CONF-8309145--1

UCRL-89328
PREPRINT

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UCRL--89328

DE83 018188

This paper was prepared for submittal to
10th Annual Energy Division Conference
American Society for Quality Control,
San Diego, Sept. 18-21, 1983

July 18, 1983

Lawrence Livermore National Laboratory

FUSION UPDATE
THE NOVA LASER ASSURANCE MANAGEMENT SYSTEM*

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ABSTRACT

In a well managed project, Quality Assurance is an integral part of the management activities performed on a daily basis. Management assures successful performance within budget and on schedule by using all the good business, scientific, engineering, quality assurance, and safety practices available. Quality assurance and safety practices employed on Nova are put in perspective by integrating them into the overall function of good project management.

The Inertial Confinement Fusion (ICF) approach is explained in general terms. The laser ICF and magnetic fusion facilities are significantly different in that the laser system is used solely as a highly reliable energy source for performing plasma physics experiments related to fusion target development; by contrast, magnetic fusion facilities are themselves the experiments.

The Nova project consists of a 10-beam, 74 cm aperture neodymium-glass laser experimental facility which is being constructed by the Lawrence Livermore National Laboratory (LLNL) for the U.S. Department of Energy. Nova has a total estimated cost of $176M and will become operational in the Fall of 1984. The Nova laser will be used as the high energy driver for studying the regime of ignition for ICF.

The Nova assurance management system was developed using the quality assurance (QA) approach first implemented at LLNL in early 1978. The LLNL QA program is described as an introduction to the Nova assurance management system. The Nova system is described pictorially through the Nova configuration, subsystems and major components, interjecting the QA techniques which are being pragmatically used to assure the successful completion of the project.

Inertial Confinement Fusion - What is it?

One technical approach to the problem of controlling thermonuclear fusion reactions is to bring small deuterium-tritium (D-T) fuel pellets to very high temperatures and densities in such a short time that the thermonuclear fuel will ignite and burn before the compressed core disassembles. This approach, known as inertial confinement fusion (ICF) relies upon a driver (e.g., a laser) to deliver the extremely high power, short duration burst of energy required. The ICF concept is illustrated in Figure 1. The basic principles were demonstrated successfully in the nuclear weapons program as early as 1952. A wealth of technical information on this subject is found in reference (1); appropriate material in this paper is derived from these publications.

A laser can initiate a thermonuclear reaction by rapidly heating and evaporating the outer layers of a spherical container. The ensuing blow-off of vaporized material drives a rocket-like implosion of the contained fuel. At the peak of the compression, the fusion reaction ignites at the center of the fuel mass and a thermonuclear burn propagates outward through the rest of the fuel during the very brief time (less than a tenth of a billionth of a second) that the pellet remains together by its own inertia. Energy is released in the form of energetic neutrons as the deuterium and tritium nuclei fuse into helium.

LLNL has been involved in the national ICF program since the early 1960's. The objectives of the program have been twofold: in the short term to develop the military application of ICF and in the long term to evaluate ICF as an energy source.[(2),(3)] The scientific objectives are the demonstration of high compression (100-1000 times liquid D-T density), ignition of thermonuclear burn, scientific breakeven (in which energy incident on the target equals the thermonuclear energy released), and significant energy gain in an ICF experiment.

A laser is used as the high energy experimental driver system required to rapidly heat the surface of the fusion target. A typical D-T fuel microsphere is shown in Figure 2 on an ordinary pin head to illustrate the size of the target upon which the high energy laser light is concentrated.

The Laser Fusion Program at LLNL - Its history and status

Over the past several years, LLNL has built and operated a series of increasingly more powerful and energetic laser systems to study the physics of ICF targets and laser-plasma interactions (Figure 3). Solid-state neodymium lasers were selected because this technology was most advanced with respect to producing high peak power. Janus[(4)], a small two-beam laser system, produced 0.4 terawatts (TW) of power. With Janus, laser-driven D-T implosions produced early proof of the thermonuclear nature of the reaction. Cyclops[(5)] was the developmental test-bed for Janus, Argus, and Shiva. It was the first laser worldwide to deliver 1 TW. Argus[(6)], designed as a 3 TW system, actually delivered 4.6 TW from its two laser beams. Shiva[(7)] was a 20-beam, 20.8 cm aperture laser system which delivered up to 30 TW or 10 kilojoules (kJ) on target. Shiva was the first laser system to produce in excess of 100 times D-T liquid densities and a record fusion target neutron yield in excess of 3 x 10^{10}.

Nova, the latest in this series, is the successor to the Argus and Shiva lasers. The Nova laser will consist of 10 beams capable of concentrating 80-120 TW of power (in 100 ps) and 80-120 kJ of energy (in 3 ns) on experimental targets by the mid 1980's. Like its predecessors, Nova will be a neodymium-glass (Nd:glass) laser system with a working wavelength near 1.05 μm. However, in experiments at the University of Rochester,[8], and at LLNL[9] the frequency of the fundamental 1.05 μm light from high-power Nd:glass laser was doubled and tripled with efficiencies exceeding 70% by using the nonlinear optical properties of potassium dihydrogen phosphate (KDP) crystals. Since shorter wavelengths are much more favorable for ICF laser target physics, this option will be implemented in the Nova facility. Nova will thus be able to focus approximately 80 kJ of green (0.53 μm) or "blue" (0.35 μm) light onto laser fusion targets. The total cost of the Nova project, including an office building and a laboratory building, will be $176 million and the experimental facility will be available to start fusion experiments in the Fall of 1984. It is expected that Nova when operated using blue light will have sufficient energy to study the regime of thermonuclear ignition.

