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ELECTRONICS ENGINEERING DEPARTMENT QUARTERLY REPORT NO. 3 — 1977

Inside: L-300 dual raster oscilloscope.
Safing, arming, and in-line fuzing system for modular weapon.
Dedicated minicomputer for online text editing.
24-MJ energy storage system for Shiva laser.

MASTER

April 3, 1978

Work performed under the auspices of the U.S. Department of
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LAWRENCE
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FOREWORD

The EE Department Quarterly Report is published with two purposes in mind: (1) to inform readers of various activities within the Department, and (2) to promote the exchange of ideas.

The articles, by design, are brief summaries of EE work. For further details on a subject covered, please contact the individual listed at the beginning of the article in question; that person is primarily responsible for the content of the article. Inasmuch as most projects are the result of the cooperative efforts of many individuals, the article contact may either provide the requested information directly or refer you to the appropriate person to answer your question.

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NEW DUAL RASTER OSCILLOSCOPE IMPROVES HYDRODIAGNOSTIC CAPABILITIES

Electronics Engineering has developed the L-300 dual raster oscilloscope, which substantially improves our hydrodiagnostic capabilities. It provides precise time-interval measurements for large numbers of pulses of unknown amplitude, shape, and duration resulting from pin switch closures that measure material motion in hydrodynamic experiments. On a recent experiment, a full complement of 26 L-300's was used for the first time to record more than 400 signals. Results showed that no signals were lost, narrow trace widths and excellent linearity were attained, and there was no defocusing from the dry run to the shot. These kinds of results were not possible with earlier instruments.

Why Raster Oscilloscopes?

A conventional oscilloscope displays visually the changes in an electric current. It projects a curve that is characteristic of those changes on a fluorescent screen. Current rise times and pulse widths can thus be measured very accurately. However, because a conventional oscilloscope display consists of only one line, it cannot usually provide enough resolution for the time required in some Laboratory experiments.

A raster oscilloscope overcomes this problem by displaying from 1 to 80 chronologically consecutive lines on one screen. Its time resolution capabilities are thereby multiplied by that number. If each line represents 2.5 μ s and if there are 40 lines in the raster, excellent time resolution over a 100- μ s period can be achieved by one raster oscilloscope. By linking several oscilloscopes together, we can measure the interval between pulses over an even wider time range. Thus, selected events in rapid experimental processes can be timed if we can devise a way to trigger an electrical pulse when the event occurs.

Introduction

Raster oscilloscopes have been used at LLL for many years to measure detonation velocities in high explosives. In measuring time intervals, the points of interest are represented by pulses that could trigger digital time-measuring equipment. However, because of the large number of signals used, the

time resolution and time intervals required, and the fact that the amplitude and shape of the pulses may not be accurately known, an analog system such as the raster oscilloscope has proven more cost effective.

The L-10 dual raster oscilloscope, designed more than 15 years ago, has been providing LLL and other Department of Energy laboratories with this capability. But because of its age, maintenance had become a problem. Therefore in 1974, we decided to design a new dual raster oscilloscope — the L-300.

Design Goals

The L-300 dual raster oscilloscope (Fig. 1) was designed for improved performance and ease of maintenance. All adjustments and test points were made accessible from the outside. The same basic operation and sweep timing format as used in the L-10 was maintained. We redesigned all circuitry using the latest integrated circuits and solid-state components. Digital techniques were used where applicable.

Each L-300 has two cathode ray tubes (CRT's), which may be operated independently or as master-slave. When operated independently, the horizontal sweep generators of both CRT's are triggered at the same time. When operated as master-slave, the slave CRT horizontal sweep generator is triggered 1 timing mark (0.5 μ s) after the master horizontal sweep generator. Controls common to both CRT's are raster length and vertical height; separate controls for each CRT are vertical position, horizontal position, intensity, focus, and astigmatism.

We added many additional features, including optional plug-in printed circuit (PC) boards to provide alternative timing formats. By changing these PC boards, the horizontal sweep frequency can be selected to any of three speeds per trace: 0.5, 2.5, and 10 μ s.

We contracted the development of a new CRT to improve the spot size and overall focus. The CRT has three sets of deflection plates: two sets presenting the raster display and time marks, with the timed pulses applied to the third set. This third set of plates makes the CRT versatile since there is isolation between raster scanning and pulse display.

