UCRL-52466

LLL HYDRODIAGNOSTICS UPGRADE PROGRAM

G. T. Carpluk
T. G. Innes
S. R. Trost

June 1, 1978

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ABSTRACT

This report summarizes the FY 1975-78 effort to modernize Lawrence Livermore Laboratory's experimental hydrodiagnostic facilities at Site 300. By 1974 it was apparent that the test equipment, especially the electronic equipment, was becoming obsolete. To upgrade the facilities, we defined our project goals (experiment complexity, fast turnaround time, improved measurement, and computerization) and undertook a $5.3-million program to provide equipment that would help us meet those goals. By replacing vacuum-tube chassis with transistorized solid-state apparatus and using digital equipment where possible, we significantly increased overall reliability, accuracy, and speed of data collection. We made improvements in four major areas: radiography, optics, electronics, and interferometry. Specific advances in radiography include increasing the dose, energy, and electron current of the linac. Our optics were improved by new framing cameras, streaking cameras, rotors, and electronic controls. To upgrade our electronic equipment, we added high-speed oscilloscopes, oscilloscope cameras, digitizers, time-interval meters, a digital delay system, trigger generators, and a computerized data-reduction center. We improved interferometry by installing a velocity-interferometry system and Fabry-Perot instruments. Now that the trend toward obsolescence has been reversed, it is important to continue upgrading Site 300 to keep abreast of technological improvements.

INTRODUCTION

For the past 25 years Lawrence Livermore Laboratory (LLL) has spearheaded the development of nuclear weapon systems for the Department of Defense. The continued success of the nuclear weapon design and test programs is a direct result of the effective hydrodynamic programs developed at Livermore. Hydrodynamic studies provide the weapon designer with experimental verification and analysis of weapon designs through the use of explosively driven, nonfissile materials. Specifically, hydrodynamic studies provide

- Experimental verification of computer codes,
- Equation-of-state data on weapon components,
- Material-behavior data at assembly joints and welds,
- Velocity-vs-time history of weapon components, which in turn yields an evaluation of the quality and uniformity of the implosion,
- Performance evaluation of post-nuclear-test design modifications.

Data is acquired from hydrodynamic tests by what is referred to at LLL as hydrodiagnostics, a set of experimental techniques for studying the time-motion history of a solid undergoing large-scale deformations due to the introduction of a shock front. Hydrodiagnostic techniques include

- Flash radiography,
- High-speed photography,
- Electrical-pin diagnostics,
- Interferometry.

The focus of all hydrodynamic testing at LLL is the Site 300 Explosive Test Area located 18 miles east of Livermore. This remote, 10-mi^2 facility consists of

- Areas for machining and assembling explosives,
- Environmental test facilities,
- Administrative and support facilities,
- Five underground, reinforced-concrete bunkers equipped with high-speed cameras, electrical data-acquisition systems, and electron accelerators for flash radiography.

Ever since Site 300 was established, multiple, simultaneous diagnostics have permeated the entire approach to hydrodiagnostic system design and development. The perfection of this approach has become the single most outstanding feature of the LLL approach and has been neither surpassed nor duplicated anywhere else in the world. The simultaneous diagnostic approach is unique to LLL and has only recently been even attempted at other weapon laboratories.

Following the initial capital investment in Site 300 diagnostic equipment in the early 1960's, appropriations for new diagnostic equipment rapidly and steadily declined. However, the development of diagnostic techniques continued despite continually reducing support. Thus, by 1974, Site 300 was in the unenviable position of trying to provide increasingly complex and intensive data gathering on much more sophisticated weapon concepts while using optical, electronic, and flash x-ray diagnostic equipment that was 10-15 years old and far from the state of the art. Moreover, a large portion of the equipment had reached the end of its serviceable life, and we were encountering several maintenance and reliability problems.

To cure equipment obsolescence, to upgrade system reliability, and to take advantage of current technology, B Division requested and received a four-year, $5.3-million budget appropriation to upgrade Site 300 bunker-system controls, hydrodiagnostic equipment, and data-reduction methods. This report summarizes the improvements we have made in radiography, optics, electronics, and interferometry, and indicates the projects that remain to be completed.

SUMMARY OF ACCOMPLISHMENTS

Radiography

- Increased the linear electron accelerator (linac) dose from 50 to 170 R at 1 m,
- Installed a new linac electron injector that reduces pulse length from 250 to 50 ns and thus decreases motion smear on the resulting radiograph,
- Increased linac energy from 85 to 120 MeV,
- Increased the electron current on the target from 3 to 6 amps,
- Added electron-beam diagnostics.

Optics

- Purchased improved framing cameras, including one new model with a larger frame size that collects four times the optical information of the older model it replaced,
- Purchased improved streaking cameras, including some with continuous access that do not require synchronization of rotor position,
- Improved rotors,
- Improved objective lenses,
- Installed new electronic controls.

Electronics

- Purchased high-speed oscilloscopes, oscilloscope cameras, digitizers, and time-interval meters,
- Developed and installed a transistorized, highly stable raster oscilloscope,
- Replaced the analog delay system with a digital delay system,
- Fielded improved camera-control electronics and trigger generators,
- Installed a new computerized data-reduction center, consisting of a film digitizer and various computer peripherals, to process and reduce the analog data generated at Site 300 and forward them to the main LLL computer system,
- Installed a minicomputer control system.

Interferometry

- Installed a velocity-interferometry system (VISAR) and Fabry-Perot instruments at operational bunkers to provide a new capability to make direct velocity measurements.

PROJECT GOALS

Before undertaking the upgrade effort, we thoroughly reviewed our capabilities and requirements. The major design criteria we established as guidelines for all projects were

- Experimental complexity,
- Fast turnaround time,
- Improved measurement,
- Computerization.

Experiment Complexity

Unlike the other weapons laboratories, LLL relies heavily on complex multiple-diagnostic techniques in its hydrodynamic experiments. The techniques used at Site 300 include flash radiography, high-speed streaking and framing cameras, fast optical and electrical pins, and neutron-detection equipment. The operator's control console for a typical firing bunker, shown in Fig. 1, indicates the complexity of test equipment. The trend over the past several years has been toward increasing use of several of these types of diagnostics on each experiment and toward more accurate and sophisticated measurements of each type.

This approach has resulted in significant economies. For example, nearly 200 hydro experiments were required for development of the W-45 in the late 1950's, whereas the W-75, if completed, would have needed less than one-tenth that number. During the 1960's, most nuclear experiments required about 10 hydro experiments during their design; now even radically new designs may require only two or three.

We decided that our experiments would continue to require a complex set of multiple diagnostics. Therefore, we needed equipment that would be reliable, easy to operate, and easy to repair.

Fast Turnaround Time

There are now only two major firing bunkers at Site 300, and equipping each bunker for a complex experiment requires considerable time. Therefore, to maintain a fast-moving weapon-design program, we needed equipment and techniques that provide as fast a turnaround time as possible. Fast turnaround also ensures a lower cost per experiment.

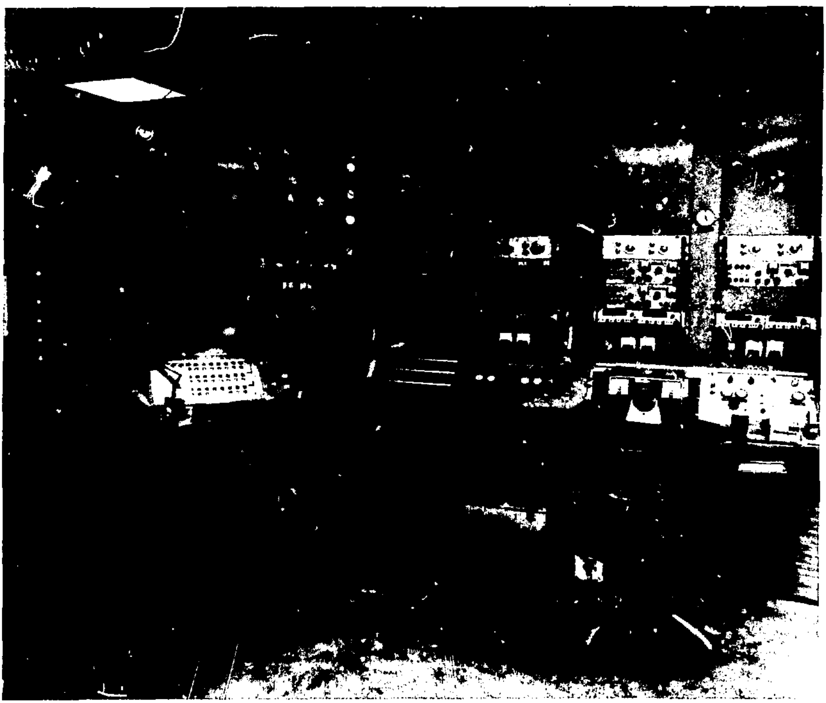

Fig. 1. Bunker control console.

Improved Measurement

We are continually trying to improve our measurement techniques. Thus, we needed equipment that would improve resolution and accuracy. Additionally, we were interested in techniques or equipment that would provide new data. Figures 2 and 3 show the new oscilloscope recording system and the high-speed camera room for obtaining these data.

Computerization

Powerful computers now available could greatly increase the speed and quantity of our data acquisition. Moreover, these computers had become available at low cost. We therefore tried to provide computer capability where possible and to specify instrumentation that would be computer compatible.