The Nova Laser System

Nova is an example of a large design, construction and installation project conducted in a research and development laboratory. It is a one-of-a-kind facility which will be operated by the same people who designed and constructed it. The Nova project management strategy is to maintain responsibility for the design and to assume the inherent risks. On-site engineering support is provided by Kaiser Engineers, Bechtel Corporation, and Bendix Corporation to supplement the LLNL Nova engineers and scientists. This allows LLNL to maintain a level work force and provides early technology transfer to industries which are likely to be involved in future fusion reactor energy applications. The management strategy is to award greater than 70% of the total project cost to industrial suppliers who fabricate Nova hardware on build-to-print contracts using well established fabrication and inspection techniques for their industry. The net result is reduced risk for the suppliers and reduced costs for Nova. Contracts for critical components are awarded to multiple suppliers whenever possible. This assures management that unforeseen problems will not jeopardize the Nova schedule and that competitive, fixed price contracts can be awarded.

The Nova laser system has a master oscillator power amplifier (MOPA) architecture. As shown in Figure 4, a laser pulse of requisite temporal shape is generated by the oscillator, preamplified, and split into 10 beams. After traversing an adjustable optical delay path (used to synchronize the arrival of the various beams at the target), the pulse enters the amplifier chain where (1) amplifiers increase the pulse power and energy, (2) spatial filters maintain the spatial smoothness of the beam profile while expanding its diameter, and (3) isolators prevent the entire laser from breaking spontaneously into oscillations that could drain its stored energy and damage the target prematurely.

When the pulse exits from the final beam-expanding spatial filter, it has been amplified to an energy level of 8-12 kJ, and its diameter is 74 cm. Turning mirrors direct the beam to the target chamber, where a focusing lens concentrates it on the target. For operation at the second or third harmonic frequency, KDP crystal arrays are located just in front of the fused silica focus lens on the target chamber vessel.

An artist's cutaway drawing of the Nova layout is shown in Figure 5. The conventional construction segment of the Nova project, the 115,000 $ft.^2$ laboratory building in which the 10 beam laser system will be installed and the 59,000 $ft.^2$ office building were completed in June 1982. The 60 megajoule capacitor bank which powers the system flashlamps is directly below the laser. Figure 6 is an aerial view of the Nova construction site showing the laboratory building and the chevroned-shaped office building.

The Foundations of the Nova Assurance Management System

The Nova laser assurance management system is based on the policies of the formal LLNL quality assurance (QA) program established in March 1978. It was developed in response to (1) the introduction of large Congressionally funded line-item projects at LLNL, such as Nova and the Magnetic Fusion Test Facility (MFTF), (2) increased emphasis on cost and schedule constraints, and (3) LLNL management's concerns about recent incidents, aging facilities, and "tenyearitis" (ie., sometime within ten years, personnel and equipment performance will naturally deteriorate to the point where a serious accident or costly equipment failure may result unless action is taken to monitor the performance and assure it is maintained above a desired level).

LLNL's approach to QA is shown in Figure 7 and emphasizes assigning responsibility for QA to the line organization, ie., the person responsible for the quality of the results. The line organization has responsibility for both achieving and assuring its organizational objectives. The approach uses planning to prevent incidents and defects. It provides feedback through the independent audit process which leads either to correction or improvement depending upon the level of quality most appropriate to the organization's programmatic objectives. The approach uses the existing "tools of quality" and "good engineering practices" which have sustained LLNL's successful achievements prior to their being formalized through the current LLNL QA program. Several of these "tools of quality" and "good engineering practices" will be described later in this paper.

The LLNL QA program is documented in a 14 page manual which scopes management responsibilities and provides guidelines for implementation [10]. A small staff of engineers (5 people) is assigned to the LLNL Quality Assurance Office to assist the line organization with planning, training, audits, and to prepare and maintain the laboratory's QA manual.

The lack of a formal DOE policy or regulation on QA allowed sufficient latitude to invent a QA system which was tailored to the Nova project. Nova's assurance management system is an integrated approach which addresses QA functions, personnel and system safety, and configuration management in a single document. Historically, these assuring activities are addressed in separate plans. Including all assuring activities in one plan greatly reduced the redundancy inherent in separate plans, the length of the plan, and the effort to implement the plan. The Nova laser assurance management system evolved from the LLNL QA Program and was initially released in September 1979. The LLNL QA office provided professional support to help Nova's project management and engineers prepare their assurance plans.

The Nova Project Manager's guidelines for preparing the Nova assurance plan were to (1) assign assuring responsibilities to those individuals responsible for the quality of the work, (2) use the good management and engineering practices established on Shiva as the base for the plan, (3) formalize the Shiva practices and provide for documenting results, (4) be consistent with LLNL safety and QA policies, and (5) provide for periodic and independent reviews and evaluations.

The controlling document is the Nova Master Assurance Plan. This document was prepared by the Nova Project Manager and approved by the Deputy Associate Director for Laser Fusion. The plan is supported by a series of informal subordinate assurance plans which were prepared by the responsible subsystem project engineers. The master plan includes all the assuring requirements for the project and is the basis for all audits. It is a good match with LLNL Laser Program Management's concerns for performance and safety. The plan is accepted by both the DOE and the Nova team as an effective means for assuring the successful completion of Nova.

A Description of Nova's Major Subsystems and How Effective Assurance Techniques are Being Applied

Figure 8 shows the building blocks that depict the system configuration of Nova. The laser chain components described earlier are shown in the bottom row of boxes. The chain is supported by (1) power systems which provide electrical energy to the amplifier flashlamps, (2) alignment and diagnostics which direct the laser beams to the target and measure the laser's performance, and (3) data acquisition systems which measure the results of the experiments. All these subsystems are activated and monitored by a hierarchical computer control system. The next several figures will pictorially present these subsystems and some of their major components. The features of the Nova laser assurance management system will be interjected in the narrative to graphically demonstrate how effective QA techniques are being implemented for Nova.

