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**DEVELOPMENT AND EVALUATION OF A WORKPIECE TEMPERATURE
ANALYZER (WPTA) FOR INDUSTRIAL FURNACES**

Phase 1

October 1991

Work Performed Under Contract No. FC07-89ID12874

**For
U.S. Department of Energy
Office of Industrial Technologies
Washington, D.C.**

**By
Acurex Corporation
Mountain View, California**

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ANALYZER (WPTA) FOR INDUSTRIAL
FURNACES (PHASE 1)

Final Report

October 1991

Work Performed Under Contract DE-FC07-89ID12874
Final Report FR-91-104/ESD

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EXECUTIVE SUMMARY

This project is directed toward the research, development, and evaluation of a viable commercial product—a workpiece temperature measurement analyzer (WPTA) for fired furnaces based on unique radiation properties of surfaces. This WPTA will provide for more uniform, higher quality products and reduce product rejects as well as permit the optimum use of energy. The WPTA may also be utilized in control system applications including metal heat treating, forging furnaces, and ceramic firing furnaces. A large market also exists in the chemical process and refining industry. WPTA applications include the verification of product temperature/time cycles, and use as a front-end sensor for automatic feedback control systems.

This project is a cooperative agreement between the U.S. Department of Energy (DOE) and the contract members: Acurex Corporation, Environmental Systems Division, the prime contractor; and Pyrometer Instrument Company (PIC) and Ogiso, the subcontractors. Acurex has overall responsibility for the WPTA system product development, and primary responsibility for the application evaluation, the field testing of the Pyrolaser™, and the conceptual development of the Raman Spectroscopy WPTA. PIC provides expertise in non-contact temperature measurement techniques, instrument development expertise, and equipment for state-of-the-art measurement evaluation. Ogiso provides expertise in laser physics applications research, particularly in Raman Spectroscopy.

This report summarizes the work performed in Phase I of this three-phase project. The work in Phase I included the application evaluation; the evaluation of present technologies and limitations; and the development of a preliminary conceptual WPTA design, including identification of technical and economic benefits. Upon successful completion of the development of the WPTA,

commercialization will be carried out by PIC, which will market, manufacture/assemble, distribute, and service the WPTAs.

The application evaluation confirmed that a large market exists for high-accuracy, high-temperature remote instrumentation. It identified the following industries as having the most promising applications for immediate benefit from the technology: petroleum refining and petrochemical production, metal heat treating, flat glass annealing and heat treatment; and the manufacture of brick, clay tile, and vitreous plumbing fixtures. Metal heat treatment was selected for initial field evaluation because of its immediate need and interest in a WPTA.

Most temperature measurement devices today measure the environmental temperature rather than the actual product temperature, with the exception of surface-mounted thermocouples and a relatively new instrument, the Pyrolaser, from PIC. The Pyrolaser is unique in that it directly measures the surface emissivity as well as radiation of the surface, at the same time, at a selected spot on the surface of a workpiece or part at elevated temperature. Typical pyrometers can only be used as reference instruments and do not provide absolute measurements. Thermocouples and RTDs must be attached to the workpiece in order to measure workpiece temperature, which is often prohibitively time-consuming, expensive, or damaging to the workpiece. Acoustic pyrometry, another relatively new technology, provides accurate, detailed, and instantaneous data on gas temperature distribution, but requires thermal modeling to calculate actual workpiece temperature.

Recommendations based on the findings of this report include near-term enhancement of the capabilities of the Pyrolaser, and long-term development of an instrument based on Raman Spectroscopy. Development of the Pyrofiber, a fiberoptics version of the Pyrolaser, will be a key to solving present problems involving specularly, measurement angle, and costs of multipoint measurement. Extending the instrument's measurement range to include temperatures below 600°C will make the product useful for a wider range of applications.

The development of Raman Spectroscopy would result in an instrument that could easily be adapted to incorporate a wealth of additional nondestructive analytical capabilities, including

stress/strain indication, crystallography, species concentrations, corrosion studies, and catalysis studies, in addition to temperature measurement.

The Pyrolaser presently being marketed sells for approximately \$20,000. The instrument contains some expensive optics that make it difficult to reduce the costs. The proposed enhancements incorporating fiberoptics and multipoint measurement capability will eliminate the optics in large part, and, therefore, provide an opportunity for lower costs/measurement point, i.e., the Pyrofiber system is expected to sell for approximately the same price, but will have much greater capabilities of great interest to the user, particularly in temperature control applications of furnaces. The instrument will be able to characterize the entire time/temperature history of parts in continuous furnaces. This information can then be used for feed-forward and feedback temperature control, making closer control of the furnace, and, hence, higher quality products possible. The Pyrolaser comparison tests reflected in this report show accuracies of $\pm 12^{\circ}\text{F}$ when compared to thermocouples on the surface of the product. This is a very good result considering that the furnace ports presented viewing difficulties, and that it was difficult to adjust the Pyrolaser to part distance accurately. Under more controlled industrial conditions, greater accuracies would be expected. Permanent Pyrofiber installations, once calibrated, would also be expected to yield greater accuracies.

The Raman Spectroscopy instrument was estimated to sell for approximately \$30,000 in small quantities. Although the laboratory components for the test system would be far more expensive, they have not been optimized for use in an industrial instrument and have many features that would not be required. Very significant cost reductions are expected for an industrial system as a result.

The above cost projections were used in the economic analysis performed that showed systems at these costs would yield high returns on capital when installed.

TABLE OF CONTENTS

EXECUTIVE SUMMARY	iii
SECTION 1 INTRODUCTION	1-1
SECTION 2 APPLICATION SELECTION	2-1
2.1 MARKET ASSESSMENT AND EVALUATION OF APPLICATION	2-1
2.2 ECONOMIC ANALYSIS	2-11
2.3 MARKET ASSESSMENT	2-15
2.4 EXPECTED END PRODUCT AND COMMERCIALIZATION	2-19
SECTION 3 TEST SITE SELECTION	3-1
3.1 TEST SITE AGREEMENTS	3-1
3.2 PRECISION SPECIALTY METALS (PSM), LOS ANGELES, CALIFORNIA	3-1
3.3 PINOLE STEEL-TREATING FURNACE, PINOLE, CALIFORNIA	3-5
3.4 TELEDYNE WAH CHANG, ALBANY, OREGON	3-5
3.5 SUMMARY—METALLURGICAL FURNACES	3-7
SECTION 4 PRESENT TECHNOLOGY ASSESSMENT	4-1
4.1 OVERVIEW	4-1
4.2 COMPARISON OF RAMAN THERMOMETRY AND PYROLASER PYROMETRY	4-4
4.2.1 Comparison of Operating Principles	4-4
4.2.2 Comparison of Capabilities and Limitations	4-4
4.2.3 Comparison of Applicability to Non-Thermometric Measurements	4-9
4.2.4 Measurement Regimes for Each Instrument	4-10
4.3 MARKET FOR APPLICATION OF PYROLASER OR RAMAN SPECTROSCOPY	4-10
4.4 ADVANCED MEASUREMENT CAPABILITIES OF RAMAN SPECTROSCOPY	4-11
4.4.1 Stress/Strain Indication	4-12
4.4.2 Crystallography	4-12
4.4.3 Species Concentrations	4-12
4.4.4 Corrosion Studies	4-13
4.4.5 Catalysis Studies	4-13
4.5 POTENTIAL PYROLASER ENHANCEMENTS	4-14

TABLE OF CONTENTS (concluded)

SECTION 5	PYROLASER-PYROFIBER INDUSTRIAL TESTS	5-1
5.1	INTRODUCTION	5-1
5.2	PYROLASER TESTS AT PRECISION SPECIALTY METALS (PSM)	5-1
5.2.1	Furnace Details	5-2
5.2.2	Test Measurements	5-4
5.2.3	Discussion of Test Measurements	5-6
5.3	PYROFIBER-BREADBOARD	5-12
5.4	PYROFIBER TESTING AT TELEDYNE WAH CHANG	5-12
5.5	RESULTS	5-17
SECTION 6	RAMAN SPECTROSCOPY—FEASIBILITY	6-1
6.1	INTRODUCTION	6-1
6.2	LITERATURE REVIEW	6-1
6.2.1	Carbon Monoxide Spectrum in a Flame	6-3
6.2.2	Temperature Profiles in a Sealed Lamp	6-4
6.2.3	Temperature Measurements in Operating Diesel Engine	6-4
6.2.4	Conclusion	6-4
6.3	LABORATORY-SCALE RAMAN WPTA SYSTEM	6-6
6.3.1	Introduction	6-6
6.4	LABORATORY-SCALE TEST PLAN	6-43
6.4.1	Introduction	6-43
SECTION 7	RECOMMENDED LABORATORY-SCALE TESTS AND SENSOR DEVELOPMENT—PHASE II	7-1
7.1	INTRODUCTION	7-1
7.2	RECOMMENDED WPTA DEVELOPMENT PROGRAM—PHASE II	7-3
	REFERENCES	R-1
APPENDIX A	-- ECONOMIC ANALYSIS	A-1
APPENDIX B	-- IMPROVED INFRARED TEMPERATURE MEASUREMENT BY UTILIZATION OF LASER TECHNOLOGY	B-1
APPENDIX C	-- EQUIPMENT SPECIFICATIONS	C-1

LIST OF ILLUSTRATIONS

Figure 2-1	Metal heat treating SIC 3398	2-6
Figure 2-2	Heat rate versus throughput (PSM)	2-13
Figure 2-3	Increased profit versus increased throughput (PSM)	2-14
Figure 3-1	PSM furnace cross section	3-2
Figure 3-2	The PSM furnace	3-3
Figure 3-3	Pinole Steel heat-treating furnace	3-6
Figure 4-1	Temperature measurements by Raman Spectroscopy	4-7
Figure 4-2	Temperature measurement by Raman Spectroscopy	4-8
Figure 5-1	PSM sintering furnace and burner operation schematic	5-3
Figure 5-2	Sample data—Pyrolaser	5-10
Figure 5-3	Composite plot of PSM test data	5-14
Figure 5-4	System schematic	5-16
Figure 6-1	CARS spectrum of CO in a flame	6-3
Figure 6-2	CARS temperature profile in sealed filament lamp	6-5
Figure 6-3	CARS temperature measurement in an operating diesel engine	6-6
Figure 6-4	Timing diagram	6-23
Figure 6-5	Laboratory-scale system layout—laser beam delivery system	6-28
Figure 6-6	Laboratory-scale system layout—Raman signal retrieval and processing camera lens system	6-29
Figure 6-7	Laboratory-scale system layout—Raman signal retrieval and processing fiberoptic system	6-30
Figure 6-8	Experimental test configuration for studying effects of luminosity, workpiece radiation, laser-modulated incandescence, and window fluorescence	6-46

LIST OF TABLES

Table 2-1	DOE workpiece temperature—applications overview	2-3
Table 2-2	SIC industry evaluation	2-5
Table 2-3	Metal Heat Treating SIC 3398	2-8
Table 2-4	DOE workpiece temperature analyzer—SIC evaluation—\$20K instrument	2-9
Table 2-5	Furnace energy losses	2-12
Table 2-6	Project data required for threshold analysis	2-16
Table 2-7	Pyrolaser (threshold input data)	2-17
Table 2-8	Raman Spectroscopy (threshold analysis input data)	2-18
Table 4-1	Pyrolaser specifications	4-5
Table 5-1	Summary of measurements	5-8
Table 5-2	Test parameters for second set of tests at PSM	5-13
Table 6-1	Documents reviewed	6-2
Table 6-2	Itemization of system components and costs	6-32
Table 6-3	Miscellaneous experimental apparatus and costs	6-36
Table 6-4	Yates' Algorithm	6-47
Table 6-5	Variable levels for test matrix (Yates' Algorithm) thermometry tests	6-48

SECTION 1

INTRODUCTION

This project is directed toward the research, development, and evaluation of a viable commercial product—a workpiece temperature measurement analyzer (WPTA) for fired furnaces based on unique radiation properties of surfaces. This WPTA will provide for more uniform, higher quality products and reduce product rejects as well as permit the optimum use of energy. The WPTA may also be utilized in control system applications including metal heat treating, forging furnaces, and ceramic firing furnaces. A large market also exists in the chemical process and refining industry.

The project places emphasis in three areas to determine the economic and technical viability of the product. They are: (1) market assessment of the product, (2) the evaluation of currently available products, and (3) the technical feasibility of the WPTA.

WPTA applications include the verification of product temperature/time cycles and use a front-end sensor for automatic feedback control systems. Most systems today measure the environmental temperature rather than the actual product temperature, with the exception of surface-mounted thermocouples and a relatively new instrument, the PyrolaserTM, from Pyrometer Instrument Company (PIC). The Pyrolaser is unique in that it measures the surface emissivity as well as radiation of the surface, at the same time, at a selected spot on the surface of a workpiece or part at elevated temperature. Typical pyrometers can only be used as reference instruments and do not provide absolute measurements.

The project is being performed in three phases:

- Phase I Application Evaluation, Evaluation of Present Technologies and Limitations, and Development of a Preliminary Conceptual WPTA Design Identifying Technical and Economic Benefits.
- Phase II WPTA Laboratory-Scale Tests and Evaluations, Full-Scale Design, and Economic Analysis Verification.
- Phase III Fabrication of a Prototype WPTA, Field Testing at an Industrial Site, and Preparation of a Commercialization Plan.

The Phase I application evaluation confirmed and quantified the applications and the technical and economic viability of the concepts in addition to the evaluation of presently available technology—the Pyrolaser at an industrial field evaluation site.

Several key decisions were made at the end of Phase I. These decisions provided recommendations for the direction of Phase II.

In Phase II, the enhancements of the Pyrolaser-Pyrofiber or the Raman Spectroscopy WPTA will be verified in laboratory-scale tests and further evaluated. A full-scale design and economic analysis will be conducted to provide sufficient data to make the necessary go/no go decision for Phase III.

In Phase III, a prototype WPTA will be constructed and evaluated at an industrial test site.

Acurex has overall responsibility for the WPTA system product development, and primary responsibility for the application evaluation, field testing of the Pyrolaser and concept development of the Raman Spectroscopy WPTA. PIC provides expertise in non-contact temperature measurement techniques, instrument development expertise, and equipment for state-of-the-art measurement evaluation. Much of the technology and expertise which PIC gained in developing the Pyrolaser is directly transferable to the Raman Spectroscopy WPTA instrument. Raman Spectroscopy requires longer-term development.

Upon successful completion of the development of the WPTA, commercialization will be carried out by PIC, which will market, manufacture/assemble, distribute, and service the WPTAs.

This report summarizes the work performed in Phase I.

SECTION 2

APPLICATION SELECTION

2.1 MARKET ASSESSMENT AND EVALUATION OF APPLICATION

The evaluation of potential applications of laser pyrometry serves two purposes. The most important and immediate is to identify markets for early commercialization and other markets suitable for subsequent commercialization or worthy of further investigation at a later date. The second purpose is to identify industries suitable for a test site for Beta-testing of this technology.

The criteria for a suitable market include the economic viability of such a product, applicability of the technology to the processes involved, relative size of the industry and whether or not the industry has a need for precise measurement and control of workpiece or process temperatures.

Although laser pyrometry is technically suited to a wide range of temperatures, most processes involving relatively low temperatures are already instrumented with thermocouples, bimetallic strips, or other conventional technologies, and do not require more sophisticated means of measurement. In contrast, such conventional technologies are often not applicable to high-temperature environments because of the interaction between radiation and convection and their influence on the measurements. Also, industries using high temperatures generally produce large volumes or expensive products and have more capital invested in process equipment than do low-temperature process industries. Thus, they can more easily justify the expense of upgraded measurement and control equipment. Therefore, relatively high-temperature processing is a rough criterion for initial market evaluation.

The first step in evaluating potential market was to compile a comprehensive list of industries requiring process heat in the form of gas or electrical energy. It was felt that large energy users would likely operate facilities at high temperatures. The GRI report "U.S. Industrial Process Heating Energy Consumption—1985" (Reference 1) provided this list. The industries comprising the list make up the "Process Heat Category" column in Table 2-1.

Initial review of these industries narrowed the list to four candidates: ferrous metal heat treating, glass annealing and forming, petroleum refining and chemical production, and clean clay firing. The reasons for rejecting the other industries are listed in Table 2-1. Note that many of the industries rejected for "instrumentation difficulties" are suitable for later investigation as markets but are not suited to providing initial sales or a test site because of the likelihood of special application engineering requirements and the associated high costs.

The next step in evaluating potential applications was to find Standard Industrial Code (SIC) classifications corresponding to these candidate industries. The SIC codes are a key to a wealth of data on various industries contained in the U.S. Department of Commerce Census of Manufactures (Reference 2) and Annual Survey of Manufactures (Reference 3). For each of the selected SIC codes, a set of statistics was collected. The "STATISTIC" section at the top of Table 2-2 shows an example of the data collected.

The Census of Manufactures also provided the histogram distribution of the number of firms per number of employees, depicted in Figure 2-1. This distribution was the basis for scaling the other statistics, as tabulated in the lower portion of Figure 2-1. The scaled data give an approximate idea of the number of firms with, for example, given levels of capital expenditure or fuel cost. Some of the statistics are distributed linearly; others exponentially, to reflect the rule of thumb assumption that each doubling of employment reflects a 10 percent increase in productivity.

Two rough criteria were established to facilitate comparison of the SIC data. Both assume a \$20K price tag for the workpiece temperature analyzer instrument.

Table 2-1. DOE workpiece temperature—applications overview

Process Heat Category	Selected for Initial Study/Reason for Rejection
Agglomeration Ferrous Nonferrous	No need for control benefits No need for control benefits, small industry
Smelting Ferrous Nonferrous	Blast furnace (instrumentation difficulties) Instrumentation difficulties
Metal Melting Steel making Steel melting Iron melting Nonferrous melting	Melting furnace (instrumentation difficulties) Melting furnace (instrumentation difficulties) Melting furnace (instrumentation difficulties) Melting furnace (instrumentation difficulties, relatively small industry)
Metal heating Steel soaking pits Steel reheat Ferrous forging Nonferrous forging Nonferrous heating	Furnace is entirely full of product (instrumentation difficulties) Furnace is entirely full of product (instrumentation difficulties) Relatively small industry Relatively small industry Small and diverse industry
Metal heat treating Ferrous Nonferrous Atmosphere generation	*Selected for initial study Low temperature Nonapplicable, item of interest is combustion products themselves
Nonmetallic melting Glass melting	Furnace is entirely full of product (instrumentation difficulties)
Curing and forming Nonmetallic curing Glass annealing/forming Rubber	Low temperature *Selected for initial study Steam process
Bonding Powdered metals Brazing Adhesives	Small market Furnace brazing is small market Small market, low temperature
Fluid heating Petroleum refining	*Selected for initial study. Very large market. Sensor detects tube temperature

Table 2-1. DOE workpiece temperature—applications overview (concluded)

Process Heat Category	Selected for Initial Study/Reason for Rejection
Petroleum extraction Chemical production	Very low temperature *Selected for initial study. Very large market. Sensor detects tube temperature.
Drying . Surface film Continuous sheet Dirty Clean	Low temperature Low temperature Low temperature and dirty Low temperature
Calcining Dirty Clean	Cheap and dirty Gypsum is low temperature. Area of future interest: Alumina (rotary kiln)
Clay firing Dirty Clean	Cheap and dirty *Selected for initial study. For large dense batches, sensor sees outer product only
Other heating Dirty Baking and frying Singeing and finishing	Cheap and dirty Complex and fragmented market, low temperature Low temperature

Table 2-2. SIC Industry evaluation

DOE WORKPIECE TEMPERATURE SIC INDUSTRY EVALUATION Rev 8 28Aug89 Lee Doss

SIC: 3398 Industry: Metal Heat Treating

STATISTIC	QTY UNITS	YEAR	SOURCE
Number of establishments:	758 establishments	1982	Census of Manufactures- Industry Series 1982, Table 4
Total employment:	17.7 K persons	1982	Census of Manufactures- Industry Series 1982, Table 4
Payroll:	324.2 \$M	1982	Census of Manufactures- Industry Series 1982, Table 4
Value added by manufacture:	684.5 \$M	1982	Census of Manufactures- Industry Series 1982, Table 4
Cost of materials:	416.0 \$M	1982	Census of Manufactures- Industry Series 1982, Table 4
Value of shipments:	1128.2 \$M	1982	Census of Manufactures- Industry Series 1982, Table 4
New capital expenditures:	42.5 \$M	1982	Census of Manufactures- Industry Series 1982, Table 4
End-of-year inventories:	98.1 \$M	1982	Census of Manufactures- Industry Series 1982, Table 4
New capital expenditures:	30.7 \$M	1982	Census of Manufactures- Industry Series 1982, Table 3d
Beg-of-yr machinery assets:	422.6 \$M	1982	Census of Manufactures- Industry Series 1982, Table 3d
New machinery cap exp:	28.2 \$M	1982	Census of Manufactures- Industry Series 1982, Table 3d
New computer cap exp:	0.3 \$M	1982	Census of Manufactures- Industry Series 1982, Table 3d
Purchased fuels and electr:	80.9 \$M	1980	Annual Survey of Manufactures 1980-81, Table 3
Purchased fuels and electr:	17.0 trillion Btu	1980	Annual Survey of Manufactures 1980-81, Table 3

CALCULATED RATIO	QTY UNITS	YEAR(S)
Value added / Machinery assets	1.620 \$M/\$M	1982
New machinery expenditures / Mach assets	0.067 \$M/\$M	1982
New computer expenditures / Mach assets	0.001 \$M/\$M	1982
Energy expenditure / Value added	0.118 \$M/\$M	1980/1982

STATISTICS SCALED BY NUMBER OF EMPLOYEES IN 1982 CENSUS	Dollar figures in \$K									
Average employment	1-4	5-9	10-19	20-49	50-99	100-249	250-499	500-999	1000-2499	>2500 Lin
Number of establishments:	109	154	206	210	60	18	0	1	0	0 Exp

Midrange employment:	2.5	7	14.5	34.5	74.5	174.5	374.5	749.5	1749.5	3250 L
Payroll:	40.64	113.79	235.72	560.84	1211.10	2836.73	6088.00	12184.12	28440.45	52833.07 L
Value added by manufacture:	56.81	183.27	419.65	1124.97	2700.77	7112.05	16954.81	37331.84	97922.90	198092.68 E
Cost of materials:	34.52	111.38	255.04	683.69	1641.37	4322.30	10304.16	22688.16	59511.95	120389.42 E
Value of shipments:	93.63	302.07	691.66	1854.18	4451.63	11722.16	27945.09	61530.72	161397.54	326498.41 E
New capital expenditures:	5.33	14.92	30.90	73.52	158.76	371.87	798.09	1597.24	3728.31	6925.99 L
End-of-year inventories:	8.14	26.27	60.14	161.23	387.06	1019.27	2429.90	5350.26	14033.95	28389.91 E
New machinery cap exp:	3.54	9.90	20.50	48.78	105.35	246.75	529.55	1059.82	2473.85	4595.60 L
New computer cap exp:	0.04	0.11	0.22	0.52	1.12	2.62	5.63	11.27	26.32	48.89 L
Purchased fuels and electr:	6.71	21.66	49.60	132.96	319.20	840.56	2003.86	4412.19	11573.36	23412.27 E
Pur fuels/elec billion Btu:	1.41	4.55	10.42	27.94	67.08	176.63	421.08	927.16	2431.98	4919.76 E

Employment distribution checksum / census total employment: 1.13

Figure 2-1. Metal heat treating SIC 3398

One criterion is the number of potential customers for the instrument. The assumption underlying its estimation is that a customer would not spend more than half of his annual new machinery capital expenditures, nor more than 2 percent of his value of shipments, to buy such a device. A company filling both these requirements would have at least \$40K new machinery capital expenditures and \$1M value of shipments. Table 2-3 shows an example of the application of this criterion to the data of Table 2-2.

The other criterion is the number of potential unit sales. The assumption underlying its estimation is that larger companies could and would possibly buy multiple units. Table 2-3 shows the method of estimating the number of potential unit sales based on level of new machinery capital expenditure. Table 2-4 tabulates the results of applying these two yardstick criteria on applicable SIC data, in the "Census: Customers/Units" columns. A major problem with this method of organizing the SIC data is that it masks captive facilities, i.e., those owned by larger businesses with a different SIC classification. Examples would be metal heat treating or glass annealing facilities owned by a manufacturer of automobiles or airplanes. Telephone conversations with industry representatives indicate that at least half of the metal and glass heat-treating facilities in the United States are captive. The "Corrected: Customers/Units" columns of Table 2-4 present figures for these two industries doubled to include captive facilities. Table 2-4 also shows the value of sales corresponding to the estimates of unit sales for a \$20K instrument. Even the corrected figures present the fluid heating (petroleum and chemicals) applications in an order of magnitude greater than other industries of interest.

At this point, it is important to emphasize that although the SIC evaluation is useful as a rough tool for sizing up potential markets, it is not the last word to use as a base for decisions. Subsequent telephone investigation of the fluid heating industry revealed a low level of interest in relatively high-cost temperature instrumentation.

The principal concern of process heater users is the tube wall temperature. If this temperature becomes too high, coking of the petroleum liquids can occur. This can lead to deposits

Table 2-3. Metal Heat Treating SIC 3398

DOE Workpiece Temperature: SIC Evaluation

Unweighted—Number of potential customers 289

Number established with $\geq \$40K$ new machinery capital expense = $210 + 60 + 18 + 1$
and $\geq \$1M$ value of shipments

Weighted—Number of potential unit sales

New Machine Cap Exp.	Weight Factor	Number Established	Weight * Number Established
$\geq \$40K, \geq 1M$ value shipping	1	210 + 60	270
> \$200K	2	18	36
> \$400K	3	0	0
> \$800K	4	1	4
> \$1.6M	5		
> \$3.2M	6		
> \$6.5M	7		
> \$13M	8		
> \$25M	9		
> \$50M	10		
> \$100M	11		
Total			310

Figures do not include captive facilities.