Fig. 2. Oscilloscope recording system.

RADIOGRAPHY

The linac (Fig. 4) at Site 300 is our most important diagnostic tool for radiography. It has been working routinely since 1960. During that time, many improvements have been made. Some were made to preclude failures; many others were made to increase capabilities in diagnostics and reliability. Continuing improvements in electronic components have been reflected in the linac.

Specific improvements in the linac have been many:

- Replacing the oil-diffusion-pump vacuum system with an ion-pump system has resulted in a clean, oil-free vacuum system with excellent performance. The accelerator structures of the original system, with constant-impedance design and World War II-type radio-frequency (RF) couplers, were designed for 5-MW operation. When these began to fail, primarily

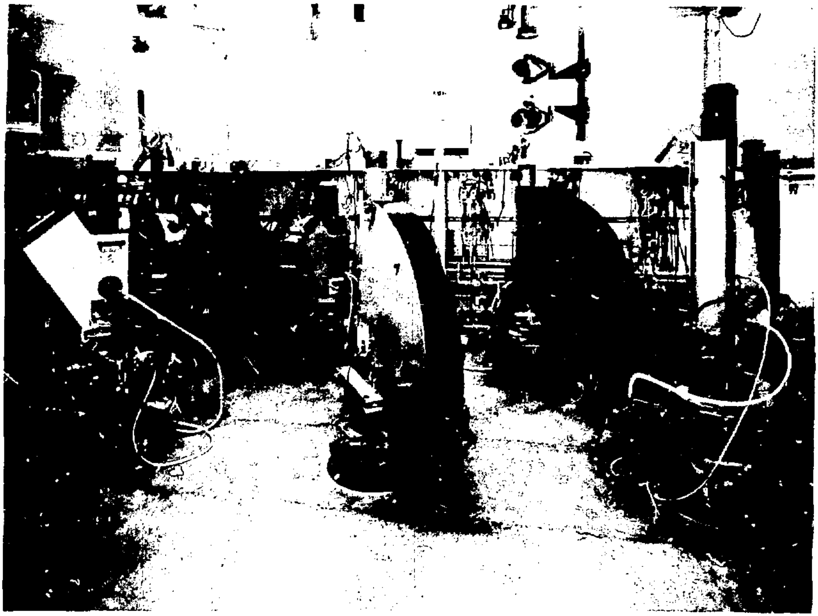

Fig. 3. High-speed camera room.

at the coupler, we replaced the accelerator sections with new, improved, constant-gradient structures. These new sections also have improved RF couplers, similar to those designed by Stanford for the machine at the Stanford Linear Accelerator Center, and are capable of 15-20-MW operation.

- The RF drive system has also been improved. A highly stable oscillator along with a traveling-wave tube amplifier now drive all the klystrons. This oscillator-amplifier chain has resulted in a simpler system for timing and maintainability.
- The original klystrons capable of 7-MW output have been changed to 10-MW-output tubes. This required only minor modification to the klystron power supply and modulators.
- A traveling-wave buncher was installed between the original prebuncher and accelerator section No. 1. This increased the electrons accelerated by about 40% and reduced some of the tuning sensitivity.
- Additional beam monitoring and analyzing have been installed along with a powerful quadrupole magnet to focus the beam on the x-ray target.

These changes have not interrupted bunker operation and have significantly improved machine capability and reliability. The 1977-78 upgrade is designed to maximize overall performance of the machine. For example, the charge delivered to the x-ray target is currently limited by the electron-injector cathode and electron optics. Also, the present klystrons and klystron modulators are limited to 10-MW output, whereas the accelerator guides are capable of 15-20-MW operation. Therefore, the major thrust of the 1977-78 upgrade has been to install a new injector, new modulators, and 20-MW klystron amplifiers. Table 1 and Fig. 5 show the improvements in linac-injector specifications. The injector control, the injector undergoing tests, and an injector pulse on an oscilloscope screen are shown in Figs. 6-8, respectively.

The new modulators will have improved electrical characteristics. As a result, the machine will be easier to tune. An RF tight enclosure will reduce electromagnetic interference at the bunker. Table 2 lists the improved modulator specifications.

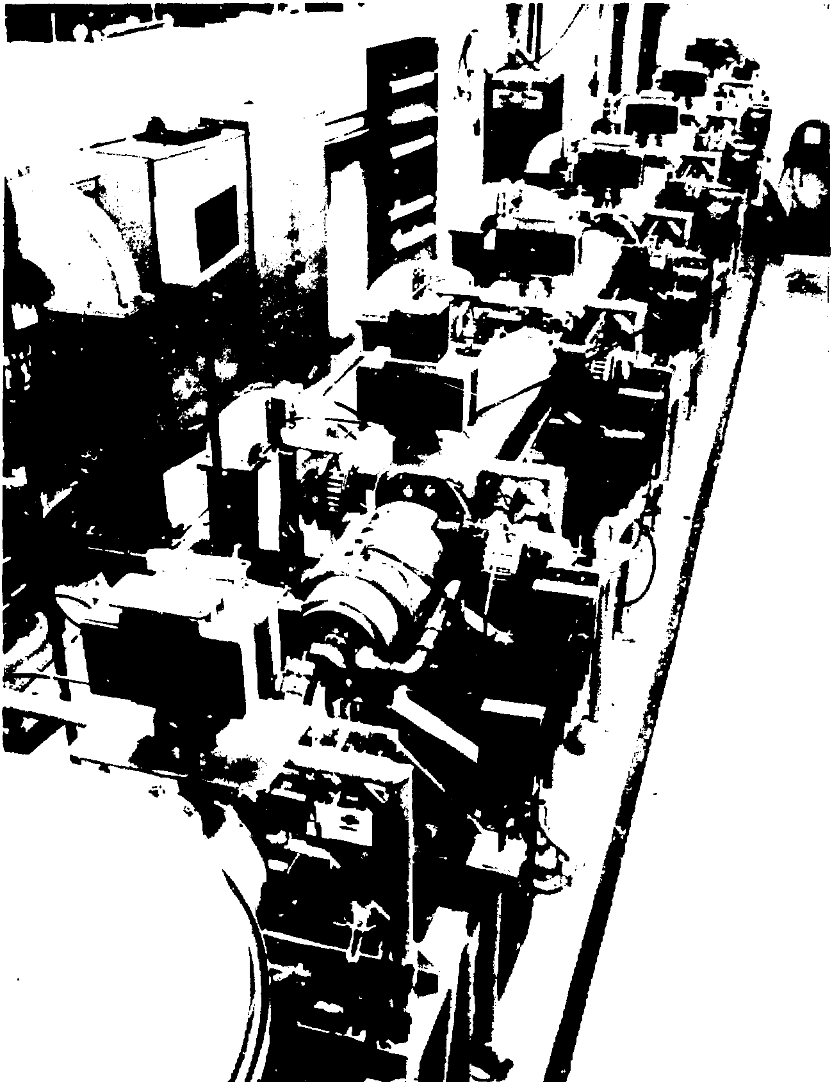

Fig. 4. Linac viewed from the injector end.

Table 1. Improvements in linac-injector specifications.

Specification	1977-78	1976-77
Current at flange	25 amps	4 amps
Pulse width	25, 50, 100, 150, 200 ns	Fixed, 300 ns
Rise time	3 ns	50 ns
Fall time	5 ns	50 ns
Multipulse	Yes	Yes

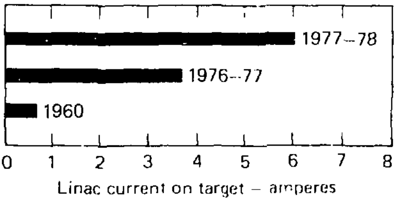

Fig. 5. Improvements in linac-injector specifications.

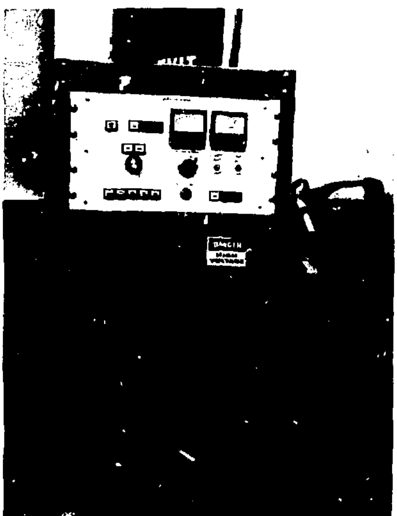

Fig. 6. Linac-injector control.

Table 2. Linac modulator specifications.

Specification	1977-78	1976-77
Power	20 MW RF	10 MW RF
Pulse width	3 and/or 12 μs	8 μs fixed
Multipulse	2 pulses with 8.0-500-μs variable spacing	None
RF noise	Low	High

Fig. 7. Linac injector undergoing tests.

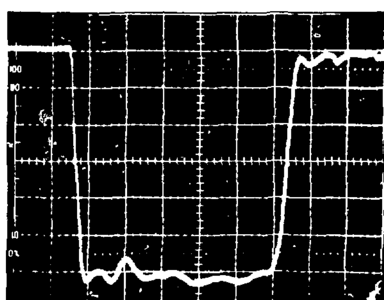

Fig. 8. Linac-injector pulse. Each vertical division is 4 amps. Each horizontal division is 10 ms.