Nova is a huge optical system and requires very stable optical supports for mounting and aligning the laser components. The south laser bay spaceframe shown in Figure 9 is 62 meters long, 3 meters wide and 10 meters high. There are two parallel spaceframes and the components for five (5) laser chains will be mounted on each frame.

Figure 10 shows the optical switchyard spaceframe upon which turning mirrors as large as 109 cm in diameter are mounted. These mirrors direct the 74 cm laser beams into the target bay and the alignment and diagnostics sensors. The target bay spaceframe is 19 meters high and covers an area of 22 x 15 meters^2. The Nova target chamber will be mounted on this frame and the chamber's center will be aligned to an accuracy of $\pm$ 0.5 mm. LLNL mechanical engineers designed all the spaceframes and presented their conceptual, preliminary and detailed designs during formal design reviews attended by a broad cross-section of Nova project management and engineers. Safety issues and corrective actions were presented in preliminary hazards analysis. Approvals to proceed with each phase of the design were obtained through the review process and design review minutes and action items were prepared. Extensive use was made of computer codes which modeled the loads and seismic forces on the frames and their resonant frequencies. The Nova spaceframe designs are similar to Shiva's. An unschedule verification test of the Shiva seismic design features occurred during a 5.5 Richter earthquake in January 1980. The seismic anchors released as designed and there was no damage to any optical component in all 20 beams. Computer aided design/computer aided manufacture (CAD/CAM) was used to assure that there are no interferences among the various components mounted on the spaceframes. The frames were fabricated off-site in modules which were field-welded in the Nova laboratory building. The resultant overall accuracy of the as-welded frame was measured to be 3 mm over the entire 62 meter length of the laser spaceframe. Shim plates provide the final mechanical pre-alignment accuracy of $\pm$ 1.5 mm over the entire vertical plane of the spaceframe. Harmonic resonance tests of the spaceframes confirmed computer code predictions for all the spaceframes.

Nova when it is completed will be the world's largest optical instrument. The finished optical surface area of all the Nova optical components is put in perspective in Figure 11 by comparing it to the 200 in. reflecting telescope on Mt. Palomar and the Large Space Telescope. A "standard man" is shown at the far left. Some of the 109 cm diameter borosilicate turning mirror blanks produced by Schott Optical are shown in Figure 12. These mirror surfaces are subsequently finished by either Eastman Kodak or Zygo Corporation to front surface accuracies of better than 1/12 wavelength at 633 nm. This represents flatness to within 5 µm.

Flat lapping facilities were constructed as part of the project at both suppliers' facilities. Figure 13 is the 4 meter diameter flat lapping machine at Kodak which can finish three 109 cm mirrors at one time. Required temperature, table revolution rate, and other critical parameters are maintained under computer control. After finishing, the mirrors are coated by either OCLI or Spectra-Physics with multiple layers of thin-film, high reflectivity dielectric coatings. A coated mirror being inspected at OCLI is shown in Figure 14.

As part of the procurement process, a series of pre-bid and pre-award reviews are conducted in a similar fashion to the formal design reviews described earlier. Suppliers included on the qualified bidders list are asked to bid on Nova procurements. This list was developed based on experiences with predecessor laser systems. During the procurement reviews, management not only selects the supplier(s) to be awarded the contracts, but also the strategy for splitting the quantities such as to assure a fallback position if difficulties are encountered. The reviews are documented and provide the basis for notifying the buyer to proceed with the awards.

Engineers in the Optics group make frequent visits to check on the suppliers' progress. Source inspections are used for acceptance because of the extensive amount of handling and shipping among the optics fabricators, finishers, and coaters. Detailed acceptance test reports are prepared and delivered with each optical component. Final acceptance of the as-finished or as-coated optic is confirmed at LLNL using inspection equipment common to that at the suppliers' facilities.

The Nova amplifiers combine mechanical, optical, and power systems designs. The Nova prototype 46 cm amplifier shown in Figure 15 is the largest amplifier in the system; there are four 46 cm amplifiers in each Nova laser chain. Each amplifier has split disks which are mounted at Brewster's angle to minimize reflections. The disks are fabricated by Hoya Optics and Schott Optical and are finished by Kodak and Zygo. The phosphate based neodymium-doped laser disks are split to suppress internal oscillations which drain the energy stored in each disk. The flashlamps run along two opposing sides of the rectangular mechanical structure, facing the installed disks. Each flashlamp is backed by a silver-plated crenulated reflector, which reflects the light into the disk faces. An electroform process is used to "grow" these reflectors. Flat, silver-plated walls form the top and bottom walls. Careful design of the rectangular Nova amplifiers has made possible an efficiency improvement of a factor of two over the cylindrical amplifiers used in the Shiva laser system. This full scale prototype was tested to confirm the design criteria prior to release for bidding of the mechanical, laser glass and flashlamp drawings.

The plasma physics experiments on Nova related to fusion target development will be performed inside the evacuated target chamber shown in Figure 16. Five 74 cm laser beams are equally spaced in angle on each of the 2.3 meter radius hemispheres. The laser beams are all focused to a common spot at the center of the chamber (<250 μm in diameter or ~3 times the diameter of a human hair) where the fusion target will be positioned.

