removal of cable effects on measured test data is required before the data can be analyzed effectively. In x-ray diagnostic measurements (NESD, L programs), the prime objec-

tive is to measure the transient response phenomenon from a carefully designed test object. Owing to the high frequencies involved in these experiments, one of the primary problems is the deconvolution of instrumentation and cables from noisy measurements. Finally, when the signal propagates through a complex medium (e.g., seismic waves), the equalization problem is usually called the inverse problem and may be difficult to solve depending on the knowledge of the medium involved. Thus, any experiment involving the measurement of transient phenomena requires removal of measurement-instrument or acquisition devices from the data before analysis can begin.

To investigate model-based solutions to this problem, we chose techniques from various signal processing areas with similar problems and applied them to typical transient measurement data to evaluate the techniques' applicability to solve laboratory problems. Once developed and applied, basic research could be initiated (research proposal for FY 85) to develop more direct approaches than those used in the past.

Two problems must first be addressed. First, during the analysis phase of any experiment, raw spectral data must be analyzed to determine the frequency content of

the measured data and therefore the effect of the channel. Here, spectral estimators are required to provide the estimated spectrum. Second, once the data is analyzed, methods must be developed to remove the effects of the channel.

Progress

Fourier transform techniques are very useful in analyzing and characterizing test phenomena. Unfortunately, when data are noisy, the Fourier spectrum not only provides spectral information about the desired signal, but about the undesired signal as well. Thus, the power spectral density provides a solution to the problem of estimating the Fourier spectrum when the data are contaminated by noise. This was the first objective that had to be satisfied to solve the deconvolution problem.

The power spectral density (PSD) function for a discrete process is defined as

$$S_x(\Omega) = E \left\{ \frac{X(e^{j\Omega})X^*(e^{j\Omega})}{N} \right\} \\ = E \left\{ \frac{|X(e^{j\Omega})|^2}{N} \right\},$$

where the expected value (averaging) accounts for the randomness.

Classical methods of estimating the PSD are based on discrete Fourier transforms (DFT). For example, the correlation method employs DFT techniques to estimate the power spectrum by first estimating the correlation function and then by using the DFT to calculate the spectrum; the periodogram method

employs DFT techniques, windows, and averaging to estimate the power spectrum.

Modern techniques of characterizing the PSD employ model-based methods. For example, consider an all-pole representation for this process, then

$$S_N(\Omega) = \frac{1}{N} X(e^{j\Omega})X^*(e^{j\Omega}) \\ = \frac{1}{N} X(z)X^*(z^{-1}),$$

where

$$X(z) = \frac{\sigma}{A(z)},$$

σ = noise standard deviation,

and

$$A(z) = 1 + a_1 z^{-1} + \dots + a_N z^{-N}.$$

Two model-based methods were developed and implemented within SIG to estimate the power spectral density. The all-pole representation using the Levinson-Durbin recursion and the so-called Lattice recursion were used to characterize the spectrum. As an example of spectral estimation, consider a bandpass system excited by noise. The raw Fourier spectrum shows the uncertainties present in the data. The classical periodogram method is applied to the raw data as well as to the model-based (all-pole) parameter estimator (Levinson). We note from Fig. 2-6 that the model-based spectrum is smoother than that in the classical periodogram method and indicates a resonance at 3 Hz, which was the designed center frequency of

the bandpass system. So, we see that the model-based methods offer an improvement over the more classi-

cal approaches, especially when the systems under investigation contain sharp resonances.

Figure 2-6. Model-based spectral estimation: (a) raw bandpass spectrum, (b) estimated bandpass spectrum.

The second objective was attacked using a similar model-based processing approach, i.e., model-based methods that can significantly improve signal estimates when noisy measurement channels occur during data acquisition. Model-based methods used to reconstruct an excitation signal after it has been "smoothed" by a measurement channel were developed.

The so-called equalization problem finds its roots in communication theory, whereby the processor attempts to design an equalizer, or deconvolver, to remove undesirable effects of a channel. The solution to this problem leads to the inverse filter of the channel. In our case we usually do not have the a-priori knowledge of the system (channel), so we must first develop a model, independently, through system identification techniques. The model-based method of deconvolution consists of first identifying a model of the channel from independent experiments and then using this model to construct the deconvolving processor. We selected the predictive deconvolution approach developed in the seismic signal processing area and applied to it some experimental data. This approach estimates the model of the channel as

$$H(z^{-1}) = k/A(z^{-1}),$$

and then develops the inverse, or deconvolving, filter as

$$H^{-1}(z^{-1}) = A(z^{-1})/k.$$

The predictive deconvolution method was applied to raw measurement data. In this case, independent channel measurements were not available, so the same data set was used to construct the channel model. The results of this application are shown in Fig. 2-7 where both the reconstructed pulse and actual excitation pulse are displayed along with the corresponding spectra. Here we also show the results using an all-zero processor designed using the Wiener filter commands in SIG for comparison. Both methods yield promising results on this data set with the all-pole method showing superior low-frequency performance as shown by the spectrum. Both methods are available in SIG.

The results of this initial investigation into model-based signal processing methods applied to solve the deconvolution problem indicate that the approach shows great promise, but that more basic research must be undertaken to extend the current algorithms, which are now somewhat limited. These extensions will enable scientists to extract more pertinent information not available previously. The extension of these techniques to handle transient data with multiple reflections is as yet an open problem that will be studied in the future.

Figure 2-7. Deconvolution of transient pulse from test data.

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3. Signal Processing Software Development Package (SIG)

Principal Investigators: D. L. Lager and S. G. Azevedo

Introduction and Objectives

SIG is a flexible general-purpose signal processing, analysis, and display program designed to perform manipulations on time- and frequency-domain signals. The program's ultimate goal is to accommodate other representations of data such as multiplexed signals and complex matrices. Many of the basic operations one would perform on digitized data are contained in the core SIG package. From these core commands, more powerful signal processing algorithms may be built. The user may define custom commands that rename existing commands, execute SIG command files, run user-written programs, or perform operating system commands (e.g., invoke the text editor).

Two user interfaces are provided in SIG: a menu mode for the occasional user, and a command mode for the sophisticated daily user. In both modes, errors are detected as early as possible in the processing and are indicated by friendly, meaningful messages. Command arguments not entered by the user will cause SIG to prompt for them or to default them at the user's option. Other options such as for multiple commands per line, command files with arguments, commenting lines, defining commands, and automatic execution for each item in a repeat sequence are also available.

Many different operations on

time- and frequency-domain signals may be performed by SIG. They include: operations on the samples of a signal, such as adding a scalar to each sample; operations on the entire signal, such as digital filtering; and operations on two or more signals, such as adding two signals. Signals such as a pulse train or a random waveform may be simulated. Graphics operations display signals and spectra.

SIG has been designed to be easily transportable. It presently runs in a multiuser mode on the VAX (VMS and Berkeley 4.2 UNIX), SUN workstation (4.2 UNIX), DEC-20 (TOPS-20), and LSI-11/23 (TSX plus). The SUN version makes use of the SUN window system for user interaction and graphics.

Finally, SIG has been implemented using the structured analysis and design techniques popularized by Yourdon and others. In particular, SIG has been designed so members of the Signal and Image Processing Research group can work independently developing signal processing algorithms and easily installing them in SIG upon completion.

Progress

By the end of FY 82, SIG had completed its first phase of development. Most of the low-level commands had been completed (e.g.,

listing the contents of the data base, adding a constant to a signal) and the two modes of operation, menu and command, had been implemented. There were about five users of SIG on the VAX including members of the Environmental Test Group of W Division in Mechanical Engineering.

At the close of FY 83, SIG had twenty-five to thirty users. At that time, the program was about to be released for use throughout the Laboratory and advertised in journals and trade magazines for release to individuals outside the Laboratory.

During FY 84, SIG grew and improved substantially. The program was released to requesters outside the Laboratory at the end of November 1983 and has been received enthusiastically by some 350 requesters. About sixty individuals within the Laboratory use SIG for a variety of applications in programs such as MFE, LIS, FTSD, NESD, ERD, and X-Ray Diagnostics. SIG is on every host computer on the interactive computer-aided engineering network (iCAEn). The version for the LSI-11/23 computer has been released throughout the Laboratory. The SIG Librarian, D. Payne, handles the details of entering commands into SIG and controlling the various releases of SIG throughout the Laboratory.

A significant amount of time was spent training people to write software according to SIG's standards and philosophy. As a result, several sophisticated signal processing commands were added to SIG:

New Commands (FY 84):

DIFFERENTIATE--Compute derivative of a time signal.

INTEGRATE--Compute running integral of a time signal.

NORMALIZE--Normalize all values of a time signal by the largest value.

TRIANGLE--Multiply a time signal by a triangle (Bartlett) window function.

COHERENCE--Compute the coherence function of a time signal.

ECOHERENCE--Compute the coherence function for an ensemble of time signals.

CORRELATE--Compute auto- and cross-correlation functions using FFT method.

SDCORRELATION--Spectral Density using the correlation method.

SDAONLY--Spectral Density using an A-polynomial only (all-pole model).

SDLATTICE--Spectral Density using a lattice algorithm (all-pole model).

LSIAONLY--Linear System Identification of A-polynomial coefficients only.

LSILATTICE--Linear System
Identification using a
lattice algorithm.

LSIABC--Linear System Identifi-
cation of A-, B-, and
C-polynomials (ARMAX
model).

LSSABONLY--Linear System Simu-
lation using A- and
B-polynomial coefficients.

LSSACD--Linear System Simula-
tion using A-, B-, C-, and
D-polynomials (ARMAX
model).

LSSIMPULSE--Linear System
Simulation of an impulse
response.

LSDLATTICE--Linear System
Deconvolution using a
lattice algorithm.

LSDAONLY--Linear System Decon-
volution using
A-polynomial coefficients
only (all-pole model).

LSDWIENER--Linear System Decon-
volution using a Wiener
algorithm.

DECIMATEINTERP--Decimate and/or
interpolate a time signal.

PMFILTER--Design a Parks-
McClellan filter and
compute its impulse re-
sponse.

ANOISECANCEL--Adaptive noise
canceller to cancel a time
signal given a correlated
reference.

SIG was ported to several
different hosts spanning a wide
range of memory sizes and operating
systems. SIG presently has versions
on the following systems (host, op
system, memory):

1. VAX (VMS) virtual memory.
2. VAX (B4.2 UNIX) virtual memory.
3. DEC-20 (TOPS-20) large fixed
memory.
4. SUN (B4.2 UNIX) virtual memory.
5. LSI-11/23 (TSX plus) small
fixed memory.

Several new graphics and termi-
nal devices were added to the VMS
version of SIG: a VT240 (black/
white), a VT241 (color), a METHEUS
(high-speed, high-resolution color
with hard copy), and a TEKTRONIX
4027 (high-resolution color). Other
device drivers were added to DIGLIB
(e.g., VECTRIX, VT125), but pres-
ently none of them are attached to
machines where SIG is installed.
The laser printer driver was modi-
fied so any user on any host compu-
ter on the network can obtain laser
printer plots from SIG.

We have also used an IBM PC
with a terminal emulator as a termi-
nal to a VAX running SIG. Soon a

custom driver for DIGLIB will be written to make maximum use of the emulator's capabilities while using SIG.

Currently, when SIG is installed it is customized for the particular devices on a given host; only one or two subroutines and one or two text files must be modified to make the custom version. Commands have been defined so a user may quickly switch among several devices without using a menu.

In addition to the graphics

changes, many internal modifications have been made to simplify maintenance, porting to new hosts, and writing of new commands.

SIG was applied to various projects throughout the year. The following example shows a custom menu used to process plasma diagnostics signals in magnetic fusion experiments. The plots produced by the menu item "Analyze Noise Canceller Performance" are given in Fig. 2-8.

Figure 2-8. MFE noise canceler performance analysis.

Custom Menu for Plasma Diagnostics

::::: MFE: Plasma Diagnostics :::::

1. Preprocess Raw Diagnostic Data
2. Extract Plasma DML Signal
3. Extract Plasma Energy Dumps
4. Exact Noise Canceller
5. Adaptive Noise Canceller
6. Analyze Noise Canceller Performance
7. RETURN to main menu
8. Exit SIG

Several SIG users have progressed far beyond the menu mode in their sophistication. Approximately twenty-five minutes a day of CPU time are spent processing data from the transient electromagnetic range. SIG is currently used as a high-level programming language for those applications that require users to define commands to customize their environment, to write command files to perform long sequences of repetitious operations, and to write their own programs to translate their data directly into SIG data base. They continually request that more capability be put into SIG.

H. Ames and T. Coupe of NESD used artificial intelligence techniques to write an expert system for spectral analysis. The expert system consisted of a natural language interface and an inference engine that translated user input into commands for SIG.

Publications and Presentations

1. No author cited, "SIG--A General-Purpose Signal Processing Code," CUBE Symposium, Los Alamos, NM (October 10-12, 1984).
2. No author cited, "SIG--A General-Purpose Signal Processing Code," IEEE Nuclear Science Symposium, Orlando, FL (October 31-November 2, 1984).
3. No author cited, "An Environment for Producing Single-Source Machine-Independent Software," Engineering Research Division Seminar, Lawrence Livermore National Laboratory, Livermore, CA (September, 1984).
4. Lager, D. and S. Azevedo, User's Manual for SIG--A General-Purpose Signal Processing Code, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19912, Revision 1 (July, 1984).

4. Signal Acquisition and Processing Station Development (SAPS)

Principal Investigators: R. D. Garron and S. G. Azevedo

Introduction and Objectives

The data acquisition requirements at the Lawrence Livermore National Laboratory (LLNL) are many and varied. The Laboratory may have to acquire data in remote areas with harsh environments. Some data are collected in the presence of high electromagnetic or radio-frequency (EMI/RFI) interference. In most cases data must be converted to digital form, archived, displayed, processed, analyzed, and reduced before becoming meaningful to the experimenter. Sometimes real-time processing or control is required. However, the costs of the acquisition system must be minimized at all times.

Currently, most data are collected on analog media (e.g., tape, chart recorders, oscilloscopes) and digitized later by a central data reduction facility. This is done because it is costly and impractical to design new collection equipment to run each "one-shot" experiment. With the cost of computer equipment and storage devices dropping at tremendous rates, it is becoming much easier and less expensive to have dedicated computers handle the acquisition task. The turn-around is accelerated from weeks or sometimes months to minutes or even seconds. In addition, the computer makes real-time control and processing available to the user.

The purpose of the Signal

Acquisition and Processing Station (SAPS) development project is to meet all of the needs mentioned above for most computers (e.g., user-friendly systems, turn-key systems) so experimenters can use its extreme power with minimal instruction. The SAPS computer system must be portable so it may be used anywhere without harm or data loss, inexpensive so many SAPS may be cloned, and it must contain all the software tools to perform data display, storage, processing, analysis, and reduction.

Progress

In 1983, a portable prototype SAPS computer system was designed and built. The software and hardware were assembled with an emphasis on low cost, reliability, ease of use, and maintainability. SAPS is housed in a roll-around cart designed to withstand most EMI/RFI environments. The system is designed for up to 128 channels of analog input at up to 100,000 samples/s aggregate system throughput to disk (or 250,000 samples/s to memory). The software integrated into SAPS provides for data storage, graphical display, processing, analysis, and reduction.

The SAPS project during the past year achieved the following milestones:

1. May 84--SAPS computers and analog-to-digital hardware were used by NESD in an experiment that characterized different types of batteries for use in the Thrust Area. The experiment exercised the programmable gain amplifiers on the A/D boards to produce the desired signal strengths. SAPS captured the signals correctly, but noise problems emerged. In this experiment, SAPS experienced several types of noise problems; all but one were explained by the cabling implementation and the design of the A/D boards. The experiment was performed in the Pulsed Power Laboratory, which has a very hostile environment typical to LLNL. This experiment provided the SAPS project investigators with the opportunity to debug the system and to educate themselves on the problems of real-world data acquisition.

Data were collected using a Nicolet 2-channel full-differential isolated-input system. A GPIB interface was programmed into SAPS for data reduction and analysis using SIG. The data were originally placed on Nicolet 5-1/4 inch floppies and transferred to SAPS 8-inch floppies for final processing on a VAX 11/750.

2. Sept 84--SAPS was called upon to acquire data during the MCX experiment. SAPS was connected to a 3478A multimeter via a

GPIB interface to place the multimeter data on disk to remove a trend in several microwave/ thermistor waveforms. The data were previewed in the field with SAPS and final analysis was done on a VAX 11/750. A final report is forthcoming. (Draft was completed on November 6, 1984).

3. April-August 84--SIG was converted to TSX, an operating system that runs under RT11, so that a SAPS major upgrade design could take place in the future.

4. April-Sept 84--SAPS software and hardware architectures were redesigned to incorporate new and recent advances in technology. This new design allows for easier maintenance and uses new software techniques that allow the SAPS computers to function and operate more effectively.

The SAPS system employs a DEC LSI-11/23 computer (Q-bus) to control the data collection and to analyze the results. Data Translation analog-to-digital hardware performs the necessary data acquisition tasks. Digital-to-analog converters provide real-time signal processing and control functions. A user-friendly menu allows a user to access powerful data acquisition and display packages with a minimum of training. In addition, a large body of signal processing, display, and analysis software designed for the

LSI-11/23 (also menu-driven) is available to users. These packages allow users to view and evaluate the acquired data immediately. Customized packages may also be implemented and easily integrated into the system.

The software architecture of SAPS is particularly interesting because two operating systems are involved and, owing to a system-independent menu driver, each is transparent to the user. This menu system permits the system software designer to develop multiple menu structures. The application routines made available on SAPS ensure system integrity. A user operates SAPS and plots the output data on an interactive graphics display terminal.

Publications and Presentations

1. Lager, D. L. and S. G. Azevedo, SIG Users' Manual, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19912 (1983).
2. Azevedo, S. G. and R. D. Garron, "A Signal Acquisition and Processing Station," Engineering Research Division Seminar, Lawrence Livermore National Laboratory, Livermore, CA (March 4, 1983).
3. Garron, R. D. and S. G. Azevedo, A Unique Portable Signal Acquisition/Processing Station, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-88583 (May, 1983).
4. Garron, R. D., "A Unique Portable Signal Acquisition/Processing Station," Real-Time Computer Applications in Nuclear and Particle Physics Conference, Berkeley, CA (May 16, 1983).
5. Garron, R. D., 1984 CUBE Symposium, Los Alamos, NM (1984).

5. Magnetic Fusion Experiment Signal Processing

Principal Investigator: J. V. Candy

Introduction and Objectives

In this report we discuss the application of various signal processing methods to extract plasma information obtained during physics Tandem Mirror Upgrade Experiments (TMX). We show how these processing techniques can be used to decrease the uncertainty in the sensor measurements. The algorithms described here are implemented using SIG, an interactive signal processing package developed at Lawrence Livermore National Laboratory (LLNL).

To evaluate the performance of the tandem mirror reactor, various sensors and equipment are employed to measure the plasma properties. Plasma measurement is an extremely difficult and complex task. Probes and detectors cannot be located in the plasma because they would vaporize; therefore, indirect methods must be used. Perhaps the most crucial measurement, in terms of machine performance, is the central cell diamagnetism. The diamagnetism indicates the strength of the distorting field generated by the plasma; this field is proportional to the plasma pressure, which is in turn proportional to plasma density and temperature. High plasma pressure is desirable in fusion reactors because it leads to higher energy densities. Thus, it is crucial to obtain a measurement of the plasma diamagnetism. The diamagnetic loop is a sensor that performs a measure-

ment proportional to the derivative of plasma diamagnetism. Many sensors are positioned along the major axis of the reactor to sample spatially the plasma diamagnetism in both the central and mirror cells. After the derivative effects are removed by integration, the expected measurement shows a buildup of the plasma from the initial injection phase through the equilibrium phase and finally to the decay phase, when the injectors are extinguished. This measurement will be analyzed in this paper.

Progress

Signal Processing of TMX Measurements

We have explored the techniques used to enhance and extract the desired signal information from noisy DML measurement data. A close examination of the preprocessed DML data indicates that the data are contaminated by trends, both linear and sinusoidal, as well as by higher frequency sinusoids and associated harmonics generated by the power supplies used in the experiment. The dominant sinusoidal disturbances occur at 120 and 360 Hz.

A processor must be developed that will eliminate these disturbances, yet preserve all of the essential features of the transient

pulse and associated energy spikes. This problem is ideally suited for a technique called noise cancelling, which requires that a reference file of noise, and of the signal and noise, be available. For best results, the signal and noise should not be correlated. These conditions are satisfied by the DML measurement data, since the onset of the measurement consists only of the disturbances (trend and sinusoids), and the signal is available at the time of the transient pulse. The measured data are modeled by

$$y(t) = s(t) + H(q^{-1})r(t) + v(t)$$

where

- y is the measured data,
- s is the signal,
- H is the sensor, or measurement system dynamics,
- r is the measured reference noise, and
- v is the random disturbance, or noise.

The measurement dynamics are given by the polynomial,

$$H(q^{-1}) = h(0) + h(1)q^{-1} + \dots + h(N)q^{-N},$$

and q is a shift, or delay, operator as with

$$q^{-1}r(t) = r(t-1).$$

The noise canceller processes the data and cancels the effects of the disturbances by developing an esti-

mate of the system dynamics, $\hat{H}(q^{-1})$, estimating the noise, and then subtracting it from the data to give

$$z(t) = s(t) + [H(q^{-1}) - \hat{H}(q^{-1})]r(t) + v(t).$$

Clearly, as $H \rightarrow \hat{H}$, the effects of the disturbances are cancelled. Note that the random or uncorrelated noise, $v(t)$, must still be processed even after cancelling, since, like the signal, it is also uncorrelated with the disturbances.

The results of the noise canceller algorithm, constructed using various commands in SIG, are shown in Fig. 2-9. Here we see the raw and processed data and corresponding spectra. Note that the sinusoidal disturbances and trends have been eliminated (see spectrum) and that the noise spectrum has been reasonably estimated.

A closer examination of the estimated transient pulse shows that not only have the disturbances been removed, but that the integrity of the pulse has been maintained and all of the high-frequency energy spikes preserved. Once these disturbances have been removed, the processed signal can be integrated to remove or deconvolve the effects of the differentiating DML probe and to provide an estimate of the plasma buildup in the machine. These results are also shown in Fig. 2-9. This process completes the disturbance removal phase of the DML signal processing.

Figure 2-9. DML disturbance removal using noise canceler: (a) raw data, (b) processed data, (c) energy spikes, and (d) energy buildup.

For diagnostic purposes, it is important to extract estimates of the energy spikes present in the transient plasma pulse. One approach to solving this problem is to apply a nonlinear filtering technique called the median filter. The cancelled data, $\{z(t)\}$, is further processed by selecting a window of a fixed number of samples, sliding it (computationally) through the data, and replacing the current sample value with the median, or middle value (in amplitude), within the window. This nonlinear operation primarily removes the high-frequency spikes and provides a smoothed estimate of the plasma buildup pulse. Mathematically, this processor can be represented by

$$\hat{x}(t) = \text{Med}_{n=0}^{M-1} z(n),$$

where Med + means select the median value in the window of length M.

Once the plasma buildup pulse is estimated, it can be subtracted from the cancelled data to provide estimates of the energy spikes of interest, as in

$$e(t) = z(t) - \hat{x}(t).$$

The results of this processing operation are also shown in Fig. 2-9. First, we see that median filtering of the cancelled data has essentially eliminated all of the high-frequency spikes and provided a smoothed estimate of plasma buildup. Next, we see the estimated energy spikes. Comparisons of these estimates to the original data indicate that this procedure offers

reasonable estimates.

In this paper, we have discussed the various signal processing methods employed to extract the desired plasma information from measured diamagnetic loop data. We have shown how fundamental signal processing methods can be employed to preprocess the noisy data. The removal of both trends and sinusoidal disturbances was accomplished using noise-cancelling signal processing methods. The estimated plasma buildup was provided by integrating the processed data. The desired energy spikes were then estimated by using a nonlinear filtering method to estimate the plasma buildup pulse and removing it from the data.

Publications and Presentations

1. Candy, J. V., T. Casper, and R. Kane, Signal Processing Methods for MFE Plasma Diagnostics, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20336 (1984).
2. Candy, J. V., "Transient Pulse Estimation: A Noise Cancelling Approach," In preparation for CDC Conference (1985).

6. Electromagnetic Signal Processing

Principal Investigator: V. McGenna

Introduction and Objectives

A wide variety of experimental programs requires the measurement and subsequent analysis of transient electromagnetic phenomena. In many instances, the data are collected in input-output pairs and the signal processing consists of estimating the transfer function between data sets. The transfer function may be a physical parameter of interest, or it may be needed to deconvolve the response of components in the data acquisition system. In either case it is necessary to use appropriate signal processing techniques to ensure that the results obtained are physically meaningful. Presently, an experimental program is underway to characterize electromagnetic coupling into a cavity. Transfer function estimation is important in characterizing the response of these test objects. Other signal processing techniques, such as power spectral density (PSD) estimation and coherence function estimation, have also proven very useful in processing these data. Experience gained in the processing of data from electromagnetic pulse (EMP) coupling experiments has been found directly applicable to the analysis of other types of transient data. Therefore selected data sets from these experiments will provide the primary examples for discussing each of the signal processing concepts.

Progress

Microwave Coupling Experiments

Microwave coupling experiments are currently performed at the electromagnetic testing facility (EMTF) to understand better the mechanisms by which microwave energy couples through an opening, or aperture, to wires in a cavity. Preliminary experiments used cavities and apertures with simple geometries to examine the phenomenology of coupling into the cavity through the aperture.

Signal processing methods can be applied readily to scattering data to help in interpreting the experimental results. For example, consider the response measurement taken with a D-dot probe located 1.5 cm behind a 6.37-cm round aperture (see Fig. 2-10).

The transfer function of the aperture can be obtained using two methods: First, the Fourier transform of this response may be divided by the transform of the incident field measured with the same D-dot probe, as shown in Fig. 2-11; second, time-domain system identification methods may be used. The fine structure resulting from noise in the Fourier transforms masks the true response of the aperture. Some improvement can be obtained by using the Fourier transform of the truncated incident field data, but

Figure 2-10. Raw cavity response measurements: (a) response, (b) spectrum.

significant improvement requires preprocessing of the response data as well. A round aperture is expected to have a low Q and thus will not produce a long ringdown. An examination of the data shows that there is no ringdown and that the response dies quickly. Following the response, noise similar to the

scattering in the tail of the incident field data occurs. The transfer function derived from these processed signals is shown in Fig. 2-11 along with that resulting from the identification. There is a substantial improvement over the estimate using raw data.

Figure 2-11. Transfer function estimation: (a) frequency-domain division, and (b) time-domain identification.

Power Spectral Density Analysis of Data

The measured response at any point within a cavity contains the superposition of reflected waveforms from all reflecting surfaces. Since the waveform transmitted through the aperture contains a filtered pulse, periodic reflections of this pulse give rise to a pulse train. The spectrum of a pulse train is rich in harmonics with the fundamental frequency determined by the period of reflections. Multiple reflection paths can result in multiple modes that are excited. Most of these are not true resonances, as signals quickly die away and fundamental frequencies can shift as path lengths change. Given the short data record available for analysis, these almost-periodic pulse trains will appear periodic. In addition, a high-Q aperture generates a long ringdown, which will excite those harmonics of the cavity resonance close to the aperture resonance. Identifying all of the resonances in the spectral response is often desirable. However, generating a smooth function that is easier to characterize and less sensitive to changes in the size and shape of the cavity is desirable as well.