The linac now has five accelerating sections. A sixth accelerating section will be added during the present upgrade. This, along with the increased RF power, will substantially increase beam energy, as shown in Fig. 9.

These improvements will also significantly increase the x-ray dose, as shown in Fig. 10. The machine will then be close to the limit of its ability to accelerate charge. Further improvements in radiography will depend on better diagnostics and better focusing methods.

A new feature of the linac is the ability to generate completely adjustable multiple x-ray pulses with time separations between 3.5 and 500 μs at full beam energy.

As operating characteristics are improved, several other tasks will be accomplished. The control console will be redesigned to accommodate the new injector and klystron modulators. The new controls and monitoring will make operator control of the linac easier. The status of the linac will be available to the bunker data base for a complete picture of the linac at the time of a shot.

To supply continuity over the next 10-15 years, the linac documentation will be improved. A linac manual, along with appropriate references to LLL or commercially supplied hardware, will be generated. Subsequent linac changes and modifications would then be reflected in the manual.

The 1977-78 upgrade has substantially improved machine capability. However, to take full advantage of the linac, several tasks remain, including further improvements in the man-machine interface and better beam diagnostics.

Much of the beam monitoring and diagnostic equipment is outdated and should be improved with new state-of-the-art components. For example, the beam position and size monitor, currently a closed-circuit television system, should be replaced with a charge-coupled device array. This would allow signals to be processed and displayed for the linac operator, thus enhancing tuning.

The present beam analyzer displays important information useful for reducing the energy spread of the beam. The analyzer needs improvement by adding a new program-loading feature, upgrading its computer for overall compatibility with the other bunker controls, and making its outputs available to the bunker data base.

To reduce linac setup time, some form of automatic startup is required. This would result in more efficiency at the bunker and would free operating personnel from routine operations. The linac is very operator-dependent. Therefore, limited automatic control would improve the reproducibility of the linac and remove many operator-related problems.

With the multipulse feature, improved x-ray diagnostics are desirable. For example, combinations of scintillation screens and image intensifiers should be studied for application to time-resolved radiography.

The spot size of the linac is about 3 mm. This could be reduced by more powerful focusing magnets, possibly superconducting magnets. There may be some x-ray loss due to a different "antenna" pattern, but the increased dose may overcome this loss. Smaller spot size will result in better resolution of the radiographs.

Work done with computer enhancement of radiographs has produced some very encouraging results. However, it is a time-consuming effort. There should be a continuing program to improve throughput and code development for image enhancement.

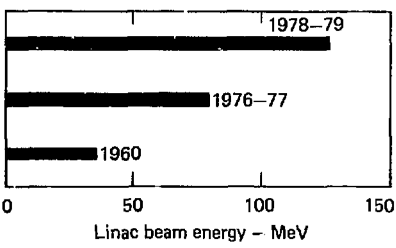

Fig. 9. Improvements in linac-beam energy.

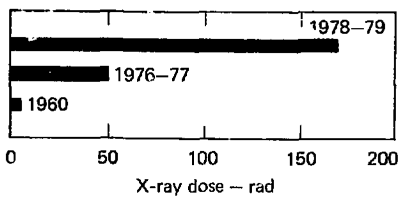

Fig. 10. Improvements in linac x-ray dose.

High-Speed Photography

High-speed photography is a prime diagnostic tool used to evaluate new weapon concepts at LLL. It shares this importance with flash x-ray and electrical-pin diagnostics. Together, these three methods of data acquisition comprise almost all the hydrodiagnostics used at LLL's Site 300 explosive-test facilities.

High-speed cameras include two basic types: framing cameras (Fig. 11) and streak cameras (Fig. 12). Each of these types is further characterized as being either *synchronized* or *continuous access*.

Framing cameras (Fig. 13) produce a sequence of short-duration, full-frame images much the same as a motion picture camera. The essential difference is that in the high-speed framing camera the film does not move; instead, a high-speed rotating-turbine mirror provides the time separation between each frame normally provided by moving the film with a mechanical shutter.

Streak cameras, on the other hand, produce a position-vs-time history of the event being filmed. Whereas the framing camera produces full-field photographs of the event, the streak camera produces a continuous,

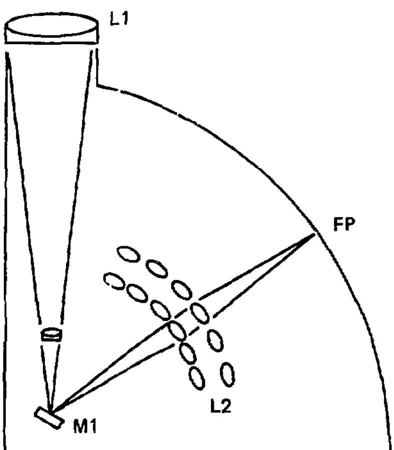

Fig. 11. Design features of a typical framing camera. The objective lens (L1) forms an image of the object at the high-speed turbine mirror (M1). The relay lenses (L2) then relay the image to the film plane (FP).

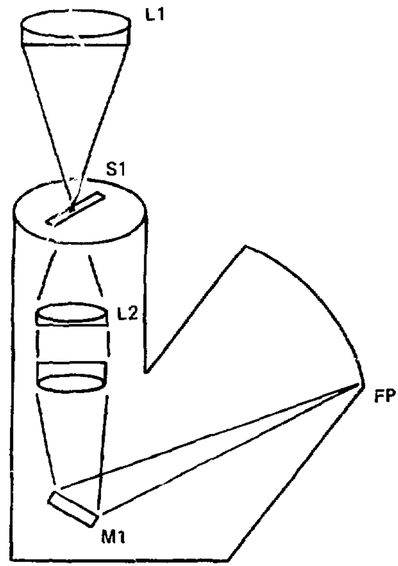

Fig. 12. Design features of a typical streak camera. The objective lens (L1) forms an image of the object at the slit (S1), which acts as a narrow field mask. The relay lens (L2) then relays the image through the turbine mirror (M1) to a focus at the film plane (FP).

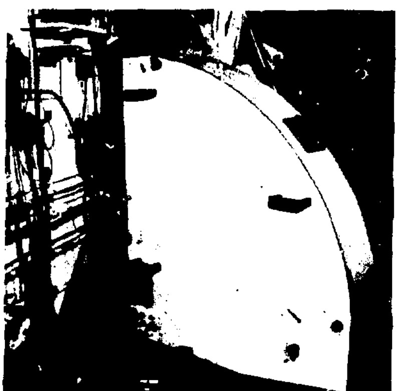

Fig. 13. Cordin Mod 121 synchronized 70-mm framing camera.

streaked image of a narrow segment of the object field and yields quantitative data of motion in the object field. Upon integration, these position-time data yield a velocity-time history of the event. Some cameras (Fig. 14) are combined streak-framing cameras.

Synchronized cameras provide electronic signals that permit triggering the event so that the beginning of the event under study occurs at the beginning of the film record. Continuous-access cameras require no synchronization, because they are always ready to record the event regardless of when it occurs. The heart of all high-speed cameras is the high-speed rotating turbine mirror used to provide the time displacement of the image along the length of the film.

Until recently, most of the precision manufactured high-speed cameras in use at Site 300 were 12-15 years old or more. Wear and tear were not the only problems associated with these venerable cameras. They also represented a technology which was approximately 20 years out of date.

The Site 300 upgrade funds have made it possible to retire from service many of the most antiquated cameras, such as the Models 100, 754, and 508 streak cameras, all designed about 1955. These obsolete cameras were replaced with the new Cordin Models 75 (Fig. 15), 132 (Fig. 16), and 136 (Fig. 17) streak cameras. This replacement introduced many new and

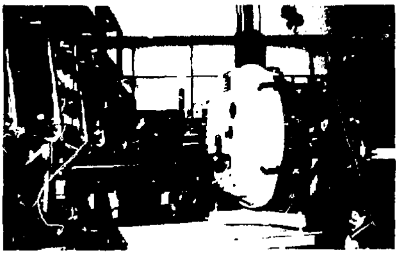

Fig. 14. Cordin Mod 330 combined streak-framing camera.

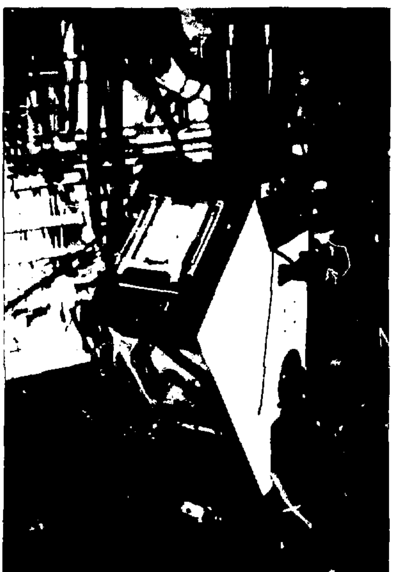

Fig. 15. Cordin Mod 75 synchronized streak camera.