The Nova target chamber was formed, welded and vacuum integrity tested at a pressure of 10^{-7} Torr by Chicago Bridge and Iron Company (CBI). It was ascertained that the Nova target chamber had a leak rate of $<10^{-8}$ STD ATM cc/sec. These tests were observed by LLNL technicians. This 13 cm thick welded aluminum chamber will accommodate component mounting without undue deflection, strain, and consequent component misalignment. LLNL designed the chamber and performed computer code stress and load analyses prior to finalizing the design. Weld samples were prepared by the fabricator and tested to qualify the weld procedures.

Mounted on the target chamber will be ten (10) frequency conversion arrays and focusing lens positioner assemblies; one of which is shown in the artist cutaway (Figure 17). The aspheric focusing lenses serve as the vacuum barrier and are finished by Eastman Kodak and Tinsley Laboratories to surface accuracies of better than 1/4 wavelength at 633 nm. Since each lens must travel several centimeters to focus the various operating wavelengths on the fusion targets, a precision drive mechanism capable of moving this massive optic against atmospheric pressure was designed and full scale prototypes were fabricated and tested.

The multi-optical-element KDP frequency conversion array is located outside the vacuum barrier and consist of two sets of KDP crystals sandwiched between transparent fused silica windows. Corning Glass Works and Heraeus Quartzschmelze are the suppliers of the high quality, essentially bubble-free, fused silica blanks for the windows and the focusing lenses. A 77 cm clear aperture prototype array is shown in Figure 18. The KDP crystals are located in a 3x3 matrix in the array. These crystals are being grown as large boules by Cleveland Crystals and Inrad (Figure 19). Growth of the boules from their seed crystals requires several months of continuous growth under carefully controlled conditions. The smaller boule shown was the state-of-the-art for this type of crystal as recently as 5 years ago. As a result of close cooperation between LLNL and these suppliers, crystal boules up to 40 cm on a side are being grown with relatively high yields.

In order to achieve the desired second and third harmonics of the fundamental neodymium wavelengths, these KDP crystals must be cut to within 30 μrad of the appropriate phase-match angles. The finished KDP crystals for Nova are 1 cm thick and 27 cm x 27 cm square as shown in Figure 20. The sides and faces of the plates are micro-machined using single-point diamond turning technology which has been proven at LLNL with full size crystals and formally technology transferred to U.S. industry. The machining accuracy is ± 1 μm and the surfaces of the plates must be parallel to within ± 1.5 μm. LLNL has developed laser phase-matching equipment which uses a KDP crystal whose phase-match angle is known to within ± 5 μrad as the reference standard for measuring all other crystals. Identical phase-matching inspection equipment will be located at Cleveland Crystals and Pneumo Precision, the two suppliers selected to diamond turn the crystals.

The majority of the Power Systems are housed in the basement of the Nova building. Figure 21 shows one of the 17 rows of capacitors which comprise the 60 megajoule capacitor bank. LLNL designed the power systems to simultaneously meet performance, cost, reliability and noise reduction goals. The approach was to improve on known performance from the Shiva system and to thoroughly test each design and component including the associated controls and software under actual operating conditions using a 1 megajoule prototype bank system. Nova will have more than 2000 capacitors supplied by General Electric and Maxwell Laboratories and 6000 flashlamps supplied by ILC and EG&G. Reliability is a major concern and extensive qualification and accelerated life-cycle test programs were conducted for these components.

Seven 1.5 MVA power supplies, furnished by Aydin Power Systems draw energy from the commercial power company to do the majority of the charging of the capacitors. Typically charging times are 30 seconds; while the capacitors are discharged through ignitron switches to the flashlamps in less than 700 μsec.

The detailed design parameters for the power supplies were specified by LLNL. Aydin prepared the detailed mechanical drawings and fabricated one pre-production model for acceptance testing at LLNL. Upon verification of acceptable performance, Aydin was authorized to proceed with fabrication of the remaining six units. The power supplies, shown in Figure 22, met all the design specifications and were delivered on schedule as part of a fixed price, competitively bid contract.

The output sensor module shown in Figure 23 is one of many components included in the alignment and diagnostics subsystems. This sensor was designed cooperatively by LLNL and Aerojet Electro-Optical Systems on a cost-plus, performance type contract. This is one of the few exceptions to fixed price, competitive, build-to-print procurements for Nova. Aerojet had worked closely with LLNL on the Shiva alignment and diagnostics sensor and had the design talents available to complement LLNL's. The deliverables on the contract were one operational prototype sensor and a complete set of detailed engineering drawings from which the 10 Nova sensors could be built. Nova system design changes caused several changes to the drawings. The final drawings were released for competitive, fixed price bidding on a build-to-print basis and resulted in a very favorable cost.

The Nova control system architecture is schematically shown in Figure 24. Complex systems like Nova, requiring literally hundreds of electronic and electromechanical control functions for a single laser target experiment, must rely upon an extensive, sophisticated computer control network. The control system architecture is designed to handle multiple tasks from a centralized location. Common hardware and software routines allow functional redundancy. A major software development in Nova was the design and implementation of the PRAXIS high level programming language. PRAXIS was conceived originally as "COL" by Bolt, Beranek and Newman, Inc. and has control system oriented features which increase the readability and corresponding maintainability of system software.

The Nova control system architecture including the software was developed by LLNL. A single Digital Equipment Corporation (DEC) VAX 11/780 computer was procured early in the Nova project in order to establish a developmental operating control system. This prototype system was used to checkout control system hardware designs and software. The development VAX will continue to be used after Nova becomes operational to make software changes off-line and thus maintain configuration control of the operating system software. A software subordinate assurance plan is being prepared to assure the software designs are controlled as effectively as the Nova hardware.