Reflections in a cavity result in a signal that is rich in discrete frequency components. The resulting line spectrum is an inefficient way to characterize the cavity; the line spectrum is also sensitive to changes in the cavity. Power spectral density is a technique used to analyze stochastic processes that

can be useful in processing data, such as from multiple reflections that appear to be random. The resulting spectrum is smooth and insensitive to small changes in geometry or to the dimensions of the reflecting cavity.

Consider the application of the PSD estimation method using the periodogram approach to noisy data from a rectangular aperture (see Fig. 2-12). In (a) we see the raw spectrum estimated and in (b) we see the smoothed estimate. The raw spectrum consists largely of discrete spectral lines. The two prominent low-frequency peaks are the aperture resonance and a harmonic of cavity resonance. The smoothed spectral estimate eliminates the discrete lines and generates a smoother estimate.

Coherence Function Estimation

Electromagnetic phenomena are governed by Maxwell's Equations, a set of partial differential equations with a solution distributed in both space and time. Thus the assumption that the response to an input excitation can be described by a linear lumped parameter model, as suggested by a linear transfer function, will not be valid for all experimental circumstances. It is desirable to determine if a linear transfer function is appropriate for characterizing data from a particular experiment. Coherence is used as a tool for examining the assump-

Figure 2-12. Spectral estimates: (a) raw spectrum, (b) smoothed estimate using periodograms.

tion that the response is related to the excitation through a linear lumped parameter model. The coherence function is a frequency-dependent correlation coefficient; that is, it determines over what frequency range two signals are correlated. A useful property of coherence states that if two signals are related by a linear transfer

function, then the coherence is unity over all frequencies. If two independent measurements are related to the same input by a linear lumped parameter model, then these measurements will also be related to each other by a linear model. Thus the coherence between them is one. Therefore, the validity of using a spatially independent model can be

examined by estimating coherence between response measurements made at more than one position. If these measurements have unity coherence, then the model is acceptable. A coherence significantly less than unity signifies that the model is inappropriate.

In addition to processing experimental data to understand a physical phenomenon, it is occasionally desirable to process data to understand more about the particular

data. Estimating a coherence function is not a stand-alone analysis technique intended to produce test results. Rather, it is a tool that can, under appropriate circumstances, offer insight into the nature and limitations of experimental data. Care must be exercised in interpreting coherence function estimates, and any interpretation should have a strong basis in the process physics.

Figure 2-13. Coherence function estimation for thin wire in a cylindrical cavity with rectangular aperture.

The coherence function technique was applied to a wire placed behind a rectangular aperture in a cylindrical cavity. After estimating the power spectra, the coherence function was estimated to determine the reliability of the estimates. As seen in Fig. 2-13, the coherence is very low, less than 0.5, over most of the frequency range. The peaks in the function do not correlate with those in the spectrum, indicating that a fine structure is a strong function of position. Further investigation is required to fully ascertain the implications of these results.

University Contracts

Three university contracts were drawn in the SCE Thrust Area this year in the signal processing area. Professor W. Gersch at the University of Hawaii investigated the use of matrix transformation in the analysis of time series. Dr. D. Goodman at Purdue University studied improvement of a nonlinear least squares identification algorithm, and Dr. M. Soderstrom investigated impulse response estimation of delay signals. The results of these efforts are summarized in Publications 3 and 4 below.

Publications and Presentations

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2. McGevna, V., "Signal Processing of Transient EM Data," URSI Conference (1984).
3. Gersch, W., Bayesian Analysis of Time Series I: Householder Transformation Analyses, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20271 (1984).
4. Johnson, J., and M. Soderstrom, Impulse Response Estimation of Delayed Signals, Lawrence Livermore National Laboratory, Livermore, CA, UCID in progress (1984).

7. Image Processing

Principal Investigator: M. R. Portnoff

Introduction and Objectives

Digital image processing has significantly benefited many of the programs at the Laboratory. However, owing to time and budget constraints, individual programs often must emphasize short-term goals and, therefore, cannot always directly fund the necessary fundamental research and development to investigate and implement new image processing techniques, even though the programs are, in fact, the long-term beneficiaries of such work. Consequently, the progress in advancing the state of the art in digital image processing at Lawrence Livermore National Laboratory (LLNL) has resulted, in large part, from the continued support from the Engineering Research Program and from the Signal and Control Engineering Thrust Area.

The major effort in digital image processing at LLNL has traditionally been and continues to be support of the Weapons Program using the capabilities of the Image Processing Research Facility (IPRF). One of the principal applications of digital image processing at the Laboratory is the routine enhancement and analysis of digitized radiographic images. Radiographs are an important diagnostic tool in experimental physics for the nondestructive and destructive testing of weapons devices. Due to the nature of radiographic image formation,

such images typically suffer from noise, blurring, and dynamic range problems. The Signal and Image Processing Research Group has implemented a variety of algorithms that significantly improve the quality and interpretability of these radiographs. In addition, digital image processing methods have been successfully applied to other weapons-related problems including time-motion studies of exploding devices, aerial imagery of underground nuclear tests, enhancement of degraded streak-camera images, and automatic analysis of diagnostic oscilloscope photographs from weapons tests. During the past year, our support of the Weapons Program has included work for the Nuclear Design Department (B Division), the Military Applications Program (W Program), the Nuclear Testing Program (L Division), non-local thermodynamic equilibrium Program (R Program), and the Chemistry Department, as well as weapons applications within the Electronics Engineering (EE) Department. Of particular note are three current research efforts: the continuation of our work with radiographs from the W-84; a new R-Program project involving the simulation of telescope views of rocket plumes; and a new Chemistry Department project aimed at investigating techniques to enhance scanning electron micro-

graphs of certain low-Z material. The work performed during FY 84 supported by the Engineering Research Program and by the Signal and Control Engineering Thrust Area as well as the work proposed for FY 85 is primarily motivated by these applications.

The image processing capabilities of the IPRF have also been used for a number of other LLNL programmatic applications, including laser fusion diagnostics for the Laser Program (Y Program), image processing of seismic spectrograms for the Verification Program, enhancement and analysis of images for Special Projects (Z Division), and automatic extraction of waveforms from oscilloscope photographs for a number of programs. Moreover, the IPRF has been used by other EE personnel to support their own projects including display of microwave and ultrasound tomograms, enhancement of railgun diagnostic images and interactive display of geotomographic images, and scattered elastic wave fields and antenna patterns. James Barryman of the Geophysics Department has also made considerable use of our facilities during the past year to develop methods for measuring spatial correlation functions of composite heterogeneous materials.

Progress

Image Change Detection

Many image processing applications, both at the Laboratory and elsewhere, involve the following scenario: One is given two or more

pictures of the same scene and is required to determine what, if any, features have changed from picture to picture. In addition to the obvious application to the analysis of photoreconnaissance imagery, other applications include those to diagnostics to study the time evolution of dynamic experiments and the destructive and nondestructive evaluation of mechanical components and assemblies. For example, we may wish to study the dynamics of material ejected from a shaped charge shortly after detonation using a sequence of high-speed photographs. In fact, using radiography and careful calibration techniques, it is possible to make accurate quantitative measurements of the evolving material distribution. Similarly, we may wish to evaluate the effects of stress loading on a mechanical assembly. In this application, we first compare images of the assembly before and after loading to analyze the deformation of the assembly under load. Then, we compare images of the original assembly to the assembly after relaxing the load to determine the degree of plasticity of the deformation and the possible formation of cracks. In another application, we may wish to detect manufacturing defects in a precision part or circuit board by comparing an image of the test item in question to an image of a standard item of known quality.

Based in part on previous experiences applying relatively simple algorithms to various programmatic problems generated by

W Program Nondestructive Evaluation (NDE), the Energy and Resource Program (K Division), and Z Division, last year we began to view image change detection as a generic image processing problem.

Image Registration

We have continued our work to improve image registration methods. Image change detection is usually based on pairwise subtraction of the images to be compared. To ensure that the resulting difference images contain only the features that differ between images, the images must be brought into registration, or alignment, prior to subtraction. The registration problem is difficult because a slight misregistration, by even one pixel or less, will cause the difference image to look like a spatial derivative of the scene, with very large values at the edges in the scene. We have developed an improved registration method that uses a local similarity measure to correct locations of operator-specified control points. This algorithm has been applied, with very good results, to real data in at least one programmatic application requiring image change detection.

Nonlinear Smoothing of Images

We are continuing to investigate the mathematical properties of median filters. J. Patrick Fitch, who recently received his Ph.D. from Purdue University, joined the Signal and Image Processing Research Group

near the end of FY 84. As part of his dissertation research, Dr. Fitch developed a remarkable superposition property for median filters. This result is not only theoretically significant, but it also has important practical implications for Very Large-Scale Integration (VLSI) implementation of median filters. Dr. Fitch is continuing to pursue this work as well as research in other aspects of median filters, including properties of "roots" of median filters and median filters for analog signals.

Migration of PDP-11/70 Software to VAX-11/750

We have completed the migration of our image processing software from the old PDP-11/70 system to the VAX-11/750. Since the VAX does not suffer from the 32K-address space limitation of the PDP-11/750, an entire image may be stored and processed in memory without resorting to sectioning techniques. Because such techniques are time consuming to program and debug, the VAX will allow us to devote much more of our software development effort to actual image processing issues.

Two-Dimensional Convolution and Convolutional Decimation-Interpolation

We have developed a general two-dimensional direct convolution code that also implements convolutional decimation-interpolation efficiently. The code was written and debugged in standard FORTRAN.

Although the FORTRAN version of the code is already used for a number of applications, it is also general and applicable enough to be converted to run on the AP-120B array processor.

Image Processing of Rocket Plumes

In support of R Program, we have recently started a new project on the image processing of rocket plumes. Using the point spread functions for various telescope configurations, we are presently simulating the images of rocket plumes that might be observed by proposed tracking telescopes. This work may lead to future research to investigate restoration algorithms to deblur such imagery.

Enhancement of TMI Reactor Imagery for Nuclear Systems Safety Program

We enhanced video imagery collected inside the Three-Mile-Island TMI-2 reactor vessel for the Nuclear Systems Safety Program (NSSP). The imagery was acquired under extremely adverse conditions and was degraded by blurring, camera motion, video dropouts, and noise. We processed the imagery by digitizing the videotaped data, performing three different noise-reduction operations on the data, then performing various types of image enhancement on each of the noise-reduced images. The preliminary noise-reduction steps reduced the noise significantly so the subsequent enhancement, which is somewhat sensitive to noise, could be performed with optimum results.

We digitized twenty-three adjacent frames of video for input to the noise-reduction process. Some camera motion occurred during the 0.77 second these frames were being acquired, so the frames were registered (translated vertically and horizontally by an integer number of pixels) so they would superimpose correctly on one another. We then combined them using three different techniques to reduce noise. Once these three noise-reduced images were generated, we applied the various image-enhancement techniques to each of them.

The image-enhancement techniques applied included the contrast stretch, the directional derivative, and the Sobel edge detector. The results of this enhancement were very encouraging: Effects of noise and dropouts were greatly reduced, and edges of parts were sharpened, making the individual parts much more visible (see Fig. 2-14).

Photographs of the enhanced images have been forwarded through the Nuclear Systems Safety Program (NSSP) to EG&G, Idaho for their review and comment.

Figure 2-14. In (a) we see a highly degraded image of the TMI reactor core, which was obtained by lowering a video camera into the core, and in (b) we see the results of applying various image processing techniques to produce the enhanced image of the core. Note the deterioration of the control rods.

Analysis and Mensuration of W Division Radiographs

We have continued to provide support to the Weapons Program, which relies on our facilities and expertise to process and analyze radiographs generated during destructive and nondestructive evaluation of weapons assemblies. We have

continued to process such radiographs by using techniques we developed last year to measure material thickness quantitatively from film densities. This technique was used to analyze a large number of radiographs resulting from tests of a key component of the W-84.

Analysis of Oscilloscope Photographs for L Division and Nuclear Energy Systems Division (NESD)

During the past year, personnel from these two divisions have continued to make extensive use of our image-processing facilities to extract, or digitize, waveforms from several hundred oscilloscope photos using an algorithm we developed for that purpose.

Image Processing of Seismic Spectrograms

The geophysics community in general and the Seismic Verification Program in particular have expressed interest in the use of time-frequency signal representations to detect and identify various seismic events. The standard representation is the spectrogram--a map of signal energy as a function of arrival time and frequency band. Because this map is nonnegative and a function of two independent variables, it may be interpreted as an image. We are beginning to investigate the application of digital image-processing methods to enhance the arrivals of seismic waves when represented as spectrograms.

Late in FY 84, we implemented a computer code on the IPRF VAX to read seismic data from mag tapes written by the Geophysics Department's PRIME computer system and to convert this data to the image format used by the IPRF. We are currently looking at seismic spectrograms of actual events and will be investigating techniques to segment the seismograms.

Analysis of Aerial Imagery

We have worked with geophysicists to analyze sequences of frames excerpted from video aerial imagery to study ground motion and spalling from underground nuclear tests.

Publications and Presentations

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7. Portnoff, M. R., R. J. Sherwood, R. E. Twogood, and N. C. Gallagher, "Digital Image Processing Applications at the Lawrence Livermore National Laboratory," Third ASSP Workshop on Multidimensional Digital Signal Processing, Stanford Sierra Camp, Fallen Leaf Lake, Lake Tahoe, CA (October 19-21, 1983).
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9. Kundu, A., S. K. Mitra, and P. P. Vaidyanathan, "Generalized Mean Filters: A New Class of Nonlinear Filters for Image Processing," submitted to IEEE Trans. ASSP.
Lawrence Livermore National Laboratory Electronics Engineering Department Computer Program Newsletter, No. 8, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19563-8 (January 3, 1983).
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11. Twogood, R. E., M. R. Portnoff, and R. J. Sherwood, "Image Processing Computer Codes,"
Lawrence Livermore National Laboratory Electronics Engineering Department Computer Program Newsletter, No. 8, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19563-8 (January 3, 1983).
12. Lytle, R. J. and M. R. Portnoff, "Cross-Borehole Seismic Probing," Disclosure and Record of Invention, Invention Case No. IL-7157.
13. Twogood, R. E. and R. L. Kirlin, Image Processing with Minicomputers and Array Processors, (to be published by Van Nostrand Reinhold Co.).

8. Large-Scale Systems

Principal Investigators: C. J. Herget, D. T. Gavel, K. D. Young, and D. Tilly

Introduction and Objectives

The large-scale systems research project has recently focused on adaptive control algorithms for decentralized systems. Control systems often must operate in environments where the plant dynamics are either partially or completely unknown, or where parameters characterizing the plant vary in time. For this reason, interest in adaptive control methods has increased.

Control systems are also currently applied to increasingly large scale plants. The electric power network of the United States is an

example. Although present control design techniques, both classical and modern, apply in principle to systems of any size, dividing large plants into subsystems and controlling each subsystem separately (decentralized control) is simpler and more reliable. In practice, this approach has worked well in many cases.

In some situations adaptive control must be used for the subsystems of a large-scale system. An example of such a situation would be when very little information is

Figure 2-15. Model reference adaptive controller.

known about the subsystem itself, or even when a good model of the subsystem is available, but very little is known about the interconnection levels between subsystems.

Progress

We have developed stable decentralized adaptive algorithms for a class of large-scale systems. This class is a subset of the class of large-scale systems that can be stabilized by nonadaptive means. Algorithms have been developed for the case when full state of the subsystem is available for feedback, and for the case when only a single output is available.

These controllers work in the following manner: A model for desired subsystem behavior is chosen and the output of the model is compared with the output of the plant or subsystem to be con-

trolled. This information is used to design a feedback compensator that will provide a driving signal to the plant (Fig. 2-15). The compensator will converge asymptotically and the closed loop system composed of plant and compensator will behave exactly as does the model. (It is important to note that convergence will occur regardless of the strengths of the interconnections between subsystems; the adaptive scheme will simply increase its feedback gains until the entire system is stable. An example of a system composed of two interconnected subsystems is shown in Fig. 2-16. Simulated decentralized adaptive-control response is shown in Fig. 2-17.

Publications and Presentations

1. Gavel, D. T. and D. D. Siljak, High Gain Adaptive Control of Decentralized Systems, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91623 (prepared for submittal to the 1985 American Control Conference).
2. Gavel, D. T. memo in preparation.

Figure 2-16. Interconnected system consisting of two subsystems (inverted pendulums).

Figure 2-17. Tracking errors to reference input of adaptive decentralized controller.

9. Multivariable Control Algorithm and Software Development

Principal Investigators: C. J. Herget, D. T. Gavel, K. D. Young, and D. Tilly

Introduction and Objectives

The objective of this project is to develop state-of-the-art software tools that will aid the control-system engineering-design process. Software can be developed in-house or it can come from many sources including consultants and literature, but we are requiring that the software be public domain. The overall control-design environment should have all of the numerical routines necessary to support the control-design process as well as user-friendly methods of specifying and manipulating system descriptions. Imported software is to be tested for both efficiency and reliability on "standard" problems, i.e., those typically encountered in practice, and on "pathological" problems designed to prove the limitations regarding size, numerical conditioning, etc.

Progress

Numerical Algorithms

A key consideration is to include in the collection algorithms from all of the main schools of control design. We have grouped the major design approaches as follows: "Classical" Methods (CM), Linear Quadratic Gaussian (LQG) techniques, Pole-Placement Methods (PPM), Optimization-Based Design

(OBD), Multivariable Frequency-Domain Methods (MFDM), Large Scale Systems (LSS) approach, and Non-linear System (NLS) control design. In addition, there are several support areas including Continuous-Time System Simulation (CTSS), Symbolic Equation Manipulation (SEM), general equation solving, and optimization. Obtaining reliable software in all of these areas should provide us with a solid computational foundation for future control design requirements, whether they be for program or research applications.

A large number of subroutines has been brought in and tested this year. These algorithms are interfaced to the DELIGHT computer-aided engineering (CAE) computer program running on a VAX-11/780. The CM, LQG, PPM, and OBD methodologies now seem to be adequately supported by appropriate software. The classical methods are largely supported by the LSAP computer program. We also have adequate software in each of the support areas mentioned above: CTSS, SEM, general equation solving, and optimization.

Human Interface—System Specification

We have completed the interfacing of the block-diagram-editor system specification to the

continuous-system simulator. This interface allows an engineer to sit at an interactive graphics terminal, specify an interconnection of linear state-space subsystems (graphical blocks) with a "mouse," then ask the computer to link the subsystems together to provide an overall system description. This system description is in a compatible form for either continuous or discrete system simulation.

To support the definition of state-space subsystems, we have written a graphically oriented matrix editor. With this editor, the user moves the cursor to the

desired matrix element and then types the desired number (See Fig. 2-18). From user experience, it seems that initializing a matrix this way is a far simpler and more user-friendly approach than the "data statement" FORTRAN approach, or even the matrix assignment methods found in DELIGHT and other modern interactive packages.

The system-definition phase is currently limited to linear subsystems without unresolved algebraic loops. The resolution of algebraic loops and extension to nonlinear subsystem descriptions is one under development at present.

```

** Welcome to PLAYMATE: a full disPLAY MATrix Editor **
**
** This matrix has 4 rows and 4 columns **

```

0	1.0	0	0
0	0	1.0	0
0	0	0	1.0
	-15.0	-15.0	-15.0

```

a - arrow keys  n - new value      z - zero out      q - quit
b - number keys  . - repeat last change  f - fill          e - exit
g - goto        i - make identity  F - change format
s - scroll       t - triangularize  R - redraw screen
                c - copy element    u - undo
                T - transpose       h - help
                r - restore

```

Hit any key to continue: █

Figure 2-18. Graphical matrix editor for state space systems.

PUBLICATIONS AND PRESENTATIONS

1. "Control-System Design Utilities Available with DELIGHT," part of DELIGHT/LLNL User's Guide, Lawrence Livermore National Laboratory, Livermore, CA.
2. Gavel, D. and C. Herget, "An Interactive Computer-Aided Engineering Package for Control Systems Design," presented at the 1984 CUBE Symposium, Los Alamos, NM (October, 1984).
3. Herget, C. J. and A. J. Laub, guest editors, Special Section on Computer-Aided Control-System Design, Proceedings of the IEEE (December, 1984).

10. Frequency Domain System Identification

Principal Investigators: D. Tilly and G. Clark

Introduction and Objectives

System identification is used in many engineering applications at Lawrence Livermore National Laboratory (LLNL). Most of these identification problems can be solved using one of the many time-domain methods that have been studied and well developed in the last fifteen years. In practice, however, frequency-response data, or Bode plots, may be the only data available to the engineer. Also, in some applications at LLNL, a time-domain model of the system is not necessary. Instead, the engineer wishes to gain a general knowledge of system frequency response. For these instances, a frequency-domain system-identification technique may be more appropriate. In this project we were interested in estimating the coefficients of a Laplace transform transfer-function system model. The transfer-function model would aid in the design of machine-

tool control systems. We studied several available parametric frequency-domain identification methods and selected three computer codes for further development as representatives of different approaches to solving the problem.

The final objectives of the project were:

1. To study and compare the available frequency-domain identification algorithms.
2. To provide the Machine Control Group with a parametric frequency-domain system-identification program.

Progress

A study was made of the available frequency-domain identification codes, three of which were chosen as representative of three different approaches taken in solving the problem. These three were further developed or modified to work as a general Laplace transform transfer-function identifier. The codes studied were Transfer Function (TF), developed at LLNL, Transfer (TRANSF), also developed at LLNL, and NAVFIT, originated at Nasa-Ames Research Center by J. Hodgkinson and further developed by M. Tischler. TF identifies the coefficients of a parametric Laplace transfer-function model by a linear least-squares method. TRANSF identifies the damping, frequency, and residues of a summation of complex pole pairs, using a nonlinear technique. Finally, NAVFIT identifies the coefficients of a parametric Laplace transfer-function model using a multivariable search method.

The report, entitled "Three Algorithms for Parametric Frequency-Domain System Identification," was completed. It includes a detailed description of each of the methods and a discussion of their advantages and disadvantages. User information is included for each code. In addition, some general issues involved in frequency-domain identification are discussed.

The code NAVFIT was chosen as the most appropriate for the Machine Control Group applications and was developed to fit those needs. Because NAVFIT uses a Rosenbrock's

multivariable-search algorithm, it needs a first guess at the Laplace transform coefficients as starting parameters. In many of the Machine Control Group applications the general form of the transfer function in question is known, so the program can be guided, through the choice of starting parameters, to identify the expected poles and zeros.

The program was made to run interactively, prompting the user for the starting parameters and other information needed to fit a Laplace transfer-function model to the measured frequency-domain transfer-function data. On input NAVFIT requires a file of transfer-function data. NAVFIT produces a list of the identified poles and zeros of the Laplace transform transfer-function model and a plot of the measured data overlaid by the transfer-function calculated from the identified coefficients. Figure 2-19 shows a plot of measured transfer-function data from a machine tool, overlaid by the fitting function estimated by NAVFIT.

Figure 2-19. Transfer function plot produced by NAVFIT.

Publications and Presentations

1. Tilly, D. M., Three Algorithms for Parametric Frequency Domain System Identification, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20255 (November, 1984).
2. Presentation at CUBE Symposium, Los Alamos National Laboratory, Los Alamos, NM (October 1984).

III. Microwave and Pulsed Power Engineering

Thrust Area Leader: W. W. Hofer

Overview

The Microwave and Pulsed Power Engineering Thrust Area is responsible for developing the short-term and long-term engineering resources required to support the growing microwave and pulsed power engineering requirements of several LLNL Programs.

Microwave and pulsed power engineering is an important part of the Laboratory's major programs. Two specific examples are in the Directed Energy Weapons Program and in the LIS Program. The Directed Energy Weapons Program presents microwave and pulsed power engineering challenges beyond the state of the art in high-voltage standoff, pulsed power sources, material performance, and diagnostic systems. The responsibility of this Thrust Area is to initiate applicable research and development projects and to provide capabilities and facilities to permit engineers involved in these and other programs to make significant contributions.

In this section, the principal contributors in the Microwave and Pulsed Power Thrust Area described the work completed in FY 84. The projects are:

- Dielectric Failure Prediction Using Partial Discharge Analysis.

- Coating Dielectrics to Increase Surface Flashover Potential.
- The Microwave Generator Experiment (MGX).

Facilities

During FY 84 the Pulsed Power Laboratory was expanded to include all of Bay 3 in Bldg. 141. The laboratory now occupies a total of 8300-ft² (Fig. 3-1). The major additions to the Pulsed Power Laboratory were the Megavolt Accelerator and the Dielectric Test Facility.

Figure 3-1. Pulsed Power Laboratory floor layout—Bldg. 141.

The Megavolt Accelerator is designed to generate a 2 MV, 0.5 TW, short-pulse (40 ns) electron beam. The output pulse rise time is less than 10 ns. Output energy is 10 kJ. The accelerator was designed around an existing Physics International Pulserad 422 Marx generator. The Marx generator design remained unchanged; however, the pulse-forming line was completely

redesigned to a 6- Ω water-dielectric coaxial line with state-of-the-art gas switches to generate pulses with less than 10-ns rise time (Fig. 3-2). It includes a 30 x 30 ft, radiation-shielded, interlocked experimental area. Instrumentation includes oscilloscopes and transient digitizers housed in a well shielded room. Figure 3-3 shows a complete layout of the Megavolt Accelerator

Figure 3-2. The 2-MV electron beam accelerator uses a 6 Ω , water dielectric pulse-forming line to generate a 0.5-TW, 40-ns pulse with a rise time ≥ 10 ns.

Figure 3-3. Megavolt accelerator system in Bldg. 141 generates a 2-MeV, 200-kA short-pulse (40 ns) electron beam.

system. The accelerator will be fully operational in the spring of 1985. Thrust Area and programmatic applications for the high-power accelerator include studying material properties at high current densities, high-power microwave generation, diagnostics development, and generation of intense bursts of radiation.

The Dielectric Test Facility is a unique, new Laboratory capability. The facility is housed in a 260-ft², double-wall shielded room and includes a 100 kV, corona-free, ac power supply and an advanced partial discharge analyzer (PDA). With this capability, we are conducting research on dielectric defect detection and failure prediction using non-destructive, partial-discharge-analysis techniques.

The Pulsed Power Laboratory continued to be used extensively for short-term programmatic projects. In FY 84, the Laboratory was used to develop a 500-kV, radiation-tolerant, high-voltage probe used to test and calibrate megampere current probes, and to develop and test a high-current (10 kA) battery current supply. The Laboratory was also used by the Military Applications Program (W Program) to test the vulnerability of a W-87 control cable to lightning. In these tests, current pulses of approximately 200 kA from a high-energy capacitor bank were injected into the control cable to test the lightning arrestor connectors (LACS). These tests closely simulated an actual lightning strike to the connector. In

addition, Thrust Area personnel used the Pulsed Power Laboratory to set up a test designed to accurately measure the erosion of various conducting materials used on a rail gun project. This test setup made possible the discharge of several coulombs of charge through the conducting material under test. An accurate determination of the material eroded away by the high-current-density discharge is made by carefully comparing the weights of the test specimen before and after the current discharge.