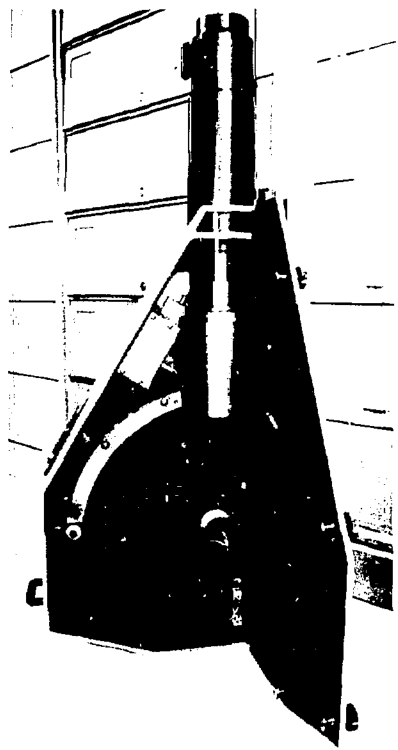

Fig. 16. Cordin Mod 132 synchronized streak camera.

desirable performance features such as greater light sensitivity, higher image resolution and contrast, solid state system electronics, state of the art optics, and high speed camera turbine technology, leading to greater system performance and reliability. System reliability has become a prime concern since technology advancement has increased the high speed camera capability from two cameras in 1958 to a system (Fig. 18) using eight simultaneous cameras today along with flash x-ray and electrical pin diagnostics.

Extensive progress in developing a wide spectrum of simultaneous hydrodiagnostic tools has produced a more precise understanding of weapon system performance with many fewer experiments between design concept and nuclear test. Along with this, today's experiments have become increasingly complex and sophisticated, thus demanding a much higher level of system reliability than before. The new Cordin streak cameras purchased with upgrade funds have done exactly that.

Fig. 17. Cordin Mod 136 continuous-access streak camera.

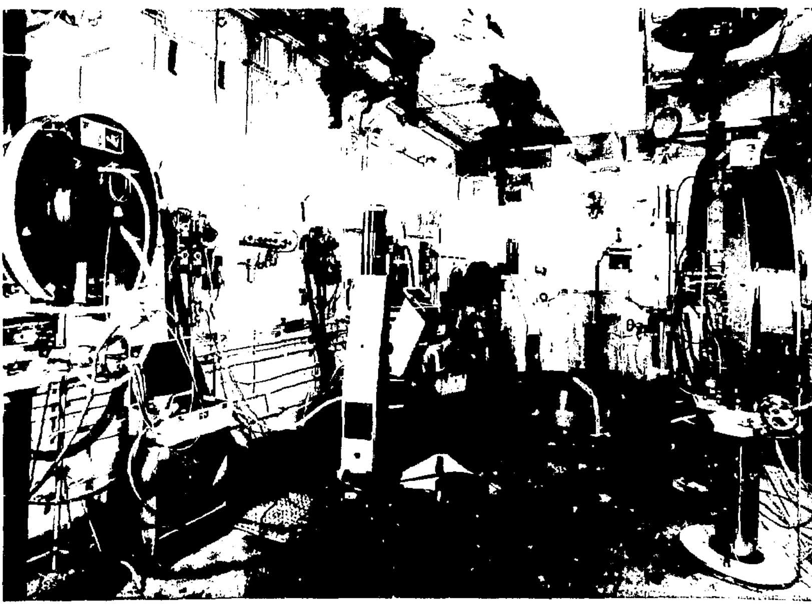

Fig. 18. Typical example of multiple, simultaneous, high-speed camera diagnostics currently used in Bunker 851.

Optical Fiducial System

Precision cross-timing of high-speed camera film records to other data-acquisition systems and to event timing is necessary to correlate data to event phenomena.

As part of the upgrade activities, we have generated a set of design and performance specifications for the commercial production of an optical fiducial system, which is undergoing final production tests at this writing. This system consists of a programmable pulse-modulated laser and fiber-optic distribution system. Upon command, this system will deliver a programmed set of crystal-controlled marker pulses to each high-speed camera. These precisely timed marker pulses will be recorded along the edge of each film record. These fiducial markers will provide absolute cross-timing of events to each high-speed camera and a precise measurement of each camera speed at the time of the event.

ELECTRONICS

Electronic systems perform key roles in hydrodiagnostics, both as diagnostic tools and as the basic timing and control systems for the experiment.

Much of our commercially purchased instrumentation was still equipped with vacuum tubes prior to the upgrade. We therefore concentrated on purchasing new solid-state equipment to improve reliability, accuracy, and stability.

While many of the LLL-designed instruments were of solid-state design, they did not take into account advances in integrated circuit and digital technology. By consciously applying these modern techniques, we were able to develop and place in operation a new digital delay generator with sharply improved resolution, stability, and accuracy. We also improved other instrumentation similarly.

We carefully evaluated digital measurement techniques and adapted them where appropriate. We also determined that many signals would still need to be recorded on oscilloscopes equipped with cameras. We therefore purchased new cameras and oscilloscopes and provided a new data-reduction center for digitizing photographic records of scope traces.

Raster Oscilloscope System

One of the primary diagnostic techniques is the measurement of material motion using electrical-pin switches. Much of our experimental work at Site 300 uses this technique. Many experiments use 400 or more pins to get precise material time-motion history. We established that the L-10 recording system was obsolete, due to problems with linearity, age, stability, and vacuum-tube reliability. Because pin transducers are too noisy, we decided that simple timing measurements would not suffice. The raster scope provides both time and waveform information, and this capability needed to continue. We determined that digitizers with the necessary bandwidth and record length were nonexistent. Therefore, we decided to design a new raster-scope system, the L-300 (Figs. 19-21). Taking a total-system approach, we improved the cameras, lenses, films, phosphors, and electronics all at once.

We first determined that a major problem with the L-10 system was the cathode-ray tube (CRT)-film combination. The main CRT problems were

- The residual beam, which caused fogged film,
- Focus, which changed as the triggers were changed from setup to fire condition,
- Short-life tubes, which had to be replaced frequently,
- The combination of film (103-0) and phosphor (P-11) used, which lowered sensitivity and reduced tube life (Figs. 22 and 23).

We therefore worked with two outside vendors to develop a new tube that would overcome these limitations. To improve the photographic sensitivity, we selected P-31 phosphors and Royal X film. Figure 22 shows the tube characteristics. It also shows that the P-31 phosphors have better visual characteristics.

New features include plug-in printed-circuit boards to provide alternate timing formats, z-axis input to the CRT, dynamic beam-current monitors, and an output connector that provides status information for computer monitoring. Timing markers are digitally referenced from a crystal oscillator. In addition to the standard 0.5-μs markers, we can now provide markers spaced 0.1 and 2 μs apart, thus significantly extending the scope's range. The z-axis input allows us to put additional timing information on the scope face. We can either intensify or blank the beam from the z-axis input. The beam-current monitor shows the actual current in the beam and is useful in evaluating CRT condition. The resultant L-300 design has overcome the above-mentioned problems, and the records we now obtain are superior to those previously available (Table 3). Figure 24 shows a typical raster record from the L-300.

Substantial improvements were also made in electronic design of the L-300. We used an appropriate combination of solid-state circuitry, integrated-circuit technology, and digital techniques. All adjustments and test points were made accessible from the outside for easy adjustment and maintenance.

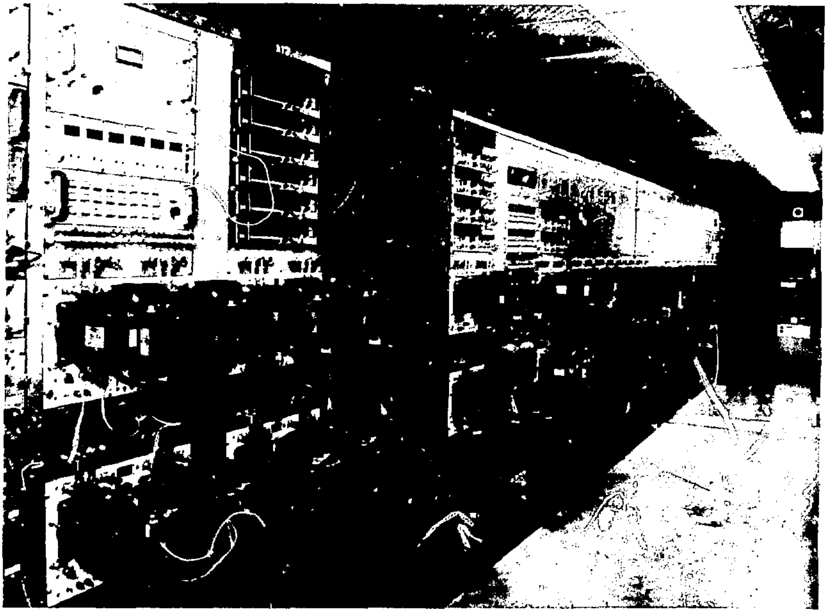

Fig. 19. Raster oscilloscope system at Bldg. 851.

Digital Delay Generator

A primary tool in controlling hydrodynamic experiments is the delay generator. Several delay generators were previously in operation, but these units, while solid state, were obsolete due to their extensive use of analog techniques and vulnerability to electromagnetic interference (EMI). We developed and have placed in operation new digitally controlled delay generators (Fig. 25 and 26) with substantial improvements in range, jitter, stability, and resistance to EMI (Table 4). Our new generator operates from a 10-MHz crystal-controlled oscillator. This oscillato. can be located in the instrument or switched from an external reference. An external reference allows all generators to be timed from the same source. A unique phase-locked oscillator multiplies the 10-MHz reference to 200 MHz. Then, by counting down this signal, we can determine the final delay. The 200-MHz signal guarantees that jitter will be 5 ns or less.

