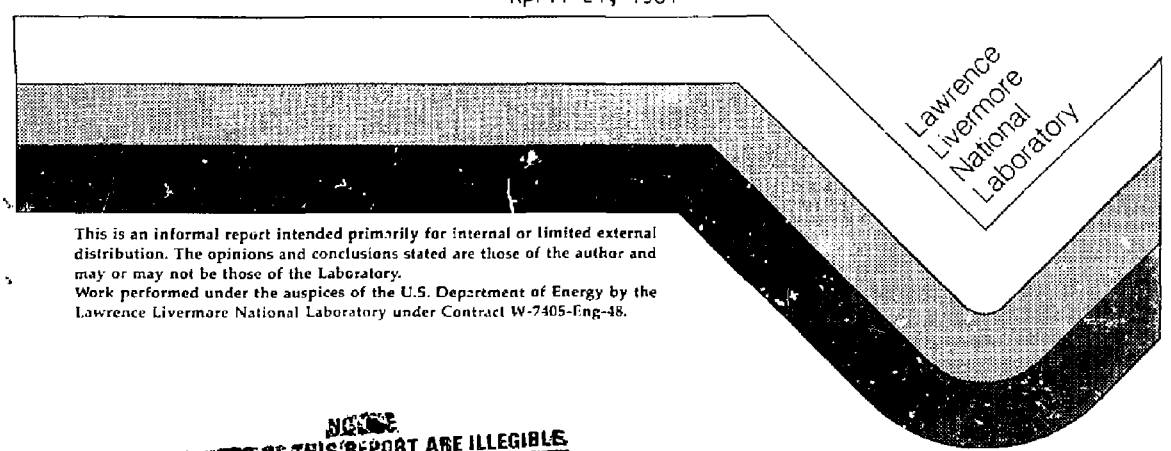
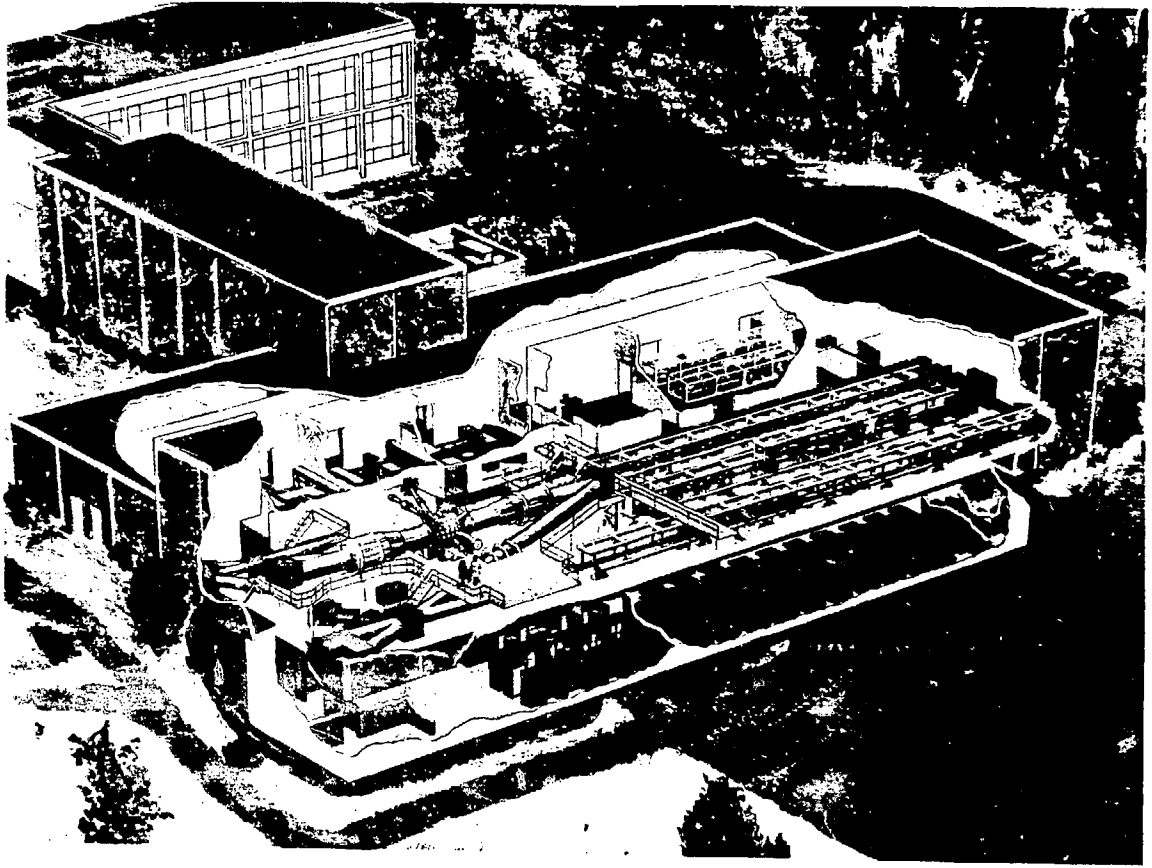
THE NOVETTE PROJECT - COST & SCHEDULE

K. R. Manes

April 24, 1984





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INTRODUCTION

When an extremely intense beam of laser light strikes a microscopic target containing deuterium-tritium fuel, it can generate an energetic plasma by imploding the fuel capsule. The rapid rise in temperature and density in the inertially confined D-T fuel produces a tiny but powerful thermonuclear explosion. The Lawrence Livermore National Laboratory has been the scene of active inertial confinement fusion, or ICF, research since 1969, with the goal of eventually achieving usable power from a future ICF reactor.

As recently as 1979, controversy raged over the relative effectiveness of different lasers as fusion drivers. Today the preponderance of evidence favors a green to near-ultraviolet laser and we have assembled such a source for multikilojoule target experiments. The Novette laser-target interaction system fulfills this requirement by combining salvaged components from earlier LLNL lasers such as Shiva, once the world's most powerful, with parts borrowed by Nova, a 100 kJ device now under construction and scheduled for completion in late 1984.

Novette was assembled on an accelerated schedule in an existing building adjacent to the new Nova laboratory. Novette includes complete Nova style controls, the refurbished Shiva target chamber, and a complete

suite of target diagnostics. The Novette test bed construction began in January of 1982 and system activation was completed in thirteen months. Today, Novette delivers 18 kJ pulses 1 nsec in duration which are then frequency doubled and focused on to targets. During 1983, a large body of data was gathered concerning the performance of Novette as a system.