Compact Torus Engineering Review

Members of the Thrust Area working group conducted an in-depth engineering review of a proposed new research project at LLNL, the Accelerated Compact Torus (ACT) (Fig. 3-4). Significant advances in microwave generation, fast-opening switching, x-ray generation, and inertial confinement fusion (ICF) may be possible using the ACT technology. By direction of the Associate Director for Engineering, the engineering review team examined the feasibility and cost of performing the ACT experiment in the Pulsed Power Laboratory. The team concluded that the laboratory would be inadequate without substantial modification, that the cost estimate for the project was correct, and that the most logical location for the project was in the Magnetic Fusion Beta-2 facility as originally planned.

Figure 3-4. Formation of compact torus. (a) Initial injection of toroidal flux. (b) Elongation. (c) Reconnection. After formation, the compact torus is compressed, accelerated and focused by a capacitor-bank-driven coaxial railgun assembly.

Short Course—Pulsed Power for Technicians

During May and June, a series of classes was held to train technicians in basic pulsed power technology. The instruction included videotaped sessions supplemented by live lectures given by engineers working in the Thrust Area. Topics included switching, energy storage, pulsed power safety, and applications.

Pulsed Power Bibliography

The Pulsed Power Bibliography is now ready for initial release. It contains approximately 3000 citations pertaining to voltage-breakdown physics, energy storage, high-voltage insulation, materials, particle-beam generation, power conditioning, pulse generation, switching, pulsed power diagnostics,

and other aspects of pulsed power. The Pulsed Power Bibliography is available in printed or computer form. The computerized database is directly compatible with the INGRES database manager and can be obtained for a VAX computer utilizing the VMS operating system. A well structured query routine is included with the INGRES-compatible database. The query routine permits on-line searches by subject, author affiliation, keywords, or title. The actual database entries require about 10 Mbytes of disk space. Additional space will be required for indexing and for other auxiliary files, with the total space required representing a compromise between speed of execution and available disk space. All information contained in the printed version is included in the computerized database.

Microwave Laboratory

A centralized microwave engineering laboratory was constructed in Bldg. 131 in FY 84 (Fig. 3-5). It consists of an 1800-ft² RFI-shielded room with excellent environment stability and a clean atmosphere. It is a convenient location for engineers engaged in microwave engineering studies. The laboratory is well-equipped with a variety of microwave measuring instruments, including automatic network analyzers (0.5-40 GHz), a spectrum analyzer (50 kHz-90 GHz), a microwave frequency counter

(10 Hz-90 GHz), power meters, and sweep generators (26-50 GHz). Several sources, ranging from a 125 kW, 35 GHz magnetron oscillator to several low-power (mW) pulsed and CW Gunn oscillators, are available in the laboratory. The laboratory is used extensively by engineers involved in accurately characterizing microwave components and systems. The laboratory is also used for microwave diagnostics development, high power microwave detector development, and microwave non-destructive evaluation (NDE) research.

Figure 3-5. An automatic network analyzer in the microwave engineering laboratory accurately characterizes various microwave components and systems.

1. Dielectric Failure Prediction

Principal Investigators: L. B. Gordon and G. A. Clark

Introduction and Objectives

The insulating materials of high-voltage systems are composed of a variety of gaseous, liquid, and solid dielectrics. These dielectrics usually determine the reliability of the system, and it is their failure that limits the electrical energy density and lifetime achievable in the design. Typically, in tests of dielectric materials, an electric-field stress is applied to the dielectric until it either survives for a specified time or fails in some sense. Often, the test (which may be at higher stress levels than those found during normal operating conditions) can internally damage the dielectric, reducing its reliability. In addition, very little is learned of the dielectric material except that it survives or that it does not. An alternative approach is to use nondestructive testing, in which the material is stressed enough to create a small response but not enough to cause catastrophic breakdown or other serious damage. The measurable, small responses of the dielectric to a low stress level can be used to predict the stress level at which catastrophic failure will occur, the location and type of failure most likely to occur, and the length of time the material might survive until such failure.

Dielectric materials usually initiate breakdown at the sites of strongest electric field stress. These sites occur at impurities, boundaries, projections, voids, and at other nonuniformities in the material. Dielectrics can be non-destructively tested by subjecting an insulating system to high-voltage ac, dc, or pulsed signals at levels less than overall breakdown levels and by measuring the minute partial discharges that occur at these sites of electric field enhancement. The partial discharge, pulse-height distribution spectrum (number of discharges per second vs ΔQ or Δi) can be used as a "fingerprint" of system behavior to predict the system's reaction to a given voltage and elapsed-time condition. This fingerprint consists of amplitude, frequency, and phase information of the partial discharges occurring, for instance, inside the voids of the dielectric. Due to breakdown statistics, the pulse-height distribution curve approximates the probability density function of a random variable. The partial discharge, pulse-height distribution spectrum can be used to predict the type, amount, and location of dielectric nonuniformities and can be used to study aging and degradation of the dielectric (due, for example, to the chemical and physical changes occurring within the voids during

each microdischarge). Figure 3-6 illustrates the application of a high-voltage stress across a dielectric containing voids. The resulting distribution of microdischarges is detected and plotted by a data-acquisition system.

Partial-discharge analysis was originally developed for testing and evaluating 60-Hz ac power-distribution components because of the need for reliability and long lifetime. Recently, the need for more compact systems, better reliability and longer lifetimes has encouraged the development of such nondestructive testing techniques for dc and pulsed systems. High reliability and long lifetime of the insulating systems in LLNL programs that employ high-voltage pulsed power and high-average-power systems are very important. These dielectric material needs are found in the

Laser Fusion, Magnetic Fusion, Laser Isotope Separation, Weapons, and other programs.

The objectives during FY 84 were

- To determine state-of-the-art methods of nondestructively testing the high-voltage strength of dielectric materials and of predicting their lifetimes under high-voltage stresses.
- To obtain the high-voltage, diagnostic, and data-acquisition equipment needed to measure the pulse height distribution spectra.
- To determine the critical study areas for applying partial-discharge analysis to high-voltage, pulsed power insulator problems.

Figure 3-6. Partial discharge detection system for multiple internal voids in a solid dielectric.

Progress

Partial Discharge Analysis

Partial discharges do not completely bridge the gap between two electrodes. The discharge may occur in a gas-filled void inside a solid insulating material, from an electrode to the surface of a solid insulating material, or around an electrode in a gas. Partial discharges can also occur in liquids and across surfaces in a vacuum. The study of partial discharges involves detecting very small electrical pulses in a high-voltage circuit. For this reason, partial discharge detection is limited by noise present or picked up in the circuit. With a controlled environment (one that includes shielding, filtered power, corona-free components, attention to circuit contacts, grounding, etc.), it is possible to detect discharges of 0.1 pC. The partial-discharge signal must be separated from the high-voltage test signal by some type of filter network, and then must be displayed on a CRT screen using an elliptical or sinewave time base, or must be displayed with a peak discharge meter, or by using a multichannel counter to produce a histogram of the number of discharge counts vs discharge size.

Historically, partial discharge analysis has been externally used in evaluating and testing power generation and distribution equipment. Typically, rotating machines, power transformers, cables, bushings,

capacitors, and gas-insulated substations are evaluated by visually observing the discharge patterns on a CRT screen. Standards are set for maximum allowable discharge sizes, primarily to reject insulation containing large voids. The CRT display, however, does not distinguish between many small discharges and a few large discharges, does not distinctly display individual discharges, and does not allow discharge detection under dc stress. These problems could be overcome by using a multichannel pulse height analyzer, provided that the analog-to-digital converter is fast compared to the discharge rate.

Discharge detection of particles and gas-bubble formation in oil is used to study oil degradation. Considerable study of voids and material degradation, especially in polyethylene and epoxy resins, has been completed. Some defect recognition has been accomplished with ac test signals, primarily for detecting contact noise, corona points, or voids in simple components. Acoustic detection of partial discharges detects and locates discharge sites in large systems.

Dielectric Test Facility

During FY 84 the Microwave and Pulsed Power Engineering Thrust Area designed and built a facility for the testing and study of dielectrics. The facility includes a double-walled screen room; filtered power, corona-free power supplies; a fast, sensitive image-converter

streak camera; two CRT analog discharge detectors; and a programmable multichannel partial discharge analyzer system. Figure 3-7 is a photograph of a typical test arrangement in the screen room, and Fig. 3-8 shows some of the analysis equipment. Figure 3-9 illustrates the CRT analog display of discharge pulses, and Fig. 3-10 is a typical histogram from the multichannel analyzer. The facility is designed to be used for state-of-the-art research in partial discharge detection and analysis.

Dielectric Materials Research

The research possibilities in the areas of dielectric failure and partial-discharge analysis are immense. The Thrust Area selected

six subjects for study during the next few years because these areas would especially impact pulsed power programs at LLNL.

It is important to investigate the use of advanced partial-discharge measurement methods to identify dielectric defects in the basic insulating structures used in pulsed power systems. Of special interest are interface regions where metals, solid dielectrics, and gases (or fluids) are in close proximity (Fig. 3-11). These "triple junctions" are weak regions because the change in dielectric constant, the electrode geometry, and the charge transport all tend to enhance the electrical stress. These interface regions are often the weakest points in many pulsed power components. A

Figure 3-7. Typical test arrangement in the screen room.

Figure 3-8. Analysis equipment setup.

Figure 3-9. Typical partial discharges displayed on an ellipsoidal time base.

Figure 3-10. Multichannel partial discharge analyzer histogram. Vertical axis is number of counts. Horizontal axis is charge quantity from 32 pC to 156 pC.

Figure 3-11. Volume and surface discharges often initiate at "triple junctions" the junction between gas, dielectric, and conductor.

study of the discharge spectrum of different forms of triple junctions, coupled with a model of the discharge region, will allow better understanding of failure mechanisms and will lead to improved designs.

Reliability is the primary concern for some pulsed systems. Nondestructive testing is essential for predicting reliability without dangerously prestressing the dielectric material. Thin-layer, parallel-strip transmission lines composed of laminated copper and Kapton are important candidates for dielectric defect detection. As seen in Fig. 3-12, several types of defects are inherent in the dielectric material; others are created in the assembly process. Analysis of the partial-discharge patterns of strip lines will provide an understanding of the reliability and the potential failure modes.

Vacuum-surface flashover is critical in particle accelerators, where tremendous potentials must exist across small spaces. Very

little has been done to determine what dielectric surface characteristics effect surface breakdown and how these characteristics might change under varying conditions. These criteria are especially important in space applications of pulsed power. We are studying the partial discharge characteristics of various surfaces in vacuum. As illustrated in Fig. 3-13, breakdown paths typically follow an irregular path known as a "tree." These paths are preceded by a small, localized charge buildup on the insulator surface.

Dielectrics fail over a period of time due to material degradation from prolonged exposure to electric and other environmental stresses, such as thermal, mechanical, chemical and radiation stresses. As illustrated in Fig. 3-14, these combined stresses act together to cause erosion, tree formation, and void formation and growth. These changes can be observed by studying the effects of prolonged stress on the partial-discharge patterns. The

Figure 3-12. Cross-section of a parallel plate transmission line showing several sites of partial discharge and insulator failure.

Figure 3-13. Vacuum surface flashover showing tree formation along insulator surface.

Figure 3-14. Dielectric aging caused by repeated internal discharges and stress from environmental conditions.

study of these dielectric aging phenomena is very important for long-lifetime, high-repetition-rate systems.

Practically all but the simplest of dielectric systems produce a complex histogram when observed on a multichannel analyzer. In order to extract useful information, signal analysis techniques are necessary. The output of the

analog-to-digital converter provides a pulse occurrence rate signal, which is a time-domain waveform consisting of "ones and zeros." The signal has a logical value of zero when no partial discharge event has occurred, and one otherwise. The goal of studying this signal is to develop techniques to recognize patterns in the occurrence of events and to correlate these patterns to

the excitation voltage parameters, such as amplitude, phase and frequency. Spectrum-analysis and pattern-recognition techniques can be used to analyze the pulse occurrence rate signal. Since the partial discharge process is time-dependent, spectrogram displays (3D displays where one of the two independent variables is time) can be built to analyze how the pulse occurrence rate signal characteristics (frequency spectrum, power spectrum, autocorrelation function) change with time.

The ideal excitation signal for studying dielectrics in pulsed power systems is a pulsed test voltage. Unfortunately, it is very difficult to measure partial discharge signals in the picocoulomb range when their frequency spectrums are superimposed upon that of an excitation signal with a magnitude in the range of tens to hundreds of kilovolts. An alternative approach is to measure the response to the pulsed electric-

cal stress with acoustic transducers, which can detect the small acoustic events associated with the partial discharges, or to measure the response with sensitive optical transducers, such as a multichannel-plate-amplified image converter camera. As illustrated in Fig. 3-15, these three techniques can simultaneously be used to obtain information on the partial-discharge process.

Publications and Presentations

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2. "Partial Discharge Measurement and Analysis," Nuclear Energy Systems Division project update, Lawrence Livermore National Laboratory, Livermore, CA (November 18, 1983).

Figure 3-15. Several detection techniques can be used to identify, locate, and monitor partial discharges.

3. "Pulsed Power and High Power Microwave Research at LLNL," University Seminar - Texas Tech University (February 10, 1984).
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5. "Pulsed Power Programs and Research at LLNL," Technical Seminar - Maxwell Laboratories (March 9, 1984).
6. Pulsed Power Training for Technicians (Several lectures on Pulsed Power Technologies), Lawrence Livermore National Laboratory, Livermore, CA (May-June 1984).
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8. "Dielectric Testing," Nuclear Energy Systems Division project update, Lawrence Livermore National Laboratory, Livermore, CA (July 20, 1984).
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2. Coating Dielectrics to Improve Surface Flashover

Principal Investigators: L. Hatfield, M. DiCapua, and M. Kristiansen

Introduction and Objectives

Voltage hold-off across electrical insulator surfaces in a vacuum is a crucial parameter in determining the reliability of pulsed power systems used at the Laboratory and at many other national and private facilities. In addition to limiting reliability, the flashover voltage across vacuum-insulator interfaces ultimately limits the power delivered to the load in most pulsed accelerators.

The payoff of research in surface coatings and of analysis to increase the voltage hold-off across insulators is to increase the maximum power delivered to the load. Also, by reducing the insulator size, the output-pulse rise time will be shortened.

A model of insulator breakdown appears schematically in Fig. 3-16. Electrons emitted at the triple point of the cathode and that strike the insulator surface initiate two processes:

- Emission of secondary electrons that results in charging of the surface.
- Desorption of gases from the surface.

A positive feedback exists when more than one electron per incident electron is ejected from the surface. In this case, the resulting

positive charge will increase the flux of electrons on the surface. Insulator flashover is believed to occur when the gases desorbed by electron impact undergo avalanche breakdown.

Figure 3-16. Model of insulator breakdown. Electrons emitted at cathode-insulator vacuum junction (triple points) reintersect insulator causing secondary electron emission and desorption of neutrals and ions. An excess of secondaries will charge the insulation surface positively, thus attracting more electrons to the surface. Breakdown occurs when the desorbed neutrals and ions undergo a Townsend avalanche.

According to this model, improvements in insulator performance result from a reduction in the emission of secondary electrons or on the retention of absorbates. Both are properties of the insulator surface.

Prior work at Texas Tech University demonstrated an empirical approach for treating an insulator surface so that its voltage-flashover potential in a vacuum was increased by at least 70%. The treatment consisted of irradiating the insulator surface with the discharge byproducts of a jet-engine ignitor plug.

In May 1984, the project "Coating Dielectrics To Increase Surface Flashover Potential" was initiated at Texas Tech University with LLNL funding. The objectives of the project were twofold. One objective was to use state-of-the-art surface-analysis techniques to determine the detailed structure of the treated surface. The second objective, after obtaining a detailed understanding of the surface, was to replace the empirical surface treatment with a controlled and reproducible process that could be applied to larger, more realistic insulator surface configurations.

Progress

Results we obtained in four areas through the end of FY 84 are detailed below.

First, Electron Spectroscopy for Chemical Analysis (ESCA) results show that composition of the Lucite surface exposed to the discharge

changes from 71% carbon and 29% oxygen for a virgin sample to 76% carbon and 24% oxygen for a treated sample. Similarly, for a Lexan sample, the change in composition is from 84% carbon and 16% oxygen to 74% carbon and 26% oxygen. These changes in composition suggest that the exposed surface differs chemically from the substrate. A more sensitive analysis is required to confirm this suggestion.

Second, preliminary observations at LLNL reveal water under the treated surface. The possibility exists that the higher flashover voltage may result because the treatment prevents water, present in the bulk insulator, from reaching the surface.

Third, the main byproducts of the jet ignitor plug are neutral carbon atoms and ultraviolet radiation. When the insulator is exposed to these byproducts through means other than the jet ignitor plug, no increase in flashover potential is observed. This result suggests that the new surface may result from a process of repolymerization of material liberated from the insulator by the discharge combined with residual gases in the vacuum chamber.

Fourth, these results underscore the importance of identifying the chemical structure of the surface so that procedures of plasma polymerization may be used to produce the surface under controlled and reproducible conditions.

In other technology areas, surface treatment of materials allows a synergism between desirable properties of the surface and desir-

able properties of the substrate. The purpose of this program is to develop an understanding of surface coatings that will achieve this synergism with vacuum insulators.

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4. Hatfield, L. L., "Progress Report on Coating Dielectrics To Increase Surface Flashover Potential," (Department of Physics and Engineering Physics, Texas Tech University, Lubbock, Texas), Lawrence Livermore National Laboratory subcontract No. 5346405.
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3. Microwave Generator Experiment—MGX

Principal Investigators: S. C. Burkhart, R. D. Scarpetti, and R. L. Lundberg

Introduction and Objectives

The generation of high-power microwaves is a continuing area of research with many approaches. For CW applications, the highest power has been obtained in gyrotrons, where 340 kW at 28 GHz has been demonstrated. Higher power is possible for short (less than 300 ns) pulses, where a cold cathode can be used to generate the electron beam in a relativistic magnetron, a backward wave oscillator, a reflex triode, or a free-electron maser.

The purpose of the Microwave Generator Experiment (MGX) is to investigate the basic physics of microwave reflex oscillators. The reflex device used is a Virtual Cathode Oscillator (VIRCATOR). The virtual cathode forms when a uniform electron beam is injected into a cylindrical waveguide, through a screen or foil, at a current density above the space-charge limit (Fig. 3-17). The potential due to the space charge exceeds the driving potential, thus reflecting subsequent electrons back toward the anode. The apparent source of these reflected electrons is called the virtual cathode.

The microwaves are generated by two different processes. The first process occurs as the virtual cathode oscillates in space and time, causing E_z to vary in the region

between the virtual cathode and the anode. This changing E_z couples naturally into TM_{0n} waveguide modes, which are characterized by $E_z \neq 0$ and azimuthal symmetry. The other process occurs as the trapped electrons bunch as they repeatedly traverse the anode mesh. Again, this bunching generates a time varying E_z , which couples into TM_{0n} waveguide modes. This virtual cathode oscillator will work with or without an axial magnetic field, and experiments have shown that the frequency increases approximately linearly with the applied B field. Also, the frequency has been shown to vary as $\sqrt{V}$, where V is the input voltage to the diode.

The physics of reflex oscillators is of great interest to several LLNL programs. The reflex devices have demonstrated high-power, high-frequency operation in an overmoded waveguide. Typically, the power tends to decrease as $(1/\text{frequency})^{2.5}$ because of the physical dimensions of the generator. In an overmoded generator, the problem of smaller size is relaxed somewhat. Other features of interest are that any magnetic fields required are weak and that the oscillating structure is simple and smooth. The cylindrical symmetry of the MGX VIRCATOR allows it to be modeled with particle-simulation codes, such as MASK or its derivatives. Com-

parison between the code and experiment is valuable, and the code has often helped to guide the experiments.

The FY 84 objectives for MGX were to

- Continue computer modeling to explore the parameter space,
- Try different materials and dimensions for anode and cathode construction,
- Determine, experimentally and theoretically, the effect of electron scattering angle on the microwave output,
- Implement physical improvements to the microwave, pulsed power, and vacuum systems, and to the microwave and pulsed power diagnostics.

Progress

Calculations

We used a 2-1/2D relativistic particle-in-a-cell computer code to model the reflex triode operation. The code is a derivative of the code MASK, originally designed for the study of relativistic magnetrons. Figure 3-17 shows a cross section of the diode geometry as it was modeled, with the cathode on the left and the waveguide and terminating section on the right. A 1-ns-rise time voltage input to the left side drives the cathode negative. The high fields (approximately 500 kV/cm) cause space-charged, limited-electron emission from the cold cathode toward the anode foil. The electrons cross the anode-cathode gap and pass through the anode foil into the waveguide.

Figure 3-17. VIRATOR model used for the code calculations.

A potential depression is generated in the center of the waveguide due to the presence of the electrons. The current is high enough so that the depression exceeds the driving anode-cathode potential. This condition forms a virtual cathode, where most electrons stop and are driven back toward the anode foil. Some electrons continue down the waveguide. No external magnetic fields are applied in the code calculations or in the experiment. The oscillating axial electric field between the virtual cathode and the anode couples into waveguide TM_{on} modes. These modes travel down the waveguide and are absorbed by the lossy structure, shown as a resistor in Fig. 3-17. Electric and magnetic field samples were taken just to the left of the absorber in the code.

Several code studies were conducted to investigate the behavior of the virtual-cathode reflex oscillator under the following conditions:

- The geometry was fixed and the input voltage was varied.
- The cathode radius was varied from 30 percent to 90 percent of the waveguide radius.
- The effects of reflexing on diode impedance were shown.
- A thick anode "drift space" was used to separate oscillating virtual cathode effects from reflexing effects.
- A reinforcement or "locking" of the reflex and virtual

cathode oscillations was demonstrated.

- The physical experiment was modeled to check code validity.

The following paragraphs outline the results of these investigations.

Voltage Dependencies

The frequency is expected to vary as the square root of the input voltage, V , because the virtual-cathode plasma frequency $\omega_p \propto \sqrt{n_0}$ and $n_0 \propto I \propto V$. Here n_0 is the virtual cathode electron density, and I is the cathode current. This result, previously reported, is shown again here to be true. This test was a good check on the code and is shown in Fig. 3-18.

Figure 3-18. Reflex triode frequency vs (input voltage)^{1/2}. The frequency varies linearly with the square root of the voltage.

Variation of the Cathode Radius

We found that the spectral purity improved with a diode impedance of 13-20 Ω . This analysis was conducted using a fixed input voltage (400 kV) and an anode-cathode gap of 8.6 mm. The cathode radius was reduced from 38.3 mm to 12.8 mm. The frequency changed very little, from 7.2 GHz down to 7.0 GHz, as the cathode radius was reduced from 38.3 to 28.7 mm. The peak power, 300 MW at 7.0 GHz, was obtained for the 28.7-mm-radius cathode (Fig. 3-19). The efficiency of beam to microwaves was 2.2 percent, and of pulsed power to microwaves was 2.0 percent. When the cathode radius was reduced below 28.7 mm, the spectral purity was lost and the output power decreased.

Figure 3-19. Microwave generation efficiency vs cathode radius as calculated by the code. Both beam-to-microwave and pulse-power-to-microwave efficiencies are plotted. The lost power is due to the transmission line-to-diode mismatch.

Separation of Reflex and Virtual Cathode Effects

A thick anode "drift space" was added to increase the reflexing electron transit time. The drift space caused a separation of the frequencies observed in the code (Fig. 3-20). The thick anode allowed electrons to pass freely, but because the anode is a conductor, electromagnetic fields were blocked. Reflexing generates the lower set of frequencies, and the oscillating virtual cathode generates the higher frequencies. This conclusion was reached by measuring the cathode voltage fluctuations in the code and by determining the spectrum, which showed most of the power to be near 9.8 GHz. The cathode fluctuations can only be caused by reflexing electrons.

Figure 3-20. A thick anode "drift space" caused a split where some power was at 9.8 GHz and the rest was at 16.3 GHz. The 9.8 GHz power is due to reflexing, while the 16.3 GHz oscillations are due to the oscillating virtual cathode.

As the anode thickness is reduced, the reflexing frequency can increase. The virtual cathode oscillations could remain unchanged; however, code calculations show that, as the reflex frequency approaches the virtual cathode oscillation frequency, the two tend to lock together at one frequency. At that point, it is not possible to

separately consider the oscillations as from a reflex triode and a virtual cathode oscillator. The two effects work together to make a reflex triode with a purer output spectrum. The progression of thinner anodes is shown in Fig. 3-21, where FFTs of the radial E-field at the wall are displayed.

Figure 3-21. As the thick anode is made thinner, the reflex frequency increases. When it becomes sufficiently close to the natural virtual cathode oscillation frequency, the two lock together to generate a single, well-defined line.

Simulation of the Physical Experiment

For code validation, one would like to build an experiment to provide results for comparison with the code results. For the VINCATOR modeling, we can only get a partial comparison, since we cannot experimentally obtain the exact waveform. We can, however, obtain the peak power and the oscillation frequency. These values will be compared with the code results.

The configuration modeled for code validation is as follows:

Cathode radius	= 38.27 mm
Anode-cathode spacing	= 8.6 mm
Anode thickness	= 0.717 mm
V+ (input voltage)	= 400 kV
Waveguide radius	= 42.5 mm

The configuration is shown schematically in Fig. 3-17.

To measure the microwave output experimentally, we sample the radial electric field at the waveguide wall and do bandpass and envelope detection of the sampled signal. The same quantity in the code is shown in Fig. 3-22. Both the time and frequency domains are plotted. From the plots and from a Poynting surface code calculation, the center frequency is 7.2 GHz, with a power output of 200 MW. The experiment produced an output power of 250 MW in the 7.25-7.75-GHz band. Agreement is within 8 percent for frequency and within 25 percent for power, which is quite good for such an experiment.

Effects of Beam Scattering Angle

The particle simulation code was modified to cause small-angle scattering for particles passing through solid material. Small-angle

Figure 3-22. Simulation of the experimental reflex triode showed a center frequency of 7.2 GHz. The radial electric field at the waveguide wall is in (a), and the FFT of (a) is shown in (b).

scattering occurs in the experiment when a foil anode is used instead of the usual screen anode. We first observed this scattering effect when we put in a 1 mil foil anode, and the power dropped off drastically. The decrease in power due to small-angle scattering can be due to several processes. One process is that the scattering tends to deflect the electrons out of the interaction region before they convert their energy to microwaves. Scattering would also tend to inhibit any collective motion from forming in the reflex region.

Code and experiment compare very well when the scattering is introduced. The code simulates 0.3-, 0.5-, and 1.0-mil aluminum foils and several values in-between, while we have experimental data for

the 0.3-, 0.5-, and 1.0-mil foils. The conclusion reached is that, for mean electron scattering angles greater than 15° , microwave generation ceases (Fig. 3-23).