Table 2-4. DOE workpiece temperature analyzer—SIC evaluation—\$20K instrument

SIC Code	Description	Census		Corrected		Value \$M	
		Customers	Units	Customers	Units	Census	Corrected
3398	Metal heat treating	289	310	578	620	6.2	12.4
3211	Flat glass	33	140	66	280	2.8	5.6
3251	Brick and structural	185	214				
3255	Clay tile clay refractories	103	126				
3261	Vitreous plumbing fixtures	35	75				
	Clay firing total	323	415	323	415	8.3	8.3
2911	Petroleum refining	433	2149				
2865	Cyclic crudes and intermediates	153	634				
2869	Industrial organic chemicals	465	2198				
	Fluid heating total	1051	4981	1051	4981	99.6	99.6

"Corrected" figures assume that roughly half of the metal and glass treating facilities are "captive," i.e., owned by a larger business such as an automobile manufacturer. Such captive facilities are not reflected in the SIC census data.

and eventual tube blockage or burnout. Excessive temperatures are usually a result of excessive radiant heat transfer which may be due to faulty design, changes in the fuel compositions, or changes in the process fluid flow or composition. From several users (Shell, Chevron), it was determined that outages often occur every six months or so due to tube failures (usually not on the same unit, though). However, they attribute the primary cause of failure to momentary or full interruptions of process fluid flow. This may be caused by an upset in the refinery or chemical process, or by some instability within the fluid manifold. At this time, they do not attribute the problems to temperature maldistributions on the combustion side. Both the manufacturers and the users feel that: (a) there is sufficient tolerance in the design to account for minor changes, (b) these changes occur rarely, and (c) the current use of thermocouples and conventional optical pyrometry to monitor temperature is adequate to detect gross upset conditions. Thus, it is not clear that highly accurate tube wall temperature instrumentation measurement provides any real benefits to justify its cost. Therefore, in the fluid heating sector, laser pyrometry and other advanced workpiece temperature analyzers seem to have their most immediate application in new R&D. Discussions with process operators tended to indicate no additional accuracy in temperature measurements where required, whereas process engineers tended to have differing opinions. Process engineers seemed to have a better understanding of the optimization of the processes and how small changes in the operation could significantly influence the output of the facility and improve efficiency. For large processors the implications are enormous.

The difficulty of penetrating such a market with a new product should not be underestimated, however, when customers do not fully understand what the new instrumentation can provide. For a small company the required resources are simply too large, and it is wiser to look for markets where receptivity to the concept is good.

This conclusion prompted further investigation of the remaining three industry candidates. Visits to facilities for firing brick showed that brick-firing kilns are densely packed with product, obscuring any view of product while insulated by the outside layer of bricks and thus interfering with

measurement. Furthermore, the value of the product is relatively low, and bricks that do not meet specifications can be easily recycled. Therefore, the brick industry could expect little real economic benefit from the proposed instrumentation. Vitreous plumbing fixtures and other relatively expensive ceramics are a more likely application in terms of both viewability/measurability and value of product. However, by themselves, they constitute a relatively small market for instruments.

The remaining market candidates are flat glass annealing and heat treatment, quite similar processes. Metal heat treating has the advantage of a relatively larger market and size. It is not surprising that this market was also perceived by DOE to have the greatest need.

The criteria for a test site industry also included relative ease of instrumentation. For example, as a noncontact measurement technology, laser pyrometry has the potential of overcoming the difficulties of instrumenting a rotary kiln or blast furnace but these difficulties would unnecessarily complicate initial testing of the technology.

2.2 ECONOMIC ANALYSIS

An estimate was made as to the cost of the user of a WPTA. The cost of a Pyrolaser is somewhat lower than the cost of a Raman Spectroscopy system. The latter has greater capabilities, however, too. Specific data were collected for the Precision Specialty Metals (PSM) site for which information was more readily available than for other sites.

Further heat balance and economic analysis of the PSM site was made. A summary of the heat transfer analysis is shown in Table 2-5. This analysis shows that at current maximum throughput of 15,000 lb/hr only 4×10^6 Btu/hr of the 5×10^6 available is utilized. At 5×10^6 Btu/hr the maximum throughput could possibly be increased to 19,000 lb/hr or a 27 percent increase. Using this same approach also shows that at low throughput (7000 lb/hr), energy savings by turning off burners after the material has reached temperature do not result in significant fuel savings (only about 5-1/2 percent) and the product cools less than 200° F due to the well-insulated furnace.

Table 2-5. Furnace energy losses

Location	Btu/hr
Walls	147,960
Burner exhaust	228,150 (Maximum firing rate, 50% excess air)
Furnace ends	335,980 (5% through each end at 2000°F)
Auxiliary stack	129,195 (5% through stack at 2000°F)
Metal exiting	$M(0.10573 \text{ Btu/lbm } ^\circ\text{F}) (2050-70)$

$$q_T = 217.8M + 841,285 \text{ Btu/hr}$$
$$M = \text{lbm/hr}$$

Figure 2-2 shows the calculated heat rate versus throughput for two different assumptions on losses from the ends and the auxiliary stack. This shows there is considerable room for improvement over the reported heat of 400 to 600 Btu/lbm. However, more precise data need to be collected to determine what other equipment contributes to the reported heat rate and how the duty cycle of the furnace influences the number (periods of down time).

From the results of the heat transfer analysis, the economics of the process were examined from a number of perspectives. Fuel savings at low throughput by shutting down burners after the product has reached temperature was shown to yield only about 130,000 Btu/hr savings from wall losses. This is only worth about \$5000/hr at \$5/10⁶ Btu and 8000 hr/year of operation. Similarly, if at the high throughput rates the product is overheated by 200°F, this will result in 330,000 Btu/hr extra heat loss. If this can be reduced, it will result in a savings of \$13,200/yr. So it is seen that fuel savings is not a strong motivation for implementing the technology.

On the other hand, if increased throughput can be realized by having a better knowledge of the temperature, a significant increase in profits can be realized. This relationship is shown in Figure 2-3 for a variety of product values. The conclusions from this economic evaluation are that fuel savings probably cannot justify the expense of the pyrometer, but that even if a small increase

Heat Rate vs. Throughput

Figure 2-2. Heat rate versus throughput (PSM)

- High Throughput — Increase 5 - 25% Base: 15,000 lbs/hr

Assume: Product Worth: \$1-\$5/lb

Profit: 5%

Hrs/Month: 666 hrs.

Figure 2-3. Increased profit versus increased throughput (PSM)

in product throughput is possible while maintaining quality control, the pyrometry can pay for itself in less than a year. On the whole, the PSM site is looking like an excellent candidate.

In addition to the above analysis, the Department of Energy performed a threshold analysis to determine the best use of funds. The analysis was performed for several cases which showed that at a unit cost of \$20,000 to \$30,000 significant payback could be realized in a very short time due to either fuel savings or quality improvements. The input parameters required are shown in Table 2-6, and specific values that were used in the analysis for Pyrolaser and the Raman Spectroscopy WPTA as shown in Tables 2-7 and 2-8. The actual results of the study can be reviewed in Appendix A.

The conclusion is that at the above projected cost, significant markets exist based on economic factors. Significant resistance to new technologies by operating personnel may slow the acceptance of these new systems, however.

2.3 MARKET ASSESSMENT

The market assessment and applications evaluation has determined that a large market for advanced, remote sensing, highly accurate thermometry instrumentation exists that will provide the opportunity for improved product quality, reduced reject rates, and lower energy consumption. This market exists at the relatively high-instrument cost of \$20,000/unit. As the unit cost decreases, the market is increased in volume of units sold, but does not necessarily increase in total dollar value. The main benefit of this project accrues at that time to the users in terms of reduced production costs of product due to lower reject rates and lower energy use.

The most attractive entry market is the heat-treating industry, which has a recognized need for this type of instrumentation. The chemical process industry attributes process-related problems to other factors, and only the process engineers appear to understand the enormous benefits that can be derived from closer operating controls. Exxon Corporation invested heavily in development of the present state-of-the-art instrumentation, since they recognized the benefit that could be derived. Exxon owns the patents for Pyrolaser.

Table 2-6. Project data required for threshold analysis

- A. Select typical production unit at one specific size.
- B. Estimate the following quantitative parameters:
 - 1. Differential Capital Cost for First Sale
 - relative to alternative scenario
 - in "year of first sale" dollars
 - a. Year first production unit is sold
 - b. End user purchase price of equipment
 - c. Installation cost to user -- if in addition to above
 - d. Profit (+,-) expected by developer
 - e. Salvage value (+,-) to user
 - f. Learning curve factor expected by developer over product life
 - 2. End User Annual Savings for First Sale
 - relative to alternative scenario
 - in "year of first sale" dollars
 - a. Non-fuel operating and maintenance costs (+,-), \$/unit/y
 - b. Other non-fuel savings (+,-), \$/unit/y
 - c. Per unit energy impact (Btu/y) by type of direct energy:
 - oil, gas, coal, other, and electricity (@ 10,000 Btu/kWh)
 - d. Production unit useful life
 - 3. Market Penetration
 - a. Production units sold during first year
 - b. Production unit sales opportunities over product life
 - c. Equivalent size unit sales opportunities over product life
 - d. Equivalent size units sold by year 2010
 - e. Market penetration of possible sales opportunities
 - f. Year by which 10%, 50%, and 90% of expected sales are achieved
 - 4. Project R&D Funding Data -- in "that-year" dollars
 - a. Sought federal investment in technology by year
 - b. Sought private investment in technology by year
 - 5. Private Post-Project Expenses to Commercialize
 - assumed to occur one year prior to first commercial sale
 - in "that-year" dollars
 - a. All front end costs including "tooling" to start production
 - 6. Federal Acceleration of Market Introduction
 - a. Years appearance of project technology advanced in marketplace

Table 2-7. Pyrolaser (threshold input data)

Petroleum Refining Industry

A. The unit size is the same in all cases.

B.1a. 1990 (4 Q)

1b. \$ 20, 000

1c. \$ 10, 000

1d. 15 %

1e. 0

1f. .9

2a. \$ 2,000

2b. \$ 464,000 Based on \$ 92,767K in shipments and .5% benefit (2149 units)

2c. \$ 17,600 Based on 1 % improvement in efficiency (2149 units)

2d. 10 years

3a. 7

3b. 10,000

3c. 10,000

3d. 500

3e. 500 by 2010

3f. 1992, 1995, 2010

4a. \$ 150,000

4b. \$ 100,000

5a. \$ 25,000

6a. 2 - 3 yrs.

Metal Heat Treating Industry (all inputs the same except those noted)

2b. \$ 182,000 (quality and throughput improvements)

2c. \$ 13,000 (10 % fuel reduction)

Specific Case

2b. \$ 150,000 (improvement in quality and throughput)

2c. \$ 13,000

Specific Case

2b. \$ 3,200,000 (quality improvement 2%, throughput 2%)

2c. \$ -

Table 2-8. Raman Spectroscopy (threshold analysis input data)

The market for the Raman Spectroscopy System is the same in part as for the Pyrolaser. Pyrolaser can not be used in dirty atmospheric environments and for remote analysis of the surface other than for temperature. The market is therefore substantially larger. The data reflected here is evaluating the semiconductor area where the return on investment appears to be very similar as for the average heat treating facility. There are some other markets such as the petroleum refining market (if fired with dirty fuels) where the payback would be higher.

A. Unit size the same in all cases.

B.1a. 1992 (4 Q)

1b. \$ 30,000

1c. \$ 10,000

1d. 15 %

1e. 0

1f. .9

2a. \$ 3,000

2b. \$ 193,000 (based on \$ 9,650K shipments of semiconductors and 2029 units)

2c. \$ 4,000

2d. 10 years

3a. 7

3b. 22,000

3c. 22,000

3d. 1,100

3e. 1,100 by 2010

3f. 1994, 1997, 2010

4a. \$ 390,000

4b. \$ 100,000

5a. \$ 100,000

6a. 5 years

Teledyne Wah Chang, a processor of specialty metals, is a very attractive candidate for a Beta-test site for the new instrumentation expected to be developed on this program. Teledyne has a strong interest in improving control strategies on their Zirconium solution annealing furnace.

Raman Spectroscopy offers exciting additional measurement capabilities in addition to thermometry. Development of this technology is a long term project, whereas the Pyrolaser offers high-quality measurement capabilities at this time.

Pyrolaser enhancements under consideration for implementation are improvements in the determination of the specularly and associated sources of measurements errors and a fiberoptics multiplexing adapter to reduce the cost per measurement point.

2.4 EXPECTED END PRODUCT AND COMMERCIALIZATION

The technologies examined both offer an opportunity to improve the measurement capabilities in difficult environments. The specific instruments are not going to be able to address all markets and all situations, however. The investment required in terms of time and research funds is lower for the enhancements to the Pyrolaser system whereas the Raman Spectroscopy WPTA will require substantial development as well as time.

The Pyrolaser offers an opportunity in the short term whereas Raman Spectroscopy has much to offer in the long term. Both technologies are similar in that they share common elements such as optics as an example. PIC is therefore in a strong position to commercialize the technology after feasibility has been firmly established and all important design parameters have been determined.

For this reason, the proposed program to proceed incorporates an enhancement program for Pyrolaser and a technology development program for Raman Spectroscopy. Both systems should have fiber optics capability to reduce cost/measurement point and to remove most of the electronics from sensitive environmental areas.

The recommended program is further discussed in Section 7.2.

SECTION 3

TEST SITE SELECTION

3.1 TEST SITE AGREEMENTS

Conclusions reached in the market assessment phase of the program confirmed that a large market exists for high accuracy, high temperature remote instrumentation. Some markets will be relatively easy to penetrate whereas others will require substantial demonstration of the benefits that can be derived from this technology.

Efforts have been made to contact companies in the heat treating business to solicit interest in working with a product development team, permitting product testing at their facilities, and developing relationships that will lead to greater understanding of the customer's perceived needs for this type of instrumentation. Response to these efforts has been quite favorable and much has already been learned, particularly about continuous sheet heat treating furnaces.

Agreements have been reached with Precision Specialty Metals (PSM), a stainless steel processor, to conduct testing at their facility and Teledyne Wah Chang.

3.2 PRECISION SPECIALTY METALS (PSM), LOS ANGELES, CALIFORNIA

PSM has a new, modern 50-ft heat-treating furnace that processes 0.006- to 0.080-inch thick by 36- to 50-inch-wide continuous stainless sheet steel. This furnace, as shown in Figures 3-1 and 3-2, has been in operation for less than a year, and utilizes 32 (16 pairs of) new North American Twin Bed Regenerative Burners distributed along the length of the furnace. Temperature control is relatively simple, however, with a single thermocouple in each zone controlling 16 burners (8 sets) per zone. The fuel/air ratio for the group of burners in each zone is fixed, and temperature is controlled by modulating the overall firing rate of the complete set of burners for that zone.

Figure 3-1. PSM furnace cross section

PLAN SECTION

Figure 3-2. The PSM furnace

Localized manual adjustment of each burner for trimming purposes is also possible. For example, at low loads PSM has had some difficulty in achieving sufficient turndown to the extent that they have had to shut down some burner sets and place restrictor orifices in the fuel lines of others.

Metallurgically, the only requirement is that the material reach 2050°F. In this process the internal microscopic structure of the material begins in a random work-hardened state. When raised to the critical temperature, the material's internal structure becomes uniform, and when cooled to room temperature, the crystalline structure then becomes organized in a regular pattern. The goal is to heat the entire cross-section up to the critical temperature; no significant time is required at temperature.

The present method of operation is based on the experience of running different metals and metal thicknesses. A table has been developed indicating the linear speed of the strip, dependent on width and thickness. Needless to say, this is an empirical process. The maximum throughput on thin material is limited not by the heat capacity of the furnace but by the maximum speed of downstream equipment (50 ft/min). Maximum throughput of thicker material is perceived to be limited by maximum firing rate of the burners and the time it takes to heat the product to temperature. However, because the instrumentation is so limited, the true maximum firing rate is not known. Currently, PSM limits maximum throughput of the thicker material to 15,000 lb/hr.

Quality control has not been a problem in that PSM has been able to achieve the critical temperature for all the current throughputs. In addition, because the furnace is so well-insulated, and because of the use of the North American regenerative burners, thermal efficiency and temperature uniformity across the furnace is perceived to be excellent. The benefit of being able to determine the product temperature accurately would be the increased throughput possible with thicker materials, and the potential for lower energy consumption when thinner materials are processed and the minimum number of burners are operated. The return on investment would be substantial, and the equipment could be paid for in a few months of improved operation.

PSM has expressed strong interest in improved temperature measuring capabilities of its product to improve productivity, quality and ease of operation of its facilities.

3.3 PINOLE STEEL-TREATING FURNACE, PINOLE, CALIFORNIA

Pinole Steel has a modern continuous heat-treating furnace that prepares sheet steel for zinc plating or prepainting. The facility, shown in Figure 3-3, consists of three sections: the direct-fired cleaner, a radiant tube annealing section, and a cooling section. The direct-fired heater takes the material to 1050°F in an oxidizing atmosphere, utilizing 60 small burners in 4 zones. The zone temperature, measured by a single thermocouple, is controlled by the firing rate to the entire zone. Adjustment of individual burners for trimming is done manually. If more temperature information was available, the number of control zones could be increased. However, this would necessitate modifying the piping, increasing the number of control valves, and increasing the number of controllers.

The second section of the furnace takes the temperature of the product to 1350°F in a controlled H₂/N₂ atmosphere, using radiant tube burners. Again, the number of zones could be increased if a more precise knowledge of the temperature was available. However, considerable hardware and control modifications would be required.

The final section of the furnace is the cooling section, in which no active burners are employed. The main problem is quality control. The instrumentation is limited to a few thermocouples, and, thus, a thorough knowledge of the temperature distribution in each zone is unavailable. Knowledge of the temperature distribution would allow Pinole Steel to adjust the burners to improve quality control.

3.4 TELEDYNE WAH CHANG, ALBANY, OREGON

Teledyne Wah Chang is a large rare earth specialty metal producer producing such exotic metals as Zirconium, Hafnium, and Columbium from Australian sand. Teledyne also processes large quantities of Titanium. Zirconium is produced for the nuclear industry to house fuel pellets in fuel elements in nuclear reactors. Hafnium is used as an additive to nickel-base superalloys

Figure 3-3. Pinole Steel heat-treating furnace

which are used in gas turbines. Columbium finds application in superconductors. What these products have in common is that they are exotic and very high in value. In order to provide the strict requirements of quality and certification, accurate processing procedures and process temperatures must be maintained. Teledyne owns many facilities that process these materials where these requirements apply.

Of particular interest among the many facilities is an electrically heated inert atmosphere solution annealing furnace to continuously treat zirconium alloy sheet. The accuracy requirements are extreme and require that thermocouples be attached to the material and travel through the furnace with the material, because no other method meets the requirements of Bureau of Standards traceability. The temperatures are high requiring very expensive Platinum-Rhodium thermocouples equal to the length of the sheet. This method of monitoring is very expensive, time consuming, and inefficient.

Teledyne Wah Chang expressed a strong interest in working with the development team to test the new products and improve the operation of the facility. Teledyne is also interested in installing active closed loop controls to improve the reliability and predictability of its processes.

An agreement with Teledyne Wah Chang to become a Beta-test site was needed, and preliminary tests were performed at this site.

3.5 SUMMARY—METALLURGICAL FURNACES

Of the three metallurgical furnace sites evaluated, the Teledyne Wah Chang continuous solution zirconium heat-treating furnace appears to offer the greatest potential for this program for Phase II and Phase III. The Teledyne facility has a sufficient number of view ports to permit observation of the material in process and measure actual process temperatures. Since Teledyne already measures the material temperature for certification purposes with travelling thermocouples that have been calibrated to Bureau of Standards requirements, it offers an ideal comparison of the new measurement technique with proven methods.

The requirements that PSM have are much less stringent, and PSM does not typically conduct calibration runs, which, if conducted by the development team, would unnecessarily increase the cost of testing of the new product.

Similar comments to those made regarding the PSM facility apply to the Pinole Steel Heat-Treating Furnace. The operation can be significantly improved with high-accuracy instrumentation, but the need is not as pressing as for Teledyne, who was willing as of these discussions to make substantial investments in time and equipment to improve the operation.

In summary, the heat-treating industry appears to have the most pressing needs for improved remote workpiece temperature measurement capability, and the need is recognized. Substantial improvements in quality and/or certification capability can be achieved with new proposed thermometry. With higher confidence in their temperature monitoring capabilities, processors can reduce energy consumption, since the conservative method of supplying more than enough will be tempered.

SECTION 4

PRESENT TECHNOLOGY ASSESSMENT

4.1 OVERVIEW

Temperature measurement devices can be broadly classified into two major categories: electronic and mechanical. Electronic devices include resistance temperature detectors (RTD), thermocouples, and noncontact techniques such as optical or radiation pyrometers, and acoustic pyrometers. Mechanical devices include bimetallic and mercury thermometers, etc. A review of the classic temperature measurement technologies needed to cover the various temperature ranges monitored in utility powerplant operations may be found in a recent paper by Gile (1986) (Reference 4). The limitations of optical pyrometers for use in measuring gas temperatures may be found in the reference book Steam/Its Generation and Use (Reference 5). Optical pyrometers, for example, have been used for several years as a way to make spot readings, primarily in combustion zones. To be reliably used, however, optical pyrometers must be responsive to a number of optical wavelengths, and they require some preliminary knowledge of thermal gradients through the gas medium to the point where the temperature measurement is to be made. Other limitations are in the inability of optical pyrometers to track temperatures throughout the furnace depth, and during furnace shutdown and startup cycles or during changes of load. Optical pyrometers are therefore not suitable to measure gas temperatures. For surface measurements the emissivity of the surface must be known. The Pyrolaser overcomes these problems as discussed later.

For gas temperature measurements in furnaces, mechanical temperature measurement systems are used that are typically configured to minimize errors due to radiation effects. An

excellent review of the measurement of gas temperature in boiler furnaces may be found in a paper by Ely (1969) (Reference 6). These types of temperature probes require that cooling water be circulated in order to keep the probe support from melting. Such water-cooled high-velocity thermocouple (HVT) probes are used to measure temperatures above 1000°F (538°C). They have been successfully used for many years, but become impractical when boiler widths exceed 40 to 50 ft (12 to 27m) since the maximum working length of a probe is 24 ft (7.3m). There is often insufficient access to ports or external clearance to permit a complete traverse. Surface temperatures are usually made with contact measurement devices which only read the temperature at one spot.

To utilize HVT to determine average temperatures requires that many point-by-point temperature measurements be taken in a very short time span within a measurement plane. Individual measurements are then averaged to obtain a final temperature. The water-cooled probes are difficult to maneuver and support, and the test procedure is quite labor-intensive. Extreme care must be taken to protect thermocouple junctions, extension wire splices, ceramic shields, and insulators from mechanical damage. This temperature measurement method is suitable only for periodic test measurements. Acurex has extensive experience in the design of high-temperature probes, and has conducted many measurement programs for the EPA and other regulatory and government agencies to characterize combustion facility operating conditions and environmental emissions.

Acoustic pyrometry is applied to gas measurements. It is not a new concept as it was first suggested by A. M. Mayer in 1973 (Reference 7). A recent paper by Green and Woodham (Reference 8) discusses acoustic pyrometry applied to a large utility boiler.

Acoustic waves propagate through a gas, or gas mixture, as a primary function of absolute temperature, and to a lesser extent as a function of the specific heat ratio and gas composition. These gas-specific variables can be predetermined (or separately determined) leaving gas temperature as the variable measured by acoustic techniques.

Green and Woodham's tests were performed under ambient conditions on a out-of-service boiler by comparing acoustically measured temperatures to thermocouples and mercury-in-glass thermometers. They repeated the experiment while the boiler was in service and compared calculated values, based on boiler operating data. They did not conduct high-temperature validation tests with HVTs.

Another approach for measuring gas temperatures based on the propagation velocity of sound has been recently reported. This non-invasive method permits continuous real-time gas temperature measurements in the hostile operating environments existing in utility, commercial, and industrial boilers and furnaces. This method, best described as an acoustic pyrometer, has several advantages over optical pyrometers and thermocouple-type probes.

In large furnaces, water-cooled HVTs can provide bulk furnace temperatures. Temperature distributions, however, can only be measured using these devices provided a means is provided to traverse the furnace to be measured. Such a method is labor-intensive, not practical for large furnaces, and is intrusive to the heating process being measured.

An acoustic pyrometer, when combined with proper signal processing methods, can provide real-time temperature measurements and isothermal contouring within a furnace.

A relatively new instrument allowing the non-contact measurement of surface temperatures is made possible with the Pyrolaser. This instrument has been available for approximately 3 years and relatively few results have been published.

The Pyrolaser differs from an optical pyrometer in that it measures the surface emissivity of the object at the same time and location as the surface radiation. The guesswork has thereby been taken out of estimating the emissivity, which has been the primary source of errors when using an optical pyrometer. Reflections from walls and other surfaces also contributed to these errors.

The Pyrolaser offers a significant advancement over standard optical pyrometers but is still saddled with limitations that would argue for a new technology development such as Raman Spectroscopy.

4.2 COMPARISON OF RAMAN THERMOMETRY AND PYROLASER PYROMETRY

This section compares the Raman thermometry approach to another method currently available for remote thermometry—the Pyrolaser pyrometer.

4.2.1 Comparison of Operating Principles

The Pyrolaser pyrometer combines a radiometer with a laser reflectometer for temperature measurements. A GaAlAs laser beam in the wavelength range of 0.8 to 0.9 μm is emitted at the target solid and part of the beam gets diffusely reflected into the collection optics. By measuring the laser power diffusely reflected into the known solid angle of the collection optics and comparing it with the incident laser power, the surface reflectivity, R , may be determined. The emissivity is then determined as $E = 1 - R$. Knowing the solid spectral emissivity, in the wavelength range of the GaAlAs laser, the solid temperature may be determined by measuring the continuum gray/blackbody radiation in the same wavelength range and using the Planck relationship:

$$e_{\lambda b}(\lambda) = \frac{2\pi C_1 \lambda^{-5}}{(e^{C_2/\lambda T} - 1)} \quad (4-1)$$

A more detailed discussion is presented Reference 9.

By contrast, the Raman Spectroscopy technique interrogates the workpiece with a laser beam of any frequency and collects the Stokes and Anti-Stokes radiation for ratioing. The ratio of these two signals can then be used to determine the temperature.

4.2.2 Comparison of Capabilities and Limitations

Advertised specifications for the Pyrolaser are listed in Table 4-1. The device is lightweight and quite versatile, and the temperature window can be moved up or down. The main limitations of the Pyrolaser are:

- It is inaccurate at low reflectivities (~ 0.1)
- It is not suited to specular surfaces

Table 4-1. Pyrolaser specifications

<u>PYROLASER™ SPECIFICATIONS</u>	
Temperature Range:	600°C - 1500°C (1100°F - 2730°F)
Resolution:	1°C (1°F)
Accuracy:	3°C (5°F) at 1500°C (2730°F), emissivity 0.80
Repeatability:	1°C (1°F)
Distance Range:	20cm - 10m (8 in. - 33 ft.)
Emissivity Range:	0.1 - 1.00 (all temperatures below 1500°C)
LED Display in Viewfinder:	4 digit LED corrected temperature
LCD Display:	40 character readout of distance, emissivity, uncorrected temperature & corrected temperature
Operating Wavelength:	0.865 microns $\pm$ 0.015
Visual Field of View:	7°
I.R. Measuring Field:	1/3° (1mm @ 20cm; .04" @ 8 in.)
Acquisition Time:	10 ms to 1000 ms selectable
Sample Rate:	35/sec; 700 record data logger filled in 20 seconds.
Storage Capacity:	700 sets of measurements (time, location, distance, emissivity, uncorrected temperature & corrected temperature) Max number of extraneous temperature readings (99).
Output/Digital:	RS 232C 110-19200 baud selectable
Output/Analog:	0-5 volt (resolution 1.25 mV)
Power Supply:	3 X 9V rechargeable NiCd batteries
Operating Time with Fully Charged Batteries:	2 hours
Operating Ambient Temp:	0 to +50°C (32°F - 125°F)
Storage Temperature:	-20°C - +70°C (0 - 160°F)
Dimensions:	318 x 211 x 74mm (12 1/2 x 8 x 3")
Weight with Batteries:	3.5 kg (7 lbs.)