Two sweep frequencies are used. The horizontal sweep is usually 2.5 μ s and the vertical sweep is typically 100 μ s (although it is adjustable from 0 to 199 μ s). The interaction of these two sweeps

For further information on this article, contact James C. Lawson (Ext. 28589).

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Fig. 1. 1-300 dual raster oscilloscope. Each CRT can operate independently as two oscilloscopes with a common horizontal sweep frequency or together as a master-slave with the slave horizontal frequency delayed $0.5 \mu\text{s}$.

produces the raster — a series of horizontal traces or lines displaced vertically. Marker pulses are applied every $0.5 \mu\text{s}$. Usually fiducial pulses are also applied to interrelate different oscilloscopes.

Z-axis inputs and dynamic CRT beam current monitors were added. The z-axis input gives another method for getting timing information onto the beam in addition to the usual x-axis (horizontal) and y-axis (vertical) inputs. The beam is intensified or blanked according to the negative or positive signal applied to the z-axis input, respectively. The beam current monitors show how much actual current is in the beam, and allows us to evaluate the condition of the CRT while in operation.

Oscilloscope camera shutter control circuits were also included. These automatically close the camera shutters at the end of the recording time.

Dead Time

In raster oscilloscopes there is a short "dead time" because of retrace time. If a signal pulse occurred during this time, it would be lost. Two methods of eliminating this loss may be used in the 1-300: master-slave and echo-line. The master-slave method uses the two CRT's on one 1-300 to look at the same set of pulses, but whose horizontal sweep triggers differ by $0.5 \mu\text{s}$. Therefore, if a pulse is lost in the retrace of one CRT, it is on in active portion of the other. The echo-line method uses a single CRT that has a $0.3 \mu\text{s}$ shorted cable in parallel with the signal input. Pulses are reflected down and back on this cable, producing an inverted signal $0.6 \mu\text{s}$ later. Thus, there is an inverted delayed image of each pulse. One of these is bound to be in an active trace region.

Fig. 3 Inside bunker 851 at Site 306. A full complement of 26 L-300's, 52 CRL's, and their cabling is ready for recording a high speed experiment.

Fig. 4 Actual trace from an L-300 operating in the echo-lag method. The trace covers a total time of 54 μ s, and a timing resolution of better than 10 ns can be measured.

- 10 μ s, 100 ns, 10 ns, and 1 ns. The time delay pulse is set to 10 μ s, and the L-300 is set to 100 ns.
- At the end of the fourth trace, a negative pulse is sent to the scope to be seen. This is done to indicate the end of the scope's range. The signal is not visible. However, the positive-going echo signal appears 0.6 μ s after between the first and second markers of the time base. By reading this signal and then subtracting it from the original signal, the timing of the incident signal can be compared.
- Other valid signals appear at 0.6 μ s, 0.8 μ s, 1.0 μ s, 1.4 μ s, and 1.6 μ s.
- Different pulse shapes can be identified: line 6 = positive; line 10 = positive short; line 8 = negative short; and line 12 = negative short.

In-Line Fuzing System

How to improve the safety of a SAF system while maintaining reliability? One way is to eliminate the sensitive primary explosives by using a slapper detonator.* The slapper detonator (Fig. 2) is a high-energy, nonexplosive detonator that can ignite directly the less sensitive booster or main charge explosives. This eliminates the need for the sensitive primary explosive and its associated physical barrier. Thus, the detonator is "in-line" with the insensitive charges.

Fig. 2. Slapper detonator. It operates by exploding a thin metal foil that drives an insulating film across a gap to set off the high-density explosive directly by high-velocity impact.

* J. R. Stroud, *A New Kind of Detonator — The Slapper*, Lawrence Livermore Laboratory, Rept. UCRL-77639 (1976).

Objectives of Weapon Program

Under contract to the U.S. Air Force, the Laboratory has developed a slapper detonator SAF system for a modular weapon program. We were to provide an alternate fuzing system to the conventional fuzing system that would function through the extremely high structural shock environment created by a modular weapon. (The slapper detonator worked so well, that the Air Force has selected the slapper detonator SAF system as a baseline, or standard, system.)

Other objectives of the program were to have a modular SAF system and to have the weapon's aft portion detonate a prescribed delay time after the forward portion detonates. These objectives presented new challenges to the design of SAF systems.