Experiments

The laboratory investigations were done with the apparatus detailed in Fig. 3-24. A 7-stage Marx bank charges a 90-ns water Blumlein. It is then fired by a command triggered, gas-filled spark gap. The pulse rise time is sharpened to 20 ns with a self-break-down-series water gap. A shunt water gap is used to divert late time energy that could damage the diode. When the high-voltage pulse reaches the diode, electrons are emitted and accelerated towards the anode mesh or foil, which covers the end of the waveguide. The potential depression from the space charge causes the virtual cathode to form on the waveguide side of the anode mesh. Microwaves generated in this device propagate to the terminator/calorimeter located 8.5 m from the diode region. The radial electric field is sampled by open-ended coaxial E-probes located 1.5 m from the diode. (The long distance between the E-probe and the terminator eliminates the possible error due to terminator mismatch or breakdown.) The power is also sampled by a directional coupler matched to the TM_{01} mode of the circular waveguide. The sampled microwave signal is attenuated, divided, filtered, and diode-detected for display on fast oscilloscopes. The temperature

Figure 3-23. Output power vs mean scattering angle for electrons transiting the anode foil. The solid line is the computer results, and the points are the experimental results.

Figure 3-24. Apparatus used for the laboratory investigations.

rise on the terminator/calorimeter was measurable but was so small (less than 0.03 C) that reliable data were not obtained.

Several experimental investigations and their results are presented here. They are:

- Code validation shot
- Variation of the cathode material
- Variation of the anode thickness and transparency.

Code Validation Shot. We mentioned earlier the comparison between the code runs and the experimental results. The diode voltage, current, and microwave output power for one such shot is shown in

Figs. 3-25 and 3-26. Three narrow-band frequency bins and one wideband bin were used. The 0.5 GHz bandwidth bins centered at 6.5, 7.0, and 7.5 GHz are time-aligned and plotted with the output from the 5-15 GHz wideband diode detector. Some power in the 5-15 GHz bin is not accounted for in the narrow bins. Two effects contribute to this problem. The bandpass-filter, time-delay frequency dependence can cause ± 4 -ns delay in the positioning of the pulses, and the filter's transient response changes the shape of the microwave pulse envelope. These two distorting effects are not present in the wideband pulse envelope. The wideband pulse results are, therefore, more reliable for indicating

the actual microwave output power envelope. The peak output power was 250 MW in the 7.25-7.75-GHz band.

Variation of the Cathode Material. We experimented with the following types of cathodes:

- Flat carbon cathode with 60° annular grooves spaced 2 mm apart. The cathode worked well, but it broke after one shot, due to the acoustical shock from the water gaps.
- Flat aluminum with a sand-blasted face. The cathode worked well, but it had a short lifetime. The aluminum melted and pitted badly on a single shot.

- Spherical face ($R = 8.5$ cm) brass with 0.6-mm-spaced, 60° annular grooves. The material worked poorly with peak power reduced to 25 percent of the flat-faced, grooved cathode.
- Flat-face stainless steel with 0.8-mm-spaced, 60° annular grooves. We achieved good results with cathode longevity with this design.
- Flat-face stainless steel with 2.5-mm-spaced, 60° annular grooves. We used this cathode the most. This design generated good results for the microwave generation and had an excellent lifetime.

Figure 3-25. The diode voltage and current waveforms for a particular shot. The microwave output power for this shot is shown in Fig. 3-34.

Figure 3-26. Experimental output power vs. time. The peak power level is 250 MW, ± 25 percent, in the 7.25-7.75 GHz frequency band. This is obtained by using the wideband 5.0-15.0 GHz envelope and observing that only the 7.5 GHz bin shows any power during the peak.

The main criterion for choosing a cathode was longevity. For that reason, we generally used the stainless-steel grooved cathodes. They produced the best microwave output with repeatable results.

Variation of Anode Thickness and Transparency. In order to study the effects of electron beam scattering on microwave production, we tested various anode materials. The anodes tested included 25- μm -, 13- μm -, and 7.6- μm -aluminum foils as well as several stainless steel meshes.

The mean scattering angle for electrons through a thin foil, (i.e., having a thickness much less than an electron range), is given by

$$\bar{\theta} = \frac{44.8YZ}{\gamma^2 - 1} \frac{\rho d B}{A}$$

$$1 + \frac{0.98}{B} - \frac{0.12}{B^2} + \dots$$

degrees, $\bar{\theta} \leq 20^\circ$,

where

- Z = atomic number,
- A = mass number,
- γ = relativistic correction factor,
- ρd = foil thickness in g/cm^2 ,
- B = parameter dependent on the number of collisions and is a function of Z, ρ , d, and γ .

Scattering due to a fine mesh is given by the expression

$$\theta = \tan^{-1} \frac{1}{m_o \gamma \beta_z^2} \frac{r E_z}{2},$$

where

- m_o = electron rest mass in eV,
- $\beta_z = v_z/c$,
- r = 1/2 the mesh wire separation,
- E_z = axial E-field in the diode in the vicinity of the anode mesh.

The above equation is the relativistic analog to the Davisson-Calbick equation.

Using the above two equations, we show in Table 3-1 the calculated mean-scattering angles for the anodes tested.

A plot of the peak microwave output power as a function of mean-scattering angle is shown in Fig. 3-23. The plot shows a linear dependence of microwave output with electron-scattering angle.

By using meshes of different transparencies, we studied the dependency of frequency on the electron number density. Two different stainless steel meshes were used: MESH 1, with a transparency of 84 percent; and MESH 2, with a transparency of 60 percent. Both mesh-wire thicknesses were on the order of the electron range. The electron number density in the virtual cathode region with MESH 1 in place will be 40 percent greater than when MESH 2 is used. Next, we

Table 3-1. Calculated mean scattering angle for the various anode materials tried using equations in text.

ANODE	CALC MEAN SCATTERING ANGLE (Degrees)
S.S. Mesh #1	2.5
S.S. Mesh #2	5
7.6 μ m Al Foil	11
13 μ m Al Foil	14
25 μ m Al Foil	20

compared the output frequencies with all other parameters fixed. The results of the comparison show a square root of the electron number density dependence.

A definite dependence of microwave-output frequency on diode voltage and anode-cathode gap spacing was observed, but no quantitative dependence has been obtained. Qualitative results were as expected: the output frequency increases with increasing diode voltage and decreasing diode gap spacing.

Improvements

The MGX system has been improved considerably over the past year. The changes made improved system reliability, turnaround time, diagnostics accuracy, and convenience. Some improvements completed in FY 84 are as follows:

- The microwave-output waveguide was put on a wheeled track for quick and convenient anode replacement,
- An additional vacuum pump was installed to reduce the system pump down time,
- A TM₀₁ specific directional coupler was designed for the system, which allows us to observe the actual mode content of the microwave power.

Improvements begun in FY 84 to be implemented in FY 85 include:

- A screen room to reduce background noise.
- Transient digitizers.
- Computer controller.
- Higher frequency microwave diagnostics capability.
- Hardware to determine electron beam emittance and current uniformity.

Other machine improvements are an upgraded 11 ohm pulse forming line, and a low inductance diode.

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IV. Computer-Aided Engineering

Thrust Area Leader: D. W. O'Brien

Overview

The Computer-Aided Engineering (CAE) Thrust Area has a central role in the Electronics Engineering Department's computer-based tools effort. The CAE Thrust Area is responsible for developing the Department's CAE technology base, and for understanding, choosing, developing, and transferring the technologies and tools in its area of expertise to other departments. Cooperative tool development with other Thrust Areas is encouraged, and the computer technologies developed by the CAE Thrust Area add value to the tools developed by all Thrust Areas.

The CAE Thrust Area is also responsible for guiding the Department in acquiring and integrating computer systems. This Thrust Area evaluates, plans, and schedules the application of computer power for the engineering tool. Computers, workstations, graphics systems, and computer networking and data-base management systems are developed and used in creating the integrated Computer-Aided Engineering network (ICAEN) of CAE systems.

FY 84 has been a year of change for the CAE Thrust Area. The development at LLNL of an advanced Electronics Engineer's Design Station has been made less feasible by the

introduction of competitive commercial products. Personnel changes have occurred, and some technologies and activities have been displaced by new interests. By the end of FY 84 the CAE Thrust Area focused its technology interests in six areas:

- Graphics and information presentation
- Data handling (computer networking and data base management)
- Computer environments and interactive techniques
- Computer architecture
- Systems software
- Expert systems

The CAE Thrust Area's tools effort in FY 84 included work in a few traditional areas. CAD tools and related systems are being developed and integrated to support engineering synthesis, design, and drafting. The CAD tools development effort is conducted in cooperation with the Diagnostic and Microelectronics Engineering Thrust Area and the EE Department CAD Facility operated by the Engineering Services Division. Graphics have also been developed for publication and presentation, as well as for the display of engineering information.

CAE systems integration, with computer networking and data base management, has also greatly extended the Department's ability to reach more engineers and to offer more resources. These efforts, along with new activities in expert systems and computer environments, are making a substantial contribution to the Department's ability to support Laboratory programs.

Facilities

The CAE Thrust Area has responsibility for planning and developing computer systems and facilities for the EE Department's tools development and use. The iCAEn network of computers, networked resource servers, and tools is made available to engineers through their locally operated and controlled computers.

Engineers participating in CAE Thrust Area R&D activities use the Interactive Computer Development Center (ICDC) VAX-11/780, illustrated in Fig. 4-1, as their primary development system. The ICDC computer is shared with the Signal and Control Engineering (SCE) Thrust Area and supports 55 terminals. Graphics devices associated with the ICDC VAX include a Ramtek 9400 and SCE's METHEUS graphics subsystems. Network communications include connections to other Department VAXs and workstations on iCAEn, the Word Processing Center's NBI system, and SCE's SUN and SYMBOLICS workstations. ICDC's LASERGRAPHIX laser printer/plotter has become a valued resource, providing high-resolution viewgraphs and publication-quality documents and graphics. ICDC offers a LASERGRAPHIX print server function

Figure 4-1. The ICDC VAX-11/780 supports R&D activities of both the CAE and SCE Thrust Areas with its complement of 4M bytes of memory, 1Gbyte of on-line disk, a tri-density tape drive, and floppy disks.

for computers on iCAEn. Until the end of FY 83, the Interactive Computer Development Center was located in Bldg. 131, Room 2539 (Fig. 4-2), along with the ERD131 VAX computer, the Engineering Design Station PDP-11/34, and Engineering Research Division's computer users area.

The Engineering Design Station provided engineers with a valued schematic capture tool during the year. The Design Station Laboratory in Room 2627 was based on a PDP-11/34 mini-computer, and had an interactive graphics DEC VS60 graphics display system, a low-resolution Versatec printer/plotter, and a pen-plotter.

The CAE Thrust Area's R&D Laboratory in Room 2631 housed the Ramtek graphics head, keyboard and tablet, sound equipment for studies in interactive techniques, an IBM-XT personal computer used for evaluation of PC-based CAD-Tools, and

RETROGRAPHICS low-resolution graphics terminals.

Facilities plans for FY 85 call for moving the ICDC and ERD 131 VAX systems from the vaulted Room 2539 to the newly built 2910-ft² CAE Computer Facility in Room 2280. This makes space for the Applied Computational Engineering (ACE) Laboratory to support classified codes and data. The Thrust Area's R&D Lab and Design Station Lab are also displaced to Rooms 2367 and 2368.

The CAE Thrust Area has responsibility for developing the ACE Lab and has procured a Silicon Graphics IRIS workstation during the year to prepare for the ACE Lab's high-performance dynamic graphics needs. A VAX-11/785 is being procured as the ACE Lab's primary computing resource. The IRIS' graphics head, keyboard, and mouse

Figure 4-2. The CAE Thrust Area's computing resources were housed in Room 2539A, with laboratories and user areas in Rooms 2539B, 2627, and 2631 during FY 84.

is located in the ACE Lab users' area in Room 2536. The Department's Nuclear Energy Systems Division has also contributed to the ACE Lab's graphics support by developing the capability to record dynamic graphical models on video tape.

The CAE Thrust Area has also specified and purchased a Tektronix Model 6210 high-performance engineering workstation, to be used in the EAGLES Project in FY 85-86, for developing an advanced engineering problem-solving environment. This joint effort with the Signal and

Control Engineering Thrust Area is expected to lead the development and use of a new generation of workstation-based engineering tools.

The EE Department's Computer-Aided Design and Drafting (CADDE) Facility, illustrated in Fig. 4-3, is composed of a ComputerVision CADS-4X system with three monochrome workstations and one color workstation. Operated and under further development by the Engineering Systems Division, this facility is located in Room 1566 with its user area adjacent in Room 1560.

CADD-E drafting/design system

Figure 4-3. Block diagram of Engineering Services Division's Computer-Aided Design and Drafting Facility. The facility is based on a ComputerVision CGP 200X CAD system, with its associated VAX-11/750 gateway computer to the iCAEn network.

1. The Electronics Engineer's Design Station and CAD-Tools Integration

*Principal Investigators: R. M. Shectman, K. O. Blackwell,
T. W. Canales, and W. G. Magnuson*

Introduction and Objectives

Over the last two years a flood of Computer-Aided-Design tools has appeared on the market to support the electronics engineer. As these tools became available, usually at least one group within the Laboratory purchased them. As the tools proliferated, and as different tools were acquired for the same purpose, it became clear that some order should be imposed on the impending chaos. What started out as the selection of a schematic capture tool for Electronics Engineering eventually evolved into an Engineering-wide selection process for a set of engineering tools. As these tools become available, they must be integrated into the engineering environment. For example, this integration process includes providing support, recognizing when a new package supercedes existing packages, and providing the capability for data exchange between packages where appropriate.

The Electronics Engineer's Design Station is a software system designed for the entry of electronic schematics onto a computer. Designed and built at the Laboratory, the Design Station also served as the seed for the Electronics Engineering Department's involvement with CAD-Tools integration.

The principal objectives for the Design Station project were:

- To build a system that is as easy to learn and use as possible. The users of such a system are engineers and technicians. Intensive training of such a group is not cost-effective.
- To build a system such that, once the data are entered, the data can be transferred to other systems, thus providing specialized "expert" capabilities. Such capabilities include printed-circuit board fabrication systems, integrated circuit fabrication systems, circuit-simulation capabilities, and the like.

To understand the benefits of such a system, it is useful to understand what happens if such a system is not available. Figure 4-4 shows a typical engineer's design cycle. The cycle starts with a basic concept, or "back of an envelope sketch." Next, the concept is refined and expanded into a full design and is then sent to the drafting department for final drawing. The results from the drafting

department are then returned to the engineer for review and revision. Revisions can range from corrections of drafting department errors, to repairs of design flaws, to changes in the basic concept. The point is that any change again means that the engineer loses some control while the drafting department works on the drawings. As typical drafting department turnaround ranges from several days to several weeks, this loss of control becomes significant. To save time, engineers often

send designs to the drafting department only at the conclusion of a project. At that point, engineers hope that the drawings actually reflect the final implementation.

With the introduction of the Design Station into the design cycle, the design cycle becomes that of Fig. 4-5. With the engineer in full control of the revision process, the design is always up to date, and the engineer retains full control of the design. Also, since the drafting department and its

Figure 4-4. Design cycle without a Design Station involves drafting with each revision.

Figure 4-5. Design cycle with a Design Station involves drafting only at the end of the process.

attendant delays are not part of the revision cycle, the design/revision process can proceed in a more timely fashion. At the conclusion of a design, the engineer can send fully updated data to the drafting department, get final copies of the schematics, and allow the drafting department to archive the design data. The Design Station also minimizes the costs charged by drafting department personnel, since they need to perform a minimum of work and perform that work only once.

Other benefits of the Design Station are shown by the capabilities it enhances, as opposed to those it replaces. The Design Station provides the engineer with a gateway to other tools, with appropriately formatted netlists and related information, thus simplifying the use of those tools. The easier it is to use a tool, the more likely an engineer will use it. For instance, manual transfer of a design for use by a simulator is a tedious, error-prone process. In contrast, the most difficult part of using an automated transfer system can be deciding which simulator to use. The more engineers use such tools to verify designs before final implementation, the less time they must spend debugging and revising the design.

The net result of using a Design Station is the reduction of design cycle time, in terms of design, implementation, and checkout.

Progress

At the end of its first quarter, the project was faced with a choice. One alternative was to continue the project in its current mode of operation. Three people would code and design the basic system for several more months; an indefinite amount of additional work would be needed to bring out new, specialized subsystems based on user requests for new capabilities. This alternative would also entail the commitment of at least some staff to handle everything from fixing problems to teaching new users how to use the system. In addition, operation of the current Design Station required a Digital Equipment Corporation VAX computer system, along with a graphics device estimated at \$20 000 per Design Station.

The other alternative was to use a commercially available system. During the Design Station's development, general industry started to offer packages with similar capabilities. These systems range from those requiring general high-performance workstations--such as the SUN or APOLLO workstations at \$50 000 to \$100 000 per workstation--to those requiring an IBM PC at \$6000 to \$10 000 per PC.

Figures 4-6 through 4-8 show the evolution of equipment needed to run a schematic capture system. Figure 4-6 shows the hardware required to support a single user on the prototype system. Figure 4-7 shows the hardware required to support several users on the system under development. Figure 4-8 shows the

hardware required to support a single user on a commercially available system for the IBM PC.

We decided that the most effective choice was to cancel the Design Station development project and to evaluate and select a commercially available product. In addition, it was decided that a predecessor to the Design Station project, which has been in general use for several years, be terminated at the end of the fiscal year.

In selecting a commercially available product to replace the Design Station, we decided to limit

prospects to those meeting the following three criteria:

1. The product must run on an IBM PC, with a minimum amount of special equipment. Due to the number and capabilities of available products, this restriction did not seem to be too great. In addition, over 2700 IBM PCs are already in place at the Laboratory. This capability greatly reduces system cost and provides users with a large number of potential work sites.

Figure 4-6. Evolution of hardware required for Schematic Capture. The initial system required two racks, and supported one user.

2. The product must have an "open file" system or its equivalent. With an open file system, the vendor either fully discloses the format details of the data generated by the system or provides tools to access the data. With an open file system, we can create the ability to move designs between systems of different vendors. For example, we must be able to move data from the IBM PC to the ComputerVision CAD system used in the Electronics Engi-

neering Drafting Facility. The Drafting Facility has final responsibility for making sure the schematics conform to Laboratory standards and for transmitting the schematics the electron-beam recorder for microfilming and long-term archival storage.

3. The product should have "hierarchical" design capabilities. This feature allows users to work basically in one of two modes. In the first

Figure 4-7. Evolution of hardware required for Schematic Capture. The system under development required a major system, and would support several users.

mode, the user defines a design as a set of high-level functions, and then defines each of those functions as a set of subfunctions, and continues until the design is fully specified (i.e., working Top-Down). In the second mode, the user works on basic sections of hardware or makes use of already existing sections, and links the sections together to form successively more complete levels of the design (i.e., working Bottom-Up).

The Mechanical Engineering Department is also simultaneously evaluating general drafting packages, and the Plant Engineering Department is evaluating packages related to their functionality. While no single package satisfies the requirements of EE, ME, and PE together, all three evaluation efforts have been loosely grouped together. The results of this effort will be three de facto standards, one for each of the major departments. The standards are de facto in that no attempt will be made to directly hinder anyone from acquiring a nonstandard package.

Figure 4-8. Evolution of hardware required for Schematic Capture. The systems currently being evaluated require just a table-top of equipment and support one user.

However, each department intends to provide some level of support for the de facto standard that will not be available for other packages. For example, the Electronics Engineering Department plans to provide the ability to transfer and translate schematics from the IBM PC to the ComputerVision system used by the Electronics Engineering Drafting Department. From there, schematics can be archived for long-term storage, or be developed into printed circuit boards, and the like.

Aside from simply selecting CAD tools, we are involved in the integration of those tools where appropriate. The activities in this area range from a joint development project with ComputerVision to allow transfer of data to the ComputerVision systems (this FASTLINK project is described in another section of this report), to a participation in and monitoring of standards development to aid in communicating design data. Currently, we are closely following two major standards. The first, which is almost ready for release, is Initial Graphics Exchange Specification (IGES) V2.0. IGES is being developed to exchange data among the major drafting system vendors. As such, IGES tries to cover all areas of drafting, not just electronics drafting. We have attended the development meetings for this new version, which principally contains changes to allow interchange of electrical data. We have also started to track the Electronic Design Interchange Format (EDIF) standard. This standard is being

developed independently of IGES and is principally designed for data exchange related to integrated circuits. While the standard is not expected to be finished for a couple of years, vendors are already beginning to indicate that they will soon have an interface available that conforms to the initial standard.

With the expertise developed in this area, we were asked to provide support to the DOE's Office of Fusion Energy (OFE) effort in a competitive procurement of Computer-Aided Design and Drafting (CADD) equipment for the five major U.S. fusion facilities (LLNL, LANL, PPPL, ORNL, and FEDC), and GA Technologies. The purpose of this procurement was to upgrade the CAD facilities at all sites and to guarantee data interchange through a single common vendor. Part of the selection process was an evaluation of each system. We were asked to provide the technical expertise in evaluating the electrical/electronic portions of these systems.

Presentation

1. Shectman, R. M., "CAE/CAD Tools for the IBM Personal Computer," CUBE Symposium, Los Alamos, NM (October 11, 1984).

2. Graphics and Text Capabilities

*Principal Investigators: L. Hatfield, B. K. Cabral S. A. Bly,
R. R. Springmeyer, and M. E. Poggio*

Introduction and Objectives

The generation of graphics and text are key both to the theoretical/experimental work of engineers and scientists and to the reporting of their work. One major commitment of the CAE Thrust Area is the improvement of the tools available to our engineers for all facets of their work with both graphics and text. During FY 84, we worked toward fulfilling this commitment in a number of separate ways, addressing both problems of special concern and "targets of opportunity." Over the longer term, we will integrate these separate tools, where appropriate, and will work to provide additional capability.

During this past year, we had a number of distinct objectives. In the area of text generation, our primary objective was to provide adequate word-processing software with appropriate hard copy devices to support the normal range of text-production needs. These needs include the generation of technical papers with heavy mathematical content, standard internal and external correspondence, reports, manuals, and presentation materials.

In the area of graphics, our most important objective was to provide adequate graphics tools to support the research and development needs of the electronics engineers

who will use the iCAEn system. The first need is for highly interactive graphics capabilities to support such diverse activities as computer-aided design of electronics circuits, VLSI design, and modeling (especially in electromagnetics). A second need is for publication-type graphics for use in presentations or in documents. A third need, only briefly addressed by the Thrust Area in FY 84, is for a simple means of producing "hard copy" of time-varying graphics on video tape or film.

Progress

We made substantial progress in providing tools for the generation and production of text. The most significant advance was the selection of the commercial word processing-package, MASS-11, as the standard package for the VAX computers on the integrated Computer-Aided Engineering network (iCAEn). MASS-11 is perhaps the most popular package of its type available for the VAX and represents the commercial state of the art. This package is now available on the network's five major VAXs. As part of the effort to provide a uniform, high-quality text-production environment across the network, Diablo printers

were purchased for each of these machines.

For applications that require more sophisticated capabilities, such as papers which are highly mathematical, the TEX package, developed by Prof. Donald Knuth at Stanford University, is supported. In FY 84, Version 1.0 of TEX became available and was brought up on essentially all VAX computers. In addition, drivers were developed for the electrostatic printer/plotters and high-resolution laser printer/plotters, our two principal output devices.

To improve engineers' abilities to generate graphics, we made progress in several areas. One of the larger efforts was a detailed study of three public-domain graphics packages, and a selection of one of these, CGS, as the most appropriate package of its type for use in the EE iCAEn environment. This evaluation continued work begun in FY 83 to select a graphics package for a major control systems project involving a number of DOE laboratories.

In FY 84, development of the PICTURE system, an interactive tool for the graphical construction of visual aids, was completed. We developed facilities for directly producing viewgraphs from these pictures or for including them as illustrations within a TEX-based document. Thus, we now can include computer-based graphics within text, a very unusual and highly desirable capability. The few commercial systems that provide this capability

tend to be both specialized and expensive.

As part of our effort to provide tools to engineers for use in activities such as modeling, we undertook several smaller demonstration and feasibility efforts. These efforts included examining a number of examples of the exploration and implementation of graphics algorithms used to model electromagnetic phenomena. These examples successfully demonstrated the benefits to be gained by having a more sophisticated graphics capability for modeling. This area will be aggressively pursued in FY 85.

We made a significant effort in FY 84 to select appropriate interactive graphics equipment. Because the emerging workstation-class of computer seems particularly well suited to highly interactive graphics for a substantial class of problems, we made a detailed investigation of engineering workstations. This investigation led to a much improved understanding of workstations and their potential role in the iCAEn environment. Based on this investigation, the Department purchased two workstations. The first machine, a Silicon Graphics IRIS, was specifically chosen for its unusual, high-performance graphics capability. This machine is targeted for use in the modeling area and will be a major addition to the Applied Computational Engineering (ACE) Laboratory currently under development. The second machine, a Tektronix 6210, is more general-purpose and

seems well-suited for a broad class of interactive design applications. During FY 85, these machines will be the subjects of substantial projects. In preparation for this class of workstation, we did some graphics work on an existing SUN Microsystems workstation. In particular, we implemented an interface between an existing general purpose graphics package and the SUN window manager. This intelligent interface allows one to transport existing graphics applications to the SUN environment to take advantage of the SUN window system without rewriting or tailoring the code to this one workstation.

Publications and Presentations

1. Cabral, B., "An Evaluation of Three Graphics Packages: The Methodology and Results," 1984 CUBE Symposium, Los Alamos, NM (October 10-12, 1984).
2. Cabral, B., An Evaluation of Three Graphics Packages: The Methodology and Results, Lawrence Livermore National Laboratory, Livermore, CA (UCRL in preparation).
3. Hatfield, L., "Engineering Workstations," 1.5 hour tutorial talk, IEEE Computer Society First International Conference on Computers and Applications, Beijing, Peoples' Republic of China (June 20-22, 1984).
4. Hatfield, L. "Engineering Workstations--Status and Trends," seminar at Sandia National Laboratory, Livermore, CA (July 19, 1984).
5. Hatfield, L., "Engineering Workstations--Status and Trends," Engineering Research Division Seminar, Lawrence Livermore National Laboratory, Livermore, CA (July 20, 1984).
6. Hatfield, L., "Engineering Workstations--Status and Trends," seminar at Rensselaer Polytechnic Institute, Troy, NY (October 10, 1984).
7. Hatfield, L., "Engineering Workstations," keynote talk at the IEEE Computer Society's Third Annual Workshop on Interactive Computing: CAE: Engineering Education, Pittsburgh, PA (October 24, 1984).
8. Joy, K. I., "An Adaptive Sampling Method for Ray Tracing," Engineering Research Division Seminar, Lawrence Livermore National Laboratory, Livermore, CA (August 24, 1984).
9. Poggio, M. E., "TEX Macro Packages," Revised Preliminary Edition, UCRL in preparation, (March 29, 1984).