SEPTEMBER 1988

- It is only suited to clean environments—no soot
- It is limited to wavelengths not absorbed by gaseous medium
- Laser wavelength must be within target's blackbody emission band
- Temperature range is high: $> 600^{\circ}\text{C}$ (with standard optics)

By comparison, the Raman thermometer has a temperature range from near absolute zero to over 4000°K (Figures 4-1 and 4-2). The resolution and accuracy are similar to the Pyrolaser value given in Table 4-1, and just like the Pyrolaser, the range (focusing distance) can be changed by changing the optics. The Raman thermometer is unaffected by emissivity and works equally well with spectral and diffuse surfaces. Actually, spectral surfaces offer the advantage that the elastically scattered signal may be largely avoided by viewing or aiming the laser at an angle. This would relax the requirements for ultra-high rejection in the collection optics. Other advantages of the Raman Spectroscope include:

- No particular laser wavelength is required
- Laser frequency does not have to be outside gas absorption windows or within emission band of solid
- Can be used for non-thermometric measurements as discussed below
- Can be used in dirty environments and combustors
- Can be used to determine both gas and solid temperatures and thus determine heat transfer effectiveness

As discussed in the previous section, Raman thermometry is resistant to interference from:

- Particulate continuum radiation and fluorescence
- Particulate (Mie) scattering
- Laser-modulated incandescence
- Gas radiation, scattering and absorption
- Stray reflections of outside light
- Surface inhomogeneities in absorption and scattering of light

Figure 4-1. Temperature measurements by Raman Spectroscopy

Figure 4-2. Temperature measurement by Raman Spectroscopy

- Window dirt and fluorescence
- Dirty environs within or outside combustors

Although the Pyrolaser pyrometer is a very versatile instrument, it is not resistant to any of these interferences except fluorescence outside the laser emission band. If these fluorescence signals are strong enough, they could make the radiometer measurements erroneous and destroy the accuracy of the measurement.

4.2.3 Comparison of Applicability to Non-Thermometric Measurements

Both the Pyrolaser pyrometer and the Raman Spectroscope can be used for other measurements besides temperature.

The Pyrolaser incorporates a reflectometer and can be used for real-time determination of surface reflectivity (in clean environments). It can therefore be applied in materials science to observe surface phenomena such as grain boundary, grain structure, and composition changes. The reflectometer itself will not yield the species on the surface but will indicate if and when changes are taking place. For example, by measuring changes in reflectivity, the device can be used to observe changes during annealing or to infer whether an oxide coating has developed.

The Raman Spectroscope can also be used for several non-thermometric measurements. It can be used for:

- Remote detection and quantification of gaseous species (number density)
- Remote detection of liquid species
- Remote detection of particulate species and subsequent quantification via fluorescence
- Remote measurement of surface properties such as composition and adsorbed species, corrosion, strain/stress, grain properties
- Remote, in situ measurement of catalyst structure, composition and poisoning
- Remote study of processes such as annealing, smelting and heat treating for material composition, properties and temperature

- Remote study and quantification of rust/oxide formation, soot and other particulate deposition and corrosion

4.2.4 Measurement Regimes for Each Instrument

From the above discussion, it can be concluded that the Pyrolaser pyrometer is best suited to measurements in particulate-free environments, at temperatures above several hundred °C (> 500 to 600°C) and with non-specular solids having emissivities over 0.10.

The Raman Spectroscope is suitable for measurements in clean or dirty environments with or without particulate luminosity. There are no requirements on workpiece emissivity ranges and specular reflection does not constitute a problem. The quantity of particulates and solid temperature determine the laser power required. Lasers in the commonly available visible wavelengths can be applied. At solid temperatures below about 1000°C, low-power (10 to 100 mW) CW-lasers can be applied. At temperatures above about 2000°C in very sooty liquid- and solid-fueled flames, pulsed lasers are needed with about 0.1 to 1.0 J/pulse and power output, $P > 10^4 - 10^6$ Watts.

4.3 MARKET FOR APPLICATION OF PYROLASER OR RAMAN SPECTROSCOPY

The objectives of Phase I were to determine whether Pyrolaser or Raman Spectroscopy is technically and economically feasible for industrial furnaces and to identify the best specific applications. Subobjectives included:

- Identifying the features and benefits of new instrumentation systems needed for improved furnace productivity, with an emphasis on new pyrometry methods
- Characterizing the technical and cost aspects of furnaces and furnace operation, with an emphasis on temperature-related quality control and productivity issues
- Determining the best contribution for new pyrometry and quantifying the benefits
- Assessing the costs and economic attractiveness of new pyrometry
- Estimating the number of furnaces and the energy use impacted by a successful new pyrometry system

- Helping to identify and qualify candidate field evaluation sites

The application study was to cover furnaces used for metals forming, metals heat treating, the fabrication of ceramic parts, and process and refining furnaces.

The market assessment identified those applications and furnace types for which the new instrumentation will provide the greatest benefits. The market assessment covered:

- The importance of the data to the process
- The ability of current and possible future control systems and burners to utilize the new information provided by the instrumentation system
- The improvements in product quality and yield implied by the improvements
- The improvements in furnace operation implied
- The economic benefits of the improvements

In addition, the market assessment identified the relative size and importance of the various submarkets in the industry, concentrating on submarkets with high premiums on product quality (especially dimensional accuracy and uniformity of bulk properties and surface quality), and a variety of product shapes or sizes being handled in the same facility. This is discussed in Section 2.

4.4 ADVANCED MEASUREMENT CAPABILITIES OF RAMAN SPECTROSCOPY

Raman scattering is the inelastic scattering of light from material media. In the Raman effect, the incident light undergoes a wavelength change while the scattering medium experiences an energy change in the process. This effect and its intensity can be used to determine the material or surface temperature. If a laser is directed at a target, the colliding photons can either lose energy to or gain energy from the target medium. The resulting Stokes scattering is monitored, and it can provide a wealth of information besides temperature about the surface condition. Raman scattering in solids has been extensively investigated. Much of the current effort in Raman Spectroscopy is devoted to this technology due to its versatility. In addition to workpiece temperature, Raman scattering yields information about stress/strain, composition, crystal orientation, impurity concentrations, charge carrier concentrations, and several other properties

simultaneously. Instrumentation to date has been primarily for laboratory purposes except for atmospheric studies, but has not been adapted to the industrial world.

Several advanced additional measurement capabilities are summarized below. The development of Raman thermometry would result in an instrument that could be easily adapted to incorporate these additional capabilities of analysis.

4.4.1 Stress/Strain Indication

The Raman effect is made possible by the strain dependence of the electronic polarizability. Raman Spectroscopy can (and has) therefore been used to indicate the effects of uniaxial and hydrostatic stresses. Some development is required before this method is applicable to general in-situ stress/strain measurements. Shear stresses and strains can also be indicated, although it is questionable whether compound stresses can be resolved in any meaningful way.

4.4.2 Crystallography

Due to the lattice-specificity, high time-resolution (order of nanoseconds), and high-spatial resolution (order of microns) of a Raman probe, the method is uniquely suited to nondestructive crystallography. Applications include the study of:

- Changes in crystal structure (e.g., FCC/BCC/HCP)
- Changes in the solid phase, ranging from diffusion through such reactions as oxidation/passivation
- Changes in grain property during heating or working
- Elastic and/or plastic deformation of crystals
- Characterization and study of point and line defects

4.4.3 Species Concentrations

Raman Spectroscopy can be used to study species concentrations in gases, liquids, and solids. This is especially useful in the solid phase for determining impurity concentrations. The concentration of solute elements affects such properties as strength, hardness, and charge-carrier

concentration. In the case of semiconductors, the type and concentration of impurity atoms is crucial, and may be studied during the deposition or diffusion process.

Gases and liquids can be examined via nonlinear Raman effects such as CARS and stimulated Raman, to improve the signal/noise ratio. In combustion gases, for example, transient reaction species and radicals may be studied to elucidate the combustion process.

4.4.4 Corrosion Studies

Raman Spectroscopy is well suited to the study of oxide formation and corrosion. Chemical profiles can be obtained of the oxide films on iron, steel, and other metals. In polluted atmospheres, Raman Spectroscopy may also be used to analyze metallic salts formed on piping elements and reaction vessels. Raman analysis can thus be used as an in-place, nondestructive indicator of reaction vessel condition.

4.4.5 Catalysis Studies

Raman Spectroscopy is well suited to in-situ studies of catalysts. This nondestructive method can be used to detect and characterize adsorbed species and poisons in-situ. The structure, reactivity and phase transitions of the catalyst and substrate can be observed during operation. The potential market for nondestructive, in-situ catalytic study is large and includes the inorganic chemical, petroleum and petro-chemical industries as well as biochemical industries. In-situ observation will allow catalyst performance to be optimized, saving energy and improving product quality. A brief sampling of catalysts is presented below.

- Hydrosulfurization catalysts such as cobalt and nickel molybdates have been studied for reactivity employing Raman spectroscopy
- Methanation catalysts— $\text{NiO/Cr}_2\text{O}_3/\text{MgSiO}_3$ —have also been studied in-situ to determine catalyst structure and the effects of reduction and sulfiding
- Petroleum refining catalysts are numerous and include:
 - Naphtha reforming catalysts such as Pt/ReCl , where Re denotes a rare earth metal
 - Dimerization catalysts such as Ni or Al_2O_3

- Polymerization catalysts such as TiCl_4 and other Ziegler catalysts
- Isomerization catalysts such as Pt or PtCl
- Fluid cracking catalysts such as zeolites
- Hydrocracking catalysts such as CoMo and NiMo, NiO, CoO, MoO_3
- Hydrogeneration catalysts such as NiO, CoO and MoO_3 , Pt, Pd
- Elemental sulfur recovery catalysts such as Al, Ti, Fe oxides
- Steam hydrocarbon reforming catalysts such as Al_2O_3 , ZnO, Fe, Cr oxides.

Other catalysts that can be studied include Friedel-Crafts catalysts such as AlCl_3 and FeCl_3 , Quinone production catalysts such as V_2O_5 and MnO_2 and Amino-synthetic catalysts such as Pd.

The Raman process is undeterred by the wide variety of processes and catalysts and applies equally to all.

4.5 POTENTIAL PYROLASER ENHANCEMENTS

The Pyrolaser represents the latest state-of-the-art remote surface temperature measurement technology. Optical pyrometers measure the energy emitted from a radiating surface. This temperature is dependent on the emissivity of the surface, which is a function of the material, temperature and surface condition such as roughness. Pyrolaser not only measures the energy emitted from the radiating surface, but also measures the reflected light from a GaAs laser beam to determine the surface emissivity at the same location where the temperature reading is taken and at the same time. A detailed discussion of the principles of the Pyrolaser can be found in Appendix B: Improved Infrared Temperature Measurement by Utilization of Laser Technology.

Measurements performed on this program at the PSM facility and many previous other facilities have shown that the Pyrolaser is sensitive to surface reflectivity. The instrument performs best when the surface condition comes closest to that of an ideal black body. When the surface of the measured body exhibits a degree of specularity, small errors in the temperature measurement persist. New approaches are being developed to address this question to implement correction factors in the measurement routines.

A second enhancement that has been identified to make the instrument substantially more attractive to the marketplace is multipoint measuring capability while the unit is located in a fixed location. A multiplexing fiberoptics capability is being investigated.

Additionally, a substantially lower temperature capability is being sought.

SECTION 5

PYROLASER-PYROFIBER INDUSTRIAL TESTS

5.1 INTRODUCTION

To gain a better understanding of the Pyrolaser temperature measurement capability, two tests were performed at PSM and one at Teledyne Wah Chang. The tests performed at PSM were conducted in conjunction with another test program to evaluate acoustic pyrometry. The test conducted at Teledyne was performed with a standard Pyrolaser and additionally with an advanced Pyrofiber-breadboard system. The Pyrofiber system utilizes two fiberoptics cables to route the signal to a remote sensor housing. The breadboard system was built as a result of observations made during earlier testing at PSM on this project. The breadboard was to demonstrate the feasibility of this concept. Efficiencies gained on the project allowed for this advanced work showing feasibility. Instrument development would be further carried out in Phase II of this project. Feasibility was demonstrated for the Pyrofiber unit although several specific problems have to be addressed in the future.

5.2 PYROLASER TESTS AT PRECISION SPECIALTY METALS (PSM)

Two tests were performed at PSM. The first test was primarily a survey test to determine what the best settings and the best system configuration would be at the site. The following objectives were set for this part of the project.

The exact furnace geometry was to be determined, the access to view the material in process, the thermodynamics and heating cycle, dynamic timing effects, the temperature irradiance conditions and other pertinent ancillary factors. During the course of the inspection several measurements of temperature were made. Expanded tests were performed at a later date in which

trailing thermocouples were passed through the furnace at the same time Pyrolaser measurements were made.

5.2.1 Furnace Details

The metal heat treating operation at PSM uses a continuous strip annealing furnace designed and constructed onsite by J. T. Thorpe in 1988. It measures 50 ft in length by approximately 8 ft in width. It is fed by a roll of sheetmetal, usually 301 Stainless Steel, which enters at ambient temperature. Furnace temperature setpoints are approximately 1950°F and 2050°F in the first and second halves (zones) of the furnace, respectively. Different materials and thicknesses require somewhat different temperatures and feedrates.

The furnace is followed by a caustic quench and a set of acid baths for posttreatment according to customer order. The treated metal then winds onto a roll at the end of the process.

A roll of metal takes about 20 to 25 min for complete processing. Before the end of a roll enters the furnace, the beginning of a new roll is welded to it, for continuity. After passing through the process, the small weld section is discarded and a new roll started.

The furnace has 16 pairs of natural-gas-fired twin bed burners. North American developed the twin bed concept to take advantage of regenerative furnace principles for fuel conservation. One burner fires while its twin serves as a flue, in which heat-storing material extracts heat from the flue gas. After 20 s, they reverse roles, and the heat reclamation bed pre-heats the cold combustion air, without additional fuel expenditure.

A schematic of the PSM sintering furnace and burner operation and description is shown in Figure 5-1.

For utilization of the Pyrolaser there was only one useable access port. This port is situated on the top of the furnace and approximately 6 ft from the steel exit. At this position the steel was in an ascending geometry from its catenary path, and the estimated distance of the steel from the viewing port ranged from 28 to 32 in. The viewing port itself was a glass window having a diameter

of 1-1/2 in, and sub-tending below the viewing port was a sighting tube with a length of approximately 10 in and an inside diameter of 1-1/2 in.

The burner installation incorporated state-of-the-art technology which recycled expended energy to preheat incoming air mixtures by alternately cycling each burner as a heat source and as an exhaust flue. Cycle time was approximately 20 to 30 s, and as such the field of view of the Pyrolaser, when positioned on the target steel, was intermittently exposed to the natural gas flame approximately 30 s/min.

The glass viewing port was visually dirty upon first investigation, and it was very difficult to see the surface of the target steel, and essentially impossible to use the Pyrolaser's split image focusing system to input the distance to the instrument. There was no other practical access to the steel target from any other position on the furnace. A possible surrogate measurement of the exiting steel could be made and correlation to the steel temperature at the viewing port location might be inferred.

5.2.2 Test Measurements

The readings of the steel were made through the apparently radiance-obscured window by mounting the instrument on a floor tripod and placing the positioning head in a vertical orientation. The first reading was made with the instrument approximately 12 in from the viewing port; and the minimum distance was set with the objective lens, which for this particular instrument, S/N #005, was 6.35 ft. The results yielded an emissivity of 1.0 and a corrected temperature reading of 1247°F. Five min later a second reading was made of the steel, having increased the height of the tripod so that the instrument was approximately 51 in from the viewing port; and results were an emissivity of 1.0 and corrected temperature reading of 1495°F. A final reading in the initial series of measurements was made in a hand-held position estimating actual distance from the viewing port to be 53 in, again with minimum distance set into the Pyrolaser; and the results were an emissivity of 0.99 and corrected temperature of 1209°F.

Simultaneously, a reading was made on the exiting steel to assess temperature correlation. At an actual and focused distance of 8.58 ft and an inputted target angle of 45°, an emissivity of 0.96 was measured and a corrected temperature of 1702°F. The time period encompassing all of the above measurements was 13 min, and during this interval the same steel product roll was being processed and the same hoped-for thermodynamic conditions within the furnace were set and controlled. These conditions were to achieve an ambient temperature of approximately 2000°F in the area or zone of the furnace where the viewing port and temperature measurements were being made.

In order to obtain access to the viewing port for measurements by the Pyrolaser, a Williamson infrared online pyrometer had to be removed, and it was noted that at that time its indicated reading on the control panel was 2030°F.

The viewing glass window was changed upon our request, and subsequent readings with the Pyrolaser were made. The first reading with the clean window in the second series of measurements was with the instrument mounted on the tripod at a distance from the viewing port of approximately 51 in, and with the viewing port approximately 30 in from the steel, or a total actual distance of 81 in, or 6.75 ft, and a set-in distance of 6.35 ft. The measured emissivity was 0.93 with a corrected temperature of 1860°F. The next reading in the series, made with the tripod extended to its maximum height, was taken approximately 61 in from the viewing port, the minimum distance set in; and the measured values were an emissivity of 0.63 and a corrected temperature of 1947°F. The final reading in the second series, with the tripod maintained in its maximum elevated position, but with an inputted distance of 6.75 ft, the computed estimated distance, yielded an emissivity of 0.85 and a corrected temperature of 1899°F.

A third series of readings was made on the target steel from the same viewing port approximately 4 hr later, and this time the automatic mode of operation was selected. It was noted that even in this relatively short time period from the second series of measurements, the visual condition of the sighting port had darkened markedly. During this approximately 2-min time

measuring period it was necessary to make some fine sighting adjustments on the instrument to assure that it continued to measure the steel through the viewing port.

A second automatic mode set of measurements was then made on the steel sheeting exiting from the furnace, with the Pyrolaser mounted on a tripod and having an angle of incidence of approximately 45° to the sheeting and having this same target angle set into the instrument.

5.2.3 Discussion of Test Measurements

The conditions of the viewport glass affected the measured parameters. The first series of readings yielded emissivities of 0.99 to 1.0 and corrected temperatures from 1209°F to 1495°F, indicative of low radiance signals and large laser reflectance radiance measurements. At the same time, the measured temperature values of the steel exiting from the furnace were approximately 1700°F and the temperature in the same hot zone as the steel measured was approximately 2000°F.

There was variation in temperature measurements as a function of actual and set-in focal distance as temperature values varied from 1868° to 1947°F (through a clean, newly replaced viewing port) and emissivity varied from 0.63 to 0.93. These differences occurred during the second series of readings. The readings were taken through a sight tube which might offer radiance interruption depending upon the target size/focal distance utilized. The measurement of both temperature and reflectance is accomplished by measuring the intensity of a cone of radiation that is defined by the optics of the instrument and the focal distance to the target. Should there be any encroachment of this radiation cone, such as might be caused by the inside diameter of the sighting tube, the amount of radiance measured will be reduced and a lower radiance temperature and reflectance value will be indicated.

The intermittent gas flames had no effect on Pyrolaser measured values.

Further tests of the Pyrolaser on the furnace were needed in view of the variations measured during initial testing and as described above. The condition of the viewing port glass seemed to be a vital component and there should be some means undertaken to maintain the glass.

Measurements of the exact distance between the steel target material and the Pyrolaser had to be made and this exact information incorporated into the instrument. An average value of focal distance had to be utilized to approximate the catenary variations of the steel sheeting as it passes below the viewport.

Measurements of the steel material by the Pyrolaser should be made with and without the presence of the sighting tube to determine experimentally what effect this tubular system has on both the temperature radiance signal from the target steel and the laser reflectance radiance signal from the Pyrolaser.

Temperature measuring tests of the sheeting utilizing a shorter focal length lens on the instrument should be made to see what effect this change of the measuring cone of radiance, vis-a-vis the sighting tube, might have on the recorded values of temperature and emissivity.

If possible, sighting of the Pyrolaser through a furnace opening of greater than 2 in is suggested to see if this larger furnace aperture (greater than the aperture of the objective lens system of the instrument) affects the measured values.

Results of the measurements made are tabulated in Table 5-1. Additionally, a sample printout of data from the Pyrolaser test is shown in Figure 5-2.

The second set of data collected at PSM during the second test yielded significantly better results compared to the first, but it also pointed the way toward possible improvements that should be made to the Pyrolaser system.

This set of tests took place from March 27 to 30, 1990. In addition to the Pyrolaser measurements, thermocouples and an acoustic pyrometry system provided data for the tests. Some of the thermocouples were welded to the metal being processed, and were covered with small radiation shields. Other thermocouples were incorporated into custom-designed ring probes, which rode through the furnace on top of the metal being heat treated. Thermocouple signals were cold-junction compensated and linearized before recording.

Table 5-1. Summary of measurements

SERIES 1:

WITH THE SIGHTING WINDOW IN A VISUALLY 'DIRTY' CONDITION:

ACTUAL DIST. FROM <u>VIEWPORT*</u>	DIST. SET-IN <u>TO PL</u>	MEASURED <u>EMISSIVITY</u>	CORR. <u>TEMP.</u>	<u>COMMENTS</u>
	MINIMUM			
12"	DISTANCE**	1.0	1247	TRIPOD MOUNTED
51"	MINIMUM	1.0	1495	TRIPOD MOUNTED
50"	MINIMUM	0.99	1209	HAND-HELD

MEASUREMENT OF STEEL EXITING THE FURNACE:

8.35'	8.35'	0.96	1702	ACTUAL AND SET-IN ANGLE OF INCIDENCE 45°
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* DISTANCE FROM VIEWPORT TO STEEL ESTIMATED AT 30" (AVERAGE OF CATENARY
POSITION)

** UNABLE TO FOCUS ON TARGET

Table 5-1. Summary of measurements (concluded)

SERIES 2:

THE VIEWING PORT GLASS WAS CHANGED AND WAS VISIBLY CLEAR:

ACTUAL DIST.FROM <u>VIEWPORT*</u>	DIST. SET-IN <u>TO P/L</u>	MEASURED <u>EMISSIVITY</u>	CORR. <u>TEMP.</u>	<u>COMMENTS</u>
6.34'	6.34'	0.93	1868	TRIPOD MOUNTED
6.35'	6.35'	0.63	1947	TRIPOD MOUNTED
6.75'	6.75'	0.85	1899	TRIPOD MOUNTED

SERIES 3:

A) MEASUREMENT OF STEEL IN THE FURNACE THROUGH THE VIEWPORT IN THE AUTOMATIC
MODE: SEE BELOW READINGS 10 THROUGH 63.