The modular concept weapon (Fig. 3) is a two-stage high explosive weapon that is designed to defeat hard targets such as reinforced-concrete structures. It contains two charges — a forward charge and a follow-through charge. When the weapon contacts the target, the forward charge detonates immediately causing a cratering of the target. The follow-through charge then continues through the blast and impacts the target in the crater created by the forward charge. After a specific time delay, the follow-through charge detonates, virtually destroying the target.

The Electronics Engineering and Mechanical Engineering departments jointly developed a new concept in-line SAF system for the modular weapon. To meet the program's objectives, we used at least three new LLL developments: a slapper detonator, a unique signal generator and receiver, and a shock mitigator. Other technologies used are a CMOS microprocessor and a novel fluidic generator.

Fig. 3. Two-stage modular weapon. The forward charge explodes when the weapon contacts a target; the follow-through charge continues through the blast, and after a specific delay time, it detonates and destroys the target.

We wanted a modular SAF system so its components could be used in other munition applications as well as minimizing the complexity of the SAF system. For this application, two initiation systems are used. One instantaneous initiation for the forward-charge and one delay initiation for the follow-through charge.

How the LLL In-Line SAF System Works

To minimize the complexity, a single control unit for both fuze modules is used instead of individual control units for each (Fig. 4). When the modular weapon is released from the aircraft, a lanyard attached to it and the fluidic generator releases a latch which opens an inlet duct that allows the air stream to blow into the fluidic generator. The fluidic generator (a sensor as well as a power source) generates power for the microprocessor, which then

checks the output of the generator to see if the weapon's environment conforms to the expected launch parameters.

If the generator output does not conform to the expected parameters programmed in the microprocessor, it will not allow the arming of the fuze modules. If the proper criteria are met, the microprocessor generates a unique signal that provides power from the generator to both fuze modules. The unique signal receivers use the power from the generator to charge the coaxial capacitors. The fuze modules are now armed. When the weapon strikes the target, the impact switch closes and simultaneously sends a signal to both fuze modules. The signal to the forward-charge fuze module allows the fire unit to transfer the arming energy within the coaxial capacitor to the slapper detonator, which then ignites the forward-charge booster. The impact signal to the follow-through fuze module starts the delay timer. After the prescribed delay time, the fire unit transfers the

Fig. 4. LLL in-line SAF system. The single control unit controls both fuze modules. Lanyard is pulled out when weapon is released from aircraft and allows air to enter the fluidic generator. The generator supplies power to the microprocessor for arming the slapper detonator. Upon striking target, impact switch sends signal to both fuze modules. Forward-charge ignites immediately, while ignition of follow-through charge is delayed by the delay timer.

arming energy into the slapper detonator of the fuze module, and its booster ignites.

Because the follow-through charge fuze module is armed with stored energy before impact, it is possible that the impact shock could damage the delay timer and energy storage mechanisms. This means that the aft portion of the weapon would not function. Therefore, we have added a rolling-tube, mechanical shock mitigator to this module (Fig. 5). The shock mitigator reduces the shock environment of the fuze module by a factor of two to three from that of the munition case environment. For additional shock protection, we also encapsulate the electronic delay timer and slapper detonator components in a microsphere-loaded epoxy potting material (Fig. 6).

Fig. 5. Rolling-tube, mechanical shock mitigator reduces the impact shock to the follow-through charge fuze module by a factor of two to three.

Advantages of In-Line SAF System

The reliability of the in-line SAF system is increased because all of its components, with the exception of the slapper detonator, can be tested and reused. An out-of-line SAF system cannot be tested as easily. Once fired the initiator, primary and lead explosives of an out-of-line SAF system have to be replaced. In the in-line system, only the initiator needs to be replaced; its fuze modules and control section are reusable.

Because the in-line SAF system does not contain any explosives, the assembling and subsequent handling of it do not require special precautions. This results in lower production and handling costs and increased personnel safety.

Fig. 6. Bottom end of follow-through charge fuze module. Electronic delay timer (not shown) and slapper detonator components are encapsulated in epoxy material for extra shock protection.

DEDICATED MINICOMPUTER IMPROVES ONLINE TEXT EDITING

The Data Director project has significantly increased programmer efficiency by placing text editing on a local minicomputer with a link from it to Octopus, the Livermore timesharing computer system. In this way, a fast, stable, and very reliable system is used for online text editing (80 to 100%) of our work, and a very good "number cruncher," Octopus, is used for number crunching.