10. Springmeyer, B., and S. Bly,
PICTURE: An Interactive Tool
for Creating Visual Aids,
Lawrence Livermore National
Laboratory, Livermore, CA,
UCID-19998 (1984).

3. iCAEn, Electronics Engineering's Integrated Computer-Aided Engineering Network

*Principal Investigators: R. K. Oberman, R. M. Shectman,
K. O. Blackwell, and D. W. O'Brien*

Introduction and Objectives

The integrated Computer-Aided Engineering network (iCAEn) is a growing network of Engineering computers designed to provide the widest possible distribution of computer-aided engineering tools to the Laboratory. The primary goal of iCAEn is to allow an easy flow of information both within and between engineering divisions, including:

- A pipeline from the engineering divisions to manufacturing for communicating design information during all phases of a project through design, drafting, and fabrication.
- A communications system to provide for easy access to, and distribution of, the variety of Department-supported computer-based tools, and for the sharing of data among the users of the network.

Network services are currently available to approximately 350 engineers, technicians, and clerical workers using 175 terminals on 12 computer nodes ranging from LSI-11s to VAX-11/780s in four divisions of the Electronics Engineering Department. Participating divisions are

Engineering Research Division, Field Test Systems Division, Nuclear Energy Systems Division, and Engineering Services Division.

The iCAEn is an operational facility and provides support to personnel in Bldg. 131, Bldg. 121, and, by low-performance modem, to Site 300. The network configuration in the unclassified-open segment is called iCAEn(0). The network currently consists of VAX computers, LSI-11 microcomputers, Microsystems SUN workstations, a Silicon-Graphics IRIS workstation, a Symbolics LISP machine, and the EE Department's ComputerVision CAD system. It is primarily a DECnet environment with TCP/IP support for communication with non-DEC workstations and CAD systems. Figure 4-9 shows the current network configuration.

iCAEn is designed to be media independent and to support new technologies as they become available. The network can use standards and equipment as they become available and show benefit to the network and its users. iCAEn uses Ethernet cable and link-level protocols in Bldg. 131. In addition, a gateway for low-speed, asynchronous communications, an atmospheric infrared link, and high-speed point-to-point links allow communication with

various systems. In the future, we expect iCAEn(O) to be expanded to provide services to foreign networks and systems and to provide tools to an increasing number of engineers.

In the first quarter of FY 85, the network will be linked to the Laser Isotope Separation (LIS) network. Plans also call for iCAEn(O) to be connected to the proposed Laboratory-wide digital backbone, to be called Labnet. This connection will allow access to unclassified systems and local networks in all Laboratory areas.

During FY 85, a connection between iCAEn(O) and DOD's MILNET should be established. This link will allow iCAEn users to communicate easily with their DOD contacts and counterparts, and with colleagues at universities and at other national laboratories. A classified segment of iCAEn is planned to support Engineering Department access to OPMODEL, providing communication to DOE-Germantown and to other laboratories and plants in the Nuclear Weapons Complex. We are already accessible from EG&G's terminal switching network through

Figure 4-9. The unclassified-open segment of the integrated Computer-Aided Engineering network, iCAEn(O), currently consists of six VAX computers, seven microcomputers, and two Microsystems SUN engineering workstations using Ethernet, point-to-point cables, infrared, and switched telephone network technologies.

the Engineering VAX operated by Field Test Systems Division.

An area of future development is the support of classified operations on a secure segment of iCAEn by creating a separate, parallel segment of the network, iCAEn(C). This network should be completed during the first half of FY 85. Its functions will be similar to those of iCAEn(O) and can serve those users who process classified data. iCAEn(C) will initially support the ACE Lab VAX-11/785 processor and a UNIX-based Silicon Graphics IRIS graphics workstation. Future plans include the expansion of iCAEn(C) to the EE Department's Image Processing Laboratory and the acquisition of new machines for use in a classified environment.

iCAEn(C) will be linked to the classified segment of Labnet. This connection is planned for mid-FY 85 to allow Department engineering access to the LLNL Central Computer Facility (OCTOPUS) as well as to classified systems and networks around the Laboratory. This connection may also provide access to OPMODEL. Figure 4-10 shows the possible future configuration of iCAEn as connected to Labnet and other local networks.

Another future project is the implementation of a one-way gateway from iCAEn(O) to iCAEn(C) to allow users to move data from the open segment of iCAEn to the classified segment without imposing security restrictions on systems in the open partition. With this gateway, codes

Figure 4-10. In fielding CAE computers to Engineering divisions and groups, it is anticipated that both the unclassified-open and the closed segments of iCAEn will use the Laboratory's Labnet communications facility as tenants, connecting engineers and engineering resources.

can be developed and debugged using unclassified data on the more easily accessible iCAEn(O) and then be moved to iCAEn(C) for execution with classified data. This gateway will make expensive, specialized graphics hard copy devices on iCAEn(C) available to users of iCAEn(O).

Possibly no area of technology exhibits more rapid growth than computers and computer-based systems. One of the most dynamic areas within the computer world is that of networking and communications. Our goal is to provide a structure to quickly implement new technologies and standards as they become available, thus providing the engineering community with as broad and as convenient a set of network-based tools as possible.

The integrated Computer-Aided Engineering network provides the Laboratory with substantial capability for developing a wide range of computer-based tools for quickly disseminating them to satisfy programmatic requirements. At the same time, the project provides the basis for improved communications and for efficient use of available expertise across organizations and project disciplines.

Progress

In FY 84, Ethernet was first expanded to include three VAXs located in Bldg. 131. As DECnet was updated to provide Ethernet support, DECnet hardware and software components replaced all others for communication among DEC systems on iCAEn.

The EE Department acquired two new VAX computers; they are attached to the network via Ethernet. One unit, a VAX-11/750 installed by Engineering Services Division, was used for systems development, for the link to the ComputerVision CAD system, for access to CAE tools, and for communication between engineers. The other is also a VAX-11/750 and was installed by Engineering Research Division for signal-processing system development and use.

A data link was established between iCAEn and the EE Department NBI word processing system. This link allows for the transfer of documents to the word-processing system without retyping the documents. The system maintains the document format, thus minimizing the time required for final editing prior to printing.

The link to the EE Department's ComputerVision CAD system was built and installed and is currently under developmental testing. The link makes use of the SDLC link-level protocol for compatibility with the ComputerVision system. It provides half-duplex data transmission at 460 kilobits per second. Software was written to emulate the ComputerVision FASTLINK system on the CADDE VAX as well as on the imbedded Z-80 microprocessor in the SDLC interface. This allows the ComputerVision system to treat the VAX as another ComputerVision system, thus requiring no modifications to either the ComputerVision hardware or software.

Two Microsystems SUN workstations were added to iCAEn. The SUN workstations will use the iCAEn Ethernet only for communication between each other, however, until TCP/IP is implemented in early FY 85. TCP/IP will support communication to the VAXs, Symbolics LISP machine, and IRIS workstation. Until the Ethernet-TCP/IP capability is operational, the SUN and the Symbolic workstations will use low-speed, asynchronous lines for transferring data to and from other iCAEn systems.

Presentation

1. Shectman, R. M., "CAE/CAD Tools for the IBM Personal Computer," CUBE Symposium, Los Alamos, NM (October 11, 1984).

4. Database Management Systems

Principal Investigator: M. E. Poggio

Introduction and Objectives

Near the end of FY 83, the CAE Thrust Area evaluated and purchased a commercial database management system for three VAXs on the integrated Computer-Aided Engineering network (iCAEn). Thrust Area personnel made the selection with the concurrence of the system managers of the three machines involved. The system selected was INGRES from Relational Technology, Inc. Selection of INGRES was made primarily because it

- Is a robust relational database.
- Has default user interfaces based on forms.
- Has consistent interfaces to a number of high-level languages.
- Utilizes good disk and file management.

Relational databases provide a simple data model that makes only relations (tables) available to the user for storage. Also, all data are stored in a uniform way. No semantic information can be placed in sets, links, associations, parent-child relationships, or other network constructs. The advantage to using a simple data structure is that databases are easier to understand, maintain, and control. INGRES follows a true relational model.

Additionally, INGRES has a number of subsystems that allow for form fill-in user interfaces. Each subsystem provides default forms so that the novice user need not define a form before utilizing the facility. However, a visual forms editor is available to provide a convenient way to customize any form.

The original reason for acquiring a database-management system was to provide a flexible, general-purpose tool for various data-management functions. Since a database is useful for storing any coherent set of data, the variety of functions is virtually unlimited. The data may include everything from informational lists for project managers and engineers to scientific data to be manipulated. The possible uses for the database system are limited only by one's imagination and by available disk space.

After INGRES became available on the different machines this fiscal year, various applications became available. The creators of the applications have included engineers, technicians, computer scientists, and coordinators.

Progress

With the guidance and support of the CAE Thrust Area, INGRES was installed on the initial three iCAEn VAXs in October, 1983, and on the

fourth VAX in July, 1984. INGRES applications utilizing different levels of sophistication evolved on all machines shortly after installation. Some of these applications are discussed below.

Pulsed Power Report Catalog

The Pulsed Power and Diagnostics Group of the Nuclear Engineering Systems Division (NESD) wanted to catalog pulsed power report titles they were receiving from an outside agency on magnetic tape. A member of the Systems Development Group of NESD created an INGRES database catalog. The database interfaced to a PASCAL program that controls a menu-driven user interface. The tape was read into a file, passed through a translator for formatting, and then read directly into the database.

CAE Tools Catalog

An essential part of the CAE Thrust Area's charter of providing computer-based tools to engineers was to provide engineers with a means of determining availability of computer-based tools. An on-line CAE Tools Catalog seemed to fit this need. After some design thought, the most natural solution was to create the catalog as a database. Using this method, searching for information, updating, and generating hard copy would all become simple operations. An INGRES database interfaced with a high-level-language program, was well-suited for this application.

The on-line tool catalog was completed this year, including selection of a librarian to perform maintenance and quality-control functions. The catalog is a menu-driven system, which allows the user to select from one of several options on different menus. Two separate facilities, retrieval and update, are available for running the catalog. The retrieval facility, used more frequently, is used to obtain information about a tool or set of tools. Figure 4-11 shows the main menu used in the retrieval mode.

The tool query menu (Fig. 4-12) appears when an appropriate main-menu item is selected. To obtain information about a tool (or set of tools), any one or any combination of the boxes may be filled in to request a description of the tool. Then the appropriate selection is made from the menu on the bottom half of the display. Finally, the information satisfying the description is obtained from the database and is displayed on the screen, one tool at a time. Figure 4-13 shows the information display for the tool "SIG," the only tool that satisfied the description in the example of Fig. 4-12.

The update facility looks and works much like the retrieval facility. It may be used by engineers, toolsmiths, the catalog librarian, or by others requesting authorization from the librarian to run the update facility. The librarian controls the quality of any catalog additions or entry updates. This quality-control function ensures

completeness and accuracy of catalog entries. Table 4-1 is a summary of CAE tool-catalog entries as of January 28, 1985.

Coordinator Databases

The Engineering Research Division's (ERD) coordinator developed a simple database for tracking purchase orders submitted to Purchasing. Although she had no previous database experience, she created the database and utilized the INGRES default query forms facility to add, update, and retrieve information. She also utilized the report writer

to create a file, sorted to her specifications, for generating hard-copy output. Currently under consideration is the implementation of more sophisticated database applications to be used by any EE coordinator who has access to an ICAEn VAX that runs INGRES.

Other Database Applications

A number of small databases have been established to suit various needs of individuals and small projects. A few of the known databases are mentioned below with a

Figure 4-11. The main menu of the CAE Tool Catalog information retrieval facility.

brief description of their applications and functions.

1. An ERD database investigates graphics heads and color hard-copy devices and keeps information regarding vendor, model, price, and features. The default query forms system allows retrieval, update, and addition of information. Also, the report writer formats information for hard-copy output for this particular application.
2. A CAE Thrust Area database includes vendor, model, price, and feature information on engineering workstations. Again, the default query forms system is used for information manipulation.
3. A summer student employee in the Microwave and EMP Group of ERD developed a database to keep track of the reports generated by that group. The visual forms editor creates a customized form to be used by the query facility when re-

Figure 4-12. The tool query menu of the CAE Tool Catalog.

trieving, adding, and updating entries. The report writer generates formatted hard copy output. This system is tied together in a menu-driven system by DEC Command Language (DCL), the command interpreter used on our VAX systems.

4. Members of the Diagnostics Development Group of the Field Test Systems Division (FTSD) have developed several applications related to equipment inventory and usage monitoring

for the EG&G network. One database using default query forms inventories is the EG&G DCA networking hardware. A second database maintains an inventory of EG&G terminals and their users. A third database interfaces with a FORTRAN program to monitor EG&G/FTS VAX usage for graphing.

5. ERD has a database that monitors usage of various tools on the ICDC VAX.

Figure 4-13. An example display of tool information.

Table 1. Summary of CAE Tool Catalog Entries as of January 28, 1985

Title	Type	Technical Contact	Thrust Area	Author	Computer
ABORC	Electromagnetic Modeling	Robert Buvensee	Modeling and Simulation	IRT Corporation	CDC-7600
ACSL	Control Simulation/Analysis	Kenneth D. Pimentel	Signal and Control	Mitchel and Gauthier, Assoc. ^a	VAX/VMS
Analyze	Signal Processing	Steve Azevedo	Signal and Control	Steve Azevedo	VAX/VMS
BLOX	Graphics	Peggy Foggio	CAE	Rubel Software a	VAX/VMS
Burn	Semiconductor Modeling	William J. Orvis	Modeling and Simulation	William J. Orvis	CDC-7600
CALAHAN	Circuit Simulation/Analysis	W. G. Magnuson, Jr.	CAE	Donald A. Calahan	CDC-7600
CAMP	Control Simulation/Analysis	Kenneth D. Pimentel	Signal and Control	Jose J. Granda a	VAX/VMS
CGS/MCAR	Graphics	Brian K. Cabral	CAE	Ted Reed	Cray CDC-7600 VAX/VMS VAX/UNI VAX/UNIX
CT-1000	Schematic Capture	W. G. Magnuson, Jr.	Microelectronics	Case Technology, Inc. ^a	IBM-PC/XT
Datebook	Utility	R. Kevin Oberman	CAE	U.S. Military Academy	VAX/VMS
Delight	Control Simulation/Analysis	Charles Harget	Signal and Control	W. Nye, et. al.	VAX/VMS
DI-3000	Graphics	Brian K. Cabral	CAE	Precision Visual, Inc. ^a	VAX/VMS
DigLib	Graphics	Brian K. Cabral	CAE	Hal Brand	VAX/VMS SUN/UNIX
Emacs	Text Processing	Brian K. Cabral	CAE	James Gosling	VAX/VMS VAX/UNIX SUN/UNIX
ENHP	Control Simulation/Analysis	W. G. Magnuson, Jr.	CAE	Bonneville Power Admin.	Cray
Enport-5	Control Simulation/Analysis	Kenneth D. Pimentel	Signal and Control	Rosencode, Associates ^a	VAX/VMS
GEN2D	Electromagnetic Modeling	Niel Madsen	Modeling and Simulation	J. C. Peterson/R. Zlotkowski	Cray CDC-7600 VAX/VMS
Graflib	Graphics	Brian K. Cabral	CAE	O'Hair, et. al.	CDC-7600 Cray VAX/VMS

^a Indicates purchased/licensed software

Summary of CAE Tool Catalog (continued)

Title	Type	Technical Contact	Thrust Area	Author	Computer
HG3D	Plasma Modeling	Rick Ziolkowski	Modeling and Simulation	J. C. Peterson/R. Ziolkowski	Cray
ILOGS	Digital Logic Simulation	W. G. Magnuson, Jr.	Microelectronics	Simutec ^a	VAX/VMS
ILS	Signal Processing	Steve Azevedo	Signal and Control	Signal Technology, Inc. ^a	VAX/VMS
LBLTools	Utility	Brian K. Cabral	CAE	Joe Sventek	VAX/VMS
LGEM3D	Electromagnetic Modeling	Brian Grant	Modeling and Simulation	J. B. Grant and N. K. Madsen	Cray
LINSYS	Control Simulation/Analysis	Diane M. Tilly	Signal and Control	Parametrics, Inc. ^a	IBM-PC/XT
LSAP	Control Simulation/Analysis	Diane M. Tilly	Signal and Control	Diane Tilly	VAX/VMS
MASS-11	Text Processing	R. Kevin Oberman	CAE	Microsystems Engineering ^a	VAX/VMS
Memo	Utility	R. Kevin Oberman	CAE	R. Kevin Oberman	VAX/VMS
NEC	Electromagnetic Modeling	Gerald Burke	Modeling and Simulation	G. Burke, E. Miller, A. Poggio	CDC-7600 VAX/VMS
NET-2	Circuit Simulation/Analysis	W. G. Magnuson, Jr.	CAE	Allan F. Halmberg	CDC-7600
NLS	Signal Processing	Dennis M. Goodman	Signal and Control	Dennis M. Goodman	VAX/VMS
SATER/LLNL	Control Simulation/Analysis	Jim V. Candy	Signal and Control	G. Journeay	VAX/VMS
SCALD	Digital Logic Simulation	W. G. Magnuson, Jr.	CAE	T. Williams/L. Widdoes/et. al.	Cray CDC-7600 VAX/VMS
SCEPYRE	Circuit Simulation/Analysis	W. G. Magnuson, Jr.	CAE	AFWL/IBM	CDC-7600
SIG	Signal Processing	Darrel Lager	Signal and Control	Darrel Lager & Steve Azevedo	VAX/VMS SUN/UNIX
SIOP1	Probability Analysis	Cherie Jo Patenaude	Systems Engineering	Cherie Jo Patenaude	Cray
SILOS	Digital Logic Simulation	W. G. Magnuson, Jr.	Microelectronics	SimuTec ^a	VAX/VMS
Spell	Text Processing	Brian K. Cabral	CAE	Dick St. Peter	VAX/VMS VAX/UNIX SUN/UNIX
Spice2	Circuit Simulation/Analysis	W. G. Magnuson, Jr.	CAE	UC Berkeley	CDC-7600 Cray VAX/VMS

^a indicates purchased/licensed software

Summary of CAE Tool Catalog (continued)

Title	Type	Technical Contact	Thrust Area	Author	Computer
TeX	Text Processing	Peggy Poggio	CAE	Donald E. Knuth ^a	VAX/VMS
TRACE3D	Plasma Modeling	Rick Ziolkowski	Modeling and Simulation	J. C. Peterson/R. Ziolkowski	Cray
TutSim	Control Simulation/Analysis	Kenneth D. Pimentel	Signal and Control	Applied I ^a	IBM-PC/XT

^a indicates purchased/licensed software
(continued)

Individuals in at least three of the EE Department's Divisions have created other, small INGRES databases to aid in more effective management of data required to perform their everyday work. The current variety and number of databases already created using the INGRES system during its first year point out the versatility and need that database-management technology fulfills.

Presentations

1. Poggio, M. E., "EE CAE Tool Catalog," CAE Systems Support Group Meeting, Lawrence Livermore National Laboratory, Livermore, CA (July 17, 1984).
2. Poggio, M. E., "Integrating VAX/VMS QIO for Direct Screen Access in an Equel Program," Bay Area INGRES Users Group Meeting, Berkeley, CA (July 18, 1984).

5. Applying Expert-System Techniques to Signal-Processing and Control-System Problems

Principal Investigators: R. R. Johnson, D. L. Lager, and T. W. Canales

Introduction and Objectives

The science of expert systems is very experimental with few general principles. Research for a particular application is generally required, and implementation is necessary for conducting the research. A brief description of two expert systems under joint development with the Signal and Control Engineering Thrust Area follows.

The first project concerns the monitoring and interpretation of seismic events to determine whether they result from a nuclear detonation. Towards this end, Earth Sciences (K Division) is developing sophisticated signal acquisition and processing techniques. Few people, however, understand these techniques well enough to use them in analyzing an event. In addition, orders-of-magnitude more events can be analyzed by these techniques.

The second project addresses a major concern of all magnetic fusion energy experiments, in which plasma generation is accomplished with a device called a neutral beam source. A trained operations staff must supervise the conditioning and operating of the source. This staff is expensive, and there is a lack of trained operators. These problems will only become more acute as the experiments mature.

The intent of an expert system is to provide, through computer software, the expertise acquired by a person through experience. No attempt is made to analyze this experience and arrive at an explanatory theory. Rather, the goal is to codify how a person represents knowledge and reasons about a problem. Using expert-system techniques for automatic conditioning is a viable alternative, since operators do quite well at the task of conditioning. Expert system techniques are desirable for seismic-event analysis since there are few experts and many events.

We have identified two research issues particular to control-type expert systems. The first issue concerns a person's model of a physical system; this model accounts for a significant portion of expertise. This model is unlike one in a conventional control system and may be vague, incomplete, and may not correspond to the physical system. Research is necessary to understand this type of model and its representation in an expert system.

The second issue concerns source conditioning, where expertise depends on the operator's perceptions and beliefs of the past four or five events. Each belief has a certainty factor, representing how strongly

the operator holds the belief. As events occur, certainty factors are modified, and new beliefs form from old ones. Research will also begin to identify how operators represent perceptions and beliefs of events.

Three research issues particular to a signal-processing expert system have been identified. Analysis may be split into two steps: signal processing and interpretation. In most systems, signal processing is a well-defined step; no expert-system techniques are necessary. However, for seismic event evaluations, a significant portion of the analysis involves selecting the signal processing techniques, determining the order, and establishing their parameters. Research of these three issues is necessary to understand how the expert system best directs signal processing operations.

A key aspect of the analyst's expertise is the ability to perceive a waveform in terms of abstract characteristics. Pattern-matching techniques can likely be used to obtain these characteristics. The nature of these characteristics and their use in the analysis process is unclear, however. The integration of pattern matching and expert-system techniques is another research topic.

Organizing the knowledge obtained from interviewing an expert and entering that knowledge into the knowledge base of the system are time-consuming components of expert-system development. This bottleneck is especially acute in seismic-event evaluation applications, since each seismic station will require a

unique set of rules for analysis. There have been attempts to replace this knowledge engineering with learning techniques that are not well understood. In particular, the method of applying learning techniques to a signal-processing expert system is unknown.

Progress

In FY 84, we spent approximately two months providing a basis for the development of the expert system for the neutral-beam source conditioning problem.

We decided to use a Symbolics LISP machine as the development environment, and we implemented two programs necessary to transfer shot data to the Symbolics machine. The first program resides on a Perkin-Elmer computer and retrieves shot data from a data base. The data are formatted, placed in a file, and subsequently written to tape. (This program will be modified later to transfer data directly to the Symbolics.) The tape is then read onto a VAX/VMS system. The second program resides on the Symbolics and retrieves the shot data from the VAX/VMS system.

During FY 84, we completed a prototype expert system that detects two operational anomalies. Signal processing routines extract features from the waveforms. These features are then given to a set of logical inference rules developed to represent an operator's knowledge about these two anomalies. The benefit of this system is that it provides

insight into the construction of a larger rule set that will detect more anomalies. This is the next step in the development of the system.

6. Engineering Problem-Solving Environments

Principal Investigators: D. W. O'Brien and S. A. Bly

Introduction and Objectives

Users of computer-based engineering tools are very interested in developing an improved computer environment for the rapid analysis and solution of engineering problems. The terms "menu-driven," "user interface," and "user-friendly" have been used in engineering and computer circles for years. Now the "mouse," the "icon," and "window management" have become part of our jargon. This interest hints at just how anxious engineers are for more usable and productive computers and computer-based engineering tools, without becoming computer or tools experts.

An objective of the CAE Thrust Area is to provide tool users with a more sophisticated computer environment for solving engineering problems. This sophistication will take several forms, such as

- More flexible communication of data between tools.
- Highly interactive use of graphics and mathematics algorithms as applied to engineering tools and data.
- Better interactive techniques with the mouse, icon, and window management.

Laboratory programs benefit from the productive use of computer-based tools by engineers for their pro-

grammatic needs. Productive use of all computer-based tools will be improved since engineers can browse through and modify data and algorithms. Engineers will also be able to make liberal use of graphics. Engineering productivity and quality will be enhanced because these tools allow the engineer to concentrate on the problem and its solution, rather than the use and limitations of the computer, its operating system, or a given CAE tool.

Computer science has made great strides in computing environments in recent years. Object-oriented software techniques grown out of research at XEROX PARC are becoming available in workstations and in personal computers such as the MacIntosh. The engineer can treat data, algorithms, and program control as independent objects, binding them into the problem specification and solution at run-time. This feature allows the engineer to instrument critical variables and to graphically monitor the solution's progress, and to stop, browse, change a mathematical method, and continue. Applying object-oriented techniques to scientific and engineering problem-solving is certainly at the leading edge of CAE tools development and support.

Progress

The CAE Thrust Area's past interest in interactive techniques has laid the groundwork for contract research on problem-solving environments in FY 84 and for some ambitious software development in FY 85. BLOX, a tool for prototyping and using interactive program interfaces, was acquired and investigated for engineering modeling and controls applications. Also, work began on interactive techniques as applied to Computer-Aided Control Systems Design (CACSD) in association with the Signal and Control Thrust Area.

The CAE Thrust Area has sponsored Prof. Kenneth I. Joy at the University of California, Davis, in a Graphics/Environments Research Project. Professor Joy's project report discusses "panels," "panel templates," and "panel production tools" as mechanisms for support of diverse, linear FORTRAN programs with the window-management systems of modern, high-performance workstations. He introduced the notion of a "software guardian," which encapsulates linear program segments, such as mathematics library routines and FORTRAN algorithms. The guardian may then become bound to an object-oriented problem solution at run-time, permitting a high degree of flexibility and user interaction during the tool's use.

Professor Joy also broke new ground for us with his experience in using engineering workstations and the UNIX operating system as the platform for engineering tools and

an advanced engineering problem-solving environment. The notion of an automatic guardian generator, adaptable to existing FORTRAN programs and routines, is also of interest. This research contract has been extended through the 1984-85 academic year, in expectation that the "panel" and "guardian" concepts will be proven and applied to real computers with window-management systems and engineering problems.

FY 84 also saw the refinement of objectives for an engineering problem-solving environment, the formation of the EAGLES project, and the development of an Environment for Advanced Graphical (LLNL) Engineering Systems. A joint effort between the CAE Thrust Area and the Signal and Control Engineering Thrust Area, this project is a two-year, eight man-year effort aimed initially at developing a highly advanced CACSD facility benefitting the Strategic Defense Initiative's Controls Technology Base. The EAGLES Project begins in FY 85 and is expected to offer the workstation-based, object-oriented environment able to support diverse engineering modeling, data handling, and circuit design tools.

Publications

1. Joy, K. I., "Graphics Environment Research Project, Final Report" (October 31, 1984).

V. Modeling and Simulation

Thrust Area Leader: R. W. Ziolkowski

Overview

The objective of the Engineering Modeling and Simulation Thrust Area is to meet the needs of the Electronics Engineering Department in computer modeling and simulation. Our goal is to increase the use and the quality of computer modeling and simulation among EE designers, thus providing computer modeling support to the Laboratory programs.