D) STEEL EXITING THE FACE: SEE ATTACHED READINGS (THROUGH 107

NOTEBOOK PRINT

LOCATION	D A T E / T I M E	DISTANCE	MODE	Nx / EM	Tunc.	Tcorr.
00-00-107	89-09-20 14:53:07	9.43 ft	E 0	0.97	1735 F	1740 F
00-00-106	89-09-20 14:53:05	9.43 ft	E 0	0.97	1731 F	1737 F
00-00-105	89-09-20 14:53:03	9.43 ft	E 0	0.97	1733 F	1738 F
00-00-104	89-09-20 14:53:00	9.43 ft	E 0	0.97	1731 F	1737 F
00-00-103	89-09-20 14:52:58	9.43 ft	E 0	0.97	1729 F	1735 F
00-00-102	89-09-20 14:52:56	9.43 ft	E 0	0.97	1731 F	1737 F
00-00-101	89-09-20 14:52:53	9.43 ft	E 0	0.97	1733 F	1738 F
00-00-100	89-09-20 14:52:51	9.43 ft	E 0	0.97	1735 F	1740 F
00-00-099	89-09-20 14:52:49	9.43 ft	E 0	0.97	1735 F	1740 F
00-00-098	89-09-20 14:52:47	9.43 ft	E 0	0.97	1731 F	1737 F
00-00-097	89-09-20 14:52:44	9.43 ft	E 0	0.97	1735 F	1740 F
00-00-096	89-09-20 14:52:42	9.43 ft	E 0	0.97	1738 F	1744 F
00-00-095	89-09-20 14:52:40	9.43 ft	E 0	0.97	1729 F	1735 F
00-00-094	89-09-20 14:52:37	9.43 ft	E 0	0.97	1735 F	1740 F
00-00-093	89-09-20 14:52:35	9.43 ft	E 0	0.97	1740 F	1746 F
00-00-092	89-09-20 14:52:33	9.42 ft	E 0	0.97	1746 F	1749 F
00-00-091	89-09-20 14:52:31	9.43 ft	E 0	0.97	1740 F	1746 F
00-00-090	89-09-20 14:52:28	9.43 ft	E 0	0.97	1737 F	1742 F
00-00-089	89-09-20 14:52:26	9.43 ft	E 0	0.97	1740 F	1746 F
00-00-088	89-09-20 14:52:24	9.43 ft	E 0	0.97	1740 F	1744 F
00-00-087	89-09-20 14:52:22	9.43 ft	E 0	0.97	1740 F	1744 F
00-00-086	89-09-20 14:52:19	9.43 ft	E 0	0.97	1738 F	1744 F
00-00-085	89-09-20 14:52:17	9.43 ft	E 0	0.97	1733 F	1737 F
00-00-084	89-09-20 14:52:15	9.43 ft	E 0	0.97	1738 F	1742 F
00-00-083	89-09-20 14:52:12	9.43 ft	E 0	0.97	1729 F	1735 F
00-00-082	89-09-20 14:52:10	9.43 ft	E 0	0.97	1733 F	1738 F
00-00-081	89-09-20 14:52:08	9.43 ft	E 0	0.97	1737 F	1742 F
00-00-080	89-09-20 14:52:06	9.43 ft	E 0	0.97	1742 F	1747 F
00-00-079	89-09-20 14:52:03	9.43 ft	E 0	0.97	1733 F	1738 F
00-00-078	89-09-20 14:52:01	9.42 ft	E 0	0.97	1731 F	1737 F
00-00-077	89-09-20 14:51:59	9.42 ft	E 0	0.97	1737 F	1740 F
00-00-076	89-09-20 14:51:57	9.43 ft	E 0	0.97	1738 F	1744 F
00-00-075	89-09-20 14:51:54	9.43 ft	E 0	0.97	1731 F	1735 F
00-00-074	89-09-20 14:51:52	9.43 ft	E 0	0.97	1728 F	1731 F
00-00-073	89-09-20 14:51:50	9.42 ft	E 0	0.97	1728 F	1733 F
00-00-072	89-09-20 14:51:47	9.43 ft	E 0	0.97	1731 F	1737 F
00-00-071	89-09-20 14:51:45	9.42 ft	E 0	0.97	1726 F	1729 F
00-00-070	89-09-20 14:51:43	9.43 ft	E 0	0.97	1719 F	1724 F
00-00-069	89-09-20 14:51:41	9.42 ft	E 0	0.97	1722 F	1728 F
00-00-068	89-09-20 14:51:38	9.42 ft	E 0	0.97	1731 F	1737 F
00-00-067	89-09-20 14:51:36	9.42 ft	E 0	0.97	1724 F	1729 F
00-00-066	89-09-20 14:51:34	9.42 ft	E 0	0.97	1722 F	1728 F
00-00-065	89-09-20 14:51:31	9.43 ft	E 0	0.97	1717 F	1722 F
00-00-064	89-09-20 14:50:15	9.80 ft	E 0	0.97	1670 F	1674 F

Figure 5-2. Sample data—Pyrolaser

00-00-063	89-09-20	14:43:22	6.81	ft	E 0	0.98	1819 F	1823 F
00-00-062	89-09-20	14:43:21	6.81	ft	E 0	0.98	1821 F	1825 F
00-00-061	89-09-20	14:43:20	6.81	ft	E 0	0.98	1821 F	1825 F
00-00-060	89-09-20	14:43:15	6.81	ft	E 0	0.98	1819 F	1823 F
00-00-059	89-09-20	14:43:13	6.81	ft	E 0	0.98	1818 F	1821 F
00-00-058	89-09-20	14:43:11	6.81	ft	E 0	0.98	1814 F	1819 F
00-00-057	89-09-20	14:43:09	6.81	ft	E 0	0.97	1809 F	1814 F
00-00-056	89-09-20	14:43:06	6.81	ft	E 0	0.98	1816 F	1819 F
00-00-055	89-09-20	14:43:04	6.81	ft	E 0	0.98	1821 F	1825 F
00-00-054	89-09-20	14:43:02	6.81	ft	E 0	0.98	1818 F	1823 F
00-00-053	89-09-20	14:43:00	6.81	ft	E 0	0.97	1814 F	1819 F
00-00-052	89-09-20	14:42:57	6.81	ft	E 0	0.97	1812 F	1818 F
00-00-051	89-09-20	14:42:55	6.81	ft	E 0	0.98	1809 F	1812 F
00-00-050	89-09-20	14:42:53	6.81	ft	E 0	0.97	1809 F	1812 F
00-00-049	89-09-20	14:42:50	6.81	ft	E 0	0.98	1807 F	1810 F
00-00-048	89-09-20	14:42:48	6.81	ft	E 0	0.98	1807 F	1810 F
00-00-047	89-09-20	14:42:46	6.81	ft	E 0	0.98	1805 F	1809 F
00-00-046	89-09-20	14:42:44	6.81	ft	E 0	0.98	1807 F	1810 F
00-00-045	89-09-20	14:42:41	6.81	ft	E 0	0.97	1805 F	1810 F
00-00-044	89-09-20	14:42:39	6.81	ft	E 0	0.98	1805 F	1810 F
00-00-043	89-09-20	14:42:37	6.81	ft	E 0	0.98	1807 F	1812 F
00-00-042	89-09-20	14:42:34	6.81	ft	E 0	0.98	1807 F	1812 F
00-00-041	89-09-20	14:42:32	6.81	ft	E 0	0.97	1803 F	1809 F
00-00-040	89-09-20	14:42:30	6.81	ft	E 0	0.97	1798 F	1801 F
00-00-039	89-09-20	14:42:28	6.81	ft	E 0	0.90	1807 F	1810 F
00-00-038	89-09-20	14:42:25	6.81	ft	E 0	0.98	1809 F	1812 F
00-00-037	89-09-20	14:42:23	6.81	ft	E 0	0.98	1816 F	1819 F
00-00-036	89-09-20	14:42:21	6.81	ft	E 0	0.98	1819 F	1823 F
00-00-035	89-09-20	14:42:19	6.81	ft	E 0	0.98	1814 F	1818 F
00-00-034	89-09-20	14:42:16	6.81	ft	E 0	0.98	1814 F	1819 F
00-00-033	89-09-20	14:42:14	6.81	ft	E 0	0.97	1814 F	1819 F
00-00-032	89-09-20	14:42:12	6.81	ft	E 0	0.97	1810 F	1816 F
00-00-031	89-09-20	14:42:09	6.81	ft	E 0	0.97	1814 F	1818 F
00-00-030	89-09-20	14:42:07	6.81	ft	E 0	0.97	1816 F	1821 F
00-00-029	89-09-20	14:42:05	6.81	ft	E 0	0.98	1818 F	1821 F
00-00-028	89-09-20	14:42:03	6.81	ft	E 0	0.97	1810 F	1816 F
00-00-027	89-09-20	14:42:00	6.81	ft	E 0	0.97	1818 F	1823 F
00-00-026	89-09-20	14:41:58	6.81	ft	E 0	0.98	1823 F	1827 F
00-00-025	89-09-20	14:41:56	6.81	ft	E 0	0.98	1827 F	1830 F
00-00-024	89-09-20	14:41:54	6.81	ft	E 0	0.98	1825 F	1827 F
00-00-023	89-09-20	14:41:51	6.81	ft	E 0	0.98	1823 F	1827 F
00-00-022	89-09-20	14:41:49	6.81	ft	E 0	0.98	1823 F	1827 F
00-00-021	89-09-20	14:41:47	6.81	ft	E 0	0.98	1825 F	1828 F
00-00-020	89-09-20	14:41:44	6.81	ft	E 0	0.98	1827 F	1832 F
00-00-019	89-09-20	14:41:42	6.81	ft	E 0	0.98	1834 F	1837 F
00-00-018	89-09-20	14:41:40	6.81	ft	E 0	0.98	1841 F	1845 F
00-00-017	89-09-20	14:41:38	6.81	ft	E 0	0.98	1841 F	1845 F
00-00-016	89-09-20	14:41:35	6.81	ft	E 0	0.98	1839 F	1843 F
00-00-015	89-09-20	14:41:33	6.81	ft	E 0	0.98	1839 F	1843 F
00-00-014	89-09-20	14:41:31	6.81	ft	E 0	0.98	1839 F	1843 F
00-00-013	89-09-20	14:41:29	6.81	ft	E 0	0.98	1832 F	1836 F
00-00-012	89-09-20	14:41:26	6.81	ft	E 0	0.98	1798 F	1801 F
00-00-011	89-09-20	14:41:24	6.80	ft	E 0	0.98	1728 F	1731 F
00-00-010	89-09-20	14:41:22	6.80	ft	E 0	0.98	1742 F	1744 F
			6.81	ft	E 0	0.98	1834 F	1839 F
							1836 F	1839 F

Figure 5-2. Sample data—Pyrolaser (concluded)

A total of 13 test runs was conducted. Seven included thermocouple and Pyrolaser data, and the other six compared readings from two thermocouple probes. Of the 13 runs, eight included acoustic pyrometry data (see Table 5-2).

Comparison of data from probes located side-by-side on the metal coil shows that the temperature across the width of the sheet is consistent over the sum of the run, but shows minor variations due to the fact that some burners are on while others are off (manually shut off, in addition to the twin bed cycling). The ring versus weld thermocouple data show similar results. An example of a composite plot of data from a test run is shown in Figure 5-3.

The Pyrolaser and thermocouple readings matched to within 23°F for the test series, and were usually within approximately 12°F. Possible sources of error include specularities/view angle effects on the Pyrolaser, and effects of radiation and thermal lag on the thermocouples. Overcoming sensitivity to specularities and view angle is a possible improvement suggested by this set of tests.

A key to the economical implementation of this goal is the development of the Pyrofiber system to eliminate the expensive optics needed for multiple imaging, whether in specularities correction or in multipoint monitoring. The testing described in the next section incorporated a prototype Pyrofiber unit.

5.3 PYROFIBER-BREADBOARD

Efficiencies gained on the originally planned program during execution allowed for expanded feasibility assessments to be performed. PIC prepared a breadboard version of the Pyrolaser. The main optics of the system were replaced with fiber optics elements. Two fiber optics cables were mounted on the system. One carried the laser light and directed it onto the target, while the other was used to collect the return signal.

5.4 PYROFIBER TESTING AT TELEDYNE WAH CHANG

An agreement had been reached with Teledyne Wah Chang to test Pyrolaser and Pyrofiber technology at the company's facility. Teledyne operates many heat treating facilities processing

Table 5-2. Test parameters for second set of tests at PSM

TEST #	DATE	TIME	CHART RECORDER RED	CHART RECORDER BLACK	THICKNESS (INCHES)	SPEED (FT/MIN)	WIDTH (INCHES)	SS MATL.	COMMENTS
1	3/29/90	10:20	RING	PYRO	0.014	48	36.5	304	
2	3/29/90	11:02	N/C	WELD	0.029	37	36.75	304	
3	3/29/90	14:32	RING	WELD	0.04	38.5	36.5	304	
4	3/29/90	15:14	RING	PYRO	0.04	38.5	36.5	304	Thermocouple Failed.
5	3/29/90	15:57	RING	PYRO	0.04	38.5	36.5	304	Ring would not clear furnace.
6	3/29/90	16:22	RING	PYRO	0.04	38.5	36.5	304	
7	3/29/90	16:40	RING	PYRO	0.04	38.5	36.5	304	
8	3/29/90	16:54	RING	PYRO	0.04	38.5	36.5	304	
9	3/29/90	17:10	RING	PYRO	0.04	38.5	36.5	304	
10	3/30/90	11:15	RING	WELD	0.025	20	36	430	Right thermocouple failed.
11	3/30/90	----	L. RING	R. RING	0.025	20	36	430	
12	3/30/90	13:47	L. RING	R. RING	0.025	20	36	430	Left thermocouple failed.
13	3/30/90	14:10	R. RING	R. RING	0.025	20	36	430	

AXIAL TEMPERATURE MAPPING

Figure 5-3. Composite plot of PSM test data

exotic materials used in the nuclear industry. Temperature measuring accuracy requirements are stringent, demanding carefully controlled processes. A continuous sheet annealing furnace similar to that tested at PSM was of particular interest, because it was electrically heated and had an inert nitrogen atmosphere. This minimized the potential problems with combustion products encountered with the PSM furnace.

The primary product heat treated is zirconium of varying thickness and width. To determine the actual temperature in the furnace and of the product as it passes through the furnace, trailing thermocouples are installed on the zirconium sheet. Teledyne installed two additional viewports near the end of the furnace to permit the mounting of a Pyrolaser and Pyrofiber unit. Teledyne also permitted the installation of a data recording PC that monitored all process parameters. These data would be invaluable in assessing the performance of the two systems, and allow comparison with the process parameters.

To accomplish control and data acquisition for a test, it was necessary to write a control program to retrieve data from the various devices. The system schematic is shown in Figure 5-4. An IMC Data Manager was used to connect the various devices via an RS 232 interface. The PC acted in the capacity of controller, directing the flow of data at specific times and also initiating data recording by the temperature measuring devices.

The facility was equipped with a Kaye Digistrip Datalogger that recorded all process parameters. These data were also routed to the PC and included in a data base for evaluation in Lotus 1-2-3 or other suitable spreadsheet program.

The Pyrolaser unit was installed on the furnace behind a sight glass and valve arrangement to protect the unit from excess heat and also to provide a seal for the furnace. The Pyrofiber unit was installed viewing the material directly since this unit was less sensitive to the heat of the process.

The system was installed and fully checked out. Initial data showed the temperature in the region where the units were installed to be much lower than expected. This meant that data could

Figure 5-4. System schematic

only be taken on special high-temperature runs of material. The section where the units were installed apparently experienced significant cooling from the end of the furnace. This was unexpected and new data for Teledyne as well. The problem experienced in this case was the low temperature measuring capability of the Pyrolaser systems, which is near 600°C.

5.5 RESULTS

Some initial test results were obtained from the system installed at Teledyne. The data were only partially available since the Pyrolaser system shuts down recording of the data when the temperature is too low. In any case, the system was functional when the temperature was sufficiently high for the material to be processed. A complete analysis of the data, however, was not possible. The results indicated several factors, however.

- To be most versatile, the design of a system must allow for the monitoring of temperatures below 600°C
- Reflectivity of the material can be a serious problem when the material is processed at low temperatures where the material does not yet behave as a black body radiator
- Fiberoptics sensors can be installed in areas that are much more restricted than the room required for a Pyrolaser system

Based on the results to date, a work program was developed that would include enhancements to the Pyrolaser. The initial results support the finding that Pyrofiber enhancements to the Pyrolaser system are economical to implement and would advance the state of the art in temperature measurements much faster than other proposed systems.

SECTION 6

RAMAN SPECTROSCOPY—FEASIBILITY

6.1 INTRODUCTION

The feasibility of a Raman Spectroscopy surface temperature measurement instrument has been discussed in Section 4.3. It has been shown that the two primary technologies investigated in this project are the Pyrolaser and possible enhancement of Raman Spectroscopy. Pyrolaser technology would offer a quicker entry into the market with an instrument that could perform quite well. This instrument would have to be carefully applied to yield good results. Raman Spectroscopy, on the other hand, offers capabilities beyond temperature measurements and could address a larger market. This technology would require significantly more research and development and would, as a result, become available only at a later date. To determine what the most recent developments have been in Raman Spectroscopy, a literature review was conducted to include any new findings in a laboratory-scale system and test program. Results of the literature review are discussed in Section 6.2 and the laboratory Raman Spectroscopy system is presented in Section 6.4. The test program planned is presented in Section 6.4.

6.2 LITERATURE REVIEW

The objective of this task was to review current literature on Raman Spectroscopy as it would apply to the DOE Workpiece Temperature Analyzer project, and to summarize relevant findings.

An extensive number of publications were reviewed, spanning the period of 1986 through 1989. These publications are listed in Table 6-1.

Table 6-1. Documents reviewed

1.	Optics Letters, all issues in 1988, 1989
2.	SPIE Optical Engineering, Volumes 27 and 28; 1988, 1989
3.	Combustion Science and Technology, 1988 and 1989
4.	Combustion and Flame, 1988 and 1989
5.	Journal of Quantitative Spectroscopy and Radiative Transfer, 1987-1989
6.	Journal of the Optical Society of America, A, 1988, 1989
7.	Journal of the Optical Society of America, B, 1988, 1989
8.	Optics and Lasers in Engineering, 1988, 1989
9.	ASM Journal of Heat Treating
10.	Optical and Quantum Electronics, 1989
11.	Optics and Spectroscopy, 1988, 1989
12.	Reviews on Solid State Science, 1988, 1989
13.	Solid State Communications, 1988, 1989
14.	Surface Science, 1989
15.	Soviet Physics—Solid State, 1988, 1989
16.	Spectroscopy Letters, 1988, 1989
17.	Journal of Physics C: Condensed Matter, 1989
18.	Journal of Physics B: Atomic, Molecular and Optical Physics, 1989
19.	Soviet Journal of Optical Technology, 1988, 1989
20.	Journal of Vacuum Science and Technology, 1988, 1989
21.	Journal of Mat. Research, 1989
22.	Advances in Laser Spectroscopy, 1986, 1987
23.	Journal of Raman Spectroscopy

The publications reviewed reported no instances of solid state thermometry applying Raman Spectroscopy. In particular, there was no report on backscatter-spontaneous-Raman Spectroscopy.

The only findings related to the WPTA project involved application of Coherent Anti-Stokes Raman Spectroscopy (CARS). The details may be found in the Journal of Quantitative Spectroscopy and Radiative Transfer, Vol. 40, No. 3, September 1988. The three important results are summarized below in Sections 6.2.1 through 6.2.3.

6.2.1 Carbon Monoxide Spectrum in a Flame

In this study, a single mode pulsed laser system was developed to measure linewidths of important gas-phase Raman lines. A spectral resolution of 0.003 cm^{-1} was achieved. CARS measurements were carried out at Sandia Laboratories on the CO spectrum in a flame. Theoretical predictions were also made and corrected for line broadening effects such as collision and Stark broadening, and for saturation from high laser intensities. The corrected predictions are in good agreement with experiments, as shown in Figure 6-1.

The relation of theory and experiment for CARS spectrum of CO in a flame.

- Measurement point
- Calculated intensities

Figure 6-1. CARS spectrum of CO in a flame

One of the most relevant aspects of this study is the high optical resolution of 0.003 cm^{-1} . By comparison, the estimates of Signal/Noise in the WPTA proposal of December 1988 were obtained with a conservative resolution of 0.1 cm^{-1} . The higher resolution (0.003 cm^{-1}) makes it easier to filter out noise from spectrally broad interference sources such as particulate luminosity and workpiece gray/blackbody radiation.

6.2.2 Temperature Profiles in a Sealed Lamp

CARS was also used to obtain temperature profiles inside a 1,000-W lamp at General Electric Co. The CARS beam geometry and temperature profile are presented in Figure 6-2. It is noteworthy that no special provisions were made for optical access in conducting these measurements.

6.2.3 Temperature Measurements in Operating Diesel Engine

Finally, CARS was applied to measure temperature as a function of crank angle in a sooty, operating diesel engine. The results are presented in Figure 6-3, where the Raman measurements are compared to a theoretical model for the engine process. The good agreement is evident.

6.2.4 Conclusion

CARS is not applicable to the opaque objects to be probed in the WPTA project. Therefore, the main result of interest in this literature review is the improved spectral resolution of the optics. The 30-fold improvement from 0.1 cm^{-1} to 0.003 cm^{-1} is a very important determinant of device accuracy. Also, the calculations of December 1988 assumed a 20 percent detector quantum efficiency. This is conservative, and currently available detectors can improve the Signal to Noise Ratio (S/N) by as much as 1.5 to 2 over the S/N calculated with 20 percent quantum efficiency.

Figure 6-2a. CARS beam geometry

Temperature profile obtained in lamp using the nitrogen CARS signal.

Figure 6-2b. CARS temperature profile

Figure 6-2. CARS temperature profile in sealed filament lamp

Figure 6-3. CARS temperature measurement in an operating diesel engine

6.3 LABORATORY-SCALE RAMAN WPTA SYSTEM

6.3.1 Introduction

This section discusses the laboratory-scale system for investigating Raman Spectroscopy as a Workpiece Temperature Analyzer Technology. The discussion covers basic system components, system tradeoffs and vendor information, system, layout, and system costs.

6.3.1.1 Basic System Components

The Raman WPTA involves six functional subsystems:

- Light Generation
- Light Delivery to workpiece
- Light Retrieval from workpiece
- Spectral Resolution of Retrieved Light

- Conversion of Resolved Spectra into Computer-Processible Signals
- Computer-Processing of Spectra and Generation of Control Signals

Each subsystem is summarized below.

Light Generation

The light source is a laser. The required laser characteristics such as power and pulsed/cw (pulsed/centiwatt) depend on the applications environment. Pulsed lasers with higher energies are required for the dirtier/sootier environments and high workpiece temperature, to overcome workpiece and background luminosity. The laser frequency, mode, repeatability and linewidths are also variables, and tradeoffs are discussed in Section 6.3.1.2.

Light Delivery to Workpiece

The delivery of laser light to the workpiece can be accomplished via a lens system or via fiberoptics. The factors to consider include safety, flexibility in beam delivery, cost per measurement for multiple simultaneous measurements, signal strengths and losses, space utilization, and operation and maintenance. Each choice has its advantages and disadvantages. These factors are discussed in Section 6.3.1.2. Although a lens delivery system will work well for a laboratory test, fiberoptics are preferable for the ultimate industrial system. They have therefore been chosen for the laboratory tests. This choice permits the evaluation of most important beam-delivery issues during the laboratory phase and reduces the number of important new variables for the full-scale evaluation.

Light Retrieval from Workpiece

Retrieval of scattered light from the workpiece can be done via fiberoptics or via a lens system. In solid Raman Spectroscopy, the scattered light signal is very weak (about 10 to 12 orders of magnitude less than the outgoing signal). For fiber collection, this means a relay lens must be attached to the fiber for increased light collection and signal, as well as reduced ambient stray light. Standard relay lenses for fibers are available from vendors such as Oriel. A fiber system with a single fiber will also require a positioner assembly to match the fiber to the spectrograph (F number

matching). The positioner is an X-Y-Z adjustable lens-filter assembly. The filter is a notch rejection filter for removal of the Rayleigh signal, which exceeds the Raman signal by about 6 orders of magnitude. Again, fiber systems introduce flexibility in system configuration during industrial use, and should be evaluated in the laboratory-scale design.

A lens recovery system is equally capable for laboratory-scale evaluations. The configuration would involve an off-the-shelf camera zoom lens with F-number set to match the spectrograph (F/4.4). The positioner discussed above could be used to recollimate/refocus the beam behind the zoom lens for better F-number matching and to save money. The zoom-lens would be preceded by a hot mirror (I.R. reflector) to reduce heating of the optical components during industrial use. Again, the hot mirror should be evaluated now, to reduce the number of new variables introduced in the transition from laboratory design to full scale. The zoom lens is followed by the Rayleigh rejection filter, which could be mounted in the positioner.

The choice of lens versus fiberoptics is important enough to warrant evaluation of both during the laboratory stage.

Spectral Resolution of the Retrieved Light

A spectrograph is used to resolve the incoming light within a very narrow spectral band (of order 50 nm). The spectrograph rejects stray light to as low as 10^{-7} of the input signal. Within its narrow bandpass, the spectrograph separates the light into a spectrum with resolution of about 0.02 nm. The spectrum is physically displayed against a plane, where different frequency bands ("each color") can be read by separate elements of a detector array.

Conversion of Resolved Spectra into Computer-Processable Signals

Spectra from the spectrograph are typically read by a diode array of 512 or 1024 separate elements, or a CCD array (typically 576 x 384). The output of this array is then A/D converted and made available for computer processing. The proposed design applies a 1024-element diode array, and the data are read via a 50-kHz, 12-bit A/D board. The Instaspec program controls the diode array and retrieves data from the A/D board after the detector "ON" time has expired. The diode

array can be read out and digitized at a rate of 20 μ s/pixel. More program details are presented in the next section, and in Appendix B.

The timing and sequencing of events are greatly simplified by the choice of lasers and by the Instaspec software. The cycle basically consists of three steps:

- The Instaspec program generates an output TTL pulse and sends it via the Instaspec interface card to the "Lamp input" of the DCR-11 laser. This starts the laser firing cycle.
- In response, the DCR-11 laser sends a TTL pulse back to the Instaspec Interface card. The laser pulse can be monitored from either the "Q-Switch Sync Out" or the "Q-Switch Advance Sync Out" BNC connectors. 50 to 100 ns later, the laser fires its optical pulse, lasting about 10 ns. (An earlier output pulse from the firing of the laser lamp could be monitored instead of the Q-switch pulses. This lamp pulse precedes the optical pulse by a few hundred ns.)
- In response to the Q-switch TTL pulse, the Instaspec program waits a set time (software determined), and turns on the detectors. The detectors remain on for a period of time determined by the software.

The detector array is then read by the Instaspec software, and the cycle can repeat after about 30 ms. A signal delay line could be installed between the computer and the laser "lamp input" terminal. This option would allow fine tuning of the detector "ON" window relative to the laser optical pulse. The positioning and gating of this window is very important for DC rejection (e.g., of blackbody radiation). When an intensified detector array is used, the intensifier can be gated so that it turns on just before the scattered laser-Raman pulse arrives and turns off just after the Raman pulse finishes. The intensifier "ON" time is only about 10 ns, allowing rejection of the blackbody DC signal.

The Noise-Equivalent-Power (radiant flux at which Signal/Noise = 1.0) for the selected detector is about 10^{-14} W, while signal levels are conservatively about 10^{-7} W to 10^{-6} W. Thus, the Raman signals are easily detectable.

Computer-Processing of Spectra and Generation of Control Signals

The Instaspec program reads diode array data from the A/D converter into standard microcomputers such as IBM-PC/XT/AT and their clones and compatibles, as well as IBM PS/2 and Apple II systems. The proposed design employs an IBM-PC/AT, or compatible, computer.

Instaspec has many other capabilities, including graphics and data manipulation. For example, the scan data can be graphed immediately on screen. The plots are displayed in 3 dimensions: x-pixel position, or wavelength; y-intensity; z-time, or scan number. A picture of a screen plot is presented in the appendices.

The plots can also be dumped onto printers, laser printers or H-P plotters. Instaspec also allows calculations to be performed on the scanned data. For example, spectra can be ratioed, subtracted, smoothed, differentiated and multiplied by a normalizing factor. Peak search, band integration and calculation of peak width are also useful capabilities. Furthermore, Instaspec can be set up to automatically take a series of scans, save them to disk and/or plot them on a printer or plotter. Different files of operating parameters can be loaded for taking different types of scans. The Instaspec data are stored in ASCII format, and can be accessed by Lotus, Fortran, Basic or other data handling programs. Finally, Instaspec can be controlled from an outside program. Subprograms, interfacing specifications and handbooks are provided in the same package. The subprograms are written in Microsoft QuickBasic.

The next section discusses the system tradeoffs for each of the subsystems discussed above in more depth.

6.3.1.2 System Tradeoffs

The proposed design involves tradeoffs in the six areas discussed above. The important design issues are discussed.

Lasers

The laser characteristics considered included cost, frequency, beam profile, linewidth, power, pulsewidth, pulse rate, versatility, size and maintenance requirements. Given the following constraints:

- The lowest laser budget consistent with laboratory evaluation of the most important experimental variables and (industrial) noise sources
- Energy requirements of ~ 100 mJ/pulse
- Power requirements of ≥ 100 kW/pulse
- OMA/Computer Data acquisition rates of about 30 ms/pulse from a 1024-diode array (= 30 pulses/s)
- Pulsewidth requirements of < 1 μ m
- Multiwavelength capability desired
- The fourth power dependence of Raman cross-section on frequency (higher cross-section at higher frequency)
- Laser linewidths of < 0.1 nm
- A Gaussian or flat spatial beam profile
- Small size
- Ease of maintenance

the chosen light source is a Nd:YAG laser. Two specific models, Spectra Physics DCR-11 and Continuum's (formerly Quantel) YG-660, are contenders. Specifications are presented in the appendices.

ND:YAG Lasers

Nd:YAG lasers satisfy the requirements outlined above. Nd:YAG lasers are capable of multiwavelength operation at 1064 nm (IR), 532 nm (green), 355 nm (UV), and 266 nm (UV), and each line can be isolated with a harmonic converter. The proposed laboratory test program will be carried out at 532 nm, and laser specifications are provided in the appendices. The visible beam

is chosen because of safety and cost concerns. The UV and IR beams are both invisible, and at the very high pulse energies and high pulse rates being considered, stray beams (e.g., from a breached, misaligned or disconnected component) pose a significant safety problem for an experimenter busy repairing other system components. Also, in the final industrial system, the laser and optics will be out of general view, and a visible beam will provide the best warning and protection of workers. In addition, visible optics are cheaper than UV or UV-enhanced optics, and more readily available off-the-shelf. Finally, visible beams are preferable to IR laser beams because Raman cross-sections increase with the fourth power of frequency, and because IR analysis will experience more blackbody noise problems from furnaces and hot workpieces.