Each of Novette's two beam lines is optically very similar to a Nova arm and so the emerging beams are seventy-four centimeters in diameter. Harmonic conversion takes place in two unique mosaic arrays of type II potassium dihydrogen phosphate (KDP) crystals. The two 4.5 TW green laser pulses so produced are concentrated onto targets by two, seventy-four centimeter aperture f/4 doublet lenses. Since the two pulses arrive at the target within five picoseconds of each other, a typical target may be irradiated essentially simultaneously from two sides by about 9 kJ in one nanosecond. About half of Novette's experimental time has been devoted to plasma physics studies whose aim is to better understand short wavelength laser-plasma interaction phenomena relevant to inertial confinement fusion. The balance has been divided between high density implosion research and non-local thermodynamic-equilibrium plasma experiments. In short, Novette provides a high energy density, flexible experimental facility which bridges the gap between Shiva and Nova while simultaneously probing each detail in the Nova design. Formally, Novette was created to address the issues listed in Table 1 during 1983 and 1984.

Table 1 - Novette Mission

* Novette should explore target physics
  - Wavelength scaling of ICF targets
    - Coupling of laser to plasma
    - Drive tests
    - Preheat generation
    - Symmetry and stability of implosions
  - X-ray laser tests
  - Weapons physics studies
* Novette should test Nova concepts
  - System design
    - Pulsed gain
    - Insertion losses
    - Cumulative aberrations
    - Nonlinear propagation
  - Operations issues
    - System maintenance
    - System alignment
    - Target focusing
* Novette should provide a test bed for
  - Large aperture harmonic generation
  - Pulse shaping
    - Nonlinear propagation
    - Gain saturation
    - Frequency conversion

ORGANIZATION

The Novette project was launched by the memorandum reproduced in Figure 1 in June of 1981. By that July, a small project office led by Ken Manes, as project scientist, Ralph Speck, the project engineer, and Greg Suski, their deputy project manager, had been created under Bob Godwin, the Nova project manager. The Novette team was given budgetary control and charged with coordinating the efforts of the Nova project staff in building Novette. In essence, Novette was the product of a matrix project management style. From the start, Novette's first priority was schedule. Its budget was drawn from the ICF program funding and was consequently somewhat adjustable; i.e., the option always existed not to carry out some less important part of the ICF agenda. Its performance was known only to the extent that Nova simulation calculations could be trusted and was, in any case, to be a "best effort."

The organization chart in Figure 2 shows how Novette fit into the larger Nova effort in early 1982. Although Novette is optically very similar to Nova, there were many practical differences. For example, Novette's beams had to be folded twice in order to fit into the space previously occupied by the Argus laser system and Novette's final optical train had to be designed. Nova's output design was still in flux at this time, but it was soon clear that Novette would be quite different since the emerging Nova plans could not be implemented on Novette's schedule. The Novette team called for design reviews of each Novette subsystem and

participated in the design of each "Novette unique" component. In March of 1982 alignment of components started in the refurbished facility necessitating the formation of an activation group. Weekly issues meetings were supplemented by daily status and coordination meetings. At about this time, computer controls coordination weekly meetings were initiated. Many technical details were worked out as they came up in these gatherings.

By early 1983 with the laser completed, Novette was turned over to the Laser Operations Group, and was integrated into the Laser Systems and Operations Program as indicated in Figure 3. Staff changes reflect our operational status and the need to transfer personnel at all levels who were skilled in activation to build Nova. Novette's first year was spent supporting target experiments, accumulating laser propagation data and debugging Nova hardware. Most of the necessary scientific and engineering talent resided within the Nova project as before. Time permitting, these workers helped to solve numerous operational problems so long as doing so did not adversely impact their primary job, building Nova.

ACTIVATION SCHEDULE

Adaptation of the Nova baseline design to fit into the Argus highbay laboratory began in earnest in early 1981 led principally by John Hunt and Ralph Speck. When the Novette team was established in July of 1981,

one of its first tasks was to arrive at an activation schedule in concert with the Nova engineers. Figure 4 is the final "as built" schedule for the construction phase of the Novette project. Figure 5 is a sampling of installation photographs.

The Argus laser fired its last shot August 31st and removal of components began the next day. Novette's master oscillator room was the first area prepared and it was ready for equipment installation by December, 1981. Meanwhile, power conditioning installation was underway in the basement. Shiva was shut down at the end of December and many components such as power supplies and oscillators moved to Novette; the Shiva target chamber went to the machine shop for rework.

Portions of the spaceframe were delivered, and clean room assembly of some of the largest components was begun, in January of 1982. In February, the various spaceframe sections were aligned, welded together, and painted. Installation of utilities, electricity, and nitrogen plumbing, began in early March. Preliminary alignment of the laser component mounting hardware continued through March, and by the second week of April the facility was ready for the installation of the first of the laser optical components. The refurbished Shiva target chamber was also delivered and installed at this time. A second shift was instituted shortly thereafter to begin the testing of the optical amplifiers and the power conditioning system that supplied energy to them. Various alignment devices were being installed at the same time. Through May and

June, the south driver chain (through the 315 mm diameter aperture) was installed and tested, and on the ninth of July, 1982, this section of the laser delivered 1 TW (96 J in 93 psec) to a calibrated laser diagnostic sensor in the southwest corner of the laser bay. The north driver chain was in operation by the end of August.

During that summer, integration of the central computer system software in the operation of the laser began. Control of the power conditioning functions was transferred to the touch-panel displays located in the Novette control room. The large laser components with optical apertures of 315 mm through 460 mm began to come from the clean room in August. By early September, all of the 315 mm disk amplifiers had been installed and output powers of 4.0 TW (north chain, 380 J in 95 psec) and 4.3 TW (south chain, 406 J in 95 psec) had been measured on separate shots. At this point Novette had become one of the two most powerful lasers in the world.

Through September, while the complex tasks of installing and aligning the Novette output sensors and assembly of the 460 mm disk amplifiers were in progress, the calibration and testing program of the laser started over at a new pulse length, 825 psec. The majority of the experiments performed on Novette have been carried out with pulse widths at least this long, although the very first testing was at 100 psec. The highlights of these tests were a pair of shots in which the north driver portion delivered 1765 J and the south driver chain, 2070 J.

Transfer of control of the laser diagnostics hardware to the control room touch-panels began in September and continued through October. Toward the end of October, the first of the 460 mm disk amplifiers were installed. Testing of these largest amplifiers continued through November, with a test shot of the south chain in mid-November delivering 11.1 TW (1097 J in 99 psec) to the east optical port of the target chamber. With this single-chain shot, Novette was the world's highest power operating laser. The first shot with the completed north chain was measured at 6 TW on November 30.

During December, 1982, the first of Novette's frequency doubling arrays was installed east of the target chamber. Testing of the conversion efficiency of this array assembly began immediately with the results showing a maximum efficiency of 78%, comparable to the theoretical maximum for these crystals. The target illumination optics were installed on the east and west ports of the target chamber and the laser beam path through the chamber determined. We found that 53 to 55% of the infrared laser energy delivered by each chain was converted to green light and delivered to targets under typical operating conditions; i.e. limited principally by losses in lenses and debris shield coated by target material. In the control room, the level of activity heightened with the addition of remote laser alignment capability to the touch-panels.