Data Director is a multiuser timesharing computer system, which allows computer file manipulation (i.e., editing, printing, paper tape punching, etc.) and file transport between it and Octopus. The major components of the Data Director system are an Interdata 7/16 HSALU minicomputer with a Diablo 10-megabyte disk, eight Datamedia 9600-baud cathode ray tube (CRT) terminals, and a high-speed paper tape punch/reader.

Background

We created the Data Director system to provide a stable and efficient programming environment for numerical control (NC) machinist-programmers in LLL's Numerical Control shop, building 321. These machinist-programmers write computer source programs that describe machine parts to be cut automatically by NC machine tools. The source programs are submitted to a CDC 7600 computer in Octopus to be run under the automatic program tools (APT) program. The outputs from APT are a listing and a tape image. The tape image is punched on Mylar tape for use on a machine tool. The listing may contain the source program or any output data the machinist-programmer requests.

Several years ago, an attempt was made to generate source files online in Octopus with its TRIX AC text editor, and to save the files in the Octopus storage system, called Elephant. But because of the complexities in Octopus and the machinist-programmers unfamiliarity with Octopus recovery procedures, the attempt failed. As a result, NC personnel decided to generate all APT source files on cards and then read them into a CDC 7600 through a remote job entry terminal (RJET). The CDC 7600 generated a paper tape image on magnetic tape that had to be carried manually to a paper tape punch

for punching. However, the turnaround time for this method was, at best, about 2 to 3 hours. The Data Director project reduces this turnaround to a few minutes by eliminating cards, speeding the editing, and having the APT tape image output punched locally in building 321.

Hardware Description

The Data Director computer system, housed in two racks, consists of an Interdata 7/16 HSALU minicomputer, 128K bytes of core memory, a Diablo 10-megabyte disk, and a data acquisition interface (located internally in the computer chassis) for communicating with the Elephant storage system.

Users may choose among several peripherals to communicate with Data Director and Octopus (Fig. 1):

- Eight Datamedia 9600-baud CRT remote terminals used to access the Data Director.
- ASR 33 Teletype used to access the Data Director.
- Omron 2400-baud CRT terminal used as system console and user terminal.
- RJET card reader and Versatec printer used for input and output, respectively.
- High-speed tape punch/reader to be used to punch and verify Mylar tapes for the NC machines.

Workflow

Figure 2 shows the steps that an NC machinist-programmer performs in order to produce a machined part. The steps include writing the APT source program that describes the part to be machined, processing the APT program through Octopus, and preparing a Mylar tape to be run on the machine tool. Figure 2 also shows the corresponding hardware that performs each step.

Advantages

Our approach in the Data Director is to remove text editing from the Octopus system and place it in a local minicomputer. Some advantages of this approach are as follows.

Because of the smaller number of system components, the Data Director is highly reliable. It often runs 6 months or more between failures. This

Fig. 1. Interconnection of Interdata 7/16 minicomputer and its peripherals.

reliability is important since 80 to 100% of our programming is editing. In fact, because of this reliability, users almost always create their source programs directly online without writing it on paper first, as shown in Fig. 3.

Data Director provides a safe and stable file space for storage on the Diablo 10-megabyte disk. A user may wish to edit the same material over several days, so files are destroyed only by an explicit command to do so.

A user is given his own file space, which he can share with other users if desired. The file space is a guaranteed size. Also, because the Data Director can communicate with the Elephant storage system, the user can use its tremendous storage capabilities — greater than 1 trillion bits.

The Datamedia 9600-baud CRT terminals are especially good for editing. They are more than 87 times faster than the ASR-33 Teletype and almost 30 times faster than the Silent 700 — the two major types of terminals that are available on Octopus.

The Data Director text editor, EDIT, is similar to TRIX AC, the Octopus text editor, and is quite easy to learn. Machinist-programmers use it daily.

Files to be processed by Octopus are sent by Data Director to the Octopus system, and the results are returned to Data Director. Thus, Octopus is used for "number crunching" and Data Director is left free for fast interactive editing.

A user's Data Director files are independent of any CDC 7600. If any one CDC 7600 is down or goes down during computing, the user may choose

Operations

Write APT source program describing part to be machined, and store program on disk.

Hardware

Fig. 2. How the work flows from writing APT source programs to machining parts.

Fig. 3. Machinist-programmer writing an APT source program directly online with a Data/media CRT terminal connected to the Interdata 7/16 minicomputer.

another CDC 7600 and send his files there to be processed.