The laser cost with harmonic converter to isolate the second harmonic is about \$32,200 for the Spectra Physics DCR-11, and \$31,800 for the Continuum YG-660. The peak pulse energies and pulse widths are 135 mJ, 6 to 7 ns, and 65 mJ, 6 to 8 ns, for the DCR-11 and the YG-660, respectively. The pulse power requirements (≥ 100 kW) are also well satisfied. Both lasers can provide a flat or near-gaussian beam profile at no additional cost.

Both the DCR-11 and the YG-660 are quite compact. The DCR-11 has the added advantage of having been ruggedized for several OEM applications in the past. These applications involve installation in helicopters and operation in the harsh environs of the Mohave desert. The laser was configured as a turnkey, turn-on-and-forget blackbox, requiring no attention from the operator. The main maintenance item is the flashlamp, which needs replacement every 30 million flashes at \$250. The DCR-11 was also recently configured for an OEM that required an interface card for complete computer control. The interface card costs an additional \$2,000 in single quantities.

The two laser vendors being considered are both local. Spectra Physics of Mountain View, California, promises a 4-week delivery, and Continuum (formerly Quantel) promises 30 to 45 days. Both laser systems are almost identical, but the Spectra Physics model (DCR-11-2) has higher output pulse energy (135 mJ versus 65 mJ), and better average power stability (± 5 percent at 10 hr

versus ± 6 percent at 8 hr). On the other hand, the Continuum model has a higher pulse rate (30 Hz versus 14 Hz), better spatial beam characteristics, and better shot-to-shot energy stability (± 4.5 percent versus ± 7 percent). Both companies have excellent reputations for quality and service.

Nitrogen Lasers

Nitrogen lasers were also considered, but they only operate in the UV at 337 nm. Nitrogen lasers are much less powerful than Nd:YAG lasers, emitting about ≤ 10 mJ per pulse. They also have relatively broad emission linewidths, and require filtration of the laser pulse. Further, the UV Raman optics are more expensive than visible optics. On the positive side, the Nitrogen lasers are cheaper (about \$21,000 to \$24,000), require low maintenance, and have no flashlamps to replace. One major problem with using them in an experimental setting is the invisibility of the beam. Errant beams could pose a safety problem for an experimenter busy repairing other system components, and for employees in industry.

Dye Lasers

Dye lasers were also considered. These have all the advantages of Nd:YAG lasers, and, in addition, are far more tunable. The major disadvantage with dye laser systems is cost. Comparable dye laser systems cost about \$20,000 more than the Nd:YAGs. Indeed, Nd:YAGs are used as pump sources for dye laser systems.

Beam Delivery

The delivery of laser light to the workpiece can be accomplished via a lens system or via fiber optics. The factors to consider include safety, flexibility in beam delivery, cost per measurement for multiple simultaneous measurements, signal strengths and losses, space utilization, and operation and maintenance. Each choice has its advantages and disadvantages. These factors, which are discussed here, are all interrelated. The choice of method is highly influenced by the fact that the device must ultimately be usable in industry. Thus, experimental conveniences are avoided if the resulting design is useless or dangerous in an industrial setting.

Beam Delivery: Safety, Space Utilization, Multiple Measurements, Flexibility

As mentioned above, the laser beams are very powerful, and capable of inflicting severe injury. In industrial settings, fires may also be started by an errant laser beam. As a result, the beams need to be confined for as much of their flight path as possible. Furthermore, any space that is criss-crossed by these beams is essentially dead space in an industrial setting. At up to \$0.5 per month per square foot per floor, this is an unnecessary expense.

If multiple measurements are needed simultaneously, e.g., in different parts of a long furnace or a long workpiece, fiberoptics allow for flexible beam delivery from a single laser to several measurement points, with confined beams and frugal space utilization. This removes the need for multiple lasers, lowering system overall cost, and improves measurement synchronization. Beam distribution from a laser can be achieved by a lens system, but would be unsuitable for industrial settings due to exposed beams as well as maintenance of optical elements.

Beam Delivery: Operation and Maintenance

The objective is to design a system that requires little attention, i.e., a fireup-and-forget system. In the final industrial design, the laser will be a blackbox positioned in a remote room with its power supply, and interfaced to a computer. The operators should not even know it exists except to the extent that they can take data, or when it comes time to replace the flashlamp. The laser end of the beam-delivery optics should be sealed to reduce dust/dirt related problems such as reduced damage thresholds and cleaning. The workpiece end of the beam-delivery optics should have a minimum of surfaces, and should be simple to clean. Fiberoptics are preferable to lens systems for beam delivery because:

- They allow remote laser location with long, sealed beam paths
- They allow an easily sealed optics/laser interface

- Lens systems require multiple components for bending the beam from the remote laser location to the workpiece. This introduces several maintenance concerns and increases the number of issues about which the user or technician must be knowledgeable (increases O&M costs).

Beam Delivery: Signal Strengths and Losses

Lenses have high transmission (typically 96 percent), and the lenses of interest have been coated to reduce Fresnel reflections which could be damaging if coupled back into the laser cavity. Lenses also collect signal from a much larger area than the beam cross section, and can acquire stray light in the process. At the workpiece-end of the equipment, however, stray signals are not a problem.

Single fibers also have very high transmissions (~96 percent), but need collection lenses to couple onto the laser signal. In addition, fibers can be used to divide the sealed laser beam for simultaneous measurements at several parts of the workpiece. Fiber bundles are less expensive than signal fibers, and are easier for signal coupling and beam division, but have lower transmissions (T) due to packing fractions of about ($P = 0.8 - 0.9$), and reflection loss of about ($R = 0.4$), where

$$T = P(1 - R)^2 e^{-kL} \quad (6-1)$$

and k is a very small ($< 0.25 \text{ m}^{-1}$) absorptance coefficient. Transmissions of about 0.55 may be experienced over 10m, making bundles less attractive than single fibers.

Although a lens delivery system will work well for a laboratory test, fiberoptics are preferable for the ultimate industrial system. They have therefore been chosen for the laboratory tests. This choice allows us to evaluate all important beam-delivery issues during the laboratory phase, and reduces the number of important new variables for the full-scale evaluation.

The maximum working temperature for the glass fibers is about 350°F. The damage threshold is listed at 10 J/cm² for the single fibers, requiring 1000-μm fibers to carry 100-mJ pulses.

Retrieval of Scattered Light from Workpiece

Retrieval of scattered light from the workpiece can also be done via fiberoptics or via a lens system, and both are discussed here.

Light Retrieval: Fiberoptic Collection

Single fibers are preferred over fiber bundles because of their higher transmission (~96 percent versus 50 to 70 percent). In solid Raman Spectroscopy, the scattered light signal is very weak (about 10 to 12 orders of magnitude less than the outgoing signal). It is also much weaker (by about 6 orders) than the elastically scattered or Rayleigh signal. For fiber collection, this means a relay lens must be attached to the fiber for increased light collection and increased signal, as well as reduced ambient stray light. Standard relay lenses for fibers are available from vendors such as Oriel. Adding a relay lens to the fiber input increases the sensitivity to viewing angle. This may be helped by defocusing the relay lens a little to spread the input beam over a larger part of the fiber aperture. On the positive side, a relay lens will reduce the amount of ambient stray light collected by the fiber, and will reduce signal dependence on the separation between the fiber and the workpiece.

A fiber system with a single fiber will also require a positioner assembly to match the fiber to the spectrograph (F-number matching) and place the fiber image exactly on the spectrograph slit. The positioner is an X-Y-Z adjustable lens-filter assembly with a notch rejection filter for removal of the Rayleigh signal. Without the F-number matching by the lens assembly, there will be stray light in the spectrograph as the fiber image overfills the grating. Again, fiber systems introduce flexibility in system configuration during industrial use, and should be evaluated in the laboratory-scale design. The cost of the fiber light retrieval system with relay lens, 2m of fiber, X-Y-Z positioner, and associated couplings is \$1,625. Additional fiber is \$257/m.

Light Retrieval: Camera Lens Collection

A camera lens is also applicable for Raman signal collection for laboratory-scale evaluations. The configuration would involve an off-the-shelf camera zoom lens with F-number set to match the

spectrograph (F/4.4). The positioner discussed above could be used to recollimate/refocus the beam behind the zoom lens for better F-number matching. The positioner could also save money since the zoom lenses with closest matching F-number are expensive: (Nikon 50 to 300 mm VIS F/4.5 zoom lens carries a suggested list price of \$3,145, while the positioner (\$722) plus 100 to 300 mm F/5.6 Nikon lens (\$645) cost \$1,367). The zoom lens would be preceded by a hot mirror (IR reflector) to reduce heating of the optical components during industrial use. Again, the hot mirror should be evaluated now, to reduce the number of new variables introduced in the transition from laboratory design to full scale. The zoom lens is followed by the Rayleigh rejection filter, which will be mounted in the positioner.

It should be remarked here that many experimenters have used camera lenses (e.g., F/5.6) for their laboratory Raman systems. These lenses have the advantage of having benefitted from significant engineering, and are generally achromatic, non-aberrant, non-reflecting, and highly transmissive (~96 percent). Finally, and as mentioned earlier, lenses can collect more signal than fibers, but they are also prone to collecting more stray light.

The choice of lens versus fiberoptics is important enough to warrant evaluation of both during the lab stage.

Spectral Resolution of the Retrieved Light

Spectrographs were evaluated from three major manufacturers, including Oriel's 1/4-m (250-mm) 77200 spectrograph, EG&G Princeton Applied Research Co.'s 275-mm model 1234 unit, and SPEX's 340-mm 340S and 600-mm 1877C triple spectrographs. The major objectives of the spectrographs and associated lenses and filters include:

- Elimination of the Rayleigh line
- Provision of both Stokes and Anti-Stokes Signals
- Resolution of 0.1 nm or better at 532 nm
- Less than 0.1 percent stray light
- Minimum consumption of photons

- Small size
- Low cost

The proposed design uses an Oriel 77200 1/4-m spectrograph with a 1200 lines/mm grating and a 10 μm slit. A smaller slit will be tried if available, as it improves the resolution. The spectrograph will carry a special Melles-Griot notch rejection filter system up front, to help eliminate the Rayleigh line. This special filter will preferentially reflect elastically scattered light with rejection of over 10^4 per stage, and with a narrow ($<7\text{ nm}$ or $<250\text{ cm}^{-1}$) bandwidth at 532 nm. Two or more Rayleigh filter stages will be required. Although each filter stage decreases the signal level by about 50 percent, the stages are far more cost-effective and more photon-conserving than 60-cm triple spectrographs, which cost over \$20,000 and can attenuate the photon count by several orders of magnitude.

Double Spectrograph. If the single 77200 spectrograph is insufficient to meet the resolution stray light and Signal/Noise requirements, a second 77200 spectrograph will be added in tandem to create the 77225 double spectrograph. (Two 77200 units in tandem with a center connecting slit are called a 77225). The input slit to this second spectrograph will be the 77207 center slit unit. The double spectrograph costs \$7,262, while the single spectrograph system costs \$3,310. Specifications are presented in the appendices. The Rayleigh signals will be about 6 orders of magnitude higher than the Raman signals. If the Notch filters work as advertised, two stages will yield Raman/Rayleigh of about 100, but will attenuate the incoming signal by about 60 to 75 percent.

Spectrographs and Data Resolution. As mentioned before, the spectrograph is used to resolve the incoming light within a very narrow spectral band (of order 50 nm). The spectrograph also reject stray light to as low as 10^{-7} of the input signal. Within its narrow bandpass, the spectrograph separates the light into a spectrum with resolution of 0.05 nm or better. The spectrum is physically displayed against a plane, where different frequency bands (each color) can be read by separate elements of a detector array.

The linear dispersion of the 77200 signal spectrograph is 3.2 nm/mm at a wavelength of 500 nm and using a 1200 lines/mm grating. With a 1-in (25-mm) long diode array, the bandpass is 3.2 nm/mm * 25 mm or 80 nm. The linear dispersion of the two 77200 spectrographs in series is half that of a single spectrograph, or 1.6 nm/mm. Combined with a 25-mm-long diode array, this gives a bandpass of 40 nm. The spectrograph resolution is controlled by the slit width rather than the grating. With a 10 μm slit, the product of slit width and linear dispersion for the 77200 spectrograph gives a resolution of $10^{-2} \text{ mm} * 3.2 \text{ nm/mm} = 0.032 \text{ nm}$ (1.12 cm^{-1}) at a wavelength of 500 nm. Likewise, the calculated resolution for the two 77200 spectrographs in series is half this value, or about 0.016 nm (0.56 cm^{-1}) at 500 nm.

The final resolution in the data depends on the width of each diode element or pixel. The diodes or pixels being employed are 25 μm wide. As a result, the final data resolution is what can be resolved by two neighboring diodes/pixels (i.e., the linear dispersion multiplied by diode width). Without any curvefitting correction, this pixel resolution amounts to 2.5 (pixel-width/slit width = $25 \mu\text{m}/10 \mu\text{m} = 2.5$) times the numbers given in the preceding paragraph. For example, pixel resolution is $2.5 * 0.56 \text{ cm}^{-1} = 1.4 \text{ cm}^{-1}$ for the two 77200 spectrographs in series. Sub-pixel resolution can be obtained by curvefitting as discussed in Section 6.4.2.3.

By comparison with the single Oriel spectrograph, the SPEX 340S spectrograph with a 1800 l/mm grating and a slit costs \$4,740, and the EG&G-PARC 1234 system with 1200 l/mm grating and 25- μm slit costs \$5,170. These spectrographs are difficult to compare exactly, as they are not clones, but the costs are representative.

The most precise spectrograph evaluated is SPEX's triplement 1877C triple spectrograph. This unit also has the highest light rejection, and will reveal structures as close as 15 cm^{-1} to the laser line. However, the unit costs about \$33,000 with gratings, and attenuates the photon count significantly.

Triple Spectrometry. Finally, on the subject of signal resolution, we note that another effective method for reducing stray light and the Rayleigh signal is to use a double spectrometer

in a subtractive mode. The output is then fed to a spectrograph for analysis. This triple spectrometry also greatly attenuates the photon count and further reduces the linear dispersion. This method will be the final contingency if the combination of notch filters and double-spectrographs are unable to extinguish the elastic signal. The equipment is essentially 3 monochrometers/spectrographs, each one similar to the 77200. The least expensive configuration employing 0.22m F/3.9 spectrometers combines a SPEX 1680A Spectramate Double Spectrometer (\$4,350) with a SPEX 1681C Minimate-2 Spectrograph (\$2,050), and includes three SPEX-12006-500A gratings (\$600*3) and a set of SPEX 1679F fixed slits (\$150) for a total of \$8,350. Evidently, two notch filters and one spectrograph (at \$5,700) will be much preferred if the elastic signal and stray light are attenuated sufficiently relative to the useful signal.

Oriel representatives are located in Southern California, while PARC is in Fremont, and SPEX is in Milpitas.

Optoelectronic Conversion of Resolved Spectra

Optical Multichannel Analysis

OMAs with Unintensified Arrays. The spectrograph output is projected onto a 1024-element diode array, which is read with a 50 kHz 12-bit A/D board specifically packaged for the purpose. Software for acquiring the data and downloading into a computer also comes with the package. The Oriel Instaspec AT system costs \$10,276, for use with PC/AT compatibles, and comes with a \$150 programmer's kit. The system interfaces to any AT computer as may be found in a typical laboratory (i.e., computer is extra). The Oriel Intraspex XT system, for use with PC/XT compatibles, is slower, and costs \$9,335. By comparison, the EG&G-PARC system costs \$11,475 without a computer. The Instaspec program controls the diode array and retrieves data from the A/D board after the detector "ON" time has expired. The diode array can be read out and digitized at a rate of 20 μ s per pixel. More program details are presented in the appendices and below.

OMAs with Intensified Arrays. Intensifiers add about \$11,500 to the detection system cost. The EG&G PARC system with a gated intensifier costs \$21,695. The Oriel system with intensifier

is relatively new, and the PC/AT version is expected to cost about \$22,000. The importance of intensifiers and gating is discussed below.

Raman Flux Detectability. Using a conservative laser power of 10 mJ per pulse and a pulse width of 8 ns, together with a conservative scattering and collection efficiency of 10^{-12} Raman photons collected per laser photon, gives a Raman flux of

$$\left(\frac{10 \times 10^{-3} \text{ J}}{8 \times 10^{-9} \text{ s}} \right) \times (1 \times 10^{-12}) = 1.25 \times 10^{-6} \text{ W} \quad (6-2)$$

Accounting for attenuation by the Notch filters and collection systems will decrease this flux to about 10^{-7} W during the laser pulse. The Raman scattering efficiency is estimated from values of scattering efficiencies typical in solids, of about $10^{-7} \text{ cm}^{-1} \text{ sterad}^{-1}$, as well as assumed penetrations of about 10^{-5} cm and collection angles of 1 sterad. The Noise-Equivalent-Power (radiant flux at which (Signal/Detector Noise) = 1.0) for the selected detector is about 10^{-14} W, which is 7 orders less than the Raman signal levels. Thus, the Raman signals are easily detectable.

DC Noise Blocking. At high workpiece temperatures and high laser pulse energy, blackbody radiation from the workpiece, laser-induced particulate incandescence, and radiation from furnace background become important. These DC noise sources can be effectively blocked by a combination of gating and signal subtraction. (Subtraction was discussed in the December 1988 proposal.) Consider workpiece radiation for example. At 2,000 K and $0.5 \text{ } \mu\text{m}$ wavelength, the blackbody intensity, I , is about $5 \times 10^3 \text{ W/m}^2 \text{ } \mu\text{m.sr}$. Using an imaging beam probe (unit 77653 of diameter $D_2 = 16 \text{ mm}$ as the fiber input and imaging a 1-mm point ($A_1 = 10^{-6} \text{ M}^2$) on the workpiece surface from a distance of 10 cm gives a view factor of $F_{12} = 2.5 \times 10^{-4}$. Here, the subscript 2 refers to the fiberoptic imaging probe of area $A_2 = 3.14 \times D_2^2/4$. Assuming a Raman linewidth of $D\lambda = 10 \text{ nm} = 10^{-2} \text{ } \mu\text{m}$, the blackbody power incident on the collection system is:

$$\begin{aligned}
& 3.1416 \times I \times D\lambda \times A_1 \times F_{12} \\
& = 3.1416 \times (5 \times 10^3) \times (1 \times 10^{-2}) \times (1 \times 10^{-6}) \times (2.5 \times 10^{-4}) \text{ W} \\
& = 3.9 \times 10^{-8} \text{ W}
\end{aligned} \tag{6-3}$$

(The radiant power is lower for lower emissivity materials as are likely to be encountered in industrial workpieces.)

This blackbody radiation is to be compared with the Raman power of 1.5×10^{-6} W. Even if the Raman linewidth increases to about 30 nm as the temperature increases, the blackbody noise only goes to about 10^{-7} W, still a factor of 10 smaller than the Raman signal. It is important to note that gating is crucial for the rejection of the blackbody signal. Without gating, the Raman signal is only present for 10^{-8} s, while the DC blackbody noise is present for the entire detector "ON" cycle (10^{-2} s). As a result, when the diode signal is sampled in the absence of gating, there is 10^4 to 10^6 as much integrated noise as there is integrated Raman signal (in this example).

Finally, unintensified arrays give about 3,000 photons per count. The Raman power after the notch filter is about 1.5×10^{-7} W = 4×10^{11} photons/s at 532 nm wavelength. If gating is done for 10 ns = 1×10^{-8} s, this amounts to a total Raman count of $4 \times 10^{11} \times (1 \times 10^{-8} / 3,000) = 1.3$ counts per gate. This is insufficient and must be intensified for data analysis. The intensifier provides a gain of about 500 to 1000 in the count rate. Thus, at high temperatures (above about 1,000 K), gated intensified arrays are needed.

The timing and sequencing of events (Figure 6-4) is greatly simplified by the choice of lasers and by the Instaspec software. The cycle basically consists of 3 steps:

- The Instaspec program generates an output TTL pulse and sends it via the Instaspec interface card to the "lamp input" of the DCR-11 laser. This starts the laser firing cycle
- In response, the DCR-11 laser sends a TTL pulse back to the Instaspec Interface card.

The laser pulse (pulse 2a in Figure 6-4) can be monitored from either the "Q-Switch

Figure 6-4. Timing diagram

Cync Out" or the "Q-Switch Advance Sync Out" BNC connectors. 50 to 100 ns later, the laser fires its optical pulse (pulse 2b in Figure 6-4), lasting about 10 ns. (An earlier output pulse from the firing of the laser lamp could be monitored instead of the Q-switch pulses. This lamp pulse precedes the optical pulse by a few hundred ns.)

- In response to the Q-switch TTL pulse, the Instaspec program waits a set time (software determined), and turns on the detectors (pulse 3 in Figure 6-4). The detectors remain on for a period of time which is determined by the software.

The detector array is then read by the Instaspec software, and the cycle can repeat after about 30 ms. A signal delay line could be installed between the computer and the laser "lamp input" terminal. This option would allow fine tuning of the counting gate and the detector "ON" window relative to the laser optical pulse. The positioning and gating of this window is very important for DC rejection (e.g., of blackbody radiation) as discussed earlier. The timing diagram is shown in Figure 6-4.

When an intensified detector array is used, the intensifier can be gated so that it turns on just before the laser-Raman pulse arrives and turns off just after the laser pulse finishes. The intensifier "ON" time is several ns, allowing rejection of the blackbody DC signal. The intensifier increases detector sensitivity and boosts the weak Raman signals by about three orders of magnitude (noise signals are also boosted in the same time window). Intensifiers are employed in practically all Research and Development Raman configurations, but increase detector cost by about \$11,500.

CCDs are also available for use in detectors. A CCD's resolution is excellent compared with an intensified diode array. With no photocathode, microchannel plate or phosphor, the CCD is not troubled by photocathode dark signal or phosphor persistence. However, the lack of an intensifier means that the CCD cannot be gated. The CCD units available are more expensive than the unintensified diode arrays, and similar in cost to intensified arrays. Since the intensified diode arrays can be gated, the data acquisition system design employs diode arrays rather than CCDs.

This way, if intensifiers are unnecessary, the cheaper detectors (diodes) will be in use. Similarly, if intensifiers are required with gating to reject DC noise, the gated detectors (again diodes) will be in use. Finally, using diodes allows the option of starting out unintensified and ungated, and later retrofitting intensification and gating as needed—flexibility in upfront commitment of funds.

Computer-Processing of Spectral Data

The Optical Multichannel Analyzers (OMA) and related Instaspec software are fully compatible with regular microcomputers such as PC/XT/AT clones. These OMA systems acquire the spectral data for delivery to a computer. The Instaspec program can feed diode array data from the A/D converter into standard microcomputers such as IBM-PC/XT/AT and their clones and compatibles, as well as IBM PS/2 and Apple II systems. The proposed design employs an IBM-PC/AT, or compatible, computer.

Instaspec has many capabilities including graphics and data manipulation. For example, the scan data can be graphed immediately on screen. The plots are displayed in 3 dimensions: x = pixel position, or wavelength; y = intensity; z = time, or scan number. A picture of a screen plot is shown in the appendices. The plots can also be dumped onto printers, laser printers or H-P plotters. Instaspec also allows calculations to be performed on the scanned data. For example, spectra can be ratioed, subtracted, smoothed, differentiated and multiplied by a normalizing factor. Peak search, band integration and calculation of peak width are also useful capabilities. Furthermore, Instaspec can be set up to automatically take a series of scans, save them to disk and/or plot them on a printer or plotter. Different files of operating parameters can be loaded for taking different types of scans. The program uses dispersion formulas and information about the spectrograph being used (e.g., focal length, gating, center wavelength) to calculate and display the proper wavelength and wavenumber for each diode element. The A/D converter readings can also be converted into other units other than counts, such as percent transmittance, irradiance, absorbance or reflectance.

The Instaspec data are stored in ASCII format, and can be accessed by Lotus, Fortran, Basic or other data handling programs. Finally, Instaspec can be controlled from an outside program.

Subprograms, interfacing specifications and handbooks are provided with the Instaspec Package. The subprograms are written in Microsoft QuickBasic. Further software in Basic, Fortran or Lotus may be required to deconvolve the spectra and separate out the useful parts for temperature calculation. These subroutines are expected to be relatively simple curvefits, and their outputs will go to I/O ports as control signals (e.g., for furnace firing rates.)

The data handling capabilities and ASCII output of Instaspec make it a very powerful program. For temperature calculations, anharmonic effects such as line broadening can be treated by Lorentzian curvefits to yield corrected peak intensities and peak frequencies for both Stokes and Anti-Stokes signals. Subsequently, the peak-ratioing capability of the program can be used to obtain temperatures. The Instaspec program package is also useful for detector calibrations as discussed in Section 6.3.2.7.

System Optimization. Optimization of the Raman thermometry system involves a number of issues. These issues are summarized below and further discussed in the sections indicated.

- The laser must be coupled to the workpiece without optical feedback and with minimal losses. This will be achieved with a dedicated coupler, unit 77597.
- Optimization of the beam delivery system involves configuration to account for the demands of an industrial system. This is discussed above, under the heading, "Optoelectronic Conversion of Resolved Spectra."
- Optimization of the beam retrieval system involves F# matching, blocking of stray light and maximization of S/N. These issues are discussed above, under the heading, "Computer-Processing of Spectral Data."
- Optimization of the optoelectronic conversion involves proper calibration, as discussed in Section 6.3.2.7, and the gating for DC rejection, as discussed above, under the heading, "Optoelectronic Conversion of Resolved Spectra."
- Optimization of the overall system involves proper choice of calibration lines to bracket the spectra chosen for thermometry, as discussed in Section 6.3.2, combined with the

equipment calibration described in Section 6.3.2.7 and the anharmonicity corrections described in Section 6.3.2.8. The overall design aims at optimizing the system for ultimate industrial use, with such measures as beam confinement, beam division capability, and choice of a non-gray temperature calibration source with temperature dependent emissivity.

6.3.1.3 Laboratory-Scale System Layout

The Laboratory system layout is presented in Figures 6-5, 6-6, and 6-7. Figure 6-5 presents the laser and beam delivery systems, while Figure 6-6 contains the beam retrieval, spectrograph, Optical Multichannel Analyzer and computer.

Beam Output

Figure 6-5 presents the beam delivery system. This consists of a Nd:YAG laser, coupled to a beamsplitter assembly (78150). The transmitted beam is coupled to a fiberoptic guide and collimated (77645) before passing out to the workpiece.