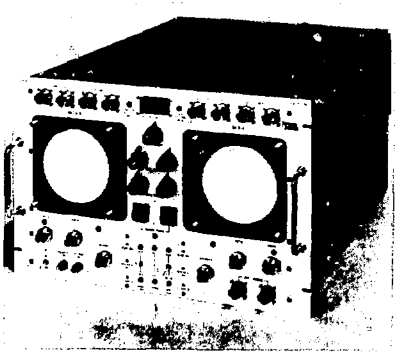

Fig. 20. Dual raster oscilloscope chassis.

Trigger Generator Discriminator

Prior to Site 300 upgrade activities, several trigger generators were available in our diagnostic bunkers for use in various pulse-shaping applications. We designed and installed a versatile new six-channel instrument

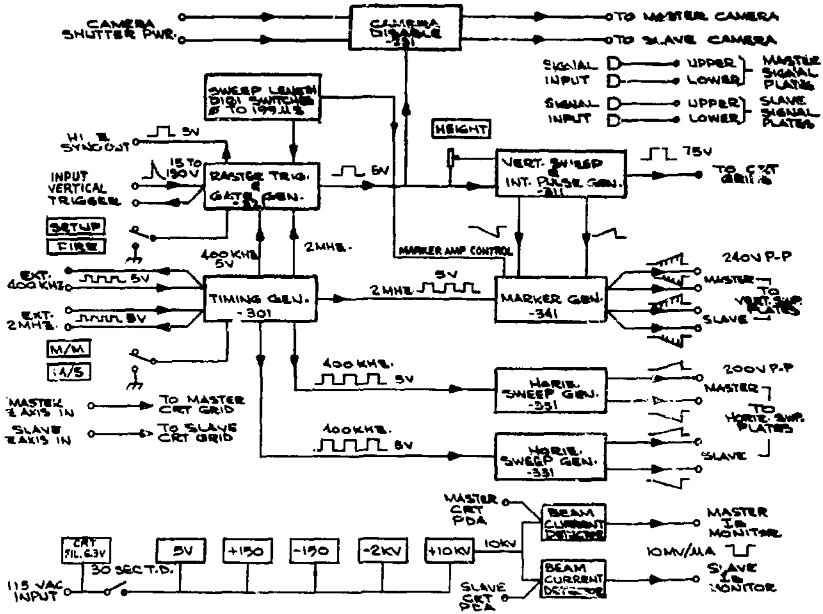

Fig. 21. Block diagram of L-300 raster oscilloscope.

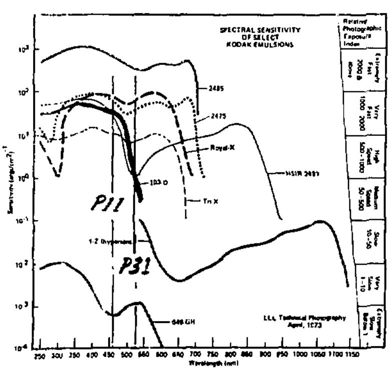

Fig. 22. Spectral sensitivity of film and phosphor.

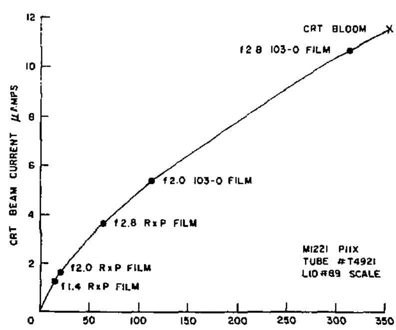

Fig. 23. Current characteristics of the L-10 cathode-ray tube.

Table 3. Performance comparison of L-10 and L-300 oscilloscopes.

	L-10	L-300
CRT spot size	16 mil	10 mil
Horizontal sweep length	2.5 μs	2.5 μs
Vertical sweep length	100 μs	175 μs
Resolution	20 ns	5 ns
Fast-sweep option	No	Yes
Slow-sweep option	No	Yes
Z-axis modulator	No	Yes
Long-term stability	Poor	Excellent
Focus	Poor	Excellent

Table 4. Comparison of old and new delay generators.

	Old delay	New delay
Delay range	0.3-100 μs	0.1-9999 μs
Resolution	20 ns (low range) 20 μs (high range)	1 ns
Jitter	20 ns (low range) 2 μs (high range)	5 ns
Long-term stability	1%	0.01%
Output-pulse voltage	120 V	80 V
Output-pulse risetime	50 ns	10 ns

(Fig. 27) with substantially improved performance (Table 5). The new generator features a discriminator threshold that is set from front-panel thumbwheel switches. The range of discriminator voltage is from −99 Vdc to 99 Vdc in 1-V steps. Propagation time through the unit is 30 ns, a three-fold decrease over previous designs.

Fig. 24. Typical raster record from the L-300 system.

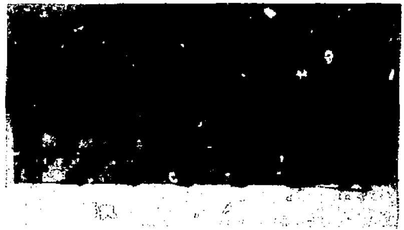

Fig. 25. Six-channel delay generator.

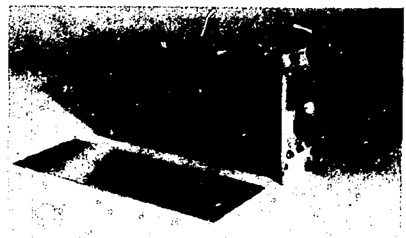

Fig. 26. Delay generator module.

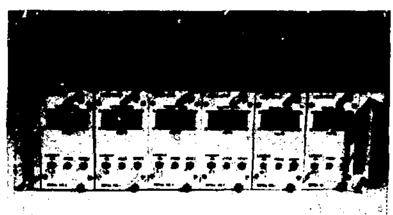

Fig. 27. Six-channel trigger generator-discriminator.

Table 5. Comparison of old and new trigger generators.

	Old unit	New unit
Channels	5	6
Discriminator level	2 to 100 V	−99 to +99 V
Input impedance	1 kΩ	1 MΩ
Propagation delay	100 ns	30 ns
Output-pulse voltage	120 V	150 V
Output-pulse risetime	50 ns	5 ns

Phase Delay and Gate Generator

As part of our efforts, we designed a new phase delay and gate generator for synchronizing high-speed cameras. Our new generator replaces a chassis that had become obsolete. Hydrodiagnostic experiments have been using increasing numbers of cameras. We therefore increased the number of channels from five to ten (Fig. 28). The delay and gate ranges were also increased to obtain a higher probability of synchronization. A comparison of the two generators is shown in Table 6.

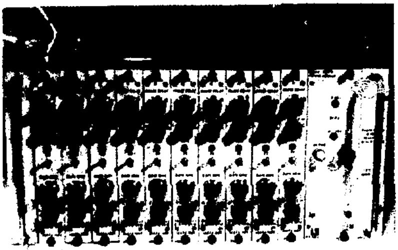

Fig. 28. Ten-channel phase delay and gate generator.

Table 6. Comparison of old and new phase delay and gate generator.

	Old	New
Channels	5	10
Delay range	1-500 µs	0.1-1000 µs
Ranges	4	4
Gate range	0.3-120 µs	0.1-500 µs
Ranges	2	4
Duty cycle	30%	100%
Output voltage	30 V	30 V
Output risetime	100 ns	10 ns

Camera Controls

Due to our continuing dependence on high-speed photography as a primary diagnostic tool, we conducted a thorough analysis of our camera-control system. Our current controller was placed in operation ten years ago. It requires a separate reference oscillator and control chassis for each camera. Furthermore, the full range of desired speeds for each camera cannot be automatically controlled, and it is necessary for the operator to intervene in some situations.

We are now designing a new control system that, when complete, will establish a new standard of reliability and control. The new controller will be based on a microprocessor design. Only one reference oscillator will be used for all cameras. Each control chassis will control up to six cameras. The high camera-turbine speeds require minimizing run time to prolong bearing life. Catastrophic failure of camera-turbine mirror assemblies at such high speeds could destroy a $60,000-140,000 camera and jeopardize the experiment. To prevent such risks, the microprocessor will tailor individual camera acceleration profiles so that all cameras will reach running speed simultaneously. The controller will also monitor operating parameters of the cameras and verify that they are within predetermined limits. If any excessive conditions are noted, the experiment will be aborted and the cameras immediately shut down.

Camera Diagnostics

Cameras used in hydrodynamic research are special-purpose, high-speed, rotating-mirror devices. Due to the high speeds involved, sophisticated balancing techniques, bearing assemblies, and close mechanical tolerances have been used to reliably attain the desired operating speeds. Most research applications of high-speed cameras involve only one such camera. To extend camera life, the unit is accelerated to the desired operating speed. As soon as the beginning of the film strip is reached, the experiment is begun and optically recorded; the camera is then immediately shut down.

At LLL, however, to attain maximum information on any given experiment, we often use up to eight multiple cameras. This requires that all camera-turbine mirrors be at the synch position when the experiment is triggered. Our newly developed camera-diagnostic system is unique and will provide increased camera reliability and better data. This is extremely significant because, by monitoring critical operating parameters, we will be able to abort an experiment before excessive operating conditions damage the cameras. These operating parameters will be recorded so that diagnostic techniques and system designs can be improved.