The Data Director tries to optimize a user's productivity. Time that a user spends waiting for a machine to respond is wasted time. The Data Direc-

tor schedules its jobs by degree of interactivity (i.e., persons editing run first and at equal priority). In this way, unlike the Octopus user-bidding system, no one person can out-bid another and restrict the productivity of all others. Since the Data Director assigns priorities, no one user can seriously degrade the productivity of any other user. Thus, there is no need to restrict a user's computer time or let users assign priorities. In essence, all users are given an infinite amount of computer time with priorities assigned by the system.

Since Data Director runs in a small controlled environment, we can hold Data Director's average response time while editing to about 100 ms.

Future Considerations

Currently, Data Director users still must know a little about Octopus in order to run APT on their files (e.g., login, assign priorities, and recover from failures). Therefore, we look forward to the Octoport system proposed by LLL's Computation Department. Octoport will allow persons with a minicomputer system, such as Data Director, to attach to Octopus and then have the minicomputer handle all interactivity with Octopus. Thus, the machinist-programmers will not need to know anything about the Octopus system.

25-MJ ENERGY STORAGE SYSTEM DELIVERS 3.5 MA IN 1 ms

A 25-MJ, 20-kV capacitive energy storage and delivery system has been built and tested for Shiva, LLL laser fusion program's giant, multiarmed fusion research laser. This system supplies more than 3.5 MA in less than 1 ms to 2400 xenon flashlamps for optical pumping of laser amplifiers. The peak power requirements of this energy need exceed the capacity of the public utility power grid. Thus, to achieve this peak power, we developed a large capacitor bank as the intermediate storage and power conditioner. Because personnel safety was a prime consideration, we implemented a grounding and fault scheme that minimizes the possibilities of faults extending outside the prescribed areas. Also, the cost and construction period were well within the original plan.

The Shiva laser is a 20-arm neodymium-doped glass laser fusion facility currently in the final phases of activation at the Lawrence Livermore Laboratory. Figure 1 shows a model of this facility. The laser is designed to explore advanced concepts in inertial confinement fusion, and we anticipate that thermonuclear energy release equal to 1% that of target incident light will be achieved with submillimeter-size deuterium-tritium targets.

The inertial confinement fusion process uses laser or particle beams to compress a small thermonuclear fuel pellet (target) to about 10,000 times

liquid density for an extremely short period of time (10^{26} ions/cm³ for 10^{-12} s). At such densities, the fuel burns so rapidly that efficient burn is achieved before the pellet blows apart and cools.

On November 18, 1977, all 20 beams of Shiva were fired, delivering 10.2 kJ of energy in a 0.9-ns pulse. This experiment bettered Shiva's design-rated performance. The energy per beam averaged 510 J.

On April 7, 1978, 10 beams of Shiva were fired into the target chamber in the 100-ps pulse mode and achieved 13 TW of energy.

A 25-MJ energy storage system with a peak output power capability of 45,000 MW is required to supply the optical pump energy for the laser.

Energy Requirements

The Shiva laser consists of 20 identical, parallel arms with each arm containing a number of Nd:glass disk amplifiers, rod amplifiers and Faraday rotators. Faraday rotators are nonreciprocal optical elements that keep reflective light from the target from re-entering the laser chain. Figure 2 shows the staging of these elements and the energy required for each of them.

Over 85% of the total energy is used for optically pumping the disk amplifiers where the quantum states of the Nd:atoms are excited with intense broadband light output from large-bore xenon flashlamps. The flashlamp light is absorbed in the Nd:glass and stored for a millisecond. The main

For further information on this article, contact Kenneth Whitham (Ext. 25940).

Fig. 1. Model showing Shiva laser and target chamber support structures as they appear in the high bay of the High Energy Laser Facility.

Fig. 2. Schematic representation of single Shiva amplifier laser chain showing the staging of the elements and the bank energy required for each of them.

laser pulse is simultaneously sent through the chain of amplifiers extracting the stored light. This results in a greatly intensified laser beam which is finally directed onto the target.

The remainder of the energy is used to establish magnetic fields in the Faraday rotator glass. These rotator coils are simple inductive loads with time constants in the millisecond regime.

Electrical energy for optical pumping is delivered to the flashlamps in about $500 \mu\text{s}$, and the peak power requirements far exceed the capacity of the public utility power grid. Thus, a large capacitor bank is used as the intermediate storage element necessary to time-compress this energy by five orders of magnitude — that is, the stored 25 MJ is taken from the grid over a period of 60 s and delivered to the loads in less than 1 ms.