Novette irradiated its first target for diagnostic timing on December 16th. Over 2 TW of green power was transmitted without measurable loss

through a 500 μ pinhole located in the target chamber center on January 7, 1983.

As a test of Novette's high power capabilities and to prove its operation, a series of full power, two beam shots was begun. On January 24th the highest powers yet recorded for a two beam laser were achieved; *24.8 TW infrared converted to 12.8 TW green.*

Following the first x-ray laser experiments in April of 1983, two additional 460 mm output amplifiers were installed and the master oscillator pulse was lengthened to 1 nsec. Target studies proceeded with infrared energies of 8 to 9 kJ per arm converted to about 4 kJ of green energy per arm at the targets. By midyear, the program had decided to drop a plasma interferometry study, thereby relieving Novette of the task of delivering synchronized 20 psec probe pulses to the target area. A new x-ray backlighting requirement was established, however, and executed *as an upgrade to Novette. It was ready by January of 1984. Long pulse* oscillator studies using an Auston switch slicer started in late summer, but it was not until January of 1984 that target studies needed this capability. In the fall of 1983 the program chose to attempt to frequency double one of Novette's green beams to produce about 1 kJ of ultraviolet light per pulse. Added to the Operations Group tasks, this new challenge required help from Nova groups once again. By February, 1984, Novette was prepared for these "four omega" experiments which were successfully completed late in April, 1984. Novette's final scheduled experimental sequence, a second x-ray laser series, began at that time.

OPERATION SCHEDULE

During a sixteen hour working day, Novette would be limited to about eight target shots by the cooling of its output amplifiers and subsequent laser system realignment. On April 25, 1984 for example, six full system shots were performed as part of a 35 shot sequence of NOVA frequency conversion array tests. In practice, however, target and target diagnostic preparation and alignment have generally cut potential system usage by more than a factor of two. Dramatic reductions in productivity, measured by number of target shots per month, come at the beginning of an experimental sequence when an entirely new target type is first introduced. Initial 100 psec pulse duration x-ray laser studies were completed at the end of March, 1983, and wavelength scaling studies using one nanosecond pulses began. No target shots were performed in July due to the appearance of optical damage in Novette's frequency conversion arrays when they were subjected to more than 1.5 J/cm^2 in 1 nsec. They were removed, cleaned and reassembled and the laser diagnostics were recalibrated at this time. One nanosecond operation resumed in August so that by October, with the shot rate still steadily rising, targets of a similar geometry had achieved about 100x liquid DT density. The transition to a different series of target experiments lowered the shot rate once again in November. Figure 6 suggests that shot rates in excess of 50 target shots per month could be achieved if a standard target design were used.

The Novette nigh energy shots shown in Fig. 6 include "Target" shots, in which energy was delivered to a target, and "other" shots, which

include laser diagnostic system calibrations and Nova component tests. The target shots are difficult to categorize, because several types of targets were used, these targets were used for different purposes at different times, and a single target shot often served several purposes. For instance, a disk target might simultaneously check the laser spot size, verify operation of an X-ray microscope, and provide scaling data on Raman scattering. The following numbers, taken from a recent memorandum by Paul Drake, indicate the mix of targets and results obtained in the green-light experiments using spherical lenses from April 1, 1983 to March 7, 1984. A total of 181 targets were irradiated, of which 37 were used solely to set up and check out the laser and diagnostic systems; and 38 target shots failed to achieve the intended physics data. These failures had several causes, including failures of the laser system, the diagnostics, and target fabrication. The remaining 106 target shots produced useful physics data, although many of them served multiple purposes as indicated above. Of the 106 successful target shots, 23 included all the implosion shots. The memorandum just mentioned discusses the planning and execution of these experiments. They were productive, but they were less productive than had been hoped.

January, 1984 was devoted to completion of green target scaling studies and preparations for fourth harmonic target experiments. These ultraviolet experiments necessitated the construction of a new tandem 5x5 mosaic array of KDP crystals during November and December of 1983. A new design was conceived and executed in time to install this unique array in early January. Although it was subjected to over 8 kJ of infrared light,

this assembly suffered no damage. Altogether, by the end of 1983 Novette had irradiated 217 targets (most of which were "set-up" shots) and performed 257 laser related high energy tests for a total of 474 high power shots. This actually exceeded the 300 shot/year estimate made for early budget planning purposes.

Essentially a user facility, Novette delivers energies as specified on shot request sheets provided by experimenters. Communication with users has been excellent and they have generally requested laser performance within Novette's capability. Delivered energy has generally been within ± 10% of the requested value. Requested and delivered 2ω energies have clustered around 8 kJ in 1 nsec, limited primarily by losses in the large final optical components. This is not to say that target experimenters would not like 10 kJ or more in 1 nsec, but Novette has not been able to achieve this performance.

CONSTRUCTION COSTS

Figure 7 is a schematic drawing of the Novette facility indicating the origin of Novette's various parts. Much of the laser is made up of the first NOVA components delivered early in order to meet Novette's accelerated schedule. These parts must be moved into the NOVA laboratory before it is completed. A detailed budget tracking system was in place for the duration of the construction and operation phases (which augmented the usual LLNL budget tracking procedures). A project cost summary for the several operating accounts used to construct the Novette unique part of the project through the end of FY 82 is presented in

Fig. 8. Manpower loading for the construction phase is represented by a histogram showing technician man-months expended building Novette in Figure 9.

OPERATION COSTS

Imbedded in the Nova project, the Laser Operations Group is not a self-sufficient entity. It is difficult to measure the value of the many hours of help and advice provided by the Nova staff. It is clear, however, that Novette would not operate for long without their help. The documented cost of operating Novette during FY 83 was very predictable since it was dominated by worker's salaries. Figure 10 shows the cumulative expenditures incurred by Laser Operations in running Novette for two shifts per day during FY 83. Figure 11 is an organization chart showing the structure of the Laser Operations Group during 1983. Two major subgroups were formed, one under Scott Hildum to operate the predominantly optical systems and another under Dale Gritton to cover all electronic systems. A great deal of cross-training of the technician staff permitted this group to cope with absences due to accident or illness and maintain 16 hr per day operation of the Novette laser-target-interaction-facility. Altogether, $4M was spent in direct support. Figure 12 is a histogram of labor devoted to Novette during FY 83.