COMPUTERIZATION

The intensive use of minicomputers at LLL led us to investigate the feasibility of incorporating minicomputers in our hydrodiagnostic systems. Since shot data occur in microsecond time frames, it is impossible to consider a real-time acquisition or control application. However, our investigation showed that computers can play an important role in hydrodiagnostics in the following areas:

- Preshot setup,
- Postshot data acquisition and analysis,
- Preventive maintenance.

Our central computer is an LSI-11 programmed in SPS BASIC language. The Tektronix 4051 graphics terminal (Fig. 29) used with this system can be both a front end for the LSI-11 and a stand-alone terminal.

A similar 4051 located in Building 111 allows ramrods to prepare preshot setup tapes (delay settings, optics requirements, etc.) (Fig. 30) in Livermore and then carry the shot setup tapes to Site 300. These tapes are read into the 4051, where the shot parameters are then placed in the LSI-11. In the full configuration, the LSI-11 then remotely programs the programmable delay generator, the camera controller, and the phase-delay and gate-generator settings.

After the shot, the time-interval measurement system can read the actual delays into the computer, where they can be compared against predicted readings (Fig. 31), and rotor synch times can be plotted (Fig. 32). Any discrepancies are then noted to the operator. Before we installed computers, many parameters (capacitor-discharge unit and current-viewing resistor waveforms, for example) were measured and recorded on photographic film. They were analyzed only occasionally due to the difficulty of proper data reduction. The computer system now allows us to analyze many such waveforms, and thus we can do routine preventive maintenance by looking for changes in desired parameters.

Other programs have been written to assist operators with optical setups, to maintain records of camera data, and to provide inventory control of various bunker equipment. In summary, computers have significantly improved our capabilities and will continue to do so in the future.

Fig. 29. Tektronix 4051 graphics terminal.

```
DATE            7/13/78
SHOT#           1202A
RAMROD          SHAW

EVENT           1
NAME            CDU1
TIME(US)        2
REF             COINCIDENCE

EVENT           2
NAME            CANDLE
TIME(US)        0.1
REF             COINCIDENCE

EVENT           3
NAME            BW1
TIME(US)        5
REF             COINCIDENCE

EVENT           4
NAME            BW2
TIME(US)        10
REF             BW1
```

Fig. 30. A shot setup dialogue.

```
DATE            SHOT              RAMROD
7/13/78         1202A     SHAW

EVENT   NAME     PREDICTED        MEASURED
1       CDU1     2                2.01
2       CANDLE   0.1              0.11
3       BW1      5                4.99
4       BW2      10               10.01
```

Fig. 31. Printout comparing actual and predicted delays.

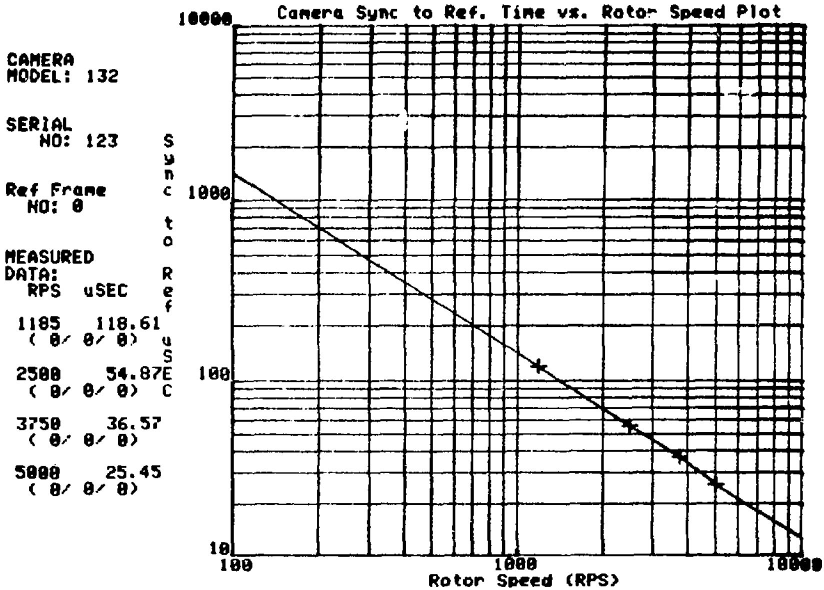

Fig. 32. Rotor synchronization time.

Time-Interval Measurement System

Time-interval measurement (TIM) is a principal hydrodiagnostic technique. For example, the sequence *of events during the firing of an experiment is carefully* controlled by a digital delay generator. To verify proper timing generation, various timing references are recorded on film taken from oscilloscope traces; many signals are also recorded on various time-interval counters.

To obtain uniform recording and to improve resolution, we wrote a specification for, and then procured, a 96-channel TIM. Detailed specifications for this system are shown in Table 7.

The TIM system is referenced to one master timing pulse (usually camera coincidence). As individual events occur, they are recorded on separate channels of the TIM. Typical recorded signals include camera true speeds, timing references, and detonation pulses. The TIM system is interfaced to the bunker computer. Immediately after the experiment, the computer records these times and prints a report, as shown in Fig. 33.

Table 7. Time-interval measurement (TIM) system specifications.

No. of channels	96
Resolution	2 ns
Range	2 ms
Accuracy	± 2 ns
Start pulse:	
No.	1 common
Discriminator level	15 V
Amplitude	30-150 V
Stop pulse:	
No.	1 per channel
Discriminator level	15 V
Amplitude	30-150 V
Remote interface	GPIB (IEEE-488-1975)
Local readout	1 display shared among channels
Power	117 V AC ± 10% 60 Hz ± 2 Hz
Construction	7 chassis, each 3½ in. × 19 in.

DATE	7/13/78
CHANNEL	TIME(US)
1	2.01
2	0.11
3	4.99
4	10.01
5	5.34
6	7.22
7	NS
8	NS
9	15.61
10	0.05
11	NS
12	14.22

Fig. 33. Printout of TIM times.

This system substantially reduces data-reduction time, in that times need not be read from film. Events that are indicated to be out of tolerance are so denoted by the computer system. This capability also allows us to perform equipment diagnostics, because malfunctioning delay generators are easily noted during dry-run conditions. We plan to add similar systems to our other diagnostic bunkers.

Transient Analysis System

We designed and developed a multichannel system (Fig. 34) for digital transient measurements. This system has been put in a portable rack and can be transported to any facility where digital analysis is desired. The system consists of a CRT terminal, a hardcopy unit, an LSI-11 microcomputer, dual floppy disks, two R7912 transient digitizers, two Biomation 8100 transient digitizers, and four CRT real-time displays. Biomations are used for slower-time-scale transients, and the 7912's for faster-time-scale transients. This system may be expanded to double the capacity, as shown in the rack. Triggering the various transient analyzers at different sweep speeds can provide multiple coverage of the same transient. We chose to use Tektronix's signal processing system (SPS) BASIC software, which allows us to do sophisticated analysis on the transient waveforms. Figures 35 and 36 show an input pulse and a differentiated waveform obtained from the SPS BASIC software. Figures 37 and 38 show an integrated waveform and a fast Fourier transform performed on the data.

This system is extremely powerful and will find many uses in transient testing situations, such as recording manganin gauge signals and performing life tests on components used with the new linear induction

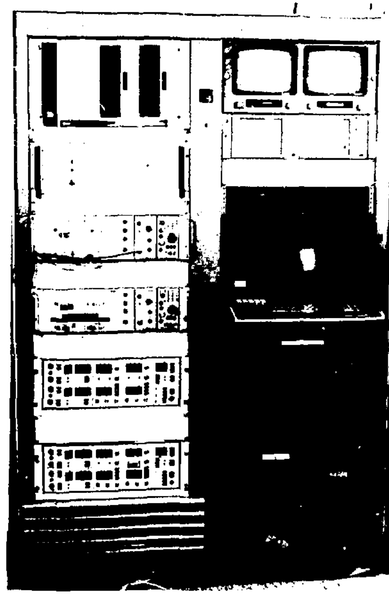

Fig. 34. Multichannel transient-analysis system.

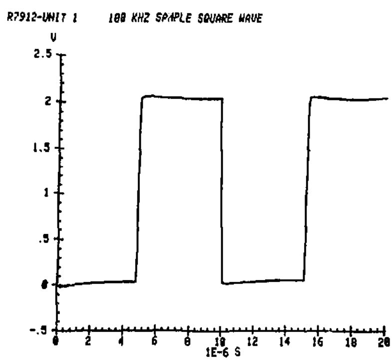

Fig. 35. An input pulse obtained from the SPS BASIC software.

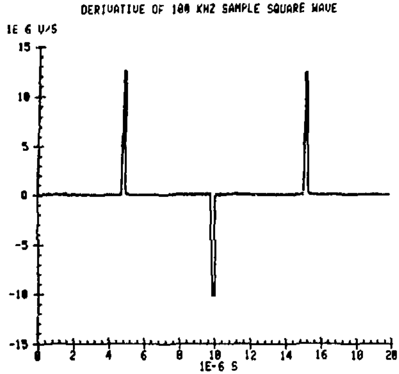

Fig. 36. A differentiated waveform obtained from the SFS BASIC software.