Flashlamp Loads

The xenon flashlamps used to optically pump the disk amplifiers are 1.1 m long, 15 mm in diameter, and are filled with xenon gas at a pressure of 300 Torr. The wall material is cerium-doped quartz. The cerium doping cuts off sharply in the ultraviolet region but allows output over more of the main pump bands for neodymium. This reduction of output in the UV region is highly important because much potential damage can occur within the optical cavities as a result of UV interaction with small dust particles.

The lamps are nonlinear resistive loads with two distinctly different impedance states — corresponding roughly to the time during which the lamps are in the ionization, or triggering mode, and

to the time at which the full volume of the lamp is conducting current. Figure 3 shows the voltage and current wave forms for a lamp pair. As shown, a high voltage pulse (25 to 35 kV) is required to initiate the ionization process.

Fig. 3. Typical voltage (a) and current (b) waveforms for flashlamps. A high voltage pulse of 25 to 35 kV is required to initiate the ionization process.

Flashlamp Energy-Storage Capacitor Module

Two 1.1-m xenon lamps are driven in series, and each series pair is driven by a capacitor module that is tailored to provide the energy and pulse shape. The capacitor module (Fig. 4) is comprised of a number of energy-storage capacitors, a pulse-forming inductor, a high-voltage insulating fuse, and appropriate charging and discharging resistors. A module typically contains six capacitors of $14\ \mu\text{F}$ each. It is assembled as a unit on a metal tray and can be installed or removed from the mounting racks with a modified fork lift. A spark gap is placed across each pulse-forming inductor to protect against fault-generated, high-voltage transients. A knife switch is included as an integral part of the capacitor bus bars in order to allow the module to be isolated and shorted for personnel safety. The modules are mounted in 18 racks 7 shelves high, and 34 ft long, and are located in the basement underneath the laser. Figure 5 shows a segment of the capacitor bank as installed in the Shiva bank.

Figure 6 shows the transient equivalent circuit referred to a single circuit. C1 is the parallel combination of energy-storage capacitors, and C2 and C3 are the bushing-to-case capacitances associated with C1. The capacitor cases are tied to the coaxial shields through damping resistor R2. This allows the displacement currents from C2 and C3 to be contained coaxially and damped by R2.

Flashlamp circuits were designed to provide the initial high voltage spike needed to fire the xenon

lamp arc and then provide energy to sustain the arc for a millisecond. Damping resistors are present to control the amount of voltage spike.

Switching, Distribution, and Power Supplies

The energy-storage capacitor modules are charged and switched in parallel segments using the circuit configuration shown in Fig. 7. Here, 32 modules, or circuits, are charged from a common power supply and switched with a dual, size-D ignitron switch assembly. The only impedance common to the circuit branches is the small inductance and resistance of the switch structure.

Thus, the current in each branch is a function of the voltage and impedance of only that branch. The number of parallel branches is limited by the Coulomb rating of the ignitrons, and our experience shows that this limit is about 60 Coulombs for the size-D ignitron tubes. This is equivalent to switching $3000\ \mu\text{F}$ at 20 kV or 32 circuits of $87\ \mu\text{F}$ each (about 600 kJ total for the 32 circuits). Generally more than one 32-circuit group is charged from a single supply, and isolating diodes and fuses are included in the supply as shown in Fig. 7.

The three-phase voltage doubler circuit (Fig. 8) provides both the aspect of constant current charging and the current limiting. As shown, C2 is the bank capacitance (generally on the order of a few thousand microfarads), and C1 is the series-doubling capacitance (about $1\ \mu\text{F}$). The peak output current is limited by the reactance of C1.

Fig. 4. Capacitor modules drive each series-pair flashlamp loads. Each module contains six capacitors of $14\ \mu\text{F}$ each and a pulse-forming inductor, a high-voltage isolating fuse, and appropriate charging and discharging resistors.

Fig. 5. More than 1200 capacitor modules were produced for the Shiva laser. A segment of the 25-MJ energy system is shown here.

Thirty-two of these voltage doubler power supplies (Fig. 9) are installed to charge the 25-MJ bank to a nominal voltage of 20 kV in about 60 s. The supplies are voltage regulated to 0.1% with silicon-controlled rectifiers (SCR's) in the primary of the transformers in order to insure the repeatability of output energy from the laser on a shot-to-shot basis.