In FY 84, our efforts were divided into several technical areas: theoretical electromagnetics; numerical analysis of nonlinear partial differential equations; fields and plasma modeling; material, device, and circuit modeling; probabilistic failure analysis; nondestructive evaluation; signal processing; and VAX-based modeling. Contributions to a variety of Laboratory programs were made.

In theoretical electromagnetics, analytical solutions to several canonical-aperture coupling problems were obtained. They are being used to study the process by which fields couple energy through apertures into cavities. They are also being used to validate the applications of general-purpose scattering codes to this class of problems. The results of this effort are of great interest to several weapons and vulnerability assessment programs.

In the area of numerical analysis, a software package, FENL, was developed that can solve a general system of two-dimensional nonlinear partial differential equations. This package provides EE engineers the means to extend several of their nonlinear modeling codes to two dimensions, thus enabling them to simulate more complete descriptions of the physical phenomena. The semiconductor device models described below are potential candidates for a two-dimensional upgrade with FENL.

In the area of fields and plasma modeling, previous developments were enhanced and extended. A general purpose three-dimensional finite-element self-consistent fields code, GEM3D, was constructed. The finite-element modeling capability is desirable because it overcomes the geometry limitations of many existing finite difference codes. GEM3D extends the field modeling capabilities of GEM2D to three dimensions. It is already being applied to the field problems of several weapons programs. The ray-tracing (TRACE3D) and power deposition profile (HG3D) codes were modified to meet the needs of particular programs. These codes model gigahertz RF heating of the plasmas in the MFE tandem mirror machines TMX-U and MFTF-B. In addition to providing important physics information concerning electron cyclotron

resonance heating, they have become the main engineering analysis and design tools for optimizing the antenna configurations in those machines.

In the materials and device areas, a one-dimensional nonlinear model was modified to describe high speed solid-state switches. This model was developed to study the electronic and thermionic processes induced by intense transient pulses in semiconductors (second breakdown phenomenology). We conducted a parameter study of the resultant model to identify the relationships between the switching speed and the power-handling capabilities of semiconductor devices. The results of these projects impact all phases of pulse power engineering since there is a significant desire for high speed, high power switches with the lifetime of a semiconductor component.

In the area of probabilistic analysis, we investigated efficient representations of families of failure states. These require the evaluation of multivariate Gaussian distribution functions and a "fast" algorithm was constructed to perform these calculations. This project was a continuation of previous efforts to develop a "superfast" algorithm to model the effects of threatening environments on complex systems. The probability that a system will fail is calculated to assess its reliability, safety, and security. The weapons, nuclear safety system, and VLSI testing programs are benefiting from the results of this effort.

In the circuits modeling area, several standard circuit analysis codes are being maintained and new codes are being imported as they become available. Also, to make them more accessible to a larger number of engineers, these codes are being transported to various computers. For instance, the program SCEPTRE is being moved from the CDC-7600 to the VAXs and to the CRAY-1. Circuit codes are the codes most utilized by LLNL electronics engineers, hence, they impact a wide variety of Lab programs.

In the nondestructive evaluation area (NDE), projects were initiated to determine the potential impact of two new imaging technologies: Nuclear Magnetic Resonance (NMR) and Microwave Vector Tomography (MVT). The NMR project demonstrated that NMR Imaging could detect water deposits in epoxy composite materials. The capability to image water or other molecules in solids would have a significant impact on many Laboratory programs. The MVT project developed and tested a rudimentary inversion algorithm for constructing tomographic (two-dimensional) images from microwave amplitude, phase, and polarization data. Potential applications include inspection for water content, identifying concealed objects, plasma diagnostics, and airborne imaging.

In the area of signal processing, support was provided to the aperture-coupling experiments on the EM transient range. These experiments present unique data reduction requirements because of the oscilla-

tions in the signals produced by the reflections from the cavity walls. We investigated several approaches to this reflection problem and the resultant models have enhanced our ability to study empirically the phenomenology of aperture coupling.

Many of the modeling codes are computationally intensive and reside on the Laboratory's CRAY-1 computers. Because available time on these machines is minimal, we acquired a VAX 11-780 and earmarked it for modeling needs. A project was then initiated to transfer some of the modeling codes to the VAX environment and to begin an assessment of the benefits and detriments of such conversions. Another important aspect of a VAX environment is its interactivity. By developing new graphics capabilities on the VAX, we felt that quality and productivity of engineering activities in this area would be enhanced.

A project was initiated to develop a centralized facility, the Applied Computational Engineering (ACE) Laboratory, to provide a variety of output formats and media for applications in engineering modeling and simulation.

Two sources of funding are available for thrust area projects: Engineering Research and Burden funds. Engineering Research projects generally involve the research and development of new modeling capabilities which will have applications to Laboratory programs. Burden projects are encouraged to develop modeling capabilities that satisfy current programmatic modeling needs, yet

enhance the EE technology base. This thrust area report has been organized to reflect these funding differences. It contains the following project reports. (The "Transient Range Data Processing" project (number 12 below) was also supported by the Signal and Image Processing Thrust Area (II). Its report appears in that section and is not repeated here.)

ENGINEERING RESEARCH PROJECTS

1. Three-Dimensional Finite Elements
2. Development of Efficient Modeling and Computation Methods

BURDEN PROJECTS

3. EM Coupling
4. RF Heating of Plasmas
5. Finite Elements for Nonlinear EM Problems
6. Fast Switch Model
7. Microwave Vector Holography-Tomography
8. NMR Imaging
9. Circuit Modeling
10. VAX-Based Modeling
11. ACE Laboratory
12. Transient Range Data Processing

1. Three-Dimensional Finite Elements

Principal Investigators: N. K. Madsen and J. B. Grant

Introduction and Objectives

Within Lawrence Livermore National Laboratory there are several important areas which require accurate and reliable three-dimensional, numerical modeling of electromagnetic fields propagation (e.g., EMP vulnerability studies, design of electromagnetic-dependent systems, and validation/support of new EM theory). Two-dimensional modeling of EM propagation is frequently inadequate since wires and structures cannot be represented in two dimensions even though the cavity of interest can be. Similarly, three-dimensional finite-difference codes require stair-stepped representations of those surfaces that do not correspond to coordinate surfaces. A three-dimensional finite-element code for electromagnetics would not have these inadequacies.

The objective of this project is to satisfy the need for an accurate, reliable, three-dimensional finite-element code solving Maxwell's equations in the time domain. In order to accomplish this, and still have a useful tool, two additional criteria must be met: 1) the enormous volumes of data usually associated with three-dimensional problems must be minimal and 2) the code must be easily run so that others can readily use it.

We have developed a finite-element code with an effort to

minimize storage (memory) requirements and maximize execution speed. Various features of input simplify running the code. In order to reduce our development task, we have used existing grid generators and post-processors developed by the Mechanical Engineering Department for their three-dimensional finite element structures codes.

Already, there have been several requests to use this tool by various divisions here at LLNL. One of these requests is providing us with experimental, theoretical, and calibration data which is helping us in the validation of our code.

Progress

The computer code which we have developed for solving Maxwell's equations in the time domain is based upon finite-element techniques. Discrete equations are obtained by first discretizing the problem domain into small hexahedral volumes (finite elements). Over each element our approximate solution is assumed to have a known polynomial form (tri-linear in our case). A Galerkin weighted residual method is now used to obtain an approximating system of ordinary differential equations of the form $M(du/dt) = Ku$. Here, the matrices M and K are commonly referred to as the mass and stiffness matrices, respectively, and u is a very long vector composed of solution values

at the corner points of all of the finite elements. Galerkin finite-element methods require the computation of various integrals over the many elements. These integrals are typically evaluated through the use of numerical quadrature methods and will be discussed later.

As the matrices M and K are extremely large, special considerations must be made to deal with them. In order to avoid storing and inverting the mass matrix M , we use a mass-lumping technique which replaces M by an approximating diagonal matrix. This saves considerable storage and eliminates costly matrix solution algorithms. The numerical effects of mass-lumping will be discussed later. To further reduce storage requirements, the stiffness matrix is not stored but recomputed at each time step (cycle). Also, word-packing is used when deemed appropriate. These efforts have allowed us to solve large problems without resorting to disk buffering techniques. To enhance execution speed, we performed vectorization of code segments where possible.

To integrate the above large system of differential equations in time, we have chosen to use explicit rather than implicit methods. A stable leap-frog technique fixed-time-step method has been used because of its low overhead. LSODE, a sophisticated LLNL package for solving differential equations, has also been incorporated to give us the ability to use variable-time-step and variable-order methods. This does, however, require a lot of

storage, which can be prohibitive for some problems.

General boundary conditions are implemented by allowing any combination of normal and tangential field components to be zeroed at a boundary. This allows for easy specification of special points such as those where two metal surfaces meet at an acute angle (total E-field is zero). In addition, symmetry planes at $x=0$, $y=0$, and/or $z=0$ can be specified.

Two types of excitations can be used: fields or current densities. With either, the input is greatly simplified by using FORTRAN-like statements to describe the spatial dependence. The temporal dependence can also be specified by FORTRAN-like statements or a tabular listing.

To supplement the ME post-processor (TAURUS) which provides contours of data on surfaces in a variety of ways, a time history post-processor was developed which plots data as graphs. This allows for plotting of any significant quantity (coordinates x , y , or z component or magnitude of the E-field, H-field, or Poynting Vector) with the abscissa being time or a coordinate.

The results of our preliminary validation of the code have shown a number of things. The difference between 8-point and 1-point quadrature has a significant impact on execution speed (a factor of 2 to 3) and a nearly insignificant impact on results. The lumped mass has two distinct effects. It causes the

loss of some phase information and, consequently, requires smaller elements. Quantitatively, the elements need be reduced by less than one half of what would be necessary without lumping. However, this is greatly overshadowed by the savings in storage and execution speed. The second effect of the lumped mass is the elimination of the precursor, which is frequently seen in numerical simulations done in the time domain. Figure 5-1 shows sample time histories of a two-dimensional simulation; the precursor of Fig. 5-1a, should not be present.

In terms of capabilities, the finite-element code nicely handles skewed elements as shown in Fig. 5-2. Here, a plane wave is propagated from the left with little distortion. (The jaggedness of the highest valued contour is a property of TAURUS.) Figure 5-3 demonstrates the ability to let a circular pulse collapse and pass through the origin. This is difficult to do with cylindrical coordinates in two dimensions.

As a first step in validation, the results of this code were compared to the results of a test problem used in GEM2D. Figure 5-4 compares the results from the two codes for two time points. Further validation continues with the examination of a B-dot sensor in a "wart" at the outer perimeter of the diode. Figure 5-5 shows this configuration. This test case utilizes symmetry planes and cannot be represented except in three dimensions.

Further work on this finite-element code will include the implementation of material interfaces and free-space boundaries. Finally, the code with an operating manual will be released to those who are in need of such a tool.

Publications and Presentations

1. Madsen, N. K., NEM Conference (July 2-6, 1984).

1a Explicit T. I. - Wave scattering from infinite cylinder - consistent

1b Explicit T. I. - Wave scattering from infinite cylinder - SIGMA = infinity

Figure 5-1a. Sample time histories of a two-dimensional simulation. Note the presence of a precursor in this two-dimensional simulation using the full mass matrix.
Figure 5-1b. No precursor appears with the lumped mass matrix.

Figure 5-2a. These snapshots in time show how well a plane wave can be propagated through a transition region of skewed elements. In (a) the plane wave is just entering the skewed elements.

Figure 5-2b. In (b) the wave front has passed through the transition region with practically no distortion.

Diode with B-dot in wart at perimeter
 Time = 2.32000e-09
 Contours of z-electric field
 Minimum = -7.181e+00 in element 900
 Maximum = -2.607e-01 in element 1889

Contour Values
 a = -1.00e+01
 b = -7.75e+00
 c = -5.50e+00
 d = -3.25e+00
 e = -1.00e+00
 f = 1.25e+00
 g = 3.50e+00
 h = 5.75e+00
 i = 8.00e+00

Figure 5-3. Top view of a cylindrical cavity (with roughly a 2-cm radius) after a 1-ns pulse has bounced off the outer wall and passed through the center. The wave shape, represented by the contours, is very close to circular as it should be.

Explicit T. I. - Wave scattering from infinite cylinder - SIGMA = infinity

Time = 2.00000e-09

Dsf = 0

Contours of y-electric field

Figure 5-4a. Output of GEM2D.

Comparison to GEM2D – infinite cylinder/plane wave intera

Time = 2.00000e-09

Contours of y-electric field

Minimum = -2.199e+02 in element 33

Maximum = 7.536e+02 in element 133

Contour Values

a = -1.50e+02

b = -3.75e+01

c = 7.50e+01

d = 1.87e+02

e = 3.00e+02

f = 4.12e+02

g = 5.25e+02

h = 6.37e+02

i = 7.50e+02

Figure 5-4b. Comparison of GEM2D (a) and the new 3D finite-element code (b). The incident plane wave has propagated in from the left. Actual numerical comparison shows a significant figure equivalence; the slight visual differences are due to the post-processors.

Figure 5-5. Cylindrical cavity with thimble-like recess for B-dot probe shown here will provide validation against experimental, calibration, and theoretical results.

2. Development of Efficient Modeling and Computation Methods for Large Probabilistic Systems

Principal Investigator: G. C. Corynen

Introduction and Objectives

One of the most difficult problems in the assessment of large system performance is the treatment of uncertainties. Not only are the inputs and the operational environment of large systems difficult to specify with certainty, but their internal mechanisms are rarely understood with sufficient confidence to avoid the use of probabilistic methods. This is especially true when reliability, vulnerability, or survivability are the performance measures of interest.

The problem of assessing large-scale system reliability is usually broken into four major areas:

1. Developing a model of the system.
2. Computing the basic causes of system failure.
3. Determining the probability of occurrence of the basic causes of failure.
4. Computing the probability of failure of the overall system.

Prior to FY 84, we have concentrated on all but the second area. In the first area, we have found that discrete models such as fault trees and networks are most appro-

priate for a reliability analysis of those large systems whose components can be adequately defined as discrete entities. Our research is based on this modeling philosophy. Any statistical dependence between these components enormously complicates this modeling process and any subsequent computations. We have developed the Π modeling method to simplify both processes.

In the third area, we have found that, with very rare exceptions, systems are "coherent" in the sense that they fail only if at least one of their components fail. The interconnection structure of most systems is sufficiently understood that probability of occurrence of basic causes of system failures can be derived from the probability of failure of the components involved in the system failure. The precise relationships for that derivation had been developed earlier.

Most of our efforts were devoted to the fourth area, where probabilities are combined to determine the overall probability of failure of the system. This led to the Σ method, which is a very fast and efficient approach to this evaluation.

Prior to FY 84, our work was based on the assumption that conditional independence could be assumed, and that the probability of

joint component failures could be expressed as a product of individual (conditional) probabilities. In some situations, such an assumption is not practical, and the accuracy of the Σ method is severely reduced. The basic objective of our FY 84 work was to extend Σ to the fully dependent case. Two major issues surfaced immediately. First, a method for accurately representing large numbers of failure states (failure causes) by just a few critical ones had to be developed. Second, a better method for evaluating the multivariate Gaussian distribution had to be found. Current methods require computation times which increase exponentially in the dimension of the distribution.

Two subobjectives were formulated in FY 84:

1. Develop an efficient representation for families of failure states.
2. Develop a fast algorithm for evaluating the multivariate Gaussian distribution.

Relevance of the Research to Weapons and Other Laboratory Programs

Both weapons and nonweapons programs will continue to benefit from this work. In the weapons area, R Program is probably the principal beneficiary, not only in the analysis of acquisition, tracking, and pointing (ATP) problems, but also in the overall evaluation of weapon platform designs and in

the analysis of relevant C^3I (command, communication, control and intelligence) issues.

In other areas, the Nuclear System Safety Program (NSSP) has been the principal beneficiary. However, the new AVLIS (Laser Isotope Separation) Program will require the use of efficient algorithms to evaluate reliability and maintainability, and active contacts have already been established with that program. The methods produced by our research will also benefit the S-1 project, where serious testing problems have been discovered, and more powerful methods are needed.

More generally, this work provides the Electronics Engineering Department with the opportunity to continue expanding its technical capabilities in systems engineering. The long-term goal of this project is to develop an automated performance-analysis tool, and this tool will apply directly to many of the systems-engineering problems encountered in Electronics Engineering and Mechanical Engineering.

As documented in references and reports, our work has advanced the state of the art in the modeling and computation of complex systems throughout the duration of this project.

Progress

Although thorough verification experiments are planned, most of our work in FY 84 has been theoretical. In accordance with our

subobjectives, we discuss our program in two parts.

1. Efficient Representation of Failure States: The Δ -Method

Recall that our fundamental problem is to evaluate the probability of failure of a system from the probabilities of the causes of failure. This is the probability that the system fails due to cause 1, or due to cause 2, . . . , or due to cause n . Mathematically,

$$P(C_1 \dots C_n) .$$

Not only can each single cause involve many components, but the number of causes of system failure can get very large.

With the Δ method, complex strings of causes (the C_i 's) can be represented by just a few elements, at a modest reduction in accuracy. Because all causes are strongly dependent, reducing the number which must be included in the computation leads to a dramatic decrease of computation time, as shown in Fig. 5-6.

This approximation reduces the accuracy of the Σ method by pushing the upper and lower limit estimates for the failure probability further apart. The exact relationship between the proportion of original causes retained and the penalty in accuracy is not known definitively at this time, and will be established experimentally on the computer in the future.

2. A Fast Method for Evaluating the Multivariate Gaussian Distribution

Each cause of system failure may involve a large number of system components. One such cause, for instance, could require the failure of component 17, together with the failure of component 23, the proper functioning of component 13, and so on. Mathematically, such a cause can be expressed as

$$C = (\bar{C}_{17} \quad \bar{C}_{23} \quad \bar{C}_{13} \quad \dots),$$

the joint condition that C_{17} fails, C_{23} fails, C_{13} functions properly, and so on.

Even if only a single cause of failure C should exist, computing $P(C)$ could involve the evaluation of a multivariate Gaussian distribution of many dimensions, one dimension for each component specified in the failure cause. Because of the exponential complexity of current

Figure 5-6. In the strongly dependent case, dramatic reduction in the computational complexity of reliability evaluation results when only critical failure causes are processed.

evaluation methods, this problem alone is sufficient to preclude the accurate computation of system reliability in the fully dependent case. We developed a new method to circumvent this difficulty, appropriately called "Gauss." The method is based on the theory of linear vector spaces, and employs standard eigenvalue and other matrix algebra algorithms, whose complexity is at worst cubic in the number of dimensions, similar to the Δ method (Fig. 5-7). The price paid for this increase in efficiency is a decrease in accuracy once again, and the severity of this penalty has not been established at this time. A combination of theoretical and experimental work is planned to ascertain this speed-accuracy trade-off.

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Figure 5-7. Evaluating the multivariate Gaussian distribution is exponentially complex with current methods but only cubic with the algebraic methods used in "Gauss."

3. EM Coupling

Principal Investigators: R. W. Ziolkowski and J. B. Grant

Introduction and Objectives

The objective of the EM (electromagnetic) Coupling project has been to develop essentially analytical solutions to canonical electromagnetic aperture-coupling problems. Until recently, even the separable geometries for which analytical solutions might be expected have not been amenable to treatment, and purely numerical techniques present difficulties resulting from the singularities that exist at the edge of the aperture rim. These canonical solutions are necessary and important in establishing the "global" features of the coupling mechanisms, to identify specific coupling features of specific geometries, and to provide benchmarks for general purpose computer codes used in electromagnetics research.

In this project, which was a continuation of a FY 83 engineering research project, we have solved several new canonical problems and are exploring their behaviors in conjunction with the FY 83 solutions to understand and to describe the coupling process. These results are leading to general "engineering rules of thumb" which make it possible to estimate for engineering analysis and design purposes the coupling into more generally shaped cavities with more generally shaped apertures. These canonical solu-

tions are the first of their kind and, therefore, of great interest to the electromagnetics and electromagnetic effects communities.

The results of our studies in the phenomenology of aperture coupling are impacting several LLNL weapons and weapons-effects programs. The major mechanisms, for example, by which a nuclear EMP (electromagnetic pulse) or a high-power microwave signal can penetrate an aircraft, a missile, or a ship is through the apertures in the outer "skin" of the structure. This project has made substantial progress in understanding and describing the EM coupling process as a function of the angle of incidence, frequency and polarization of the incident field, and of the size and shape of the cavity and its aperture.

Progress

In FY 83, we developed generalized dual-series solution techniques for the scattering of an E- and an H-polarized plane wave from an infinite cylinder having an infinite axial slot. In FY 84, we used these approaches to develop solutions for the problems of a capacitive and an inductive iris in a rectangular waveguide and the scattering of a normally incident plane wave from a spherical shell having a circular aperture. The waveguide-iris problem is a model of

an experiment currently being performed by Ray Alvarez in E Division for the electromagnetics-effects program. His experiment is investigating the effects on the propagation of a wave through an aperture when a plasma is present in the aperture region. The plasma is formed when the incident field amplitude, which is enhanced by the presence of the edges of the aperture, surpasses the breakdown threshold of a gas located in the aperture region. The open spherical-shell problem encompasses the coupling of a plane wave into a cavity as well as the scattering of a plane wave from a spherical reflector. Its solution represents the first of its kind in three dimensions. Both solutions represent excellent benchmarks for the finite-difference and finite-element electromagnetic modeling codes.

We conducted parameter studies of the dual-series solutions to the H- and E-polarized slit-cylinder problems to further our understanding of the aperture-coupling process. The configuration of the E-pol case is shown in Fig. 5-8. This problem is particularly interesting because currents along the concentric wire in the interior of the slit cylinder can be calculated as a function of the frequency, the angle of incidence of the incident field, or of the size of the aperture. It has been shown that the modal patterns induced in the interior of the slit cylinder-wire cavity closely correspond to the natural modes of

the closed-circular coaxial waveguide system. Moreover, this effect persists even for large aperture openings. This behavior is illustrated in Figs. 5-9a and 5-9b with log-log plots of the magnitude of the current along the interior wire as a function of the frequency of the incident field. In both figures the radii of the cylinder and the wire are 1.0 and 0.1, respectively, and the plane wave is normally incident into the aperture (i.e., $\phi^{inc} = 180^\circ$.) In Fig. 5-9a the extent of the aperture is 10° ; it is 30° in Fig. 5-9b. The locations of the peaks in the current scan in Fig. 5-9a nearly coincide with those of the closed-coaxial waveguide. They are actually shifted slightly from the exact values because of the presence of the aperture which

Figure 5-8. The configuration of the scattering of an E-polarized plane wave from a perfectly conducting infinite cylinder having an infinite axial slot and enclosing a concentric impedance surface.

detunes the cavity. As the aperture size is increased, the detuning of the cavity is increased. However, Fig. 5-9b demonstrates that the resonance effects persists although their locations and appearance reflect the increased detuning and are shifted even further from the closed-coaxial waveguide values. An unexpected result was the actual form of the resonance features. The standard resonant peak only appears

for the TM_{0n} waveguide modes, while the "anti-resonance" peak appears for all other modes. For instance, in Fig. 5-9a the resonant peaks near 8.199 and 8.515 correspond to the TM_{01} and TM_{02} modes; the anti-resonant peaks at 8.274 and 8.389 correspond to the TM_{11} and TM_{21} modes. Moreover, the nulls in Fig. 5-9b are a result of detuning the anti-resonance features of Fig. 5-9a.

Figure 5-9. Frequency scans of the current induced on a perfectly conducting wire in the interior of a slit cylinder when the angle of incidence of the plane wave is $\phi^{inc} = 180^\circ$ and the ratio of the wire and cylinder radii $(a/b) = 0.1$. The angular extent of the aperture is varied from: $a = 10^\circ$ to $b = 30^\circ$.

The capacitive iris configuration (the iris is along the width of the rectangular waveguide) is shown in Fig. 5-10. The dual-series solution generates the transfer function for this problem; thus, time-domain results can be produced. An input pulse corresponding to the actual experimental one was constructed and convolved with the transfer function to produce time-domain movies that described the behavior of the pulse as it interacts with the iris. One distinctive feature of the physics was the very close similarity of the electromagnetic process with the analogous fluid case. Vortices were found to form in front of the iris and behind it much like the flow patterns that result from water flowing over a

dike. We found that these vortices influence the power flow of the pulse over the iris. This effect is illustrated in Fig. 5-11. The wave is incident on the iris from the left. The cut-off frequency of the waveguide is 3.83 GHz; the incident wave frequency is 9.16 GHz. A contour plot of the real part of the power is given in Fig. 5-11a and the corresponding vector plot is given in Fig. 5-11b. The vortices in front of the iris are readily apparent in Fig. 5-11b and those behind the iris correspond to the nulls of the power shown in Fig. 5-11a. It was shown that the iris "sheds" these vortices as the frequency increases, their creation being stimulated by the onset of the high order waveguide modes.

Figure 5-10. The configuration of the propagation of a wave in a rectangular waveguide in the presence of a capacitive iris.

Figure 5-11. Vortices form in the iris region of the waveguide when the frequency of the incident wave is such that higher order waveguide modes are present. They appear as nulls in the contour plots of the real part of the power given in Fig. 5-11a. They are clearly discernible in the corresponding vector plots of the power flow given in Fig. 5-11b.

The open spherical-shell problem geometry is illustrated in Fig. 5-12. One of the commonly used aperture-coupling diagnostics for problems of this sort is the ratio of the energy density of the total field to the incident field measured at the origin of the sphere. This result for a 5° aperture ($\theta_0 = 175^\circ$) is plotted in Fig. 5-13 as a function of $ka = (2\pi \times \text{sphere radius}/\text{wavelength})$. The resonance behavior of the cavity response is again immediately apparent. The peaks occur near the locations of the TE_{nm} and TM_{nm} modes of the closed-spherical cavity. In analogy with the two-dimensional slit-cylinder problems, the anti-

resonance features predominate. The resonant peaks now occur near the locations of the TM_{1n} and TE_{1n} modes. For instance, the resonance peaks near $ka = 2.744$ and 4.493 correspond to the TM_{11} and TE_{11} modes; the anti-resonance peaks near $ka = 3.870$ and 4.973 correspond to the TM_{21} and TM_{31} modes. We are currently studying this and other scattering descriptors (scattering cross sections and total energy stored in the open spherical cavity) to further our understanding of the differences and similarities between the coupling process on two and three dimensions.

Figure 5-12. The configuration of the scattering of a normally incident plane wave from a perfectly conducting spherical shell having a circular aperture: a) side view, b) top view.

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Figure 5-13. A scan in ka of the total energy density of the field at the origin normalized to the energy density of the incident field there for an open spherical shell having an aperture angle of 5° ($\theta_0 = 175^\circ$).

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4. RF Heating of Plasmas

Principal Investigators: R. W. Ziolkowski and J. C. Peterson

Introduction and Objectives

This project deals with the modeling of the power deposited in a magnetically confined plasma by microwaves launched from an array of antennas. This modeling problem is represented diagrammatically in Fig. 5-14. The computer codes, TRACE3D and HG3D, numerically model the propagation and the absorption of the microwaves in the plasma.

They were developed in support of the Magnetic Fusion Energy (MFE) program through the Modeling and Simulation Thrust Area during FY 82 and FY 83.