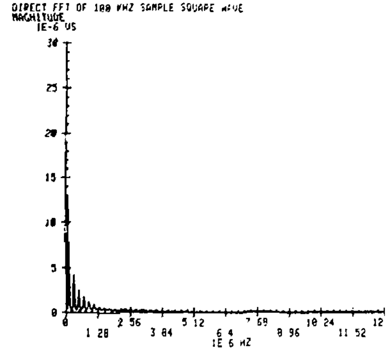

Fig. 38. A fast Fourier transform

accelerator. In life tests, a fast pulse is provided to the Blumlein trigger generator. The system measures the output of this generator, analyzes it, then statistically measures repeated transients—computations that would be impossible for humans to do. We plan to take a million shots and compare the transient waveforms from one shot to the next for predictive-failure analysis.

Charge-Coupled Device Digitizer

Recording very fast transient waveforms is critical to hydrodiagnostic efforts. Our recording method has been and continues to be photographic recording of oscilloscope traces (Fig. 39). Because the pin signals must be tediously analyzed by hand, only the most important signals are viewed. These are usually digitized manually for later computer reduction. Other waveforms, recorded for maintenance purposes, are usually ignored unless a problem is found.

An on-line digitizer and a computer could analyze these signals rapidly and regularly. Signals from various transducers could be digitized and recorded, then sent to remote computers for processing and archival storage. The importance of a charge-coupled device (CCD) digitizer, then, is that it lays the groundwork for automated pin recording, something the Laboratory has desired for years. This instrument could be significant for the entire Department of Energy, but completing this very important work will require substantial additional funding to continue the upgrade project.

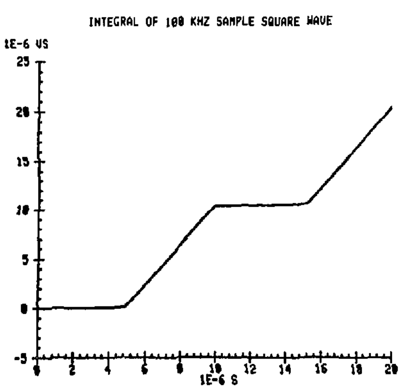

Fig. 37. An integrated waveform.

Fig. 39. Oscilloscope trace of a fast transient waveform.

At the beginning of the upgrade effort we investigated available fast transient recorders. Only two were commercially available with digitizing speeds anywhere near our requirements. These units, however, were prohibitively expensive on a cost-per-channel basis. We did acquire four units to use as needed, but did not consider fully equipping a diagnostic facility.

In the meantime LLL's Engineering Research Division had developed a charge-coupled shift register (Fig. 40). Such a device was successfully designed into a complete transient recorder and used on a Nevada nuclear experiment.

We feel that CCD's hold great potential as fast transient recorders. Part of our upgrade activities therefore includes the design and fabrication of an engineering prototype. We plan to use a substantial number of these recorders in future facilities and during further upgrade activities.

The CCD is used as an analog shift register that stores a signal in sampled analog form. The signals are stored at very high speed and shifted out at low speed, when there are digitized by a conventional A/D converter (Fig. 41).

These specifications have been established for the engineering prototype:

Maximum conversion rate	500 MHz
Amplitude resolution	8 bits
Record length per channel	4000 points
Number of channels	2

The manufacturable units will be expanded to eight channels and will have a target conversion rate of 1000 MHz. We estimate that the cost per channel will be at least four times lower than comparable commercial units.

Data-Reduction Center

Analysis of B Division data-acquisition methods indicated that almost entirely experimental results are recorded on photographic film. To reduce this analog data and extract information of interest, a sequence of distance measurements on this data is necessary.

The method of measurement had been a Benson-Lehner Oscar Model N-2 graphic digitizer, which was put into service in 1958. An operator mounts the film in transparency form, projects it on a screen, adjusts crosshairs over the data of interest, and causes numerical coordinates to be punched on IBM cards for later computer processing.

We determined that the Oscar had reached the end of its useful life. Although we were interested in pure digital recording techniques, they did not seem practical to pursue fully. We further felt that some film recording would always be necessary. Therefore, we wrote a specification and procured a new system to replace the Oscar.

The new system, or B Data Center (Fig. 42), consists of the following elements:

- A large table digitizer with a hand-held cursor (Fig. 43).
- A high-Q overhead projector for transparencies and opaques.
- An HP 2108A computer with disk storage.

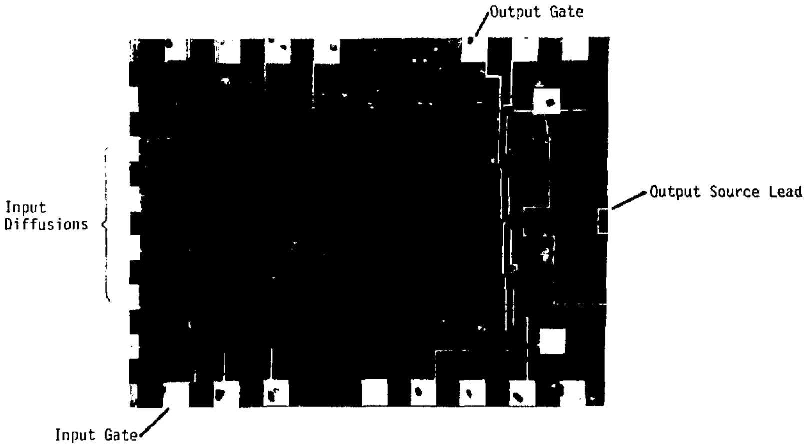

Fig. 40. Photomicrograph of a transient recorder chip.

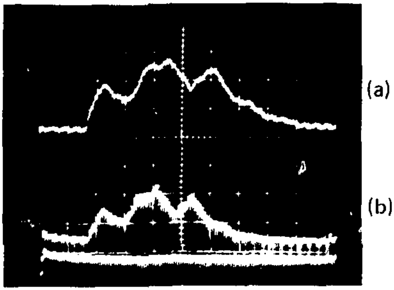

Fig. 41. Response to a general transient signal. (a) Input: 1 V/div, 50 ns/div. (b) Output: 10 mV/div, 20 μs/div.

- A Tektronix 4015 graphics terminal.
- A Tektronix 4631 hard copy unit.
- An HP 7970B magnetic tape unit.
- A computer link to the LLL computer center

In operation, film may be either placed directly on the digitizing table or mounted in the overhead projector and projected onto the table. System software controlled by the minicomputer guides the operator through data acquisition. Instructions are interactively displayed on the graphic terminal as they are digitized. A data file is produced and can be locally stored on magnetic tape. Furthermore, the minicomputer can convert the data into files that are compatible with existing codes on the Octopus system; the files can then be transferred to Octopus for further processing. Local processing capabilities include facilities for integration, differentiation, convolution, deconvolution, areas, velocities, and other general graphics.

Fig. 42. New data-reduction center.

Fig. 43. Film digitizing with hand-held cursor.

INTERFEROMETRY

A primary diagnostic method is measurement of velocity-time information of moving surfaces. These measurements have traditionally been made with rotating-mirror cameras and with electrical pins. Both of the old techniques yield distance vs time (D/T), but velocity vs time can only be inferred. As demonstrated in Fig. 44, a D/T plot is a very smooth curve, resulting from integration of velocity. No finesse can be seen at all, and details of velocity are lost.

As part of the Site 300 upgrade, we have been working on optical interferometry as a method to make direct velocity measurements. These techniques, Fabry-Perot (F-P), and velocity interferometry system for any reflector (VISAR) are making a significant contribution to our understanding of hydrodiagnostic phenomena. For the first time we have been able to make a direct quantitative comparison between theoretical codes and experimental data. Early experiments with interferometry were done with flying plates

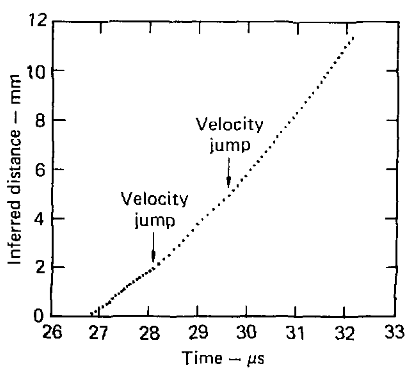

Fig. 44. Distance-time history obtained by integrating the measured velocity-time history.

accelerated from gas guns in laboratory conditions. In early January 1978, we had a chance to combine F-P and VISAR interferometer systems to measure the imploding shell velocity of a complex hydro device. The result was very successful even under such adverse conditions as the distance (more than 35 ft) from the experiment, the presence of argon candles, seven rotating-mirror cameras, a lucite flasher dome, and flash x-ray diagnostics. We are now installing the interferometer system as a standard diagnostic tool in Bunker 851 at Site 300.