The reflected beam from the beamsplitter is used for sampling output energy, and is coupled to a photomultiplier tube assembly (77344). The PMT assembly and the other components shown in the dashed box of Figure 6-5 are used to monitor the laser pulse power. This helps prevent damage to the glass fiber from the intense laser beam, and provides a more accurate measurement of laser output than the gauges on the laser panel. Accurate knowledge of outgoing intensity will help determine scattering efficiencies more accurately, but is not crucial for thermometry via Stokes/Anti-Stokes ratioing. Also, optical damage can be prevented by simply turning the laser to a lower power (10 mJ instead of 100 mJ per pulse). As a result, the PMT assembly is being treated as an option in this design.

Signal Retrieval and Processing

As discussed earlier, signal retrieval can be achieved by camera lens or by fiberoptics.

SUPPLIER	PART No.	PART DESCRIPTION
SPEC-PHYS	DCR-11	Nd:YAG LASER
SPEC-PHYS	HG-2B	HARMONIC GENERATOR
Oriel	79218	MOUNTING ADAPTER
	77597	FIBER COUPLER
	77519	1,000 μ m SINGLE FIBER (x 1m) WITH 2 SMA FIBER TERMINATIONS
	77670	FERRULE ADAPTER
	77645	COLLIMATING BEAM PROBE
Oriel	78150	BEAM SPLITTER HOLDER
MRC	10Q10NC.1	BEAM SAMPLER
Oriel	77829	FLANGE CONNECTOR RING
	77802	CABLE MOUNT
	77670	FERRULE ADAPTER
Oriel	77344	UV-VIS-NIR PMT
	70680	PMT HOUSING
	70705	PMT POWER SUPPLY
	70710	PMT CURRENT PREAMP
	70702	READOUT
	77519	1,000 μ m SINGLE FIBER (x 2m) WITH 2 SMA FIBER TERMINATIONS
	77670	FERRULE ADAPTER
	77645	COLLIMATING BEAM PROBE

Figure 6-5. Laboratory-scale system layout—laser beam delivery system

KEY.

SUPPLIER	PART No.	PART DESCRIPTION
MELLES-GRIOT	03-MHG-007	HOT MIRROR
ORIEL	12500	NIKON CAMERA LENS MOUNT
NIKON		100-300MM AF VIS ZOOM LENS 35-135MM AF VIS ZOOM LENS
MELLES-GRIOT		SPECIAL RAYLEIGH LINE REMOVER
ORIEL	77260	X-Y-Z LENS/FILTER/SHUTTER
	40340	50 MM FL LENS
	42540	100 MM ACHROMAT LENS
ORIEL	77225	DOUBLE SPECTROGRAPH
	77222	INPUT SLIT
	77233	1200 L/MM GRATING
	77207	CENTER SLIT
	77233	1200 L/MM GRATING
ORIEL	77161	INSTASPEC AT DETECTOR
	77178	INSTASPEC PROGRAMMERS KIT
		40-MB PC/AT CLONE WITH 1-MB RAM, EGA, 80287

Figure 6-6. Laboratory-scale system layout—Raman signal retrieval and processing camera lens system

KEY.

SUPPLIER	PART No.	PART DESCRIPTION
MELLES-GRIOT	03-MHG-007	HOT MIRROR
ORIEL	12500	NIKON CAMERA LENS MOUNT
ORIEL	77653	COLLECTOR LENS WITH SHUTTER
	77670	FERRULE ADAPTER
	77519	1,000um SINGLE FIBER (x 2m) WITH SMA TERMINATIONS
	77670	FERRULE ADAPTER
	77357	FIBER HOLDER W/ FEMALE FLANGE
MELLES-GRIOT	SPECIAL	RAYLEIGH LINE REMOVER
ORIEL	77260	X-Y-Z LENS/FILTER/SHUTTER
	40340	50 MM FL LENS
	42540	100 MM ACHROMAT LENS
ORIEL	77222	INPUT SLIT
	77200	SINGLE SPECTROGRAPH
77225	77233	1200 L/MM GRATING
DOUBLE SPECTROG	77207	CENTER SLIT
	77200	SINGLE SPECTROGRAPH
	77233	1200 L/MM GRATING
ORIEL	77161	INSTASPEC AT DETECTOR
		40-MB PC/AT CLONE WITH 1-MB RAM, EGA, 80287, AND LASER PRINTER OR PEN-PLOTTER

Figure 6-7. Laboratory-scale system layout—Raman signal retrieval and processing fiberoptic system

Camera Lens Retrieval

In the lens option, the Raman signal is retrieved via a Nikon zoom lens arrangement with an optional hot mirror (03-MHG-007). It then passes through the Melles Griot Rayleigh-Filter to a condenser/focusing assembly (77260). The focusing assembly (77260) matches the spectrograph's F-number, and focuses the Raman signal through a slit (77222) into the spectrograph assembly (77200 or 77225). This focusing assembly is essential to make sure the Raman signal is properly imaged on the spectrograph slit to reduce stray light and signal wastage, and to optimize the throughput in the spectrograph. Both focusing assembly lenses are achromatic, non-aberrant and non-reflecting.

The 77225 double spectrograph consists of two 77200 spectrographs with a coupling slit (77207). The second spectrograph will only be used if the first unit gives insufficient resolution and noise reduction. The spectrographs feed into the Optical Multichannel Analyzer (77161), which is connected via its interface card to the personal computer. The system is very modular and conceptually simple. As mentioned earlier, if the Rayleigh line is not successfully attenuated by the notch filters, a double-spectrometer will be needed in place of the first spectrograph. This double spectrometer will operate in the subtractive mode and will assist the notch filters to attenuate the Rayleigh signal. The double spectrometer will be followed by a spectrograph, which will feed into the Optical Multichannel Analyzer.

Fiberoptic Collection

If signal is collected by fiberoptics, the zoom lens will be replaced by a fiber capped with a collection lens (77653). The lens (77653) has a shutter to enable zero checking. The fiber system and ancillary fittings are shown in Figure 6-7. As suggested earlier, both lens and fiber retrieval systems should be evaluated and compared.

6.3.1.4 Laboratory-Scale System Costs (Feasibility Evaluation Costs)

The laboratory-scale system components are called out in Table 6-2 and 6-3, and the costs are presented. Note that these costs reflect only a one-of-a-kind laboratory system for evaluating

Table 6-2. Itemization of system components and costs

INSTRUMENT GROUP (1)	SUPPLIER (2)	PART No. (3)	PART DESCRIPTION (4)	BASIC COMPONENTS PRICE (5)	OPTIONAL COMPONENTS PRICE (6)	ALTERNATE VENDOR PRICE (7)

A. LASER						

	SPEC-PHYS	DCR-11	Nd:YAG LASER	\$26,400		
	SPEC-PHYS	HG-2B	HARMONIC GENERATOR	\$5,800		
	CONTINUUM	YG660-30	Nd:YAG LASER			\$27,500
	CONTINUUM	DS	HARMONIC GENERATOR			\$4,300
B. LIGHT DELIVERY SYSTEM						

	ORIEL	79218	MOUNTING ADAPTER	\$35		
		77597	FIBER COUPLER	\$225		
		77519	1,000um SINGLE FIBER (x 1m)		\$257	
		77574	2 SMA FIBER TERMINATIONS		\$189	
		77670	FERRULE ADAPTER		\$25	
		77645	COLLIMATING BEAM PROBE		\$68	
		78150	BEAM SPLITTER HOLDER		\$599	
	NRC	10Q10NC.1	BEAM SAMPLER		\$210	
	ORIEL	77829	FLANGE CONNECTOR RING		\$32	
		77802	CABLE MOUNT		\$129	
		77670	FERRULE ADAPTER		\$25	
		77519	1,000um SINGLE FIBER (x 2m)	\$514		
		77574	2 SMA FIBER TERMINATIONS	\$189		
		77670	FERRULE ADAPTER	\$25		
		77645	COLLIMATING BEAM PROBE	\$68		
OUTPUT LIGHT SAMPLING						

	ORIEL	77344	UV-VIS-NIR PMT		\$930	
		70680	PMT HOUSING		\$378	
		70705	PMT POWER SUPPLY		\$1,125	
		70710	PMT CURRENT PREAMP		\$475	
		70702	READOUT		\$895	

Table 6-2. Itemization of system components and costs (continued)

INSTRUMENT GROUP	SUPPLIER	PART No.	PART DESCRIPTION	BASIC COMPONENTS PRICE	OPTIONAL COMPONENTS PRICE	ALTERNATE VENDOR PRICE
(1)	(2)	(3)	(4)	(5)	(6)	(7)
C. RAMAN SIGNAL RETRIEVAL SYSTEM						
	MELLES-GRIOT EALING	03-MHG-007 35-6863	HOT MIRROR HOT MIRROR		\$52	\$144
	ORIEL	12500	NIKON CAMERA LENS MOUNT	\$79		
	NIKON		100-300MM AF VIS ZOOM LENS	\$645		
		N-2000	CAMERA BODY		\$295	
		BR3	RIGHT ANGLE EYEPIECE ADAPTER		\$147	
LENS SYSTEM	QUANTA RAY		DOUBLE RANGER TELECONVERTER		\$85	
			35-70MM MANUAL ZOOM LENS			\$100
			75-300MM AF ZOOM LENS			\$360
			500MM F/8.0 TELEPHOTO LENS			\$200
	ORIEL	77653	COLLIM PROBE LENS W/ SHUTTER	\$97		
		77670	FERRULE ADAPTER	\$25		
FIBER SYSTEM		77519	1,000um SINGLE FIBER (x 2m)	\$514		
		77574	2 SMA FIBER TERMINATIONS	\$189		
		77670	FERRULE ADAPTER	\$25		
		77357	FIBER HOLDER W/ FEMALE FLANGE	\$53		
	MELLES-GRIOT	SPECIAL	RAYLEIGH LINE REMOVER	\$1,200		
	ORIEL	77260	X-Y-Z LENS/FILTER/SHUTTER	\$587		
		40340	50 MM FL LENS	\$50		
		42540	100 MM ACHROMAT LENS	\$85		
D. SPECTRAL RESOLUTION OF RAMAN SIGNAL						
	ORIEL	77200	1/4 M SPECTROGRAPH	\$2,783		
		77222	INPUT SLIT	\$238		
*** see attached notes at end of Table		77233	1200 L/MM GRATING	\$289		
		77225	DOUBLE SPECTROGRAPH		\$6,350	
		77222	INPUT SLIT		\$238	
		77233	1200 L/MM GRATING		\$289	
		77207	CENTER SLIT		\$96	
		77233	1200 L/MM GRATING		\$289	
	SPEX	340S	SPECTROGRAPH			\$3,990
		33519	MULTICHANNEL ADAPTER			\$455
		33519	MULTICHANNEL ADAPTER			\$455
		1679F	FIXED SLITS			\$150

Table 6-2. Itemization of system components and costs (continued)

INSTRUMENT GROUP (1)	SUPPLIER (2)	PART No. (3)	PART DESCRIPTION (4)	BASIC COMPONENTS PRICE (5)	OPTIONAL COMPONENTS PRICE (6)	ALTERNATE VENDOR PRICE (7)
	SPEX	180068A	1800 L/MM GRATING			\$600
		1673C	CONTROLLER			\$980
	EG&G PARC	1234	TRIPLE GRATING SPECTROGRAPH			\$4,410
		3801-0139	1200 L/MM GRATING			\$760
E. OPTOELECTRONIC CONVERSION OF SPECTRAL DATA - (OPTICAL MULTICHANNEL ANALYSIS)						
	Oriel	77161	INSTASPEC AT DETECTOR	\$10,276		
			ADDITIONAL COST FOR THE DIODE ARRAY INTENSIFIER		\$11,500	
		77178	INSTASPEC PROGRAMMERS KIT	\$150		
	EG&G-PARC	1461	OMA DETECTOR INTERFACE			\$3,990
		1462	DETECTOR CONTROLLER MODULE			\$905
		1453	DETECTOR			\$6,365
		1461/88	PC SOFTWARE			\$1,050
			ADDITIONAL COST FOR INTENSIFIED, GATED, DIODE ARRAY SYSTEM			\$9,200
F. COMPUTER PROCESSING OF SPECTRA						
			40-MB PC/AT CLONE WITH 1-MB RAM, EGA, 80287		\$1,600	
			LASER PRINTER OR PEN-PLOTTER		\$1,500	
			SUBTOTAL	\$50,541	\$27,778	

NOTES:

*** If the Rayleigh Filter and double spectrograph fail to reduce stray light and Rayleigh signal sufficiently, a double-spectrometer in the subtractive mode plus spectrograph plus Rayleigh notch filter will be tried. The costs appear below:

Table 6-2. Itemization of system components and costs (concluded)

INSTRUMENT GROUP	SUPPLIER	PART No.	PART DESCRIPTION	BASIC COMPONENTS PRICE	OPTIONAL COMPONENTS PRICE	ALTERNATE VENDOR PRICE
(1)	(2)	(3)	(4)	(5)	(6)	(7)

*** NOTES (cont'd)						
The items listed below would replace the double spectrograph system which costs \$8,462 and is composed of items: (77225 + 77222 + 77233 + 77207 + 77233 + Rayleigh Filter)						
SPEX		1680A	0.22m DOUBLE SPECTROMETER	\$4,350		
		1681C	0.22m SPECTROGRAPH	\$2,050		
		12006-500A	1200 1/mm GRATINGS (x3)	\$1,800		
		1679F	FIXED SLITS	\$150		
MELLES-GRIOT	SPECIAL		RAYLEIGH LINE REMOVER	\$1,200		

		SUBTOTAL FOR TRIPLE SPECTROMETER		\$9,550		

Table 6-3. Miscellaneous experimental apparatus and costs

INSTRUMENT GROUP (1)	SUPPLIER (2)	PART No. (3)	PART DESCRIPTION (4)	BASIC COMPONENTS PRICE (5)	OPTIONAL COMPONENTS PRICE (6)	ALTERNATE VENDOR PRICE (7)

G. MISCELLANEOUS ITEMS						

	Oriel	10770	OPTICAL TABLE - 4'x6'	\$4,040		
		44990	QUARTZ WINDOW	\$248		
		7761	MINIATURE VICE	\$32		
		14200	MASSIVE BASE (x2)	\$306		
		17281	LARGE VERTICAL JACK		775	
		12350	STANDARD ROD-6 IN. (x2)	\$30		
		10420	ROD COLLAR (x2)	\$48		
		14423	STABLE ROD HOLDER (x3)	\$90		
		77612	ROD MOUNT PROBE HOLDER	\$75		
	NEWPORT	G-LGS-NDGA	GOGGLES VIS (x2)	\$336		
		G-LGS-NDGA	GOGGLES UV (x2)	\$336		
	MIKRON	370	NBS TRACEABLE TUNGSTEN TEMPERATURE CALIB SOURCE	\$11,300		
	Oriel	63356	NBS TRACEABLE 200W CALIB LAMP	\$865		
		68830	PWR SUPPLY FOR 200W CALIB LAMP	\$1,675		
		63366	200W LAMP MOUNT	\$96		
			BN, TiO2, Na2SO4, AND OTHER WAVELENGTH CALIB. CHEMICALS	\$200		
			FIBER WICKS, CONTAINER, FUELS	\$500		

		SUBTOTAL		\$20,177	\$775	

the feasibility of Raman Spectroscopy as an Industrial WPTA technology. System cost issues and projections for production-scale cost reductions are discussed in Section 6.3.1.5.

For the laboratory-scale system components in Tables 6-2 and 6-3, the subsystem containing each instrument is listed in column 1 (e.g., Light Delivery System). Vendors are tabulated in column 2, parts numbers in column 3, and parts descriptions in column 4. The costs for basic system components are tabulated in column 5, optional items are tabulated in column 6, and column 7 presents comparative costs for the major items such as the laser and OMA. The total system cost is presented for both the base system and the base system with options. The basic system cost is \$50,541, while the additional cost of optional equipment is \$24,468. The three major options are the image intensifier, the second spectrograph and the PMT light sampling assembly. The additional option cost is the total of column 6 less items that would be replaced by the option. Specifically, this equals \$27,778 less the costs of the single spectrograph:

$$\$27,778 - (\$2,783 + \$238 + \$289) = \$24,468 \quad (6-4)$$

In addition to these Raman system costs, several other items, totalling \$20,177, are required for experimentation. These items include the Mikron 370 NBS-traceable tungsten lamp temperature calibration source (\$11,300), the NBS traceable white light calibration source (\$2,636), fiberfrax wicks, and hydrocarbon fuel, all of which are listed in Table 6-3. The Mikron 300 NBS-traceable blackbody temperature calibration source is cheaper, at \$7,400, than the Mikron 370, but cannot provide non-unity emissivities or non-gray spectra. The Mikron 370 emissivity varies slightly with temperature and is non-unity (~ 0.44)—a condition more likely to be found in industry than constant, unity emissivity. Thus, the 370 is the preferred unit. The unit will also enable calibration and comparison of the PIC Pyrolaser pyrometer. Equipment specifications are presented in the appendices, and this issue is further discussed in Section 6.3.2.6.

The Quanta Ray Zoom lenses in Table 6-2 are an after-market brand and are listed as alternatives because their quality is uncertain. Nonetheless, they cost so much less than name brands such as Nikon and Minolta that they should be evaluated for possible future application.

Contingencies

The development and final versions of the Raman Spectroscope will have a printer or plotter attached, and will require software for the implementation of controls. The costs for these items are presented in Table 6-3. A good, low-end dot matrix printer currently retails for about \$180. Plotters cost about \$1,500 to \$2,000 for small (8-in by 11-in units), although a small postscript capable laser printer, such as the HP-IIP with special fontware, retails in the same price range and may be more versatile. Finally, the Mikron 370 is only useful above 800°C. It will be necessary to buy or lease a Mikron 300 (or Mikron 330) for any calibrations below 200°C (or 100°C). The costs for these and other contingencies are estimated at 15 percent of the base, optional and miscellaneous costs from Tables 6-2 and 6-3. This brings total experimentation hardware costs to

$$115\% \times (\$50,541 + \$24,668 + \$20,177) = \$109,694 \quad (6-5)$$

6.3.1.5 Production-Level System Cost Issues—Economic Feasibility

System Costs

The system presented above for laboratory evaluation costs about \$50,000 without options and about \$70,000 with the options considered important. With labor and gross margin added, this would seem to indicate a market price of about \$150,000 to about \$200,000 for a high-end Raman thermometry system like the proposed design. The price objective for production-volume Raman systems is about 25 to 30 percent of these levels, and seem unobtainable at first glance. However, Raman system components are currently treated as specialty research items, and there is very much room for prices to come down to the \$40,000 to \$50,000 per system range for a high-end system

comparable to the one detailed in this report. Low-end systems with less laser power requirements, and operating in clean environments at low temperatures (several hundred °C), are expected to cost about half this range.

Electronics and Electrooptics

The price reductions will come about because the industrial Raman systems will be multiple replicas of an identifiable OEM unit with volume production savings, rather than collections of specialty items. For example, the price of a 20-MB Winchester hard disk is listed by EG&G-PARC in their R&D components price list as \$3,310. The street price for these items in single quantities is about \$190 to \$200—with controllers. All the computer-related hardware in Raman systems show similar distortions in pricing. These systems are generally sold in packages, allowing 500 percent or more markup in the computer system, interface board and related systems prices. The package deals include items such as detector power supplies, software and analog interface boards that are required to make the Raman detectors work, and are not readily available by themselves at lower price. (The researcher is thus compelled to buy the entire package.) The related software is also priced high, and seems to reflect an expectation of low sales volume. (A package of BASIC with manuals is offered at \$525, while the single quantity street price is about \$200 for Microsoft Basic or \$70 for Microsoft Quickbasic.)

The laser and optical components also show prices that reflect both the specialization of the field and manufacturers' expectations of low sales volumes. For example, Oriel sells about 4 OMA Instaspec systems per month. The market assessment performed by Acurex for this project reveals that sales of 0.5 percent of the total unit base per year would double Oriel's OMA sales volume. A major part of the Instaspec system cost lies in manufacturing setup. Discussions with Oriel, assuming their current cost structure, sales expectations and production setup, indicate discounts of about 20 to 30 percent at a sales volume of 50 to 100 units/yr. The actual discount depends on both volume and timing. If the sales are bunched in time, Oriel need not carry significant stock or incur multiple setup costs, and the discounts will be higher. (Under their current cost structure and

sales volume, Oriel projects discounts of 25 to 30 percent at 500 units/yr, and 30 to 35 percent at 1000 units/yr.)

Oriel indicates that the base price for the 20 percent discount will also go down as the total sales volume increases. This is partly because, if the development costs have to be recouped in a given time (e.g., 5 years), a higher sales volume indicates a lower required price per unit to recoup the costs. Thus, it is possible that OMAs and other optics will fall by over 30 percent from their current base prices before discount. It is worth noting that these items are not only used for Raman Spectroscopy, but in other spectroscopic and optical fields. As a result, the demand could increase as the prices go down (further introducing economics of scale and lowering prices). In addition, such items as intensifiers can find application in other consumer products such as telescopes, scanners and consumer imaging systems if they become low enough in price. Thus, supply and variety will also increase.

In summary, the optical and optoelectronics systems costs are expected to decrease significantly if Raman Spectroscopy makes the transition from a specialty post-graduate research technique to a basic form of industrial instrumentation. The exact amount of decrease is difficult to predict since the economics, methods and objectives of production will change significantly. However, discussions with producers indicate that base prices before discounts could fall by up to 30 percent, while the additional volume discounts are projected in the range of 20 to 35 percent. These price changes are projections and assume:

- The same cost structure as currently exists, including high setup costs per unit (few units per setup)
- The same sales volume expectations as currently exist

The computer and peripherals packaged with current Raman systems show clear room for cost decrease. Electronics systems costs are expected to fall by at least 50 to 60 percent with the increased sales discussed above and better packaging. In some electronic units, this price reduction level can already be exceeded by simply repackaging.

Lasers

The DCR-11 laser system by Spectra Physics has been ruggedized for several OEMs. This laser has been customized as a maintenance-free blackbox for several uses including helicopter, submarine and desert environment applications. They have also been mounted next to jet engines for testing. The OEM volume discounts depend on several factors including laser specifications such as lineshape and housing, power and computer interface, as well as location of use (application in offshore locations will be more expensive since the corresponding service centers must be paid for warranty service). Spectra Physics provides the following conservative estimates for OEM discounts on the DCR-11 laser:

- Up to 50 units/yr gets 10 to 12 percent discount
- 50 to 100 units/yr gets 15 percent discount
- Over 100 units/yr gets 15 to 20 percent discount

It should be noted that these are very conservative estimates, and the company expects actual reductions to be higher. Offshore laser production by Spectra Physics and competing firms will also mean cheaper lasers. Finally, we note here that the DCR-11 is intended for the most difficult applications such as measurement of very high temperature (~ 2000 K) parts in very sooty environments. It has far more power (135 mJ/pulse) than would be required in the large number of heat treating applications where temperatures are below ~ 1000 K, and there is little or no soot, laser-induced particulate incandescence or background luminosity. The proposed system, therefore, would be a high-end system in industry. As was demonstrated in Section 6.3.1.2, under the heading, "Optoelectronic Conversion of Resolved Spectra," even a 10 mJ pulse energy overcomes the workpiece $2,000^{\circ}\text{K}$ blackbody radiation when gating is applied. (This calculation was done assuming no soot.) At these high temperatures, one DCR-11 could be used for simultaneous measurements at 14 points and still overcome the workpiece radiation. Thus, the laser price savings for multiple-measurement systems could be as high as 90 percent since one laser would service 14 measurement stations (i.e., 14 individual Raman systems, each with one laser, would not be

required). The DCR-11 was chosen for this project to allow evaluation of most ranges of factors likely to be experienced in industry. A smaller laser would be cheaper but could not evaluate thermometry at high dirt/ash/soot loadings and 2,000 K temperatures.

Operation and Maintenance Issues

Current Raman equipment is built for R&D, and typically contains several user-serviceable and user-adjustable parts. Indeed, graduate students, faculty, industrial and post-graduate researchers spend significant amounts of time adjusting and fine tuning their lasers, optics, electronics and computer programs. This is the exact opposite of the intent of the system envisaged for industrial applications. In the industrial unit, the laser will be a black box with a sealed beam output (much like current OEM applications of the DCR-11 laser). The entire optical system will be sealed, as much to exclude stray light as to exclude unauthorized adjustments. The idea is to relegate the operator/system interface to a few innocuous and foolproof touchpads. Required operator training must be kept to a minimum, ideally less than 1 week. The final production system will be self diagnosing, and will generate information that can be accessed by modem from the manufacturer. This way, the manufacturer can execute remote diagnostics tests and keep the operator unencumbered. The laser has proven its worth in existing OEM systems where the only maintenance item is the lamp replacement after 30 million flashes.

The lenses, optics and computer systems are also simple and rugged, and require minimal operator contact (outside of occasional cleaning of the beam delivery and signal retrieval lenses). The laser and most of the Raman system will also be remote so that all the operator sees is the touchpad with simple English instructions, a display screen, and possibly a printer or plotter. Thus, operation and maintenance costs of the system will be minimal, and could be covered in a service contract purchased with the system for a low price.

One of the major operator training issues will be safety around intense laser beams. Besides safety goggles, fire drills and emergency response actions will need to be practiced. In particular,

the work environs must be made laser-safe, and possibilities for beam reflections toward worker areas removed.

The service contract and required operator training could also be combined with the warranty and service coverage provided by the laser and optical manufacturers. Spectra Physics, for example, provides a 1-yr parts and labor warranty on mechanicals and electronics, and a 90-day warranty on optics and crystals. Travel time is not covered, and their nearest service advisor will respond at a set zone charge. Complete service warranties can be arranged, including items such as training, warranty to cover parts and labor, and service response times of 4, 8, 12, 24 hr, etc. The service charges are \$90/hr plus air fare plus \$200/day per diem for overnight jobs. Training also costs \$90/hr. Spectra Physics has service centers in Mountain View, California; Chicago, Illinois; Albuquerque, New Mexico; New Jersey; and several other urban areas in the United States, Canada, and Europe. They estimate that an average site visit to troubleshoot costs about \$1,000. The warranties provided by Quantel are similar.

Oriel provides a 1-yr warranty on all products, and free software upgrades for 2 yr. Repairs are done in Connecticut, and repair cycles take about 1 week or more. Most of their optics stock is off-the-shelf and can be shipped within 7 days. They will provide free telephone help on software. (Competing optics manufacturers have similar warranties and services.)

6.4 LABORATORY-SCALE TEST PLAN

6.4.1 Introduction

The laboratory tests are designed to investigate the suitability of Raman Spectroscopy for workpiece temperature measurement. These tests have two major objectives:

- To investigate the impact of noise sources on measurements, and determine S/N ratios and accuracies to be expected in Raman WPTA systems
- To identify the design bottlenecks preventing wide application of Raman thermometry in industry.