Nova has an effective and demonstrated assurance management system - Novette

In August 1981, Laser Program management decided to construct a two beam laser system named Novette. Novette was required to continue laser-target experiments after the Shiva system was shut down. Novette uses two arms of Nova each of which has the total energy capability of all 20 beams of Shiva.

In addition, Novette operates at the second harmonic (green light) which is essential to confirm target yield scaling at shorter wavelengths. Novette was constructed in the Argus system laser building.

Novette is an operating test bed for Nova. Each of Novette's arms has demonstrated short-pulse (100 ps) operation at 1.05 μm of 12 to 13 TW and subsequent conversion to 6 to 7 TW at 0.53 μm. Novette is currently operating in a longer pulse (1 nsec) configuration and has delivered >5kJ of 0.53 μm light to targets. Initial experiments are confirming the Nova system design parameters.

The photographs shown in Figure 25 demonstrate the effectiveness of the Nova laser assurance management system. In December 1981 the Argus laser system was completely removed from its building and Novette construction began. In January 1983, thirteen months later, Novette was performing laser fusion plasma experiments. The assurance techniques developed for Nova were used on a day-to-day basis to successfully construct Novette; proof positive that Nova has an assurance program that works.

Summary - An effective QA program can result from formalizing and properly performing a significant few assurance actions.

The Nova project is an excellent example of how quality assurance techniques can be effectively applied to a state-of-the-art, one-of-a-kind, large research and development project. The Nova laser assurance management system applies these techniques primarily where they are most beneficial, ie., to design and procurement as was described in this paper. The effect on the Nova project is positive and is assisting management toward the successful completion of the project in the Fall of 1984.

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*Research performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