The F-P interferometer is a very simple system, as shown in Fig. 45. Its main parts include a pair of highly reflective mirrors, called the F-P interferometer, and a fast electronic streaking camera. The Doppler shift of the laser frequency reflected from a fast-moving object is recorded continuously as fringes on film in the streaking camera. Immediately after the explosion, one

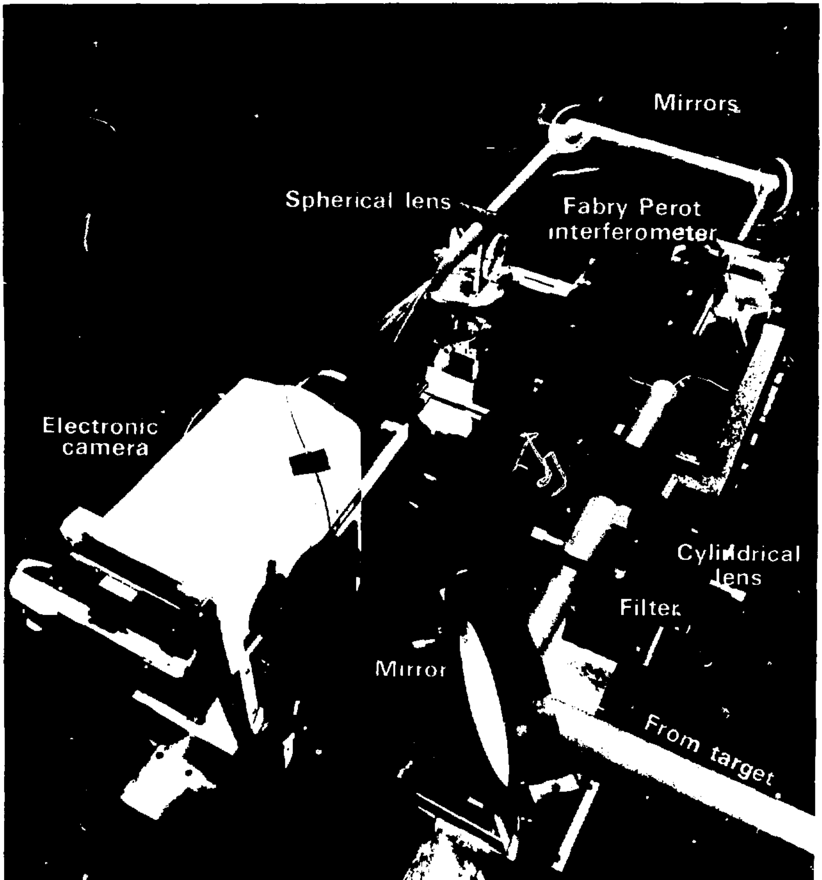

Fig. 45. Fabry-Perot interferometry system.

can tell the velocity characteristics just by looking at the Polaroid picture. And the data reduction is indeed very straightforward, which is one of the advantages of using F-P.

The VISAR (Fig. 46) is more complex than the F-P. Its basic components are the two-arm wide-angle Michelson interferometer and phototubes that view the movement of the interference fringes and record the amplitude information on the oscilloscopes. So the main difference between VISAR and F-P is that VISAR records fringe amplitude and F-P records fringe position.

The final velocity-vs-time (V/T) plot of the implosion (Fig. 47) shows the combined results of F-P and VISAR data. They match up closely, and have an uncertainty of less than 2%. The results of modeling using theoretical codes (Fig. 48) compare quite favorably with the VISAR and F-P results. Interferometry is contributing significantly to our understanding of hydrodynamic phenomena.

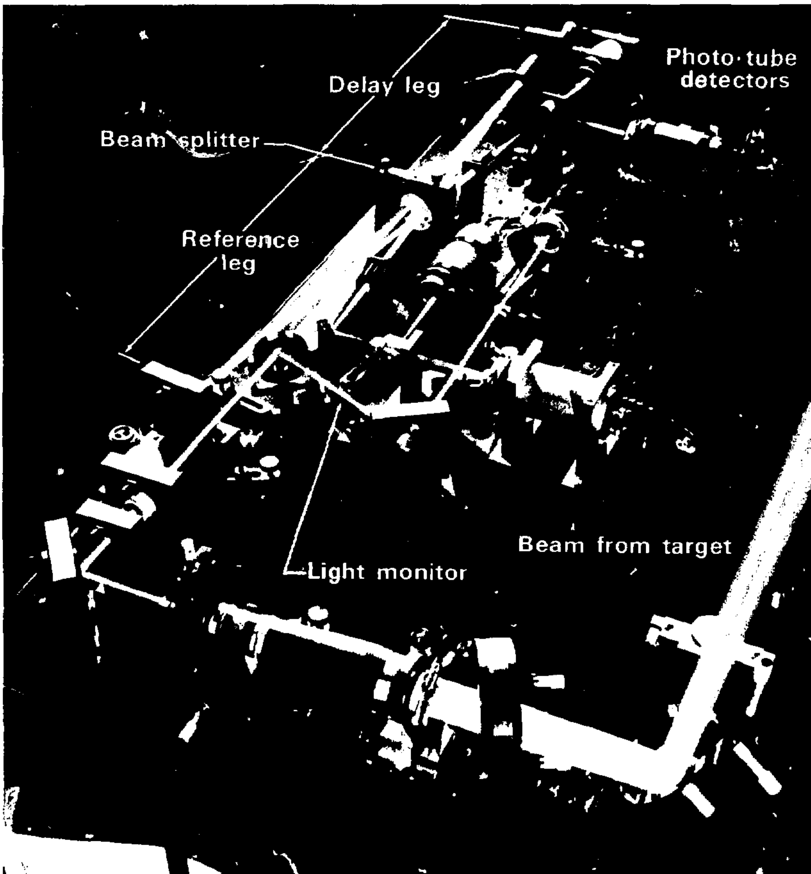

Fig. 46. VISAR system.

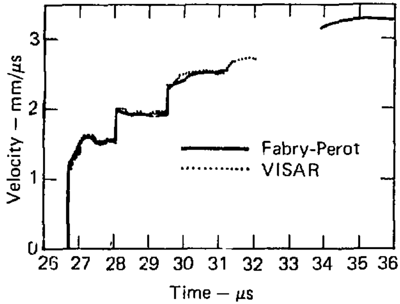

Fig. 47. Velocity-time history (measured).

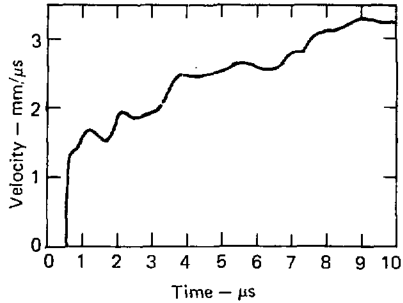

Fig. 48. Velocity-time history (calculated).

Data analysis for the VISAR is complex, involving fringe count, phase shift, amplitude variation, and gain change. However, VISAR data yield a better time resolution because of the many scopes with various recording speeds. On the other hand, F-P uses only one streaking camera with one speed recording, although the speed of the camera is variable. We hope that a multicamera F-P system can be developed if more laser light is available.

HEAVY EQUIPMENT

The routine setup of weapon experiments at Site 300 requires the use of specialized heavy equipment. This equipment is used for rigging and transporting test stands, massive x-ray film cassettes, and associated hardware, along with earth removing and grading. Several forklifts (Fig. 49), loaders (Fig. 50), and cherry picker-type cranes (Fig. 51) were purchased with upgrade funds for this purpose.

Fig. 50. Loader grading firing table.

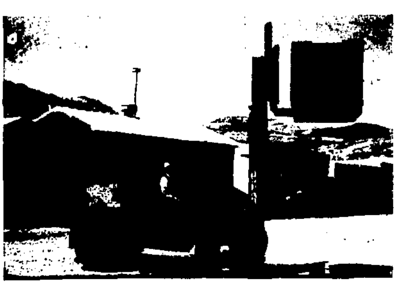

Fig. 49. Forklift rigging experimental hardware and test stands.

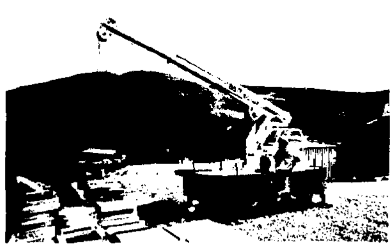

Fig. 51. Cherry-picker crane rigging x-ray film cassettes.

CONCLUSION

The Site 300 Upgrade Project has been extremely successful in revitalizing the hydrodiagnostic capabilities of LLL. Enhancements have been made in many areas. Especially noteworthy are improvements to linac performance and the addition of interferometry to multiple diagnostics. On-line computers have been introduced to the bunkers and promise to lay the groundwork for substantial future improvements. Additionally, a new data center is available for digitizing film. Development work has also begun on digitizers; future facilities may be able to use this instrumentation as a means of complete direct digital recording.

To successfully conclude the uprade efforts we must complete several projects in progress, make funds available to complete the purchase of equipment that became available at the end of the upgrade, and provide funding for the continued replacement of equipment as it becomes obsolete. In particular, the design of the camera control and monitoring system, installation of the linac RF components, and development of the CCD digitizer should be completed. Funding should be made available for the purchase of newer camera types and additional TIM systems.

Finally, the projected life cycle of most equipment is less than 10 years. We have invested $5 million in upgrading Site 300. A replacement program of $500,000 per year is required to prevent a repetition of obsolescence. Only by incorporating state-of-the-art equipment and techniques can we meet our responsibility to continually advance the nation's nuclear-explosive research program.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions to the Site 300 Upgrade Project made by Site 300 bunker and support personnel, B Division staff, and members of the Electrical and Mechanical Engineering Departments. Their countless suggestions and enthusiastic participation significantly affected the outcome of the project.

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