The laboratory-scale tests are planned to be divided into the following eight tasks:

- Task 1—Documentation of Useful Raman Lines
- Task 2—Development of Deconvolution Software
- Task 3—5-Factor Noise Tests
- Task 4—General Optics Tests
- Task 5—Identification of Design Bottlenecks
- Task 6—Temperature Calibration
- Task 7—Equipment Calibration Issues and Temperature Calculation
- Task 8—Modeling of and Correction for Anharmonic Effects

Tasks 7 and 8 will be concurrent with Tasks 3, 4, and 6. The tasks are discussed in the subsections that follow.

6.4.2.1 Task 1—Documentation of Useful Raman Lines

This task will involve a literature search for Raman lines that are useful for solid thermometry. The lines will include modes from ceramics and insulating materials, metal crystals, metallic oxides, nitrides, silicides, carbides, sulfates and other salts. The findings will be documented for subsequent tasks. Information on temperature-related anharmonicities will also be documented. This information will include linewidth changes, line frequency shifts and parameters from analytical models of anharmonicity in useful lines.

6.4.2.2 Task 2—Development of Deconvolution Software

A program will be written to interface with the Instaspec II program and to process workpiece Raman spectral data, using the results of Task 1. The program will be able to deconvolve Stokes and Anti-Stokes bands in various WPTA applications, and will calculate and display the temperatures. The program will also generate control signals for external hardware, based on temperature reading. Programming will be done with the subroutines and programmer package provided with Instaspec II. Because of the substantial capabilities of Instaspec II, the programming effort is not expected to be extensive.

6.4.2.3 Task 3—5-Factor Noise Tests

This task will study the effects of background luminosity, workpiece radiation, laser-modulated incandescence, window fluorescence, and rejection. The proposed test schedule will involve measuring the temperature of a known solid while it is being viewed through flames of varying optical thicknesses. The test objective will be an electrically heated tungsten filament in a Mikron 370 NBS-traceable temperature calibration source. The flames will be provided by a row of fiberfrax wicks burning liquid hydrocarbon fuels (methanol, iso-octane, cyclohexane, kerosene, toluene). The experimental configuration is shown in Figure 6-8. Background luminosity noise can be varied by changing the fuel and/or number of wicks. The soot content will also allow the effects of laser-modulated incandescence to be evaluated. The third major source of noise, workpiece blackbody radiation, will be varied by changing the current through the tungsten.

The experimental design consists of a two-level, four-factor configuration with the following factors:

- Luminosity (L)
- Workpiece solid radiation (B)
- Laser-modulated incandescence (I)
- Window fluorescence (W)

The fifth factor, Rejection (R), will also be evaluated. The Yates' Algorithm table is presented in Table 6-4, where the response is the temperature difference between the NBS-traceable tungsten temperature and the Raman indicated temperature ($T_{\text{NBS}} - T_{\text{R}}$). The two levels of luminosity could be provided by four wicks burning toluene (+), and no flame/methanol flame (-). The two levels of workpiece radiation will be provided by tungsten at 2000 K (+) and at 300 K (-). The two levels of laser-modulated incandescence will be provided by toluene at maximum laser power (+) and at 10 percent laser power. The two levels of window fluorescence will be provided by placing a dirty quartz window between the laser and the first wick (+) and having no window (-).

Figure 6-8. Experimental test configuration for studying effects of luminosity, workpiece radiation, laser-modulated incandescence, and window fluorescence

Table 6-4. Yates' Algorithm

$$\text{Response} = (T_{\text{NBS}} - T_{\text{R}}) = (\text{NBS-traceable temperature} - \text{Raman temperature})$$

Test	Input Variables	Yate's Algorithm (°C)				Divisor	Estimate (°C)	Combination of Factors
	L B I W	T*	(1)	(2)	(3)	(4)		
1	- - - -						16	Average
2	+ - - -						8	L
3	- + - -						8	B
4	+ + - -						8	LB
5	- - + -						8	I
6	+ - + -						8	LI
7	- + + -						8	BI
8	+ + + -						8	LBI
9	- - - +						8	W
10	+ - - +						8	LW
11	- + - +						8	BW
12	+ + - +						8	LBW
13	- - + +						8	IW
14	+ - + +						8	LIW
15	- + + +						8	BIW
16	+ + + +						8	LBIW

T^* = Tungsten Temperature (T_R) or Temperature error ($T_C - T_R$) where
 T_C = calculated tungsten temperature.
 L = Background luminosity level.
 B = Workpiece blackbody radiation.
 I = Laser-modulated incandescence.
 W = Window fluorescence.

The two levels of rejection ratio will be provided by using two or three filters (+) and one filter (-). These levels are summarized in Table 6-5. The (-) level for workpiece radiation will be changed to the 800°C to 1200°C range if the other important variables show a need for less contrast in the blackbody radiation (-) and (+) levels. Using this higher range for the (-) level will also allow more accurate evaluation of the breakpoints for employing cheaper lasers.

Other important factors may be identified as the experiment commences, and these will be noted and incorporated into the factorial design if DOE wishes to evaluate their impacts.

Factorial designs at two levels were chosen for the experiments because:

- They require relatively few runs per factor studied; and although they are unable to fully explore a wide range in the factor space, they can indicate major trends and so determine a promising direction for further experimentation
- When a more thorough local exploration is needed, factorial designs can be suitably augmented to form composite designs
- The 2-level factorial designs form the basis for 2-level fractional factorial designs. Fractional factorials allow very efficient evaluation of a large number of factors superficially instead of a large number thoroughly. In this development phase, several factors are expected to impact the Raman system and a fractional factorial design greatly reduces the effort required to assess these factors for importance.

Table 6-5. Variable levels for test matrix (Yates' Algorithm) thermometry tests

Variable	(-) Level	(+) Level
Luminosity	No flame	4 wicks toluene
Solid radiation	300K	2000K
Incandescence	10% laser power	100% laser power
Window fluorescence	No window	Dirty quartz window
Rejection ratio	1 filter	2 or 3 filters

- Factorial designs and fractional factorial designs may be used as building blocks so that the degree of complexity of the final design can match the sophistication of the problem
- The interpretation of the observations produced by the designs can proceed largely by elementary arithmetic and common sense

The traditional experimental design is the "One-Factor-At-A-Time" (OFAAT) method. In this method, experimental factors are varied one at a time, while the remaining factors are held constant. This was formerly held as the only correct way to conduct research. The OFAAT method provides an estimate of the effect of a single variable (A) at selected fixed conditions of the other variables (X_1, Y_1, Z_1). For this estimate to be generally relevant, we must assume that the effect of variable A is the same at all settings of the other variables—(X_2, Y_2, Z_2), (X_3, Y_3, Z_3), etc. In other words, for the OFAAT estimate to be generally relevant, we must assume that over the ranges of interest, the variables act additively. However, the factorial design is superior to the OFAAT method because:

- If the variables X,Y,Z do act additively, the factorial design provides the estimates of effects with more precision. To obtain estimates of the main effects of K factors acting additively, the OFAAT method requires at least $(k + 1)/2$ to k times as many runs as the factorial design.
- If the variables do not act additively, the factorial, unlike the OFAAT method, can detect and estimate interactions that measure the nonadditivity

6.4.2.4 Task 4—General Optics Tests

This task will examine the impact of the various subsystems on Raman temperature reading. The components will be shaken, wiggled, turned, saturated, realigned and misaligned to investigate system ruggedness. Fiberoptic connections, lenses and filters, and attenuation and reflection will be examined for their impact on system stability. Gratings will be turned at various angles, and different orientations will be investigated. Spectrographs will be misaligned and placed out of focus to varying degrees, and the diode detector arrays saturated to find recovery times. The Rayleigh

filter will be removed or turned down to investigate blooming and related effects. All optical components will be wiggled about their aligned positions, room lighting will be changed, and objects repositioned in the room to investigate the impact of stray light and reflections. Both quantitative and qualitative findings will be documented.

Finally, future evaluations should:

- Investigate the UV and IR lines for Signal/Noise performance
- Compare holographic gratings against classically ruled gratings to quantify stray-light performance
- Investigate the impacts of grating line density and slit widths

6.4.2.5 Task 5—Identification of Design Bottlenecks

This task will identify and discuss the engineering issues that must be overcome to make Raman Spectroscopy a competitive WPTA technology. Findings from the earlier tasks will be incorporated. Areas to be investigated include:

- Photon delivery
- Photon collection
- Spectrograph performance: resolution, noise, photoprocessing
- Data acquisition and processing: detectors, A/D boards, computers
- Deconvolution and other software issues

6.4.2.6 Task 6—Temperature Calibration

This task will involve comparison of Raman temperatures against NBS-traceable temperature standards. For this purpose, a Mikron Model 370 Temperature Calibration Source will be used, and the Raman system employed to measure its temperature. The 370 delivers temperatures between 800°C and 2300°C at 1°C resolution. Its specifications are presented in the appendices. By comparison, the Mikron 330 blackbody calibration model delivers temperatures between 100°C and 1700°C with 1°C resolution. This unit costs \$12,400, and provides optical access to the molybdenum disilicide heating element. The Mikron 330 does not provide the

emissivity variation and non-gray spectrum of the Mikron 370, but allows calibrations at the lower temperatures. The Mikron 300, at \$7,400, is also a blackbody calibration source, with a range of 200°C to 1200°C. This model also does not provide emissivity changes and non-gray behavior with temperature. As noted earlier, the Mikron 370 is preferable because its emissivity variations and non-gray spectrum are similar to industrial workpiece behavior. This task will include an effort to lease one of the blackbody calibration units from Mikron for use at lower temperatures. The lease cost is uncertain, and an allowance of 20 percent of purchase price has been included in the 15 percent contingency figure for the costs noted in Section 6.3.1.4.

Raman temperatures will be plotted against NBS-traceable standards for all the 5-factor settings in the Yates' Algorithm of Task 3. Analysis of Variance (ANOVA) techniques will be used to compare the Raman and NBS temperature readings, and to determine the degree of difference between them. The techniques will include 1-way parametric ANOVA (F-tests), prediction intervals, and 1-way non-parametric ANOVA such as the Kruskal-Wallis tests (CHI-squared). If significant differences are found, the noise factor causing the differences will be isolated, and the extent of disagreement documented. Methods will be suggested for addressing significant differences between the Raman temperatures and the NBS standards.

6.4.2.7 Task 7—Equipment Calibration Issues and Temperature Calculation

This task is designed to help obtain quality results from the experiments. Task 7 will run concurrently with Tasks 3, 4, 6, and 8.

Equipment Calibration Issues

The band frequency and intensity measurements must both be precise to obtain meaningful temperature measurements from the Raman spectra. In addition, if there are several Raman peaks, as there will be in a practical system, the frequency axis has to be accurate. The remainder of this subsection discusses the important calibration issues that will be addressed in Task 7.

Wavelength-Axis Calibration

In a linear array based system such as the proposed design, the effective slit width varies from pixel to pixel due to the detector array's manufacturing processes which include such effects as imperfect registration of photolithographic masks. The observed spacing between array elements also varies due to field curvature of the optical system. If an intensifier is employed, we must additionally compensate for this component's non-linearity. These factors preclude a simple two-point, linear calibration of the wavelength axis. The calibration will involve measuring known standard Raman lines from a few solid materials in the same geometry as will be used for the experimental measurements. (Recall that a band of wavelengths is spread across the 1024 detector elements. This band can contain several spectral lines. Since spectral lines have finite widths, each spectral line is spread across a number of detector elements.) A detector element is mapped to each spectral line by assigning the wavelength of the spectral line peak to the element with the highest number of counts within the spectral line. For example, if elements 2 to 10 lie within spectral line W, and element 7 has the highest number of counts in this group, then the wavelength represented by element 7 is identified as the wavelength of the spectral line peak. In other words, the spectral line W peaks at element 7 or the wavelength corresponding to element 7.

These assignments are precise to within ± 1 element. A cubic fit is then used with these known spectral lines to calculate wavelengths at other array elements. The uncertainty at any of the other array elements is $\geq \pm 1$ element, and the magnitude of uncertainty is determined by the number of spectral lines used in the calibration and the choice of curvefit (a cubic fit accounts for system non-linearities better than a linear fit).

Sub-pixel calibrations will be carried out for the OMA. The goodness of fit is expected to hold to within 1/5th of an element (the repeatability in wavelength assignment is expected to be within 1/5th of the nominal spectral dispersion per element. For example, 0.016 nm repeatability is expected for a nominal element resolution of 0.08 nm). The method takes each standard spectral line used in the calibration, and calculates the centroid by numerical integration. Only portions of

spikes above 10 percent of the peak count will be used in the integrations, and the interpolation will use steps of 0.01 element. The centroid is assigned the input wavelength to the nearest 0.01 element. The correction curve for the wavelength axis is then generated via a cubic fit. The standard spectral lines will be identified in Task 1, and these will be chosen to bracket the wavelength range under test around the 532 nm line. This wavelength range depends on the spectral line chosen for temperature measurement in Task 1. The calibration standard Raman lines will include the Stokes and Anti-Stokes spectra from BN hexagonal phase, Na_2SO_4 , and the anatase modification of TiO_2 .

Intensity Axis Calibration

Calibration of the intensity axis must compensate for:

- Changes in the effective element width and sensitivity with wavelength
- The intensifier
- The non-uniform spatial response of the array detectors

Since the effective element width varies across the array, the wavelength axis needs to be calibrated first. Knowledge of the wavelength assigned to each element is then used to calibrate the Intensity axis' relative response per element. The uniformity of response varies by as much as ± 20 percent from one element to another, and the overall system deviation from linearity is about 1 percent. Corrections also need to be made for detector dark count and transmission characteristics of the Rayleigh notch filter. The calibration method involves exposing the detector array to an NBS standard white light source and comparing measured intensities to the known spectral irradiance of the source. A compensation factor is determined at each of several standard pre-set frequencies (calibration points). By virtue of the wavelength axis calibration, these pre-set frequencies correspond to particular pixels, and linear interpolation is used to assign compensation factors to other pixels. This method compensates for the factors discussed above.

These calibrations will be carried out periodically during the entire laboratory evaluation to assess drift and repeatability.

Temperature Calculation

The temperature can then be calculated from the corrected band intensities and band frequencies using

$$\frac{I_s (w_0 + w)^4}{I_a (w_0 - w)^4} = \exp \left(\frac{hcw}{kT} \right) \quad (6-6)$$

where I_s and I_a are the Anti-Stokes and Stokes band intensities, w_0 is the pump laser wavelength (532 nm), w is the Raman frequency shift, h is Planck's Constant, k is Boltzmann's Constant, and c is the speed of light. In this notation, the quantized energy is $E = hcw$.

Application of Different Raman Lines over Different Temperature Ranges

Task 1 involves searching for Raman lines that can be used for WPTA measurements. The Raman intensities of the lines identified in this search may indicate that it is impossible to apply one line over the entire measurement range. For example, the Anti-Stokes signal may be too weak at low temperatures for a vibrational mode that provides excellent line strengths above 1,000°C. In such a case, a backup line and a changeover temperature or temperature range specified for switching from one line to the other will be sought.

Another reason for seeking alternative lines is that the workpiece atmosphere might change and render the primary spectral line unusable. For example, if a workpiece is in an oxidizing atmosphere for part of a cycle and in a strongly reducing atmosphere for another part, an oxide spectral line may be suitable in the oxidizing atmosphere but absent in the reducing atmosphere. It will therefore be necessary to use different lines in the different atmospheres.

6.4.2.8 Task 8—Modeling of and Correction for Anharmonic Effects

Mode anharmonicity as related to mode frequency and linewidth variation with temperature will be investigated in this task. Two basic approaches will be adopted: analytical calculation, and experimental measurement plus curvefits. Both approaches are summarized below.

Analytical Modeling

The analytical calculations will employ two methods:

- The pseudoharmonic approximation, which accounts for thermal expansion and phonon-phonon interactions in evaluating the temperature dependence of phonon frequencies and linewidths. A phonon decay model will be employed for linewidth estimation.
- The quasiharmonic approximation, which solely considers lattice thermal expansion in accounting for the temperature dependence of phonon frequencies

Calculations will be performed for each ceramic or metallic compound (i.e., oxides, nitrides, sulfates, metal crystals, carbides, silicides) whose line is being considered for use in WPTA Raman thermometry. The temperature dependent frequency shifts and linewidth changes calculated for each of the metallic compounds will be compared with experimental observations on spectra from the pure compound. Using these comparisons, the analytical model parameters will be adjusted to obtain the best fits over the measured temperature range (~ 300 K to 200 K).

With the linewidths and line frequencies thus determined, the raw OMA scan data can be corrected and Instaspec can be used for band integration and peak ratioing to find temperature.

Experimental Measurements with Curvefitting

The second approach will seek to determine if the lineshifts and line broadening can be measured. If the shifted lines can be identified and the lineshapes measured, then 2-parameter Lorentzian curvefits can be combined with Instaspec's capabilities to determine the shifted line frequency and peak height. Knowing these parameters, Stokes/Anti-Stokes ratios can be taken with Instaspec, and temperatures calculated from the corrected band intensities and band frequencies using Equation (6-6).

These temperatures will then be compared with the NBS temperatures and correction curves drawn up. In effect, the mode anharmonicities will be accounted for or bypassed without rigorous calculations.

This second, non-analytical approach is conceptually simpler and more direct, and would be preferable for the industrial system. For example, some lines, such as the 1366 cm^{-1} E_g line of BN, are found to broaden and shift to lower frequencies as temperature increases. The linewidth can triple between 300 K and 2000 K. The new lineshape at each temperature can be obtained by curvefitting a Lorentzian to obtain the band intensity peak and central frequency. Indeed, the frequency variation of the linepeaks may be useful for independent temperature determination and will be investigated for this purpose.

SECTION 7

RECOMMENDED LABORATORY-SCALE TESTS AND SENSOR DEVELOPMENT—PHASE II

7.1 INTRODUCTION

The objective of the project is to develop a commercially viable WPTA for accurate temperature control of loads in industrial furnaces. Successful completion of this program will result in substantial benefits to users. They are:

- Improved quality of products
- Lower cost of production
- Lower use of energy (conservation)

With present technologies, it is not possible to remotely measure temperature accurately unless very special conditions are met. Remote temperature measuring instrumentation needs are only partially met by radiation pyrometers. The critical surface emissivity must be estimated to utilize radiation pyrometers.

Strength and corrosion resistance of materials are often dependent upon precise heat treatment. Chemical reactions in process plants are controlled via process temperatures. Unnecessary exposure to high temperatures often causes a weakening of the material due to undesirable grain growth in the crystallography.

Quality of products is presently often determined by post-treatment destructive or nondestructive testing. The cost of rejection is high, since most heat treatments are the last step prior to completion of parts. Some products discolor if improperly heat treated, lowering the value of the product.

Lower production costs can be realized. Chemical reactions often have an optimum temperature which provides the highest yield. Lower reject rates result in lower cost to the producer and the consumer. Present accurate measuring techniques require direct contact sensors. These sensors are difficult to attach, and in some cases it is dangerous to do so. Very high temperature measurements are virtually impossible relying on other indirect means of temperature measurements.

Many heat treatment processes require that a minimum temperature be met. Operators make sure that the temperature of a product gets high enough, wasting valuable resources. Precise knowledge of temperature will allow operators to optimize their processes.

A market assessment was made based on U.S. Industrial Process Heating Energy Consumption Data. Assessment data were:

- Viability of the product
- Applicability of the technology
- Size of the industry
- Need for precise measurements or control

Contacts were made with the various industries to gain direct information.

The result of the market assessment showed that four industries have sufficient resources to allow for early market penetration. They are:

- Metal heat treating facilities
- Glass annealing and forming industries
- Petroleum refining and chemical production industries
- Clean clay firing industries

The initial market size is approximately 5000 units at \$20,000 each. This is based on expenditures never exceeding 2 percent/yr of revenues. Unit market size increases substantially with lower price. The industry culture will in some cases be difficult for market penetration. Some industry clients understand the benefit accurate temperature measurements can offer whereas much

education will be required for others. In some industries an attitude prevails that the "good old way" is the best method.

The risk of development for a small company may be quite high if it addresses only a single market. A multipurpose instrument could defray costs over a number of applications. A short-term as well as a long-term development effort is likely to be the best combination to meet the needs of industry. Much effort was expended by Exxon to develop the basic principles of Pyrolaser, and implementation of the Pyrolaser concept was carried out by PIC. It is being recognized, however, that the instrument could be significantly enhanced to offer a broader measurements capability and that this effort would be a relatively short-term effort compared to the Raman Spectroscopy type of instruments.

Support for the project is needed, because it is unlikely that a small company could fund long-term development of the technologies without outside help. The benefits to society would accrue in the form of lower energy use to produce many varieties of products at a lower cost. Lower energy consumption will contribute to lower pollution levels, which is also beneficial. As production of the instrumentation increases, lower instrument costs will be realized leveraging the beneficial effects.

7.2 RECOMMENDED WPTA DEVELOPMENT PROGRAM—PHASE II

The short-term project goals recommended are to enhance Pyrolaser to provide an instrument with enhanced capabilities to industry.

The enhancements recommended for implementation are:

- Improve the performance of the instrument in relation to surface specularly
- Provide the fiberoptics multiplexing capability to lower cost per measurement point
- Extend the measurement range of the instrument for lower temperatures

The long-term development objective recommended is the development of a Raman Spectroscopy technology based WPTA system. This would allow measurements to be made in environments that are presently precluded such as:

- Atmospheres containing particulate mater
- Surfaces having high specularity

Development of Raman Spectroscopy instrumentation promises a reduction in sensitivity to these temperature measurement interferences. Furthermore, Raman Spectroscopy has multimedia appeal providing for other surface property measurement capabilities.

In summary, the proposed project can achieve the objectives of providing a new high accuracy remote temperature measurement capability in the long-term that does not exist today. Raman Spectroscopy has the potential to make many positive contributions to industry, and, as a result, to society. The state-of-the-art portable Pyrolaser offers a shorter term solution to industry needs, when requirements for proper operation are met.

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APPENDIX A
ECONOMIC ANALYSIS

CASE SPECIFIC ECONOMIC PARAMETERS

Workpiece Temperature Analyzer by Acurex
 Pyrolaser - Petroleum Refining Industry

OIP Improved Combustion Efficiency

Industrial Sector SIC 28 Code per THRESH.....=	14
Enter System Type -- Three Choices	
1 -- New Technology	1
Salvage Value as a % of Capital Cost -- Proposal.....=	0.00
Salvage Value as a % of Capital Cost -- Baseline.....=	0.00
First Year of Market Penetration.....=	1992
Diff. Capital Equip. Cost in Base Year Dollars.....=	\$20,000
Diff. Install. Cost in Base Year Dollars.....=	\$10,000
Total Capital Cost in Base Year Dollars.....=	\$0
Front End Costs to Commercial Production.....=	\$25,000
Diff. Non-Fuel O & M Costs per Unit per Year.....=	\$2,000
Other Non-Fuel Savings or Costs/Unit/Year.....=	\$464,000
System Useful Life in Years -- Proposed.....=	10
System Useful Life in Years -- Baseline.....=	10
Depreciation Life in Years.....=	7
Number of Units Sold in Initial Year.....=	7
Maximum Market Potential (cumulative units).....=	10,000
Market Fraction.....=	0.05
Years of Market Acceleration.....=	3
Market Penetration Efficiency.....=	1.000
Market Unit Sales Limit.....=	100
Learning Curve Factor.....=	0.90

Energy Savings per Unit per Year (Btu)

Nat. Gas	4.00E+09
No. 2 Oil	0.00E+00
No. 6 Oil	0.00E+00
Coal	0.00E+00
Electric	0.00E+00
Other	0.00E+00

First Year of Federal Investment.....= 1990

Federal Investments in Sequence (\$000)

Yr 1990 150

First Year of Private Investment.....= 1990

Private Investments in Sequence (\$000)

Yr 1990 100

February 20, 1990

Page 2

JWLarson

DOE/OIP

GENERALLY USED FINANCIAL PARAMETERS
(costs per first of year; profits, end of year)

Finance Base Year.....	=	1990
R&D Base Year.....	=	1990
Cost of Capital -- Discount Rate.....	=	0.080
Cost of Capital -- Equity + Debt.....	=	0.200
Tax Rate.....	=	0.340
Investment Tax Credit.....	=	0.000
Capital Costs Escalator.....	=	0.040
Installation Costs Escalator.....	=	0.030
O & M Costs Escalator.....	=	0.030
Past Federal Investment Cost Escalator.....	=	0.040
Past Private Investment Cost Escalator.....	=	0.040
Future Federal Investment Discount.....	=	0.070
Future Private Investment Discount.....	=	0.080
Sellers Profit Margin (first unit).....	=	0.150
Hurdle Rate -- Corporate minimum ROR.....	=	0.200
Market Years.....	=	20

Energy Cost per Million Btus

Nat. Gas	=	3.630
No. 2 Oil	=	4.560
No. 6 Oil	=	3.320
Coal	=	1.880
Electric	=	5.690
Other	=	1.000

Energy Cost Escalators

Nat. Gas	=	0.070
No. 2 Oil	=	0.060
No. 6 Oil	=	0.060
Coal	=	0.060
Electric	=	0.050
Other	=	0.060

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONQIP2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Pyrolaser - Petroleum Refining Industry

ENERGY SAVINGS POTENTIAL (Btu/YR)

Fuel Type	1995	Annual			Cumulative 2010
		2000	2005	2010	
Nat. Gas	1.23E+12	2.00E+12	3.23E+12	4.00E+12	6.23E+13
No. 2 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
No. 6 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electric	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	1.23E+12	2.00E+12	3.23E+12	4.00E+12	6.23E+13
B/DOE*	5.72E+02	9.32E+02	1.50E+03	1.86E+03	

POTENTIAL MONETARY SAVINGS (\$/yr)
(Discounted to 1990 dollars)

Fuel Type	1995	Annual			Cumulative 2010
		2000	2005	2010	
Nat. Gas	4.63E+06	7.19E+06	1.11E+07	1.31E+07	2.10E+08
No. 2 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
No. 6 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electric	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	4.63E+06	7.19E+06	1.11E+07	1.31E+07	2.10E+08

ECONOMIC ATTRACTIVENESS

End User's ROI: 1061.7 %
Payback Period: 0.1 years
Developer's ROI: 309.2 %

Benefits Rating: 0.4

PROGRAM EFFICIENCY

ETI: 554.8
MEI: 314.2
RFD (1995): 21.7
RFD (2000): 33.7
RFD (2005): 51.9
RFD (2010): 61.4

* B/DOE = Barrels per Day Oil Equivalent.