Beyond the manpower costs associated with reworking the two second harmonic crystal arrays after they failed in June, Novette has suffered few setbacks. Unlike Shiva, which required continual clean room support

for amplifier rework,(in late 1981, second shift Shiva operation had to be suspended because second shift clean room operation could not be supported) Novette very rarely damages components. Damaging fluxes can easily be reached within Novette, however, at pulse durations longer than half a nanosecond. In addition, Novette's environmental control systems are ten times less effective than Shiva's or Nova's at controlling the temperature and cleaning the air in the facility. Novette's relatively damage free operation is due to cautious operation aided by an online risk analysis code, which is included in the computer control system and can provide a dollar estimate for the risk involved in taking a given laser shot.

Novette operating costs in FY 83 breakdown as follows:

- Labor, including all personnel costs	$ 3.21 M
- Maintenance, including shop charges, technical photography, computer and instrument maintenance, and all subsystem maintenance except optics	$ 0.64 M
- Stores purchases	$ 0.14 M
- Upgrades, not including 4 omega array	$ 0.06 M
	$ 4.03 M

When spare optics were needed, Nova components were used. In general, however, no major components that met construction specifications before installation in Novette were damaged. Because we expect that Novette components will have to be delivered to Nova in the third quarter of FY 84, we have estimated 600 K$ in moving and rework expenses.

The labor breakdown for 1983 was approximately as follows:

- Operations LLNL		16 my
- Operations Bendix		20 my
- Nova		5 my
- Custodians		2 my
- Shops		3 my
	Total	46 my

During FY 83 Novette was briefly operated for a single shift per day. Productivity during this period was disappointingly low. Table 2 seeks to quantify this experience with estimates of the benefit to cost ratio associated with three operating scenarios.

Table 2 - Benefits/Costs of Multi-Shift Novette Operation

Shifts/Week	Manpower	OP Costs	#Shots/Wk	Maintenance	Benefits/Cost
5x8 hrs	32 mwk	64 K$	3	little	1.0
4x10 hrs	32 mwk	64 K$	3 to 4	some	1.0 to 1.3
2x(5x8 hrs)	48 mwk	80 K$	8 to 9	adequate	2.2 to 2.4

Table 2 reflects our feeling that lasers like Novette are best operated two shifts each day. Poorly planned activities leading to unscheduled overtime efforts not only risk equipment, but also personnel. Novette has enjoyed an excellent safety record largely because of a diligent effort on the part of all of the workers and users in the facility.

SUMMARY

Novette is the latest embodiment of the rapid evolution of powerful ICF laser systems. Each of its two relatively compact arms have exceeded the total output of all of Shiva's 20 arms. Equally striking, Novette was assembled in well under a third of the time required to build Shiva, needs less than half of Shiva's manpower to operate and has achieved a shot rate on target twice Shiva's. An evolutionary step of this magnitude in so short a time approaches a revolution in high power laser technology.

As a test bed for the Nova laser, Novette has provided the first operational test of many new technologies. For example, we have used segmented laser disks, which can be scaled to reach almost arbitrarily large apertures, and successfully propagated beams over long distances. New types of high damage threshold coatings overcome the limitations of simple thin films. Neutral solution anti-reflection coatings have moved our nominal damage threshold from 3-5 J/cm^2 to 15 J/cm^2 in one nanosecond. Novette has shown that NOVA style digital control and diagnostic techniques can be made to work by achieving up to six full system shots during a single day. Laser beam to target alignment issues have been identified in Novette studies and new designs formulated for NOVA. Harmonic conversion to the 2nd, 3rd and 4th harmonic using KDP mosaic arrays has been demonstrated and target experiments conducted with 2nd and 4th harmonic energy. Novette has completed the ICF experiments planned for it, delivering up to 9 kJ of 0.53 μm light to a fusion target in one nsec.

Interdepartmental letter pad

Mail Station L

Ext

June 18, 1981
FLP 81-59

To: ICF Staff

From: J. F. Holzrichter

Subject: Novette Construction

Please begin building Novette. Purchasing should begin immediately. We will work around ongoing Argus experiments through August 30, 1981. On August 31, 1981, we will remove the Argus laser and remodel the Argus high-bay for Novette installation.

We apologize for the uncertainty in the Novette schedule. However, we now have the financial certainty for the remainder of FY 81 and FY 82 to be sure that we can begin the 2ω target experiments on schedule, October 1982.

Please assist the Argus team to finish their important experiments comfortably before the August 30 date.

Please assist the Novette team to finish their project in our usual style -- on schedule, on budget, and over performance.