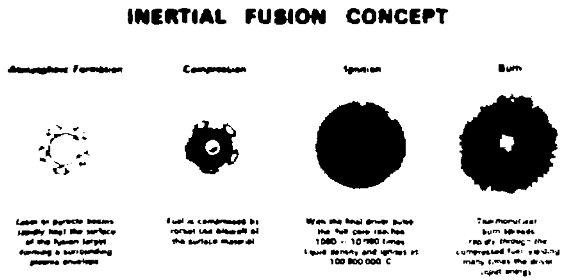


Figure 1

Figure 2

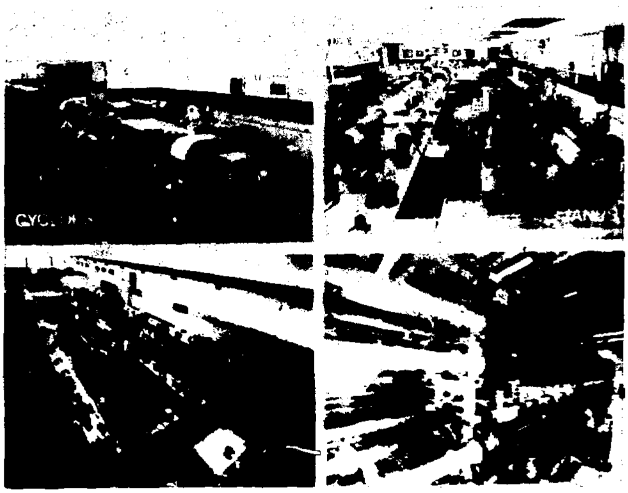


Figure 3

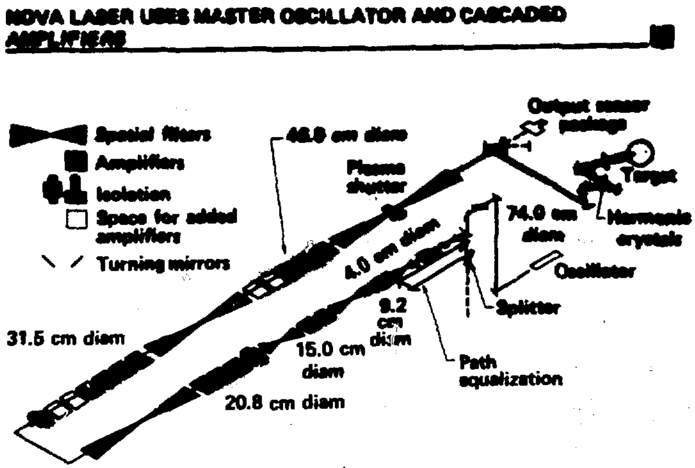


Figure 4

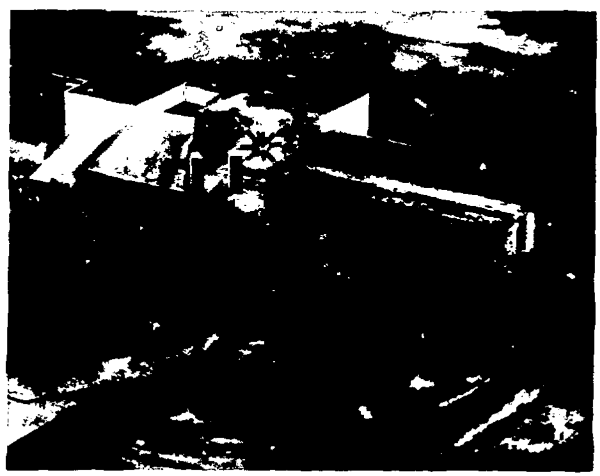


Figure 5

Figure 6

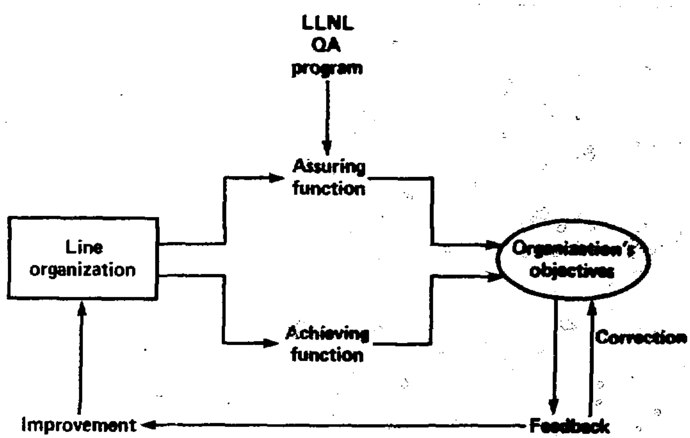


Figure 7

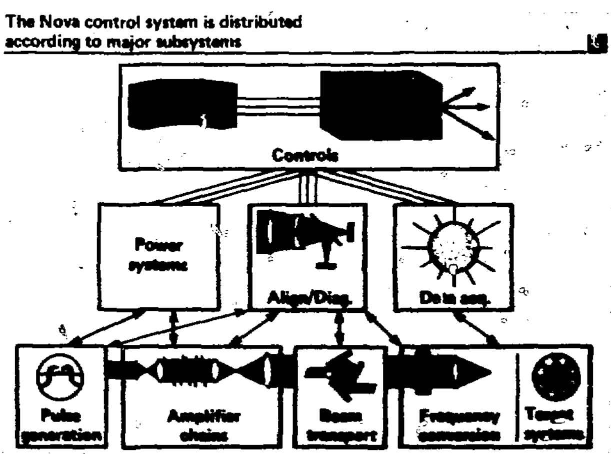


Figure 8

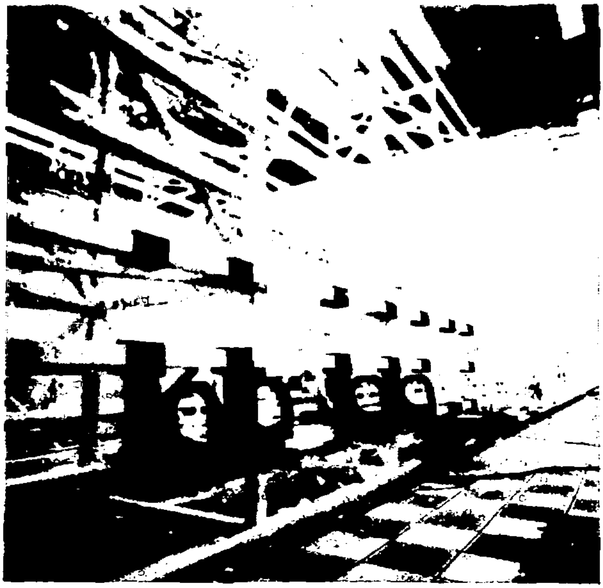


Figure 9

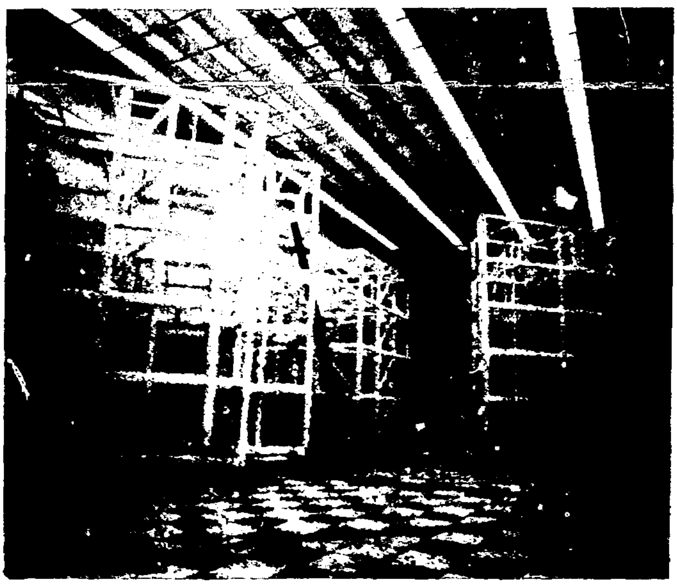