In FY 84 the "RF heating of plasmas" project continued to satisfy the specific modeling needs of the MFE program. We constructed enhanced numerical models describing the microwave power deposition resulting from the electron-

Figure 5-14. The power deposited in a magnetically confined plasma by microwaves launched from an arbitrary array of antennas is being modeled.

cyclotron resonance heating (ECRH) for thermal-barrier creation in the LLNL tandem mirror machines, TMX-U and MFTF-B. In addition, we developed basic refinements of the original modeling codes, TRACE3D and HG3D.

Progress

The ray-tracing code, TRACE3D, originally described only power absorption at the fundamental harmonic (ω_{ce}) for heating of a particular region of the end-cells of the LLNL machines. However, as shown in Fig. 5-15, there are actually two heating locations in each end-cell of TMX-U. The plasma parameters are different in each region and heating occurs at different resonance frequencies. Heating occurs at $2\omega_{ce}$ in the "thermal barrier" region. In MFTF-B there are 5 gyrotrons planned for each end-cell; 1 each at ω_{ce} and $1.25\omega_{ce}$, and 3 at $2\omega_{ce}$. The second harmonic heating region posed a particularly difficult modeling problem because the electrons are very relativistic in that region (e.g., 450 KeV in MFTF-B) and the physics in the original absorption package was not adequate.

A relativistic absorption package was constructed and incorporated into TRACE3D to allow modeling of the second harmonic heating. In addition, the presence of the hot electrons in the thermal barrier region causes a "beta-depression" of the magnetic fields. This necessitated an associated modification of the magnetic field profiles in

both the TRACE3D and HG3D codes. Results generated with the modified code are shown in Fig. 5-16.

The modified code results have been of particular interest because the actual TMX-U experiment is capable of qualitatively measuring the amount of second-harmonic power absorbed in the plasma. We accomplished this by placing a set of receiving antennas opposite the $2\omega_{ce}$ launch antennas and reconstructing the power deposition profiles from the transmitted power patterns. To match the experimental arrangement, TRACE3D was modified further to handle bundles of rays originating at distinct locations with different beam directions. In contrast to Fig. 5-16 where all of the rays originate at a point on cones representing different launch directions, the rays in Fig. 5-17 have distinct launch positions and angles. This allows better modeling of the actual antenna patterns when the microwaves enter and leave the plasma. Preliminary results have shown good agreement between the predicted and the experimentally measured values. Diagnostics and antenna optimization studies with TRACE3D have also benefited from the modified ray-launching scheme.

We also improved the power deposition code HG3D. The power absorption profiles generated by the original code suffered from an anomalous singularity near the axis of the machine. This $1/r$ (r being the radial distance from the axis) behavior is symptomatic of problems that arise when a cylindrical coordinate system is used. A cure for

Figure 5-15. Electron-cyclotron resonance heating in the LLNL tandem-mirror magnetic fusion energy machine TMX-U occurs at two locations and at two separate frequencies in each end cell: a) ω_{ce} in the plug region and b) $2\omega_{ce}$ in the thermal barrier region.

this problem based upon a nonuniform grid concept was formulated and tested. As illustrated in Fig. 5-18, the anomalous behavior near $r = 0$ is removed with the nonuniform grid scheme. HG3D was modified to incorporate this scheme.

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Figure 5-16. The ray-tracing code TRACE3D is capable of modeling the propagation and power absorption in a magnetically confined plasma of microwaves launched from an arbitrary set of locations and with an arbitrary set of launch angles. Shown are TRACE3D calculations of the second harmonic absorption in the thermal barrier region of MFTF-B with constant temperature and varying density. The electron temperature is 46.6 keV and the constant magnetic-field contours are 4.81, 4.90, 4.95, 5.00, and 5.03 kG in both figures. The propagation and absorption characteristics of the plasma are significantly altered as its electron density is raised from $2.0 \times 10^{12} \text{ cm}^{-3}$ in Fig. 5-16a to $1.0 \times 10^{12} \text{ cm}^{-3}$ in Fig. 5-16b. The numbers along the rays and the corresponding absorption levels are: 1 = 10%, 2 = 20%, 3 = 40%, 4 = 60%, 5 = 80%, 6 = 90%, and 7 = 99%.

Figure 5-17. The ray-tracing code TRACE3D is also being used to model the second harmonic-heating in the thermal barrier regions of TMX-U. Shown are TRACE3D calculations of microwave absorption in the TMX-U thermal barrier region with constant density and varying temperature. Constant magnetic field contours (kG) are noted, as are absorption contours of 60% and 90%. The numbers along the rays and the corresponding absorption levels are: 1 = 10%, 2 = 20%, 3 = 40%, 4 = 60%, 5 = 80%, 6 = 90%, and 7 = 99%.

Figure 5-18. The power deposition profile post-processor HG3D was modified to include a nonuniform gridding scheme to circumvent a singularity characteristic of modeling in cylindrical geometries. Depicted are profiles of the integrated power density (ω/cm^2) generated with the previous uniform and the new and improved nonuniform gridding schemes.

5. Finite Elements for Nonlinear EM Problems

Principal Investigators: N. K. Madsen and S. L. Ray

Introduction and Objectives

Shortly after the Fields, Materials, and Plasma Modeling Group was formed in 1983, we anticipated that there would be a definite need to be able to solve EM modeling problems characterized by systems of multi-dimensional nonlinear partial-differential equations. We also anticipated that these problems would potentially involve geometrical shapes or objects that are not easily handled by conventional finite-difference techniques. The specific problems that provided us with the motivation to start this project are the microwave air-breakdown and propagation studies and also the studies of the breakdown and failure of semiconductors when subjected to unusual perturbations or transients. The present modeling work being conducted for these problems is limited to one space dimension only and as such has limited applicability to the real three-dimensional setting. This research and development effort is specifically directed at producing a computer modeling tool that can be applied to the two problems mentioned above.

Specifically, the goal of this effort is to produce a computer modeling code, FENL, that solves, in the time domain, general systems of nonlinear partial-differential equations in two space dimensions

using finite-element techniques. Finite-element techniques were chosen to more easily model irregularly shaped objects and problem domains.

Progress

Mathematical Formulation

FENL is currently applicable to systems of partial-differential equations of the form:

$$\partial_t u_m = \sum_{i=1}^M \nabla \cdot (\bar{D}_{mi} \nabla u_i) + F_m(\bar{u}, \partial_x \bar{u}, \partial_y \bar{u}, x, y, t),$$

$$m = 1, 2, \dots, M$$

where

$$u = [u_1, u_2, \dots, u_m]^T,$$

$$u_m = u_m(x, y, t),$$

and

$$\bar{D}_{mi} = \bar{D}_{mi}(x, y, t)$$

is a 2×2 matrix. The term F_m above is a function, possibly nonlinear, of the unknowns and their first derivatives. Several types of boundary conditions can be handled by the code. First, simple forced-boundary conditions of the form,

$$u_m(x, y, t) = f_m(x, y, t)$$

$$m = 1, 2, \dots, M$$

where x and y are on the boundary and f is specified. A more general forced-boundary condition,

$$\begin{aligned} \sum_{i=1}^M a_{mi}(x, y, t) u_i(x, y, t) \\ = g_m(x, y, t), \end{aligned}$$

$$m = 1, 2, \dots, M$$

is allowed which permits linear combinations of the unknown functions to be specified on the boundary. In addition, a natural-boundary condition can currently be imposed when the problem space is a rectangular grid. This condition can be expressed as

$$\hat{n} \cdot \nabla u_m = z_m(x, y, t)$$

$$m = 1, 2, \dots, M$$

where $\hat{n}$ is the unit outward normal.

Several features distinguish FENL from earlier two-dimensional PDE solvers. FENL permits coupling between the PDEs in the second derivative terms and, for most problems, can be used on an irregularly shaped region. Neither of these capabilities were available in previous codes. The generalized forced-boundary conditions are also unique to FENL. These features permit the solution of a wider class of problems than had previously been possible.

Numerical Methods Used

Many different methods are available for possible use in constructing a code which will attempt to solve problems of the type described above. We have adopted what is known as a "method of lines" philosophy in specifying a numerical method for solving our partial-differential equations. This means that we first specify discrete approximations for the two-dimensional spatial variables x and y . This first approximation step leaves us with a system of ordinary differential equations in the time variable that approximates the above original system of partial-differential equations. This system is then numerically solved using sophisticated variable-time-step, variable-order numerical techniques. This "method of lines" approach offers numerous advantages in reliability, robustness, and versatility, particularly for difficult nonlinear problems.

Because of favorable past experiences, we have chosen to use a two-dimensional Galerkin finite-element approximation method for the spatial discretization. The finite-element approach also provides us with the needed variable-geometry capability. For the time integration, we have chosen the differential equations techniques embodied in Hindmarsh's code, LSODE. LSODE has proven to be robust, reliable, and tolerably efficient in a broad range of application situations. It was created by and is also fully

supported and maintained by LLNL personnel.

Validation Efforts

During the summer 1984, FENL was tested on a number of simple waveguide propagation problems. These were essentially one- and two-dimensional linear problems on a rectangular grid. The numerically generated solutions agreed very well with known analytic solutions. FENL is currently being tested on a cylindrical obstacle in a waveguide problem. This is a linear problem defined on an irregular grid with a known solution. To examine the nonlinear capabilities of the code, we are studying a system of nonlinear PDEs that describe the prop-

agation of microwaves through air. We are limiting our preliminary studies of this problem to the one-dimensional case where results from other, well validated, codes are available.

In the future we intend to continue the validation efforts and to further generalize the code. In particular, the natural-boundary conditions will be extended to the case of a nonrectangular grid. Upon validation, the code will be used extensively for microwave air-breakdown and semiconductor failure studies. We will also investigate, and implement if necessary, internal-interface conditions and various types of nonlinear boundary conditions.

6. Fast Switch Modeling

Principal Investigators: W. J. Orvis, J. H. Yee, and G. H. Khanaka

Introduction and Objectives

During the last couple of years, we have developed a number of different techniques for modeling the operation of semiconductor devices in various environments. These models include: band structure calculations and photovoltaic efficiency calculations for solar cell materials, and calculations of device operation and failure during the application of an EMP-induced transient pulse. These computer models have been giving us more

insight into the operation of electronic devices under various conditions, especially under the application of high-voltage transient pulses and high temperatures. For example, using our codes, we have identified the two most important types of failure phenomena in pulse stressed semiconductor devices: current-mode and thermal-mode second breakdown (see Fig. 5-19). From our calculations, we can clearly see how the two breakdown phenomena occur and how

Figure 5-19. Current versus time for a small signal diode during a high-voltage pulse, showing current mode and thermal mode second breakdown. The mode depends on the applied voltage pulse.

analyzed by the modeling codes. For example, Fig. 5-21 shows the doping profile and grid spacing for the device modeled in Fig. 5-20. Note that in areas of the device profile where there are rapid changes in doping, we are using much denser gridding (the distance between grid points is smaller) whereas in areas where there is little variation in the device structure, we spread the grid points farther apart. We have increased the complexity of the external circuit, including series and parallel capacitors and resistors to more realistically model the testing circuits involved in pulse testing of semiconductor diodes here at LLNL (Fig. 5-22). We have also moved the equations describing the external circuit into the solution matrix for the device equations, eliminating the need to iterate the

solutions of the device equations with the solutions of the external circuit equations. This increases the speed of the calculation by nearly a factor of 10.

We have expanded the analysis capability of the codes by adding the ability to create color movies. We can, therefore, create color movies of the pertinent parameters of device operation giving us an opportunity to observe the inside of a semiconductor device during an electrical transient. For example, we have produced color movies of the IMPATT oscillations described above. These movies show the details of electron and hole movements and variations in the electric field that result in the oscillations. Without these movies, identifying the type of oscillations involved would have been much more difficult.

Figure 5-21. Doping profile and grid spacing for the device modeled in Fig. 5-20.

the device being modeled. The figure shows oscillations in both the experimental and modeling results. These were originally thought to be "ringing" in the external circuit; however, the modeling results show them to be IMPATT oscillations in the device itself.

As we use these codes, we are also expanding their capability and efficiency. We have rewritten the device equations to allow nonlinear gridding of the device structure. In any code of this type, the continuous variables (electron density, hole density, potential, and temperature) are represented with a discrete set of values located on a grid. The density of grid points must be great enough so that all variations in the continuous variables can be resolved. For example, a rapidly changing variable requires a much higher density of

grid points than a constant variable. A problem that uses uniform gridding must grid the whole problem at a density sufficient to resolve the smallest variations in the continuous variables. This causes other parts of the device to be considerably overgridded, making the problem much larger than is necessary. The addition of the nonlinear gridding capability allows us to use dense grids in those areas where it is necessary and to use less dense grids elsewhere. This feature immensely decreases the number of grid points needed to describe the structure of a device. Thus, we can model more realistic devices much more efficiently.

In support of this nonlinear gridding capability, we have developed a grid- and doping-profile generator to create the nonlinear grids and doping profiles to be

Figure 5-20. Comparison of experimental and code results for an avalanche diode during a high-voltage pulse.

they switch from one mode to the other. We have also been able to correctly predict the position of hot-spots formed during the second breakdown as compared with experimental data.

In spite of these successes, we identified three areas where further development was needed:

1. Code run times. The codes run too slow, requiring many hours of computer time for a single run.
2. External circuit. More elements were needed in the external circuit that drives the modeled device. The existing circuit consisted simply of a resistor and a variable voltage source in series with the modeled device. In order to more accurately model a device in a real circuit and to be able to compare the results to experimental data, we needed to make the external circuit more complex.
3. Validation. The accuracy of the codes must be tested by comparison with experimental data.

Based on the deficiencies described above, our objectives for FY 83 were as follows:

1. To evaluate and implement ways to improve the speed of the operating code, looking especially at the gridding method used.

2. To increase the complexity of the external circuit to more closely model the environment encountered by a real device.
3. To compare the code results to some experimental results in cases where the device structure and circuit parameters are well known.

Switching devices are some of the most important elements in a diagnostic system. Currently LLNL has an experimental program to investigate the potential of avalanche diodes and avalanche transistors for use as high speed switching devices. The environment of an avalanche device during switching is quite similar to that encountered by a device during an EMP. Therefore, our device-failure modeling codes are capable of modeling the normal operation of avalanche diodes as well. We are using this capability to help the LLNL experimental program understand the switching process in avalanche devices.

Progress

We have used our codes to examine the pulse operation of avalanche diodes. Avalanche diodes are being used for pulse sharpening in high speed switching applications. Figure 5-20 shows a comparison of the experimental and code results for one such device. Much of the difference between the two curves is due to a lack of detailed information about the structure of

Publications and Presentations

1. Orvis, W. J., G. H. Khanaka, and J. H. Yee, A Review of the Physics and Response Models for Burnout of Semiconductor Devices, final report, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19900, Rev. 1 (1983).
2. Orvis, W. J., G. H. Khanaka, and J. H. Yee, "An Evaluation of the Models Depicting EMP Induced Failures in Semiconductor Devices," presented at the NEM 1984 Conference, Baltimore, MD (July 2-6, 1984).
3. Cabayan, Breakall, Burke, Candy, Corynen, Hudson, Khanaka, King, Kunz, Martin, Madsen, Magnuson, Mensing, Orvis, Yee, and Ziolkowski, Phenomenological Investigations in High-Altitude EMP (HEMP), Lawrence Livermore National Laboratory, Livermore, CA, UCID-20135 (1984).
4. This work was presented to the JASON committee on July 20, 1984. The committee made favorable comments on this work.

V = Applied voltage pulse
 V_B = Bias voltage
 R_B = Bias resistance
 R = 50 ohm line resistance
 C_P = Parallel capacitance
 C_S = Series capacitance

Figure 5-22. External circuit currently available in the device code.

7. Microwave Vector Holography—Tomography

Principal Investigators: R. J. King and R. M. Bevensee

Introduction and Objectives

The objective of this project is to develop the theoretical technology base to construct microwave (≈ 1 GHz to ≈ 50 GHz) two-dimensional tomographic (slice) images and corresponding three-dimensional images of perfectly conducting and scalar dielectric bodies. Measurement technology presently allows accurate and rapid acquisition of amplitude, phase, and polarization data of vector electric fields over sizeable apertures at many frequencies. After acquiring data on the radiated- or scattered-vector electric field over a small-size aperture, our emphasis during FY 84 has been to advance the state of the art of data processing so as to make use of dispersion, spatial, and (indirectly) polarization information more efficiently than in the past. The initial goal has been to achieve a resolution enhancement for perfectly conducting bodies of ~ 1 wavelength at the highest frequency used.

Development of the reconstruction algorithm is being accomplished using synthetically generated data rather than actual experimentally measured data. When the reconstruction has been satisfactorily demonstrated using such techniques, we intend to apply it to experimental data measured on one of many outside field-mapping facilities before

actually developing an in-house experimental capability.

A microwave-tomography capability to resolve distant objects from data which is limited in the space and frequency domain has several potential applications: 1) radio-wave airborne reconnaissance of the terrain (Treaty Verification Program), 2) plasma diagnostics of electron-density profiles (MFE), 3) subsurface imaging of buried objects (EE-Earth Sciences Departments), 4) identification of contrasting tissue and bone with nonionizing radiation (Biomed), and 5) evaluation of composites and plastics which are semi-transient to microwaves. Such a capability will also support a complimentary effort to resolve anomalies in materials by proper data processing of scattered ultrasonic waves.

Earlier work reported in the literature concerned with object reconstruction by microwaves is largely based on assumptions justified for the x-ray or optical regime, i.e., straight-ray propagation and first-order (Born or Rytov) scattering or diffraction by weakly perturbing objects. Also, most inversion work is based on scalar field measurements made over a wide-angle aperture. Little attention has been given to polarization effects; i.e., the ability to resolve object edges and corners by rotating the polarization of the

incident waves, or to observe the depolarization of scattered fields caused by curved surfaces. Our research effort has been devoted to extracting as much information as possible from scattered-vector fields over limited spatial apertures, utilizing frequency and polarization information.

Progress

We have developed a vector-tomography algorithm for the VAX, based on a fundamental expression for the spatial solenoidal (no divergence) portion of the electric field in an aperture. This field is generated by equivalent k-space vector currents in the scattering body (k-space and r - or real-space currents are Fourier transformations of each other). Fourier transformation of the spatial aperture field from the (x, y) domain into the (k_x, k_y) domain at each of a number of discrete frequencies yields information about the object current in (k_x, k_y, k_z) space. If this information is carefully interpolated and Fourier-transformed according to sampling-theory rules, we obtain a hybrid-body current distribution in mixed (x, y, k_z) space. Upon transforming this current from k_z to z space, one obtains--not the equivalent-vector current $\vec{J}(x, y, z)$ in the object as one might think--but rather $\text{curl } \vec{J}$. However, the vector components of $\text{curl } \vec{J}$ will have rapid changes across an object boundary just as $\vec{J}$ will, and thus will indicate body shape.

To test the algorithm, a 6-cm-long thin wire with spatially uniform current was chosen to radiate at ten discrete frequencies from 1 GHz to 10 GHz toward a 15 cm x 15 cm aperture. The vector-tangential field was specified on a 10 x 10 spatial grid at each frequency. First, the wire was placed "transversely" in an (x, y) plane parallel to the aperture plane and 37.5 cm away as shown in Fig. 5-23. Then, the wire was placed "axially" along the z -axis and perpendicular to the aperture plane with its center about 39 cm away. The results of the tomographic inversions are shown in Figs. 5-24 to 5-28.

Figures 5-24 to 5-26 show the resolution of the y -directed transverse wire (horizontal black or white line). Each figure shows the intensity of a component of $\text{curl } \vec{J}$ in each of ten tomograms spaced at intervals of 3 cm along the z -axis in the vicinity of the wire. The fifth tomogram actually intercepts the wire. Figures 5-24 and 5-25 show the resolution by $(\text{curl } \vec{J})_x = \partial J_y / \partial z$ and $(\text{curl } \vec{J})_z = \partial J_y / \partial x$, respectively, according to one interpolation scheme in (k_x, k_y, k_z) space. The wire is actually resolved transversely by the fifth tomogram in Fig. 5-24 within the diffraction limit set by the wavelength at the highest frequency ($\lambda = 3$ cm at 10 GHz). However, the wire is not well resolved in Fig. 5-25. When a second interpolation scheme was tried, the converse was true; the wire was fairly well resolved in Fig. 5-26 by $(\text{curl } \vec{J})_z$ but was not

as well resolved by $(\text{curl } \vec{J})_x$ (not shown) as in Fig. 5-24. These results indicate the need for better interpolation schemes depending on which component of $\text{curl } \vec{J}$ is employed in the reconstruction.

Figures 5-27 and 5-28 show the resolution of the axial, z-directed wire by $(\text{curl } \vec{J})_y = -\partial J_z / \partial y$ and $(\text{curl } \vec{J})_x = -\partial J_z / \partial x$, respectively, using the second interpolation scheme. Here, the wire extends from the white dot in the fourth tomogram to the dot in the eighth tomogram. In Fig. 5-27, the two white squares in the fifth tomogram and the one white square in the sixth tomogram indicate the presence of the wire. Better resolution would show a white square in the seventh tomogram as well, and a more definite indication

of the ends of the wire in tomograms 4 and 8. In Fig. 5-28, the resolution is not as good; there is one spurious white square in tomogram 4, several spurious ones in tomogram 5, and the one bright white square in tomogram 6 is further away from the wire position than in tomogram 6 of Fig. 5-27. Nevertheless, the resolution in Figs. 5-27 and 5-28 is better than that achieved by the first interpolation scheme.

Our next step should be to illuminate a basic three-dimensional body, such as a perfectly conducting box, with a plane wave and try to resolve its shape by processing the scattered field on the aperture according to each of the above-mentioned interpolation schemes. The images obtained from the various

Figure 5-23. Current element to be imaged by specifying the tangential-vector electrical field at ten frequencies on a 10×10 point aperture plane.

components of $\text{curl } \vec{J}$ should suggest further improvements in these schemes and in also the manner of interpolating in "hybrid" (x, y, k_z) space.

Publications and Presentations

1. Bevensee, R. M. and R. J. King, "Microwave Imaging by Holography and Tomography: Review and Assessment," talk delivered to the URSI/AP-S Meeting, Boston, MA (June 25-29, 1984).

2. Bevensee, R. M. and R. J. King, "Microwave Tomographic Reconstruction of Conducting or Dielectric Bodies by Frequency-Domain Far-Field Data," Abstracts of the Open Symposium on Data, Signal and Image Processing, p. 7, URSI XXI General Assembly, Florence, Italy (September 4-5, 1984).
3. Bevensee, R. M., "Acoustic Tomographic Reconstruction of Anomalies in Three-Dimensional Bodies," Review of Progress in Quantitative Nondestructive Evaluation, 4, (Plenum) (1985).

Figure 5-24. Array of tomograms using $(\text{curl } \vec{J})_x$ for a y-directed current element as shown in Fig. 5-23. The tomograms (slices) are spaced 3 cm apart along the z-axis. The black line in tomogram 5 shows the location of the actual current element. The first interpolation scheme was used.

Figure 5-75. Array of tomograms using $(\text{curl } \vec{J})_z$ for a y-directed current element as shown in Fig. 5-23. The white line in tomogram 5 shows the location of the actual current element. The first interpolation scheme was used.

Figure 5-26. Same as Fig. 5-25 except that the second interpolation scheme was used.

Figure 5-27. Array of tomograms using $(\text{curl } \vec{J})_x$ for an axial z-directed current element. The second interpolation scheme was used.

Figure 5-28. Array of tomograms using $(\text{curl } \vec{J})_y$ for an axial z-directed current element. The second interpolation scheme was used.

8. Nuclear Magnetic Resonance (NMR) Imaging

Principal Investigator: P. E. Harben

Introduction and Objectives

Nuclear Magnetic Resonance Imaging (NMR Imaging) has generated tremendous excitement and research in the medical community and is proving to be an invaluable aid in medical diagnosis and metabolic research. (Figure 5-29 represents a typical medical NMR-imaging facility.) This technique poses exciting research possibilities for non-medical applications as well; yet very little effort has been directed

towards assessing the potential impact of NMR imaging to these applications. Furthermore, there is a complete lack of expertise in this new technology within the Laboratory.

The thrust area objective of this project for FY 84 was to develop the needed background and expertise in NMR imaging to assess the possible potential of this technology to LLNL programs and, if this technology proves of value to LLNL programs, to outline the needed

Figure 5-29. A schematic layout of a medical NMR-imaging system.

equipment and options available to the Laboratory in developing an NMR-imaging facility for research purposes.

The NMR-imaging educational process involved reading numerous technical papers, attending a workshop, and visiting two NMR-imaging facilities. Knowing the strengths and limitations of this technique and current problems to be overcome in the future, various Laboratory programs and departments were contacted for problems and needs to which NMR imaging could be applied. Many Laboratory programs showed problem areas for which NMR imaging showed potential. As a result, equipment and development costs in building an NMR-imaging facility were explored. Although the cost of such systems is very high, a low cost alternative was found making use of an existing NMR-spectroscopy magnet.

Progress

Facility Visits

In the process of learning the state of the art in NMR imaging, we visited two facilities. The first facility was the Shell Research Center in Houston. It represents the only significant NMR-imaging effort towards nonmedical applications in the country. The second facility was the Health Science Center in Dallas. The Health Science Center was using a low cost method of imaging that relied upon a conversion of an NMR spectrometer. Identical equipment exists and is available at LLNL.

The visit to Shell Research Center allowed us the opportunity of obtaining images of some samples of interest to Laboratory programs. Figures 5-30a and 5-30b show the imaging results from a sample of Kevlar fiber epoxy composite and

Figure 5-30a. Kevlar fiber epoxy composite boiled in water for one week. The white areas are regions of high water content.

Figure 5-30b. Water-saturated balsa pith material. The vertical banding reflects actual structure.

balsa pith, respectively. Both materials were water saturated prior to imaging. Much of the structural detail was lost in transferring a polaroid photograph to paper. Nonetheless, the crude images still reveal the potential usefulness of NMR imaging. Furthermore, even though the Shell NMR system is in the very early stages of development, it is already providing new insight into basic polymer absorption processes and flow through porous media.

The Health Science Center had modified a Nicolet 1280 NMR-spectrometer CPU to perform imaging and designed gradient coils for a spectrometer magnet. Software was developed to perform the gradient-coil pulse sequencing and back-projection image reconstruction on the Nicolet 1280. In terms of additional capital equipment, only three additional amplifiers for the independent X, Y, and Z gradient coils were required. The magnet, pulse programmer, RF amplifier, and computer used were those of the spectrometer. Such a Nicolet 1280-based NMR spectrometer exists at LLNL as well.

LLNL Applications

Departments and projects throughout the Laboratory were contacted for problems and research thrusts to which NMR imaging could be applied. The following list of departments, divisions, and projects all could benefit from an NMR-imaging capability within LLNL:

- Chemistry
- Nondestructive Evaluation
- Environmental Science Division
- Lasers
- K Division
- Biomed
- Hazards Control

NMR imaging can be applied to such diverse areas as fiber-composite evaluation, flow and migration studies, porosity and permeability studies, polymer characterization, fracture growth and propagation, and water uptake in plants and soils. Although most NMR imaging is currently done on mobile hydrogen nuclei such as those found in water, other nuclei can also be imaged. A further application of NMR imaging that opens tremendous possibilities is chemical-shift imaging wherein a given nuclei, say hydrogen, can be imaged for only those nuclei in a given chemical species. This allows the production of images of such quantities as fat-to-water ratios, etc.