J. F. Holzrichter

phg/7254P

Figure 1

University of California
Lawrence Livermore
National Laboratory

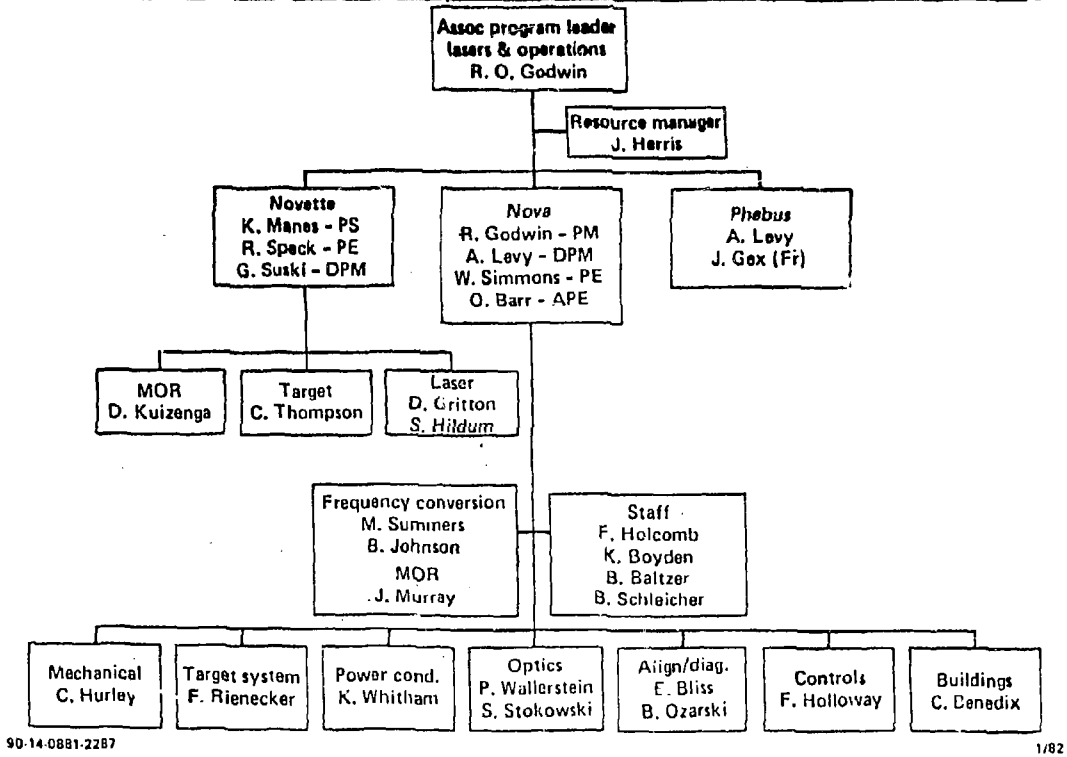

Assoc program leader
lasers & operations
R. O. Godwin
Resource manager
J. Harris
Novette
K. Manes - PS
R. Speck - PE
G. Suski - DPM
Nova
R. Godwin - PM
A. Levy - DPM
W. Simmons - PE
O. Barr - APE
Phebus
A. Levy
J. Gex (Fr)
MOR
D. Kuizenga
Target
C. Thompson
Laser
D. Gritton
S. Hildum
Frequency conversion
M. Summers
B. Johnson
MOR
J. Murray
Staff
F. Holcomb
K. Boyden
B. Baltzer
B. Schleicher
Mechanical
C. Hurley
Target system
F. Rienecker
Power cond.
K. Whitham
Optics
P. Wallerstein
S. Stokowski
Align/diag.
E. Bliss
B. Ozarski
Controls
F. Holloway
Buildings
C. Benedix
90-14-0881-2287
1/82

Figure 2

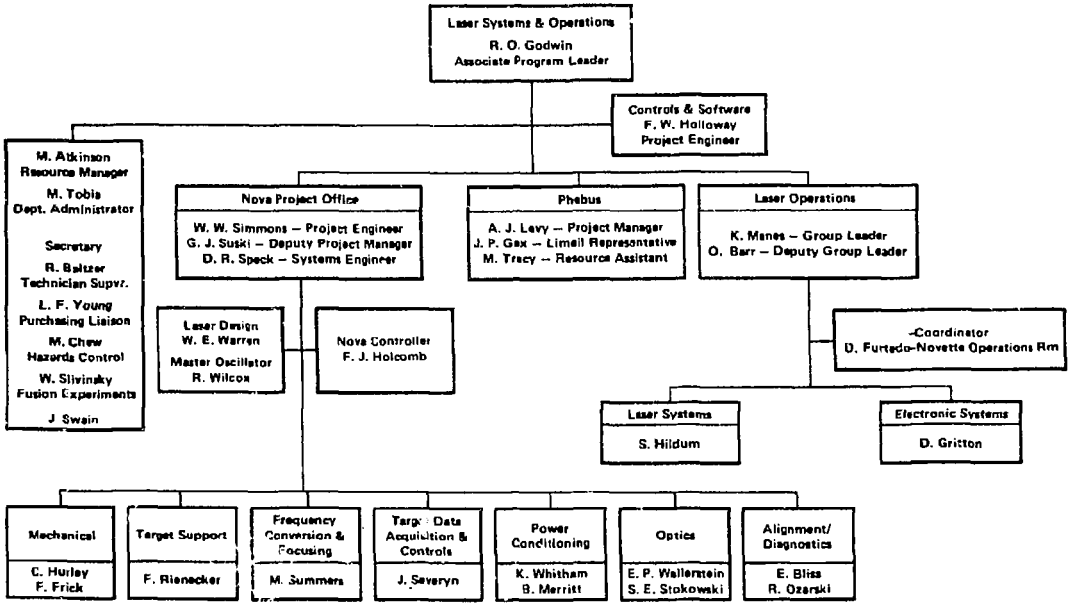
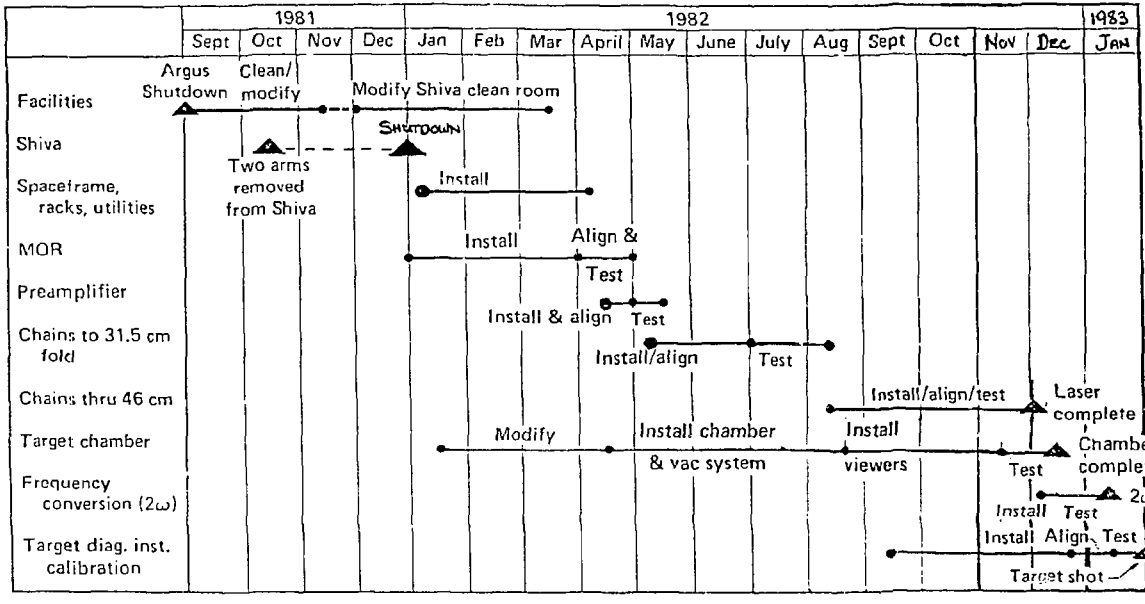

Laser Systems & Operations
R. O. Godwin
Associate Program Leader
Controls & Software
F. W. Holloway
Project Engineer
M. Atkinson
Resource Manager
M. Tobis
Dept. Administrator
Secretary
R. Baltzer
Technician Supvr.
L. F. Young
Purchasing Liaison
M. Chew
Hazards Control
W. Slivinsky
Fusion Experiments
J. Swain
Nova Project Office
W. W. Simmons – Project Engineer
G. J. Suski – Deputy Project Manager
D. R. Speck – Systems Engineer
Phebus
A. J. Levy – Project Manager
J. P. Gex – Limeil Representative
M. Tracy – Resource Assistant
Laser Operations
K. Manes – Group Leader
O. Barr – Deputy Group Leader
Laser Design
W. E. Warren
Master Oscillator
R. Wilcox
Nova Controller
F. J. Holcomb
Coordinator
D. Furtado-Novette Operations Rm
Laser Systems
S. Hildum
Electronic Systems
D. Gritton
Mechanical
C. Hurley
F. Frick
Target Support
F. Rienecker
Frequency Conversion & Focusing
M. Summers
Target Data Acquisition & Controls
J. Severyn
Power Conditioning
K. Whitham
B. Merritt
Optics
E. P. Wallerstein
S. E. Stokowski
Alignment/ Diagnostics
E. Bliss
R. Ozarski