Figure 10

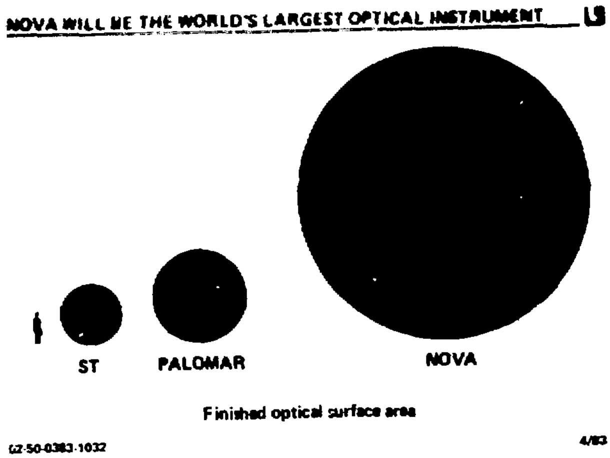


Figure 11

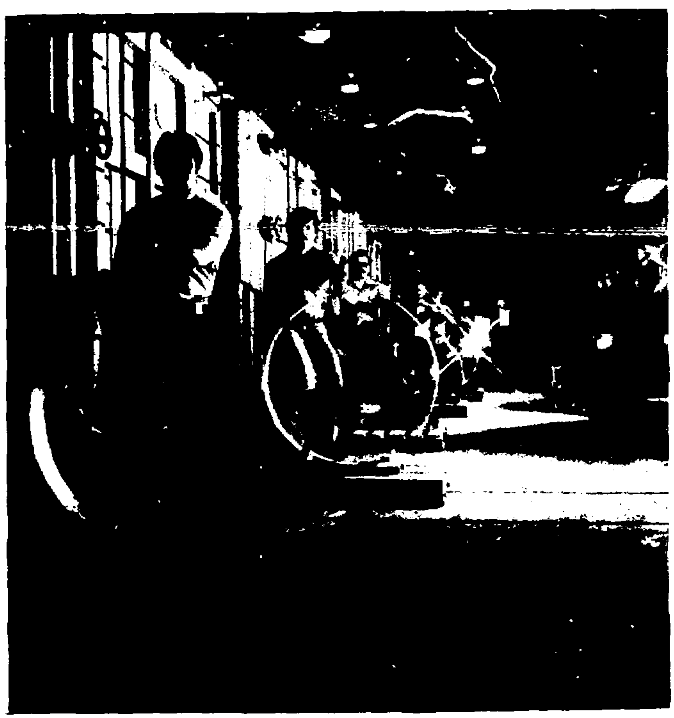


Figure 12

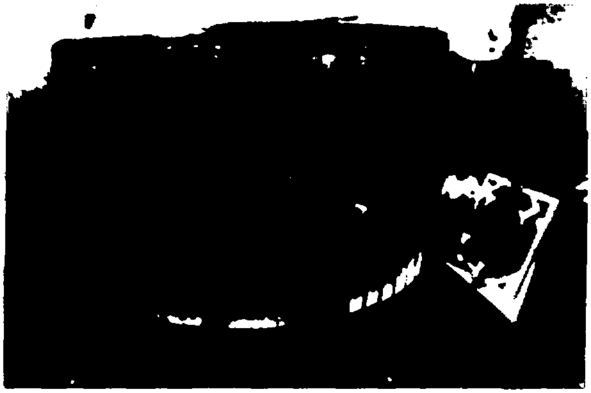


Figure 13

Figure 14

THE LARGE NOVA/NOVETTE 46 cm SEGMENTED AMPLIFIERS HAVE A SMALL SIGNAL GAIN OF TWO AND STORE 8 kJ OF OPTICAL ENERGY

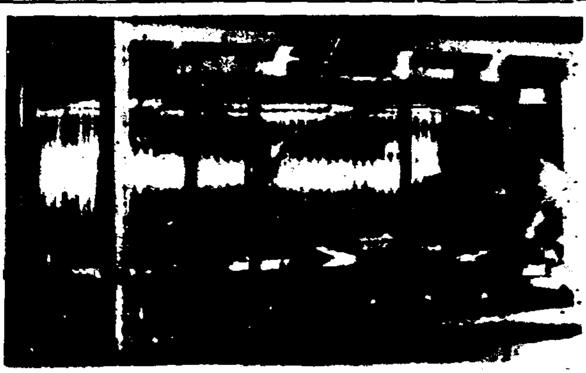


Figure 15

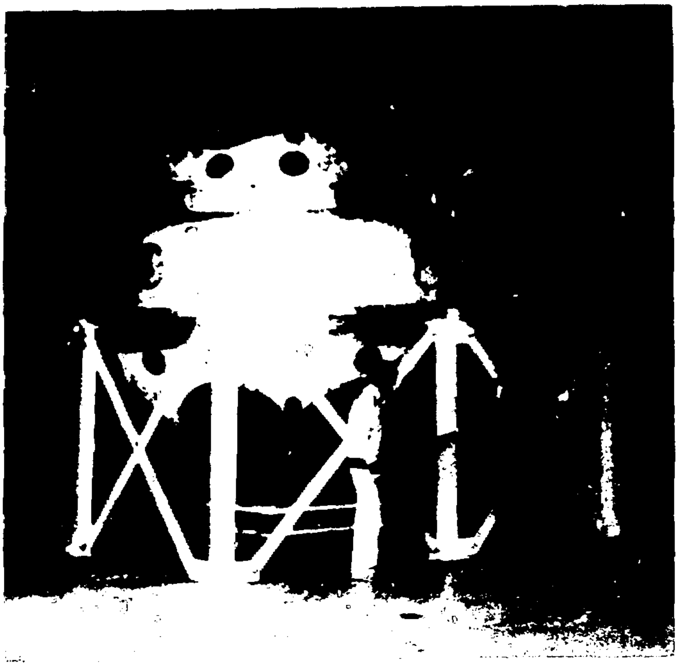


Figure 16