NMR Imaging at LLNL

Because of the broad spectrum of applications NMR imaging has within LLNL and the potential this new technology promises, we concluded an NMR-imaging effort should

be undertaken at LLNL. The initial cost outlay for a complete vendor-supplied imaging system would be over \$500 000, a prohibitive initial cost. Hence, we explored the low cost alternative of developing an initial "home built" NMR-imaging facility.

A system diagram of a proposed NMR-imaging system is included in Fig. 5-31. This diagram differs from conventional systems in separating the data acquisition from the data processing steps. This would allow imaging-software enhancement to occur independently of data-acquisition modifications and allow for easy upgrading to a larger magnet or superior acquisition electronics. Within the Chemistry Department of LLNL, the disk storage unit, CPU, pulse programmer, signal averager, receiver, preamp, RF transmitter, and RF power amp are all available. The LLNL magnet, however, would be unsuitable for imaging. Sandia National Laboratory has a high-field 8-cm-bore superconducting magnet with high speed data acquisition that is both suitable for NMR imaging and available. Furthermore, for \$20 000, the magnet vendor, Nalorac Cryogenics, will build the gradient coils for imaging. We feel that LLNL, without a large capital equipment outlay, can develop an NMR-imaging facility and begin evaluating this technique for new, unique, nonmedical applications.

Publications and Presentations

1. Harben, P. E., "NMR Imaging: Usefulness in Laboratory Programs," Engineering Research Division technical seminar, Lawrence Livermore National Laboratory, Livermore, CA (July 6, 1984).
2. Harben, P. E., "Trip Report and NMR-Imaging Results at Shell Research Center," Lawrence Livermore National Laboratory, Livermore, CA, 4-0042 (March, 1984).

Figure 5-31. System view of an NMR imaging facility. Note the data processing and acquisition are proposed as separate systems.

9. Circuit Modeling

Principal Investigator: W. G. Magnuson, Jr.

Introduction and Objectives

The Circuit Modeling project of the Engineering Modeling and Simulation Thrust Area has the broad charter of developing internally and importing from sources outside the Laboratory circuit-analysis computer software for simulation of electronic systems.

The objectives of the project are the following:

1. Provide circuit-analysis capabilities for design engineers at LLNL.
2. Document the software through user manuals and other material.
3. Give user assistance on their modeling problems, help new users gain access to the analysis programs, provide help when software or modeling problems occur, and provide training when needed.

To meet objective 1 above, the project has adapted and maintained several circuit-analysis codes on the Octopus computer network, on the MFE computer network, and more recently on the EE Department VAX computer network. Specific programs will be listed in a later section.

As engineers have moved away from detailed circuit design to

design of systems, analysis and, in particular, computer-based analysis have become of increasing importance. The circuit-analysis codes running at LLNL together represent a very strong capability for analysis in many areas. Besides the classical time- and frequency-domain analysis of electrical circuits, the software offers many other analysis features frequently found extremely useful to engineers.

With the increase in the number of computer terminals and workstations, it is important that the analysis codes be coupled more tightly to the terminal than in the past. The analysis tools must also span a broader area of analysis. For example, a design may require not only analog circuit modeling and analysis, but some parts of the circuit may require digital circuit analysis. Other issues such as testability analysis and the generation of test patterns for testing final circuits must be addressed by designers.

The analysis codes are used over a wide range of applications in support of projects and programs all over the Laboratory. The circuit-analysis programs running at LLNL represent the state of the art in the general purpose circuit-simulation software. Some of the programs are maintained outside of the Laboratory and others are primarily maintained and further enhanced internally.

Progress

Five circuit-analysis software programs are currently supported at LLNL on our computer networks. They are:

SCEPTRE on CDC-7600
SPICE2 on CDC-7600, Cray-1,
and VAX
NET-2 on CDC-7600
CALAHAN on CDC-7600
EMTP on Cray-1

We have been working on moving the SCEPTRE code to the Cray-1 and the VAX computers. The VAX implementation was started in May and an effort is being made to restructure the program so it will be easier to move to other computers. Extended SCEPTRE is being translated which offers several analysis advantages over the earlier SCEPTRE software. After the VAX version is running, the plan is to move that version over to the Cray-1 computers. SCEPTRE is a general purpose program that is very flexible. LLNL is the only facility actively maintaining the program and moving it to other computer systems.

Plans for FY 85

We plan to continue support of the circuit-analysis codes through user help and program maintenance. We hope to formalize the training to a higher degree than in the past by starting a series of training seminars on the programs next spring and summer. We had hoped that this

training would have started in FY 83 but it did not. When the Extended SCEPTRE is running, a short course will be given. In preparation for this, the user manuals are being updated.

Figure 5-32 shows a representative output of the SCEPTRE program using the printer plotter. In the conversion of SCEPTRE to the Cray and VAX computers, we hope to improve the graphics output.

The conversion of the Extended SCEPTRE software is being translated now to the Cray-1 computer and a running version is planned for March 1985. The VAX version may be available in early summer 1985.

In the past three years, digital simulation has been addressed using the ILOGS program on the VAX computers. In late FY 84, we converted to the more modern code called SILOS which was developed by SimuTec. A short course will be given to design engineers sometime in January or February of 1985.

Testability of circuits is becoming increasingly important. In the summer of 1984 we worked on the SCALD timing verifier which (with the help of a summer student) we got running on the VAX computer. We next plan to integrate it with schematic-capture software running on IBM PC and on the VAX computers. Figure 5-33 illustrates one output of SILOS relating to the generation of appropriate test sequences for testing digital circuits.

Presentations

1. Magnuson, W. G., "Electronic Circuit Analysis at LLNL," Seminar given at Sandia National Laboratory, Livermore, CA (July 16, 1984).
2. Magnuson, W. G., "Overview of Circuit Analysis Programs," Seminar given at Oregon State University, Corvallis, OR (October 18, 1984).

Figure 5-32. The SCEPTRE computer program analysis circuits and systems. This example output shows the voltage across a diode junction and illustrates the nonlinear response. This and other plots were used to study power supply transients.

- I L O G S 2T.1 - FAULTS MAR29/85 14:53:14

16-BIT BINARY FULL ADDER W/ FAST CARRY

DETECTION VS. TIME

Figure 5-33. This histogram output of SILOS shows the network faults detected as a function of inputs.

10. VAX-Based Modeling

Principal Investigator: J. K. Breakall

Introduction and Objectives

Many computer codes exist inside and outside Lawrence Livermore National Laboratory which would greatly benefit the electromagnetics modeling area. It is very desirable to collect and install these codes on the Engineering Research Division VAX computer. An exploration has been made into the feasibility of converting and running these codes on the VAX.

The primary objectives of this research project for FY 84 were as follows:

1. The acquisition and conversion of the computer codes will provide a more cost-effective utilization of computer resources in the EE Department.
2. Use of the VAX will provide more user friendliness because of its superior interactive capabilities.
3. This coupled with the related graphics efforts in the department will hopefully overshadow the reduction in speed of the VAX.

Progress

The following codes have been acquired and are either installed or presently being installed on the VAX

in a system-wide access directory on the Engineering Research Division computer. Most of these codes have also been installed on the NESD VAX computer for CAE applications.

1. Numerical Electromagnetics Code (NEC) - Antenna modeling code developed at LLNL.
2. MININEC - Smaller version of NEC which also runs on a PC.
3. INEC - Interactive version of NEC.
4. G3DXL3 - Generalized 3-Dimensional Finite-Difference EM Code.
5. BSCAT - Basic scattering and diffraction code using Geometrical Theory of Diffraction (GTD) (from Ohio State University).
6. GENREF - General reflector antenna code using aperture integration and GTD (from Ohio State University).
7. GEM2D - General Finite-Elements EM code which uses Mechanical Engineering pre- (INGRID) and post- (ORION) processors (VAX version - J. Peterson).
8. SLATEC - General collection of mathematical routines which can

be accessed in a very convenient interactive format (from Sandia).

9. MOVIE.BYU - Large interactive 3-D hidden and shading graphics package (from BYU).
10. MATHLIB - General purpose mathematical modeling and utility programs written in an extremely interactive and graphical format; also includes a symbolic calculator and a collection of useful parsing routines (from Harvey Mudd University).
11. HIDDEN - Hidden-line graphics package (from NASA Ames).
12. RLC - Interactive SPICE program which allows interactive graphical circuit input and analysis with a light pen (from University of Pittsburgh).

This research has also investigated and recommended the acquisition and installation of DISSPLA (graphics), IMSL (math and statistics), VAXIMA (symbolic algebra), MINPACK (minimization), EISPACK (Eigen), LINPACK (linear algebra), and FUNPACK (functions).

Example Results

A small sampling of actual output or CRT screen hard copy from some of these programs is given in the following figures. Figure 5-34 shows an example of built-in "help" documentation in the interactive SPICE program RLC. The screen menu display in this program RLC is shown in Fig. 5-35 where circuits can be interactively drawn and analyzed.

The final result of an AC analysis of this circuit is shown in the plot which is produced by RLC in Fig. 5-36. In Fig. 5-37, an example of INEC (Interactive Numerical

```

5 RLC
This package implements a procedure of interactively drawing circuits
on the screen and analyzing it using the SPICE circuit simulation
program. This is a Fortran-77 program which uses RCLT 10. The program
runs on the ILL-11/750 as a VT100 terminal retrofitted for graphics
which is bitstream 8000 compatible.

This program implements most of the options of SPICE except the
subcircuit option, transmission line model, waveform for voltage and
current sources and the .PRINT statement. The size of the circuit that
can be analyzed is limited to the size of the circuit that can be drawn
on the screen. These options can be included by tacking on a file to the
end of the input file to SPICE. This can be done by using one of the
output options.
  
```

```

DO YOU WANT TO GENERATE A NEW CIRCUIT (N FOR YES) (Y/N) ? Y
SHOW A TITLE ROW (UP TO 70 CHARACTERS)
--> TEST CIRCUIT [
  
```

Figure 5-34. Example of Interactive SPICE program RLC (actual CRT-screen output as seen on terminal).

Figure 5-35. Sample graphics from RLC illustrating light-pen menu-driven features for drawing circuit and performing analysis on terminal screen.

Electromagnetic Code) as seen on the CRT is given which shows the beginning of an interactive antenna-modeling session. A sample hidden-line plot of a section of an ellipsoid as drawn by MOVIE.BYU is shown in Fig. 5-38. This package also has the capability to draw hidden-surface and shaded-color

plots of objects which can be transparent and/or illuminated by multiple light sources. The use of its interactive movie frame control, interfaced with the VCR movie making equipment on the ACE lab, should provide excellent graphical presentation of modeling results. Figure 5-39 shows an actual model

Figure 5-36. Sample output after analysis has been performed on the circuit shown in Fig. 5-35.

**** INTERACTIVE NEC PROGRAM ****

is an interactive routine that solves simple antenna problems using the Numerical Electromagnetics Code. The program will prompt you for information concerning the problem, run the problem, and then present you with some options concerning the output of the results. Notice that default values appear in square brackets at the end of some of the prompts. These values will be used by the program unless other data is entered. Simply press return if the default value is satisfactory.

1. If a ground plane is specified, it will be located in the x-y plane. Thus it is essential that all structure specifications be located on or above the x-y plane.

ENTER CURRENT (C) or to continue:

Figure 5-37. Sample output from the Interactive NEC program as seen on the terminal screen.

Figure 5-38. Sample output of a section of an ellipsoid as drawn by MOVIE.BYU.

Figure 5-39. Sample output of a finite-difference model used in G3DXL3 as drawn with HIDDEN.

called PLUTO (Preliminary Livermore Universal Test Object) which is being used to study HEMP coupling phenomenology using the Finite-Difference code G3DXL3 and the experimental EM transient range (EMPEROR facility). The object is drawn with the NASA code HIDDEN.

11. ACE Laboratory VCR Movie-Making Subsystem

Principal Investigators: R. D. Merrill and T. C. Coupe

Introduction and Objectives

With the increased sophistication of electronic engineering studies, it has become important to provide a "hands-on" means of quickly producing recordings of the temporal qualities and certain detailed characteristics of physical phenomena. Sometimes these characteristics can best be understood and assimilated by viewing them in animated movie form. In the development and use of electromagnetic modeling codes, for example, this could afford the electronics engineer a means of studying the transient behavior of electromagnetic (EM) fields in geometric space as a slow motion animated movie. In education, this could provide the teacher with a means of portraying certain physical laws or electronic circuits in animated cartoon-like movie form for faster, more thorough student understanding.

This project's primary objective was to develop a peripheral subsystem for the Applied Computational Engineering (ACE) Laboratory computer with which the engineer could directly produce color graphics animations depicting results from these modeling codes and have them recorded on video tape one frame at a time for later viewing in continuous motion while being played back at normal VCR frame rates. Another important objective was to

make it possible to locate this subsystem in the engineer's work area, if necessary, even though it may be remote from the ACE Laboratory. A third objective was that the facility support a short-term project on computer graphics in engineering education.

Progress

This need was met in the ACE Laboratory with a movie subsystem which automatically records sequences of color graphic images produced by computer program on video tape using a stop action, animated procedure. This system has been configured with one frame buffer, an RGB-to-NTSC encoder, an editing VCR, and a VCR editing controller. The frame buffer is connected to the VAX-11 computer by a fast serial line and the VCR editing controller is connected to the computer by a slow serial line so that the recording control program running on the VAX can produce a continuous sequence of images on video tape using the following procedure: initialize the VCR and workstation, retrieve the next image from storage and send it to the frame buffer, command the editing controller to record a specific number of video frames of that image on tape concatenated after the last recorded frame on the previous step, then repeat the process for the next

image so that on completion the tape contains a continuous recording of the image sequence.

This subsystem was built as phase 1 of a three-phase plan (shown in Fig. 5-40). Phase 1 includes a color graphics workstation integrated with a video recorder and its editing controller, phase 2 features a continuous-tone color frame buffer also integrated with the video recorder, and phase 3 combines a film camera station with a Polaroid "Quick Shot" print camera and a 16 mm cinema camera interfaced through a computer-controlled RGB switch with both frame buffers.

Hardware Integration and Software Support

The movie subsystem shown in Fig. 5-41 is composed of a Sony VO-5850 3/4" video editing recorder, Lyon/Lamb VAS-IV VCR controller, a Tek4113B workstation with a 640 x 480 pixel, 16-color frame buffer, a Lenco color video sync generator, a Lenco RGB-to-NTSC encoder, and a Sharps 13" NTSC color monitor. This hardware, assembled in a 19" cabinet and interfaced with the workstation in May 1984, cost \$34 000. These parts are connected so that the Tek4113, NTSC encoder, and recorder are all driven externally by the sync generator so that the encoder produces the standard

Figure 5-40. Ace Lab-Animation Color-Graphics Movie Facility.

525 line NTSC format. The workstation is driven by the host computer by the use of a 9600 baud RS232 serial link under program control. With the help of the Tek4113 processor, this program produces a plot list which generates the color graphics display in the terminal frame buffer. The output of the frame buffer includes three video signals in RS170 format; the red, green, and blue (RGB) outputs that drive the terminal's RGB monitor and provide external outputs. These RGB outputs drive the encoder and its NTSC composite video which in turn drives the recorder. The recorder functions (record, pause, rewind, and stop) are invoked by the NCR controller. It accepts commands from the host computer through the 300 baud RS232 serial link. Concurrent with the recording of each frame on tape, the controller in-

serts a unique frame code in video lines 12-15. This code is assigned consecutively to successive frames.

Software support for this subsystem includes two parts: the VCR controller driver and the workstation driver. As the Tek4113 is Tek4014 compatible and the Lyon/Lamb VCR controller has a small command set, it only required 0.2 FTE to develop these drivers and a demonstration program that used the DIGLIB plot software and the ORION modeling-code graphics-output data-file handler.

The VCR controller driver invokes commands that will retrieve the status information from the controller, record on tape a specified number of frames of the current image being displayed by the workstation frame buffer, search for a particular frame with the specified ID code, optionally display the current frame ID code superimposed over the image, or selectively edit a frame with a specific ID code using the current frame buffer image.

DIGLIB has been the only plotting software package used so far. The Tek4113 driver was incorporated into the DIGLIB library. Other plot packages such as CGS or DI-3000 could be used with the addition of Tek4113 drivers to their libraries.

Figure 5-41. Operator at the VCR Movie Facility.

Program Development for Animated Graphics

The general programming procedure to produce animation is as follows:

1. Initialize VCR controller and workstation.
2. Record title frame on the video tape.
3. Load an image of the next animation into the workstation frame buffer.
4. Record the buffer image onto one or more video tape frames.
5. Repeat steps 3 and 4 until the movie is complete.

Practical Applications

This subsystem has been used so far in two application areas: in support of electromagnetic modeling software development and applications and in support of the AWU 1984 summer program jointly sponsored by LLNL Engineering and the University of California at Davis to do computer modeling and computer graphics in engineering education.

Engineering Modeling. Thus far, this facility has been used to study the behavior simulated by modeling EM wave scattering of a plane wave by complex geometric structures and refraction/reflection characteristics of EM waves striking an interface of dissimilar dielectrics. Numerous video tapes have been recorded covering these topics using results from the GEM2D time-domain finite-element electromagnetic code

ORION, the modeling-code graphics-output data-file handler, and the VCR control program. The VCR subsystem was moved to the NESD CAE Users Area in Bldg. 131 for this application following the completion of the education graphics project. It will be moved to the ACE Laboratory users area when it is operational (some time in the first or second quarter of calendar '85). Thus far, the facility has been used on modeling-code results from runs on the Cray computer that have been transferred to VAX computer files. With ORION's help the VCR control program extracts successive images from these files, interpolates as necessary to obtain regularly spaced samples that smoothly portray the temporal behavior of the EM phenomenon being simulated, sends them as output to the frame buffer, then commands the VCR controller to record each image on one or more video tape frames directly after the last frame recorded so that it plays back smoothly. Typically, it takes 5 to 10 seconds to extract data from the VAX file, send it to the Tek4113, convert it to a visual image in the frame buffer, and finally, record it on one or more video frames.

So far, tapes have been recorded that depict the EM behavior in terms of a plane wave striking a slotted cylinder (see Fig. 5-42 which shows a sequence of six images extracted from those results), a plane wave traveling in a wave guide striking a slot, etc.

Plane electrical field wave response of a slotted cylinder

Figure 5-42. Electromagnetic modeling-code output-sequence example. Plane electrical field wave response of a slitted cylinder.

Engineering Education. June through September, 1984, five university professors with student-programmer assistance produced five video taped movies with voice descriptions. The video movie-making subsystem located remotely in the professors' work area (T1450 west during this time) was linked by leased telephone lines to the NESD VAX in Bldg. 131.

Each educational tape contains a set of concatenated scene clips. The scenes in turn were created from a library of basic elements: circles, squares, crosses, arcs, pro-

jected surfaces, etc. These basic elements were produced using the DIGLIB plot software. It took between 5 and 10 seconds per image to record these animations. This time interval is proportional to the number of shaded polygons used to paint the image. (See Fig. 5-43 for a block diagram of this organization, and Fig. 5-44 for an example of how these elements were combined to produce one image illustrating light-interface interaction.) Each tape includes a voice narration of the animated sequence.

Figure 5-43. Education Graphics Programming Organization.

The tapes produced were:

- Potentials, gradients, and fields. Explains the basic concepts of potential fields using 3D graphics. (Prof. Rodney Cole and John Jabusch.)
- Superposition and the electric potential. Explains the transition from a discrete distribution to a continuous distribution of a charge and the resultant potential field. (Prof. Rodney Cole and John Jabusch.)
- Light interaction at an interface. The reflection and refraction of incident beams are illustrated with an emphasis on phase relationships. (Prof. David Chimino and Andy Cordes.)
- Latching operation of a simple latch. In this movie the static states of a simple latch are explained, followed by the dynamic illustration of a latching operation. The effects of propagation delays are considered. (Prof. Michael Soderstrand, Curt Edmondson, and Dan White.)
- Propagation of plane electromagnetic waves of linear and circular polarization in lossless nondispersive media. (Prof. Andrew Dienes and Curt Edmondson.)

Reports containing scripts of these tapes along with sample snap shots extracted from the associated video are listed below:

1. Cole, R., "Potentials, Gradients, and Fields."
2. Cole, R., "Superposition and the Electric Potential."
3. Chimino, D., "Light Boundary Phase Dielectrics - Parts 2 and 2."
4. Soderstrand, M., "Latching Operation of a Simple Latch."
5. Dienes, A., "Propagation of Plane Electromagnetic Waves of Linear and Circular Polarization in Lossless, Nondispersive Media."

Publications and Presentations

1. Merrill, R. D., "Applied Computational Engineering Laboratory Video Movie-Making Capability," presented at the 6th Biennial CUBE Symposium (October, 1984).
2. Miller, E. K., "The LLNL Summer Program," presented at the EDCOMPCON Conference, San Jose, CA (November, 1984).

Figure 5-44. Educational Graphics Sample Image: Light ray at dielectric boundary.

VI. Systems Engineering

Thrust Area Leader: W. F. Rousseau

Overview

The Systems Engineering Thrust Area develops and promotes the application of systems engineering tools and techniques to a wide range of Laboratory activities. The scope covers reliability, safety, risk, and decision analysis; systems modeling and simulation; human factors engineering; integration of engineering tools to meet the needs of engineers in systems design or analysis; research in systems engineering methods and computer algorithms; and development of software tools to support applications. Examples of existing activities include research in probability computation, as applied to seismic safety of nuclear power plants; systems engineering, applied to space weapons platforms; and human factors engineering, applied to nuclear activities.

Systems Engineering is a new Thrust Area for FY 84. Some activities, however, were associated with the Engineering Modeling Thrust Area, and others developed through direct support to Laboratory Programs. For example, research in probability computation was part of the Engineering Modeling Thrust Area in FY 84 and will be part of Systems Engineering in FY 85. Also, human factors engineering research was

supported through the Nuclear Systems Safety Program (NSSP) with NRC and DOE funding.

Two efforts were funded in FY 84. The first was to establish better contacts with EE Divisions in order to assess their needs and capabilities and to make the Divisions aware of capabilities found elsewhere. Also part of this first effort was the definition of the initial scope of the Systems Engineering Thrust Area and the development of Thrust Area plans. The second effort funded was support of the initial application of systems engineering techniques to space weapons platforms.

1. Weapons Platform Systems Engineering

Principal Investigator: G. C. Corynen

Introduction and Objectives

During FY 84, we laid the groundwork for the platform simulation work required to evaluate various Acquisition, Tracking, and Pointing (ATP) approaches for Directed Energy Weapons (DEW). To coordinate our work with that of other laboratories and agencies contributing to and benefitting from this work, I made several trips to communicate with others and to help organize working groups and periodic meetings. LLNL appears to be one of the most aggressive organizations in implementing the systems approach to weapon platform design, and our suggestions are influencing future directions in the ATP community, particularly with respect to DEW. A plan for ATP research and development was developed at the Laboratory for the DOD. This plan includes a detailed description and schedule of the systems engineering work required and is currently used by the Army and other DOD organizations to plan their work and their budgets.

At a more technical level, we developed an initial systems model of the ATP and Surveillance, Acquisition, Tracking, and Ill Assessment (SATKA) problem for DEW. The purpose of our systems simulation effort is to develop a computerized model of ATP and SATKA systems associated with DEW. A block diagram of this model (shown in

Fig. 6-1) indicates the variety of disciplines and technologies that must be brought together to ensure that weapons platforms will work satisfactorily as systems. Even in the highly aggregated form of Fig. 6-1, our model fulfills an essential role in clearly identifying technical issues and how these issues are interrelated and in formulating a management strategy for our interdisciplinary weapons platform problems.

Progress

Systems Engineering Thrust Area Plans

A number of needs for systems engineering have been found within the Laboratory. Based on this assessment, I have identified several key areas for initial emphasis. Roughly in order of priority, the areas are

- Systems engineering of space weapons platforms
- Human factors engineering
- Failure modes-effects, reliability, and safety analysis
- Systems analysis modeling tools

Figure 6-1. ATP and SATKA systems model.

We will add decision analysis to this list if we can establish sufficient capability and if the applications expand as we expect.

A working group has been organized for the Thrust Area. These plans are partially the result of contacts with working group members. This group is expected to play an important role in guiding the Thrust Area and in transferring the technology to EE Divisions.

Systems Engineering of Space Weapons Platforms

Plans for FY 85 in this area are directed toward acquiring and tracking targets and pointing the weapons system in the right direction (ATP). We must determine the most appropriate models for the ATP subsystems and the overall ATP system for engineering design purposes. Then, we must develop models for realistic performance assessment in the actual environment. We must determine the appropriate mix of analytical and simulation techniques, the critical uncertainties, and the approximations that can safely be made. We expect this work on space weapons platforms to be supported by the Military Applications Program and possibly by others.

Human Factors Engineering

Two programmatically supported projects outside of the NSS Program in human-factors engineering have been initiated, and additional

applications are expected. These initial projects involve task analysis and design of security consoles, and the improvement of computer-generated displays for operators of a laser isotope separation process. Figure 6-2 shows an example of proposed design improvements for a computer-generated display developed in one of the projects. A human factors short course-seminar funded by DOE will be offered at the Laboratory through the NSS Program. The working group has recommended that LLNL human factors engineering guidelines be produced for video displays to be used by process or experiment operators. Possible avenues for funding the production of these guidelines in FY 85 will be explored; otherwise, this activity will be proposed for FY 86.

Failure Mode-Effects, Reliability, and Safety Analysis

Easier-to-use tools and demonstrations of effective use of the probability-computation algorithms to LLNL-scale problems (as opposed to the very complicated nuclear reactor problems done for NRC) are needed to assist engineering applications at the Laboratory. The working group has recommended that we explore the use of both failure mode-effects, reliability and safety analysis, and human factors engineering to improve the handling of tritium at the Laboratory. Support from NRC (through the NSS Program) exists for research, development,

Figure 6-2. The top display is the original design. The bottom display incorporates human factors improvements that make it easier for the operator to find pertinent information and identify key system components. Note the left to right numerical sequence of the "loads," the use of background (color) pads to show elements within the "Gas Cooling Skid," and the "South Glove Box," and the better association of measurement values with the system by putting the reading within a symbol representing the component. NOTE: Actual CRT displays are in color. Effective use of color is also an important design consideration that cannot be shown effectively in this monochrome figure.

and applications tests of the probability computation methods.

Systems Analysis Modeling Tools

Systems analysis (including specifically the mission analysis that is part of the systems engineering of weapons systems) and decision analysis depend heavily on building computer models and processing the results in ways that facilitate interpreting the model results and communicating the insights to others. Various software has been built to facilitate this in the context of programmatic applications. We see a need to develop methods that are generally useful and will facilitate transfer of models between related efforts. Work may be proposed in this area for FY 86.