Figure 3

NOVETTE ACTIVATION SCHEDULE



90-1J-0881-2296

Figure 4

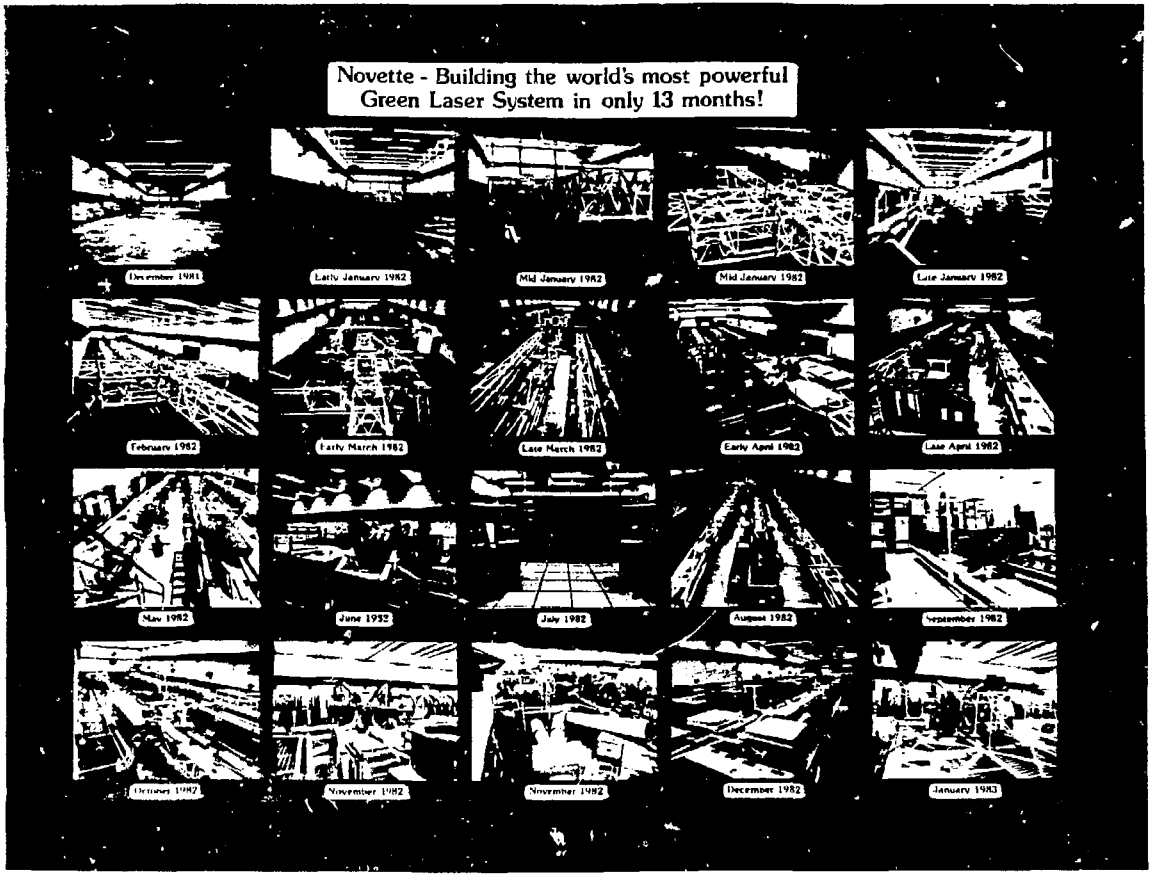

Novette - Building the world's most powerful
Green Laser System in only 13 months!
December 1981
Early January 1982
Mid January 1982
Mid January 1982
Late January 1982
February 1982
Early March 1982
Late March 1982
Early April 1982
Late April 1982
May 1982
June 1982
July 1982
August 1982
September 1982
October 1982
November 1982
November 1982
December 1982
January 1983

Figure 5

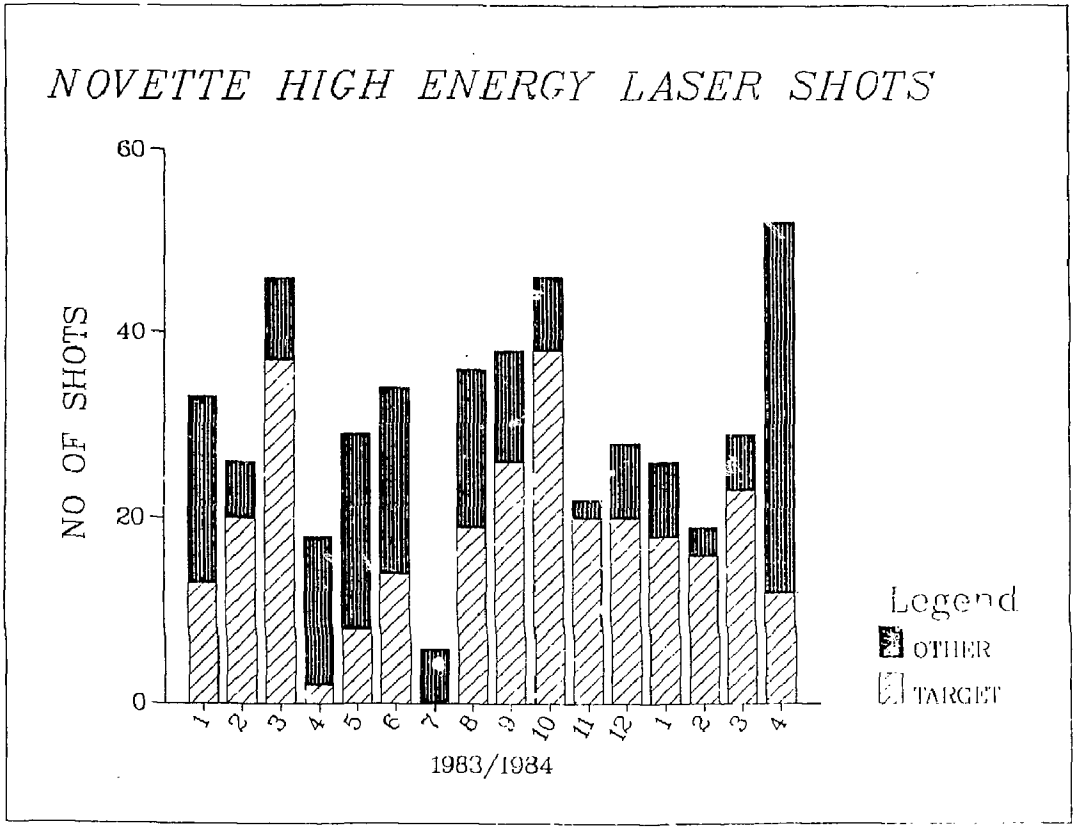

NOVETTE HIGH ENERGY LASER SHOTS
NO OF SHOTS
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4
1983/1984
Legend
OTHER
TARGET