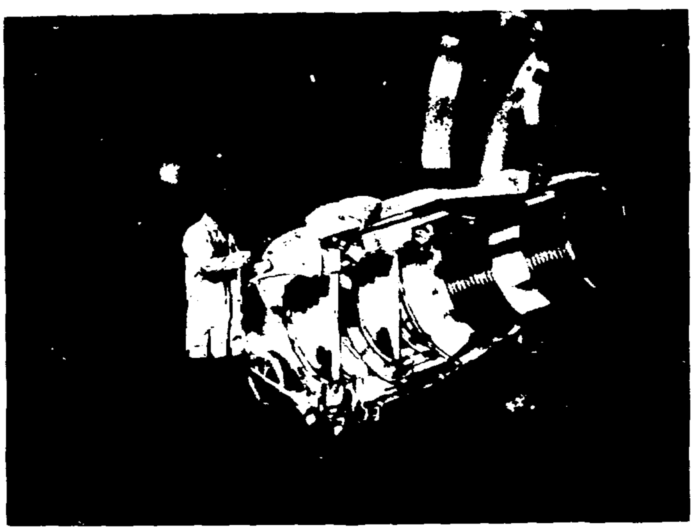


Figure 17

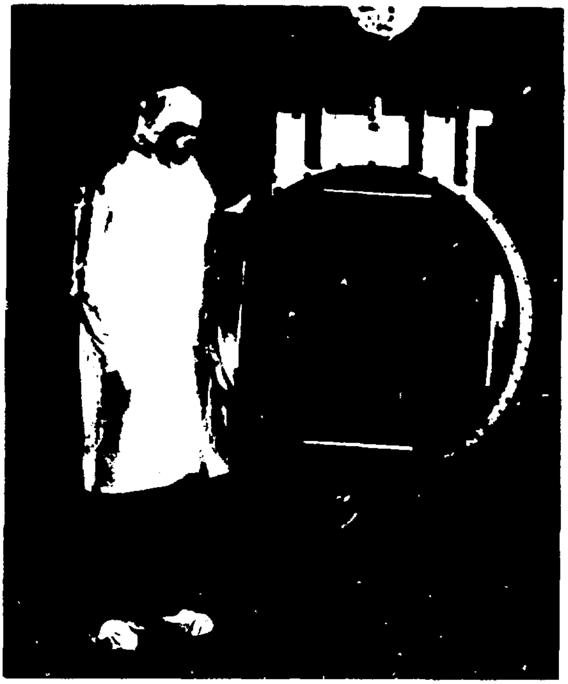


Figure 18

Figure 19

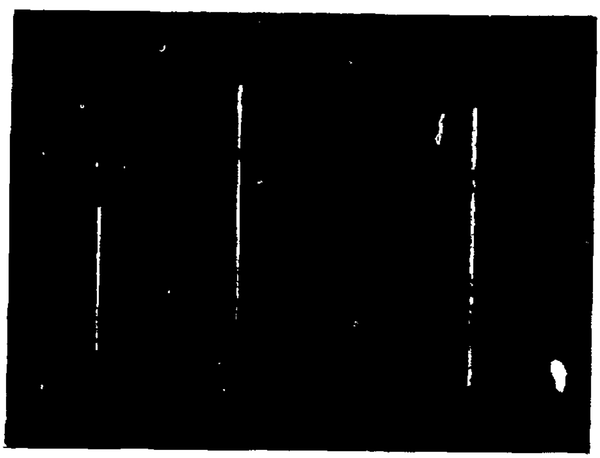


Figure 20

Figure 21

Figure 22

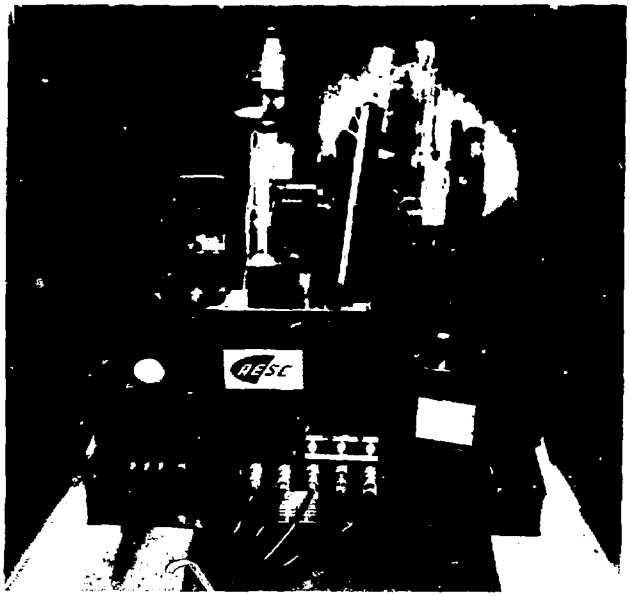


Figure 23

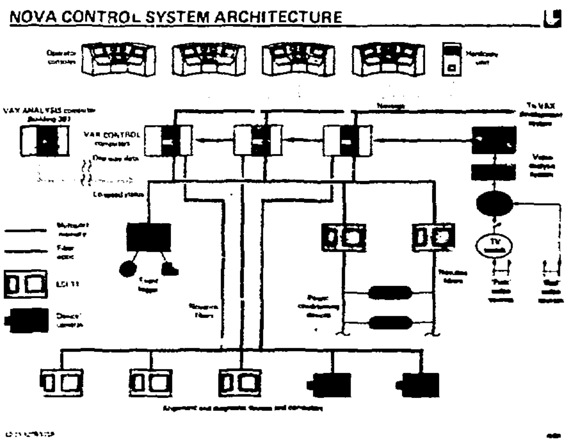
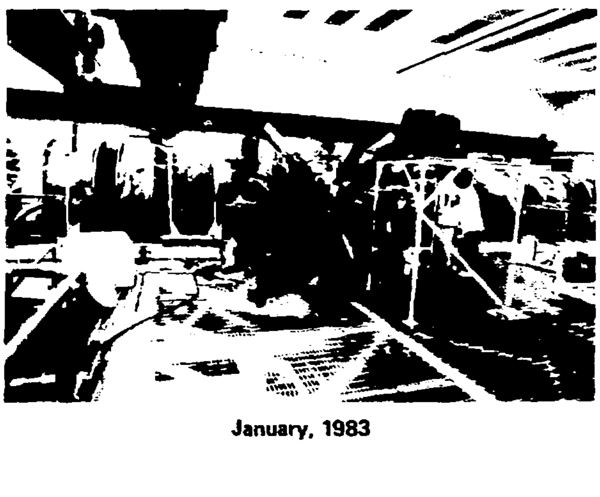


Figure 24

NOVA HAS AN ASSURANCE PROGRAM THAT WORKS

December, 1981



January, 1983

Figure 25