Grounding, Safety, and Fault Considerations

Safety is a foremost consideration in the pulse power system design. Although hazards (such as lethal voltage and current) of similar high voltage capacitor banks developed for magnetic fusion energy and accelerator communities are well known, these banks present new and unique problems.

The banks are required to deliver energy to a large number of loads distributed throughout the laser bay. Thus, potentially hazardous voltage and energy levels are extended to almost every point in the laser room. We gave a good deal of thought to the problems of routing and terminating the high voltage coaxial cables from the bank to the flashlamp and Faraday loads.

Coaxial geometry is maintained throughout the pulse power circuitry in order to reduce electromagnetic radiation and displacement currents. In addition, a grounding scheme has been implemented that minimizes the possibility of high energy faults extending outside the pulse power environment.

Fig. 6. Transient equivalent circuit for a single energy-storage module.

Fig. 7. Energy-storage capacitor modules are charged and switched in parallel. If more than one group of modules is charged from a common supply, isolating fuses and diodes are used as shown.

Fig. 8. Simplified schematic of the 3-phase voltage doubler circuit that provides both the aspect of constant current charging and the current limiting.

Fig. 9. Voltage doubler power supplies as installed in the Shiva system.

Figure 10 shows the basic elements of this grounding scheme. The flashlamps and their associated reflectors in each of the amplifiers are insulated from the amplifier cases and tied to the shield of the coaxial cable from the Lank. The shields are in turn tied to the pulse power ground bus that is insulated from the laser space frame and connected directly to the substation ground. This arrangement establishes the lamp reflector as an electrostatic shield between the pulse power circuitry and the laser space frame, as well as providing a well-defined path for fault and displacement currents that are insulated from the space frame.

This has proven to be an effective approach in that the many low-level diagnostic and control circuits that are located near the pulse power loads operate reliably and are not affected by pulse power noise.

Control System

A large number of tasks must be executed by the control system in the course of supervising the operation of the pulse power system. In addition, a large volume of system status information is collected, stored, and displayed for each target shot. By necessity, the control interface circuitry is located near the pulse power equipment where high levels of electrical noise exist. This combination of functional requirements and severe operational environ-

ment presented a difficult design task. On one hand, the functional requirements and the large amount of components are well suited to digital-based control system technology; on the other hand, a pulse power environment is a hazardous place to locate low-level, 5-V digital circuitry. For Shiva, we have designed and implemented a digital-based control system with a high degree of electrical noise immunity.

The design is shown in block diagram form in Fig. 11. Redundant LSI-11 microprocessors address each control or diagnostic function by way of a parallel data bus. Each system element is assigned a unique digital address, and these addresses are simply extensions of the internal memory space of the LSI-11. Bus interface units (BIU's) provide common mode isolation and transfer digital information between the data bus and each element of the control or diagnostics.

The LSI-11's are isolated from the data bus at a level of 60 kV, and the BIU's are isolated input-to-output at a level of 3.5 kV.

We have a good deal of operating experience with this system, and it is performing well.

Budget and Schedule

The target cost goal of 27¢/J (1977 dollars) has been achieved for the operating system. Table 1 lists the cost breakdown for the pulse power system.

Fig. 10. Grounding scheme for the pulsed power system. Flashlamp reflectors act as electrostatic shields between the high voltage circuitry and the laser frame.

Fig. 11. The digital-based control system used for the Shiva pulsed power elements uses two levels (3 kV and 60 kV) of optical isolation to provide high noise immunity.

Those components and subassemblies with high cost leverage were subjected to intense manufacturing and cost engineering analysis to ensure that the system would be completed within the allotted resources.

In general, almost all components and subassemblies were manufactured by outside industry on fabrication contracts. The final assembly of the system was carried out on a small production line at the site using contract technicians.

Construction was scheduled and carried out over an 18-month period and has in fact proceeded well within the original plan.

Table 1. Cost breakdown of the pulse power system for the 25-MJ installation.

Component	Cost (\$/J)
Energy storage modules	15.9
Flashlamps	3.5
Controls, diagnostics and interlocks	2.55
Power supplies	1.9
High voltage cabling	1.3
Ignitron switches and triggers	0.97
High voltage junction boxes	0.57
Bank dump hardware	0.5
Total	27.19