Figure 6

Novette construction

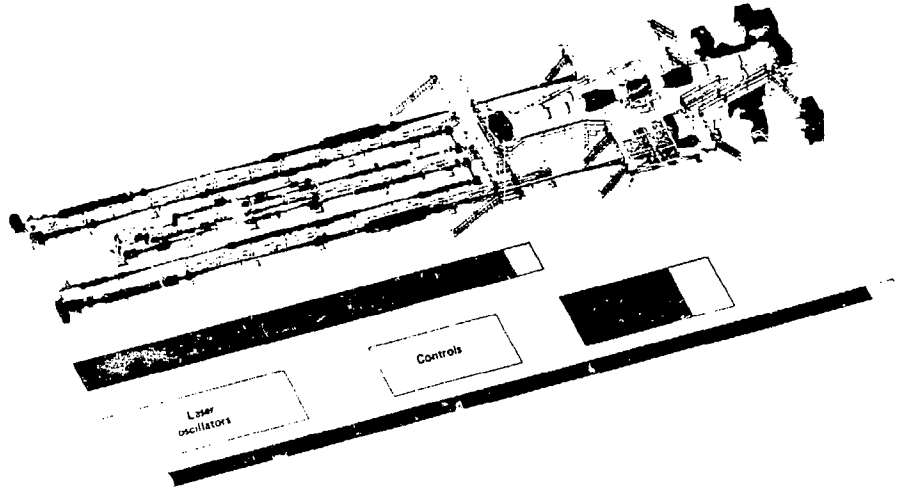


Figure 7

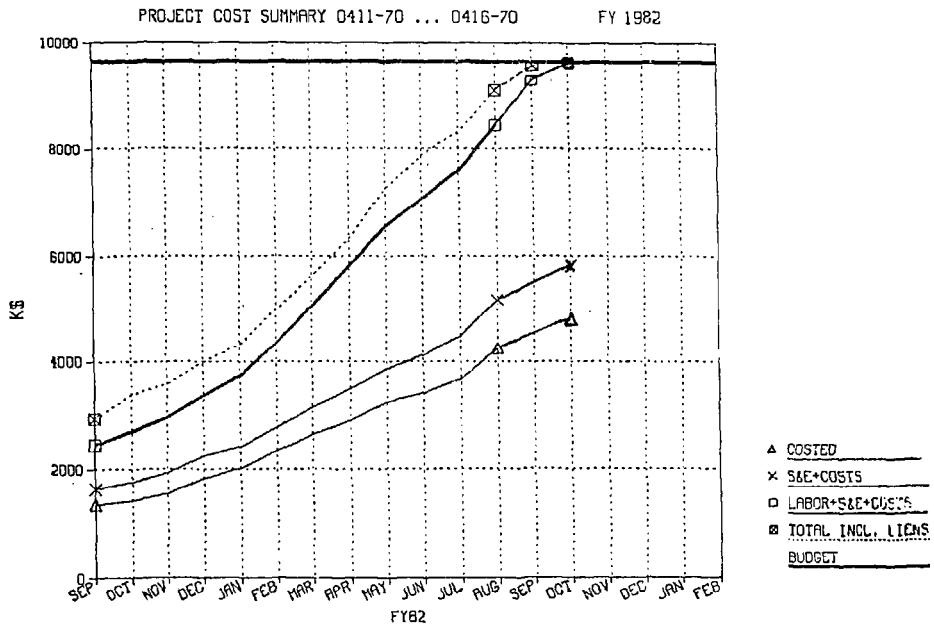
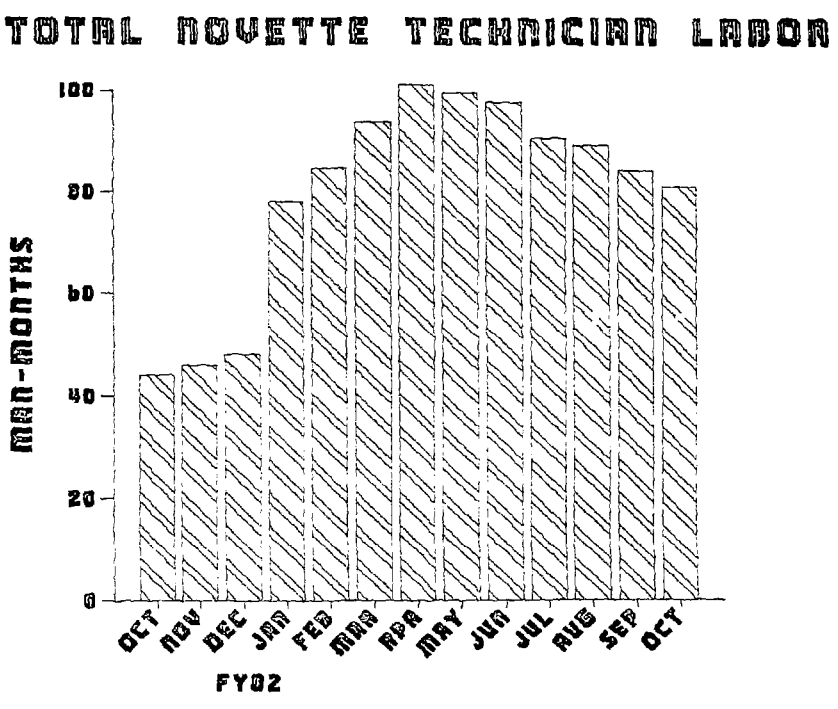

NOVETTE
PROJECT COST SUMMARY 0411-70 ... 0416-70
FY 1982
10000
8000
6000
4000
2000
0
K$
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
FY82
COSTED
S&E+COSTS
LABOR+S&E+COSTS
TOTAL INCL. LIENS
BUDGET

Figure 8


TOTAL NOVETTE TECHNICIAN LABOR
MAN-MONTHS
100
80
60
40
20
0
OCT
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DEC
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FEB
MAR
APR
MAY
JUN
JUL
AUG
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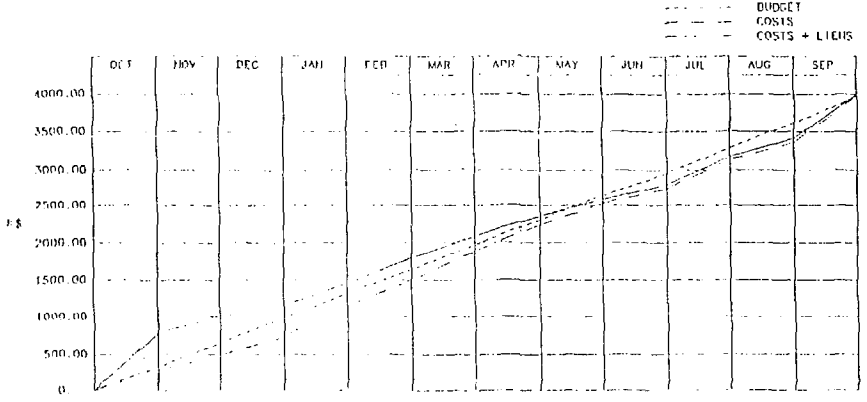
OCT
FY02

Figure 9

LASER SYSTEMS PROGRAM - FINANCIAL STATUS

NOVETTE OPERATIONS - 0323

CUMULATIVE EXPENDITURES THROUGH 09/30/1983



COST SUMMARY

	BUDGET	USED	% USED	% YEAR
LABOR	2160.	2255.	104.43	100.00
M.S.&.E.	1790.	1709.	95.49	100.00
TOTAL	3950.	3965.	100.37	100.00

M.S.&.E. USE

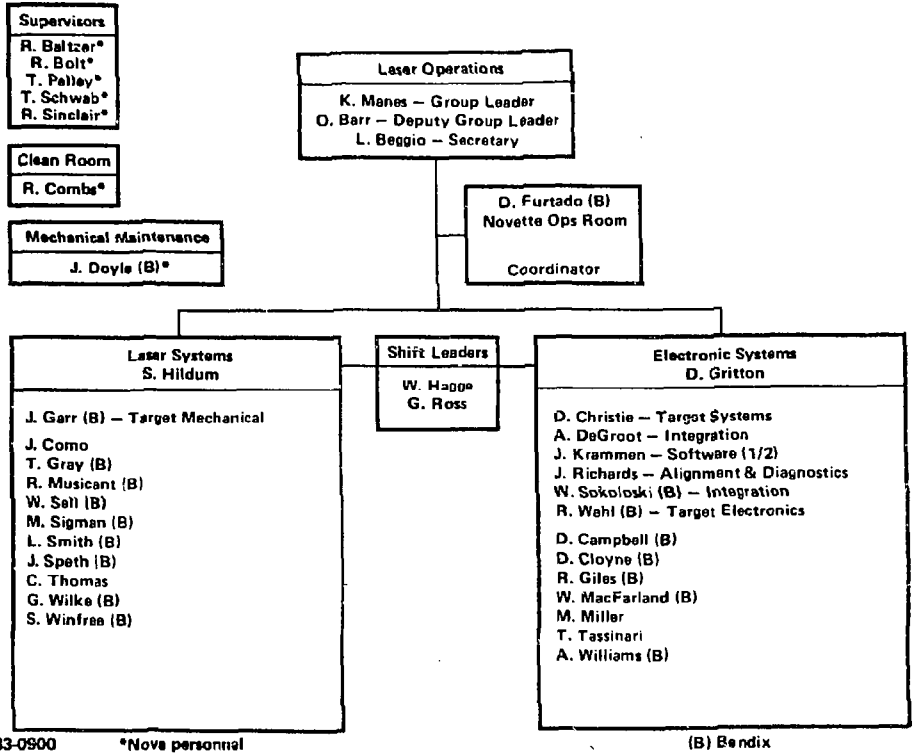
PROCUREMENTS	1073.
MTRNS	161.
MATL FAB IN	81.
MATL FAB OUT	46.
MAINT/MC ALT	74.
TRAVEL	4.
SUPPLS	141.
COMPUTER	0.
CONSULTANTS	0.
CONTR. LABOR	51.
T. V. O.	52.
OTHER	25.

L.T. USE

YR PLAN	27.00
MON AVE	22.33
SEP	25.14
% USED	101.74
% YEAR	100.00

Figure 10

Laser Operations (Novette)



90-14-0383-0900 *Nova personnal (B) Bendix 12/83

Figure 11

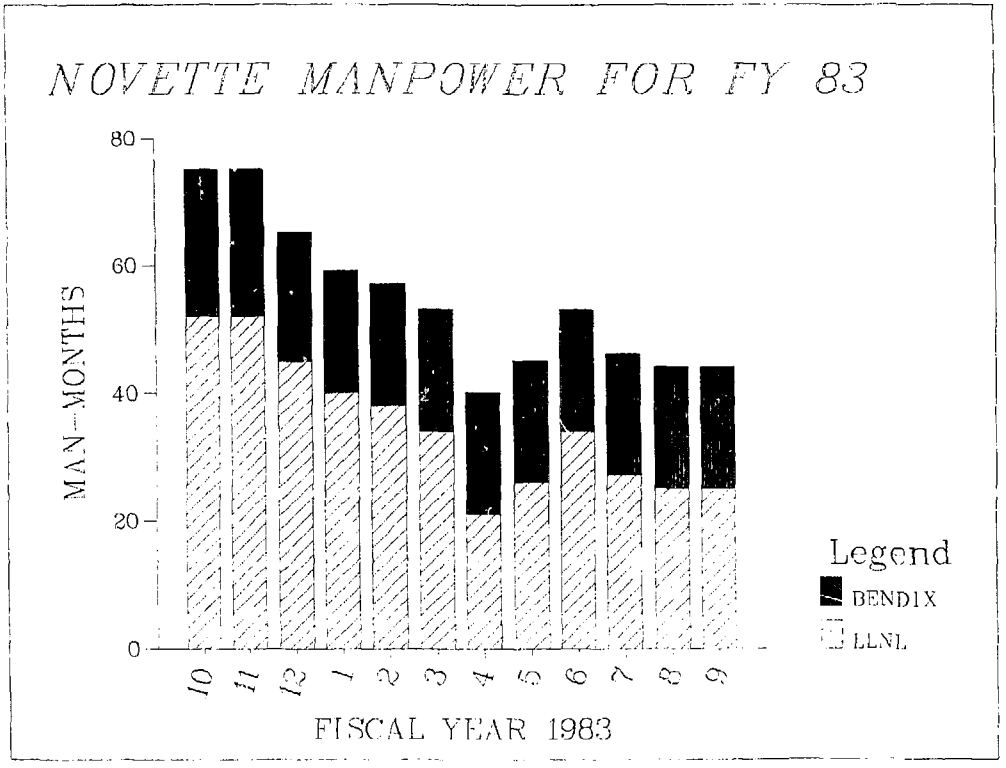

NOVETTE MANPOWER FOR FY 83
MAN-MONTHS
80
60
40
20
0
10
11
12
1
2
3
4
5
6
7
8
9
FISCAL YEAR 1983
Legend
BENDIX
LLNL

Figure 12