DOE/OIF THRESHOLD ANALYSIS MODEL -- (ECONOIF2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Pyrolaser - Petroleum Refining Industry

Year	Annual Units	<----- Annual Cash Flow (actual \$000) ----->				
		1st User	Developer	All Users	DOE+IRS	Nation
1990	0	0	-66	0	-184	-250
1991	0	0	-25	0	0	-25
1992	7	309	61	2,163	1,242	3,465
1993	100	353	1,578	34,321	19,938	55,837
1994	100	363	1,884	71,783	39,035	112,701
1995	100	374	2,049	111,483	59,317	172,849
1996	100	386	2,186	153,557	80,880	236,624
1997	93	398	2,150	195,638	102,265	300,053
1998	0	410	0	205,441	104,436	309,881
1999	0	422	0	211,740	107,955	319,694
2000	0	435	0	218,228	111,610	329,838
2001	0	449	0	225,001	115,323	340,324
2002	7	0	196	234,966	120,894	356,056
2003	100	0	2,931	285,941	150,695	439,567
2004	100	0	3,078	344,692	180,711	528,481
2005	100	0	3,226	406,953	212,492	622,671
2006	100	0	3,376	472,802	246,229	722,406
2007	93	0	3,281	539,038	279,905	822,224
2008	0	0	0	561,663	287,321	848,984
2009	0	0	0	579,552	296,936	876,488
2010	0	0	0	598,045	306,913	904,958
2011	0	0	0	617,285	317,149	934,434
2012	7	0	298	641,261	330,138	971,697
2013	100	0	4,438	721,768	376,811	1,103,017
2014	100	0	4,633	813,764	423,831	1,242,229
2015	100	0	4,833	911,136	473,563	1,389,532
2016	100	0	5,040	1,014,023	526,291	1,545,354
2017	93	0	4,885	1,118,073	579,241	1,702,199
2018	0	0	0	1,162,800	596,095	1,758,895
2019	0	0	0	1,201,204	616,457	1,817,661
2020	0	0	0	1,241,001	637,610	1,878,610
2021	0	0	0	1,282,419	659,416	1,941,834
2022	0	0	0	1,325,449	681,985	2,007,434
2023	0	0	0	1,370,107	705,409	2,075,517
2024	0	0	0	1,416,486	729,705	2,146,191
2025	0	0	0	1,464,915	754,653	2,219,568

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name:		Workpiece Temperature Analyzer by Acurex				
Description:		Pyrolaser - Petroleum Refining Industry				
Year	Cumulative Units	<----- 1st User	Cumulative Developer	Cash Flow (actual \$000) All Users	DOE+IRS	>----- Nation
1990	0	0	-66	0	-184	-250
1991	0	0	-91	0	-184	-275
1992	7	309	-30	2,163	1,058	3,190
1993	107	662	1,548	36,484	20,996	59,028
1994	207	1,025	3,432	108,266	60,031	171,729
1995	307	1,399	5,480	219,749	119,348	344,578
1996	407	1,785	7,667	373,306	200,229	581,202
1997	500	2,182	9,817	568,944	302,493	881,254
1998	500	2,593	9,817	774,390	406,929	1,191,136
1999	500	3,015	9,817	986,129	514,884	1,510,830
2000	500	3,450	9,817	1,204,358	626,493	1,840,668
2001	500	3,899	9,817	1,429,359	741,817	2,180,992
2002	507	3,899	10,013	1,664,325	862,711	2,537,049
2003	607	3,899	12,944	1,950,266	1,013,406	2,976,616
2004	707	3,899	16,021	2,294,958	1,194,117	3,505,097
2005	807	3,899	19,247	2,701,911	1,406,609	4,127,767
2006	907	3,899	22,623	3,174,712	1,652,838	4,850,173
2007	1,000	3,899	25,904	3,713,750	1,932,743	5,672,397
2008	1,000	3,899	25,904	4,275,414	2,220,064	6,521,381
2009	1,000	3,899	25,904	4,854,966	2,517,000	7,397,869
2010	1,000	3,899	25,904	5,453,011	2,823,913	8,302,827
2011	1,000	3,899	25,904	6,070,296	3,141,061	9,237,260
2012	1,007	3,899	26,202	6,711,557	3,471,199	10,208,950
2013	1,107	3,899	30,640	7,433,325	3,848,010	11,311,970
2014	1,207	3,899	35,273	8,247,090	4,271,841	12,554,200
2015	1,307	3,899	40,106	9,158,225	4,745,404	13,943,730
2016	1,407	3,899	45,146	10,172,250	5,271,696	15,489,090
2017	1,500	3,899	50,031	11,290,320	5,850,937	17,191,290
2018	1,500	3,899	50,031	12,453,120	6,447,032	18,950,180
2019	1,500	3,899	50,031	13,654,320	7,063,489	20,767,840
2020	1,500	3,899	50,031	14,895,320	7,701,099	22,646,460
2021	1,500	3,899	50,031	16,177,740	8,360,515	24,588,290
2022	1,500	3,899	50,031	17,503,190	9,042,500	26,595,720
2023	1,500	3,899	50,031	18,873,300	9,747,909	28,671,240
2024	1,500	3,899	50,031	20,289,790	10,477,610	30,817,430
2025	1,500	3,899	50,031	21,754,700	11,232,270	33,037,000

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIF2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Pyrolaser - Petroleum Refining Industry

Year	Cumulative Units	<----- Cumulative Cash Flow (discounted \$000) ----->				
		1st User	Developer	All Users	DOE+IRS	Nation
1990	0	0	-61	0	-170	-231
1991	0	0	-82	0	-170	-253
1992	7	245	-34	1,717	815	2,498
1993	107	505	1,126	26,944	15,471	43,540
1994	207	752	2,408	75,798	42,037	120,243
1995	307	988	3,699	146,051	79,417	229,167
1996	407	1,213	4,974	235,650	126,610	367,235
1997	500	1,427	6,136	341,347	181,860	529,344
1998	500	1,633	6,136	444,121	234,104	684,361
1999	500	1,828	6,136	542,197	284,108	832,442
2000	500	2,015	6,136	635,791	331,976	973,903
2001	500	2,193	6,136	725,142	377,772	1,109,051
2002	507	2,193	6,208	811,539	422,224	1,239,972
2003	607	2,193	7,206	908,891	473,530	1,389,627
2004	707	2,193	8,176	1,017,552	530,498	1,556,226
2005	807	2,193	9,118	1,136,338	592,522	1,737,978
2006	907	2,193	10,030	1,264,121	659,070	1,933,221
2007	1,000	2,193	10,851	1,399,015	729,116	2,138,982
2008	1,000	2,193	10,851	1,529,159	795,692	2,335,702
2009	1,000	2,193	10,851	1,653,500	859,399	2,523,751
2010	1,000	2,193	10,851	1,772,305	920,369	2,703,526
2011	1,000	2,193	10,851	1,885,849	978,705	2,875,406
2012	1,007	2,193	10,902	1,995,065	1,034,933	3,040,900
2013	1,107	2,193	11,602	2,108,888	1,094,355	3,214,845
2014	1,207	2,193	12,278	2,227,712	1,156,242	3,396,233
2015	1,307	2,193	12,932	2,350,899	1,220,269	3,584,100
2016	1,407	2,193	13,563	2,477,841	1,286,153	3,777,557
2017	1,500	2,193	14,129	2,607,441	1,353,295	3,974,865
2018	1,500	2,193	14,129	2,732,241	1,417,273	4,163,643
2019	1,500	2,193	14,129	2,851,613	1,478,534	4,344,277
2020	1,500	2,193	14,129	2,965,805	1,537,205	4,517,139
2021	1,500	2,193	14,129	3,075,067	1,593,387	4,682,583
2022	1,500	2,193	14,129	3,179,630	1,647,188	4,840,947
2023	1,500	2,193	14,129	3,279,710	1,698,714	4,992,554
2024	1,500	2,193	14,129	3,375,513	1,748,068	5,137,710
2025	1,500	2,193	14,129	3,467,252	1,795,327	5,276,709

February 20, 1990

Page 7

JWLarson

DOE/OIP

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF FIRST USER

Year	<----- Annual Dollars ----->			Cumulative Dollars	
	Tax Break	Operations	Cash Flow	Actual	Discounted
1992	1,566	339,655	308,980	308,980	245,279
1993	2,685	350,299	352,984	661,964	504,732
1994	1,918	361,294	363,211	1,025,175	751,927
1995	1,370	372,652	374,022	1,399,197	987,625
1996	1,141	384,388	385,529	1,784,726	1,212,577
1997	1,141	396,514	397,656	2,182,382	1,427,418
1998	1,141	409,047	410,188	2,592,570	1,632,614
1999	0	421,999	421,999	3,014,569	1,828,081
2000	0	435,388	435,388	3,449,958	2,014,812
2001	0	449,230	449,230	3,899,187	2,193,207

February 20, 1990

Page 8

JWL:arson

DOE/OIP

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF DEVELOPER

Year	Units Sold	Unit Cost	Annual \$ Cash Flow	Cumulative Dollars Actual	Cumulative Dollars Discounted
1990	0	0	-66,000	-66,000	-61,111
1991	0	0	-24,737	-90,737	-82,319
1992	7	43,057	60,551	-30,186	-34,252
1993	100	44,673	1,578,269	1,548,083	1,125,823
1994	100	46,351	1,883,507	3,431,590	2,407,706
1995	100	48,092	2,048,723	5,480,314	3,698,749
1996	100	49,900	2,186,322	7,666,636	4,974,446
1997	93	51,777	2,150,426	9,817,062	6,136,254
1998	0	53,725	0	9,817,062	6,136,254
1999	0	55,747	0	9,817,062	6,136,254
2000	0	57,846	0	9,817,062	6,136,254
2001	0	60,026	0	9,817,062	6,136,254
2002	7	62,289	196,224	10,013,290	6,208,405
2003	100	64,638	2,930,501	12,943,790	7,206,126
2004	100	67,076	3,077,629	16,021,410	8,176,321
2005	100	69,608	3,225,582	19,247,000	9,117,837
2006	100	72,236	3,375,687	22,622,690	10,030,180
2007	93	74,965	3,281,081	25,903,770	10,851,270
2008	0	77,799	0	25,903,770	10,851,270
2009	0	80,741	0	25,903,770	10,851,270
2010	0	83,795	0	25,903,770	10,851,270
2011	0	86,966	0	25,903,770	10,851,270
2012	7	90,259	298,341	26,202,110	10,902,080
2013	100	93,677	4,438,110	30,640,220	11,601,970
2014	100	97,227	4,632,716	35,272,930	12,278,420
2015	100	100,913	4,833,165	40,106,090	12,931,880
2016	100	104,740	5,039,968	45,146,070	13,562,810
2017	93	108,714	4,885,156	50,031,220	14,129,070
2018	0	112,840	0	50,031,220	14,129,070
2019	0	117,125	0	50,031,220	14,129,070
2020	0	121,574	0	50,031,220	14,129,070
2021	0	126,195	0	50,031,220	14,129,070
2022	0	130,993	0	50,031,220	14,129,070
2023	0	135,975	0	50,031,220	14,129,070
2024	0	141,148	0	50,031,220	14,129,070
2025	0	146,521	0	50,031,220	14,129,070

DOE/OIF THRESHOLD ANALYSIS MODEL -- (ECONOIF2)

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF FEDERAL SECTOR

Year	1st User Tax Break	Developer Tax Break	Annual \$ Cash Flow	Cumulative Dollars	
				Actual	Discounted
1990	0	34,000	-184,000	-184,000	-170,370
1991	0	1,263	0	-184,000	-170,370
1992	1,566	2,165	1,241,769	1,057,769	815,386
1993	2,685	1,546	19,938,340	20,996,110	15,470,660
1994	1,918	1,105	39,035,130	60,031,230	42,037,310
1995	1,370	920	59,317,070	119,348,300	79,417,110
1996	1,141	920	80,880,350	200,228,700	126,610,000
1997	1,141	920	102,264,600	302,493,300	181,860,400
1998	1,141	0	104,435,900	406,929,000	234,104,300
1999	0	0	107,954,800	514,883,800	284,108,200
2000	0	0	111,609,600	626,493,500	331,975,600
2001	0	0	115,323,300	741,816,700	377,772,000
2002	0	0	120,893,800	862,710,500	422,224,400
2003	0	0	150,695,300	1,013,406,000	473,530,200
2004	0	0	180,711,000	1,194,117,000	530,497,800
2005	0	0	212,492,400	1,406,609,000	592,522,300
2006	0	0	246,228,600	1,652,838,000	659,070,100
2007	0	0	279,905,500	1,932,743,000	729,116,100
2008	0	0	287,320,800	2,220,064,000	795,691,800
2009	0	0	296,935,500	2,517,000,000	859,398,600
2010	0	0	306,912,900	2,823,913,000	920,368,600
2011	0	0	317,148,700	3,141,061,000	978,705,000
2012	0	0	330,137,600	3,471,199,000	1,034,933,000
2013	0	0	376,810,700	3,848,010,000	1,094,355,000
2014	0	0	423,831,400	4,271,841,000	1,156,242,000
2015	0	0	473,563,100	4,745,404,000	1,220,269,000
2016	0	0	526,291,400	5,271,696,000	1,286,153,000
2017	0	0	579,241,100	5,850,937,000	1,353,295,000
2018	0	0	596,095,400	6,447,032,000	1,417,273,000
2019	0	0	616,457,100	7,063,489,000	1,478,534,000
2020	0	0	637,609,800	7,701,099,000	1,537,205,000
2021	0	0	659,415,500	8,360,515,000	1,593,387,000
2022	0	0	681,985,400	9,042,499,000	1,647,188,000
2023	0	0	705,409,400	9,747,909,000	1,698,714,000
2024	0	0	729,704,800	10,477,610,000	1,748,068,000
2025	0	0	754,653,100	11,232,270,000	1,795,327,000

CASE SPECIFIC ECONOMIC PARAMETERS

Workpiece Temperature Analyzer by Acurex

Pyrolaser - Metal Heat Treating Industry

OIF Improved Combustion Efficiency

Industrial Sector SIC 28 Code per THRESH.....= 14

Enter System Type -- Three Choices

1 -- New Technology= 1

Salvage Value as a % of Capital Cost -- Proposal.....= 0.00

Salvage Value as a % of Capital Cost -- Baseline.....= 0.00

First Year of Market Penetration.....= 1992

Diff. Capital Equip. Cost in Base Year Dollars.....= \$20,000

Diff. Install. Cost in Base Year Dollars.....= \$10,000

Total Capital Cost in Base Year Dollars.....= \$0

Front End Costs to Commercial Production.....= \$25,000

Diff. Non-Fuel O & M Costs per Unit per Year.....= \$2,000

Other Non-Fuel Savings or Costs/Unit/Year.....= \$182,000

System Useful Life in Years -- Proposed.....= 10

System Useful Life in Years -- Baseline.....= 10

Depreciation Life in Years.....= 7

Number of Units Sold in Initial Year.....= 7

Maximum Market Potential (cumulative units).....= 10,000

Market Fraction.....= 0.05

Years of Market Acceleration.....= 3

Market Penetration Efficiency.....= 1.000

Market Unit Sales Limit.....= 100

Learning Curve Factor.....= 0.90

Energy Savings per Unit per Year (Btu)

Nat. Gas= 3.00E+09

No. 2 Oil= 0.00E+00

No. 6 Oil= 0.00E+00

Coal= 0.00E+00

Electric= 0.00E+00

Other= 0.00E+00

First Year of Federal Investment.....= 1990

Federal Investments in Sequence (\$000)

Yr 1990 150

First Year of Private Investment.....= 1990

Private Investments in Sequence (\$000)

Yr 1990 100

February 20, 1990

Page 2

JWLarson

DOE/OIF

GENERALLY USED FINANCIAL PARAMETERS
(costs per first of year; profits, end of year)

Finance Base Year.....	=	1990
R&D Base Year.....	=	1990
Cost of Capital -- Discount Rate.....	=	0.080
Cost of Capital -- Equity + Debt.....	=	0.200
Tax Rate.....	=	0.340
Investment Tax Credit.....	=	0.000
Capital Costs Escalator.....	=	0.040
Installation Costs Escalator.....	=	0.030
O & M Costs Escalator.....	=	0.030
Past Federal Investment Cost Escalator.....	=	0.040
Past Private Investment Cost Escalator.....	=	0.040
Future Federal Investment Discount.....	=	0.070
Future Private Investment Discount.....	=	0.080
Sellers Profit Margin (first unit).....	=	0.150
Hurdle Rate -- Corporate minimum ROR.....	=	0.200
Market Years.....	=	20
Energy Cost per Million Btus		
Nat. Gas	=	3.630
No. 2 Oil	=	4.560
No. 6 Oil	=	3.320
Coal	=	1.880
Electric	=	5.690
Other	=	1.000
Energy Cost Escalators		
Nat. Gas	=	0.070
No. 2 Oil	=	0.060
No. 6 Oil	=	0.060
Coal	=	0.060
Electric	=	0.050
Other	=	0.060

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Pyrolaser - Metal Heat Treating Industry

ENERGY SAVINGS POTENTIAL (Btu/YR)

Fuel Type	1995	2000	Annual 2005	2010	Cumulative 2010
Nat. Gas	9.21E+11	1.50E+12	2.42E+12	3.00E+12	4.67E+13
No. 2 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
No. 6 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electric	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	9.21E+11	1.50E+12	2.42E+12	3.00E+12	4.67E+13
B/DOE*	4.29E+02	6.99E+02	1.13E+03	1.40E+03	

POTENTIAL MONETARY SAVINGS (\$/yr)
(Discounted to 1990 dollars)

Fuel Type	1995	2000	Annual 2005	2010	Cumulative 2010
Nat. Gas	3.47E+06	5.39E+06	8.31E+06	9.83E+06	1.58E+08
No. 2 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
No. 6 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electric	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	3.47E+06	5.39E+06	8.31E+06	9.83E+06	1.58E+08

ECONOMIC ATTRACTIVENESS

End User's ROI: 431.8 %
 Payback Period: 0.2 years
 Developer's ROI: 309.2 %
 Benefits Rating: 0.4

PROGRAM EFFICIENCY

ETI: 416.1
 MEI: 235.7
 RFD (1995): 16.3
 RFD (2000): 25.3
 RFD (2005): 38.9
 RFD (2010): 46.0

* B/DOE = Barrels per Day Oil Equivalent.

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Pyrolaser - Metal Heat Treating Industry

Year	Annual Units	<----- Annual Cash Flow (actual \$000) ----->				
		1st User	Developer	All Users	DOE+IRS	Nation
1990	0	0	-66	0	-194	-250
1991	0	0	-25	0	0	-25
1992	7	106	61	740	509	1,310
1993	100	144	1,578	11,910	8,394	21,882
1994	100	147	1,884	27,102	16,018	45,004
1995	100	152	2,049	43,190	24,136	69,375
1996	100	156	2,186	60,246	32,811	95,244
1997	93	161	2,150	77,492	41,402	121,044
1998	0	167	0	83,676	41,706	125,382
1999	0	171	0	86,232	43,299	129,531
2000	0	177	0	88,864	44,967	133,831
2001	0	183	0	91,658	46,632	138,290
2002	7	0	196	95,595	49,096	144,887
2003	100	0	2,931	113,939	62,088	178,957
2004	100	0	3,078	138,174	74,323	215,575
2005	100	0	3,226	163,946	87,307	254,479
2006	100	0	3,376	191,241	101,182	295,799
2007	93	0	3,281	219,002	115,038	337,321
2008	0	0	0	231,713	117,347	349,060
2009	0	0	0	239,368	121,689	361,058
2010	0	0	0	247,298	126,225	373,522
2011	0	0	0	255,632	130,842	386,474
2012	7	0	298	265,737	136,686	402,721
2013	100	0	4,438	296,082	157,518	458,039
2014	100	0	4,633	335,133	177,264	517,030
2015	100	0	4,833	376,645	198,219	579,697
2016	100	0	5,040	420,618	220,598	646,257
2017	93	0	4,885	465,603	243,120	713,609
2018	0	0	0	489,832	249,415	739,247
2019	0	0	0	507,059	258,867	765,926
2020	0	0	0	524,973	268,747	793,720
2021	0	0	0	543,779	278,904	822,683
2022	0	0	0	563,439	289,435	852,873
2023	0	0	0	583,941	300,415	884,355
2024	0	0	0	605,348	311,846	917,194
2025	0	0	0	627,959	323,494	951,453

February 20, 1990

Page 5

JWLarson

DOE/OIP

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Pyrolaser - Metal Heat Treating Industry

Year	Cumulative Units	<----- 1st User	Cumulative Developer	Cash Flow (actual \$000) All Users	DOE+IRS	>----- Nation
1990	0	0	-66	0	-184	-250
1991	0	0	-91	0	-184	-275
1992	7	106	-30	740	325	1,035
1993	107	249	1,548	12,651	8,719	22,917
1994	207	397	3,432	39,753	24,737	67,921
1995	307	548	5,480	82,943	48,872	137,296
1996	407	704	7,667	143,189	81,684	232,540
1997	500	866	9,817	220,681	123,085	353,583
1998	500	1,033	9,817	304,357	164,791	478,965
1999	500	1,203	9,817	390,589	208,090	608,496
2000	500	1,380	9,817	479,453	253,058	742,327
2001	500	1,563	9,817	571,111	279,689	880,617
2002	507	1,563	10,013	666,705	348,785	1,025,504
2003	607	1,563	12,944	780,644	410,873	1,204,461
2004	707	1,563	16,021	918,818	485,196	1,420,036
2005	807	1,563	19,247	1,082,765	572,504	1,674,515
2006	907	1,563	22,623	1,274,006	673,686	1,970,315
2007	1,000	1,563	25,904	1,493,008	788,724	2,307,636
2008	1,000	1,563	25,904	1,724,721	906,071	2,656,696
2009	1,000	1,563	25,904	1,964,089	1,027,760	3,017,753
2010	1,000	1,563	25,904	2,211,387	1,153,985	3,391,276
2011	1,000	1,563	25,904	2,467,019	1,284,827	3,777,749
2012	1,007	1,563	26,202	2,732,756	1,421,513	4,180,470
2013	1,107	1,563	30,640	3,028,838	1,579,031	4,638,509
2014	1,207	1,563	35,273	3,363,971	1,756,295	5,155,539
2015	1,307	1,563	40,106	3,740,616	1,954,514	5,735,236
2016	1,407	1,563	45,146	4,161,234	2,175,112	6,381,492
2017	1,500	1,563	50,031	4,626,837	2,418,232	7,095,101
2018	1,500	1,563	50,031	5,116,669	2,667,647	7,834,348
2019	1,500	1,563	50,031	5,623,728	2,926,515	8,600,274
2020	1,500	1,563	50,031	6,148,701	3,195,262	9,393,994
2021	1,500	1,563	50,031	6,692,480	3,474,166	10,216,680
2022	1,500	1,563	50,031	7,255,919	3,763,601	11,069,550
2023	1,500	1,563	50,031	7,839,859	4,064,015	11,953,910
2024	1,500	1,563	50,031	8,445,207	4,375,861	12,871,100
2025	1,500	1,563	50,031	9,073,166	4,699,355	13,822,550

February 20, 1990

Page 6

JWLarson

DOE/OIP

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIF2)

Project Name:		Workpiece Temperature Analyzer by Acurex				
Description:		Pyrolaser - Metal Heat Treating Industry				
Year	Cumulative Units	<----- 1st User	Cumulative Cash Flow (discounted \$000) Developer	All Users	DOE+IRS	>----- Nation
1990	0	0	-61	0	-170	-231
1991	0	0	-82	0	-170	-253
1992	7	84	-34	588	234	787
1993	107	189	1,126	9,342	6,403	16,871
1994	207	290	2,408	27,787	17,305	47,500
1995	307	385	3,699	55,005	32,514	91,218
1996	407	476	4,974	90,158	51,659	146,792
1997	500	564	6,136	132,024	74,027	212,188
1998	500	647	6,136	173,883	94,891	274,910
1999	500	726	6,136	213,825	114,947	334,908
2000	500	802	6,136	251,937	134,232	392,306
2001	500	874	6,136	288,336	152,750	447,222
2002	507	874	6,208	323,486	170,803	500,497
2003	607	874	7,206	362,277	191,941	561,425
2004	707	874	8,176	405,836	215,371	629,383
2005	807	874	9,118	453,690	240,855	703,663
2006	907	874	10,030	505,376	268,202	783,608
2007	1,000	874	10,851	560,181	296,990	868,022
2008	1,000	874	10,851	613,872	324,181	948,904
2009	1,000	874	10,851	665,228	350,289	1,026,368
2010	1,000	874	10,851	714,355	375,364	1,100,570
2011	1,000	874	10,851	761,376	399,431	1,171,658
2012	1,007	874	10,902	806,635	422,711	1,240,248
2013	1,107	874	11,602	853,327	447,551	1,312,480
2014	1,207	874	12,278	902,262	473,435	1,387,976
2015	1,307	874	12,932	953,185	500,234	1,466,352
2016	1,407	874	13,563	1,005,841	527,850	1,547,254
2017	1,500	874	14,129	1,059,811	556,031	1,629,971
2018	1,500	874	14,129	1,112,383	582,800	1,709,313
2019	1,500	874	14,129	1,162,773	608,526	1,785,426
2020	1,500	874	14,129	1,211,079	633,255	1,858,463
2021	1,500	874	14,129	1,257,409	657,018	1,928,556
2022	1,500	874	14,129	1,301,856	679,851	1,995,838
2023	1,500	874	14,129	1,344,512	701,795	2,060,436
2024	1,500	874	14,129	1,385,455	722,886	2,122,470
2025	1,500	874	14,129	1,424,780	743,145	2,182,054

February 20, 1990

Page 7

JWLarson

DOE/OIF

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF FIRST USER

Year	<----- Annual Dollars ----->			Cumulative Dollars	
	Tax Break	Operations	Cash Flow	Actual	Discounted
1992	1,566	136,423	105,748	105,748	83,947
1993	2,685	140,857	143,541	249,290	189,454
1994	1,918	145,447	147,364	396,654	289,747
1995	1,370	150,200	151,569	548,223	385,262
1996	1,141	155,123	156,264	704,488	476,440
1997	1,141	160,223	161,364	865,852	563,620
1998	1,141	165,507	166,648	1,032,500	646,986
1999	0	170,983	170,983	1,203,483	726,184
2000	0	176,659	176,659	1,380,143	801,950
2001	0	182,544	182,544	1,562,687	874,441

February 20, 1990

Page 8

JWLarson

DOE/OIF

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF DEVELOPER

Year	Units Sold	Unit Cost	Annual \$ Cash Flow	Cumulative Dollars Actual	Cumulative Dollars Discounted
1990	0	0	-66,000	-66,000	-61,111
1991	0	0	-24,737	-90,737	-82,319
1992	7	43,057	60,551	-30,186	-34,252
1993	100	44,673	1,578,269	1,548,083	1,125,823
1994	100	46,351	1,883,507	3,431,590	2,407,706
1995	100	48,092	2,048,723	5,480,314	3,698,749
1996	100	49,900	2,186,322	7,666,636	4,974,446
1997	93	51,777	2,150,426	9,817,062	6,136,254
1998	0	53,725	0	9,817,062	6,136,254
1999	0	55,747	0	9,817,062	6,136,254
2000	0	57,846	0	9,817,062	6,136,254
2001	0	60,026	0	9,817,062	6,136,254
2002	7	62,289	196,224	10,013,290	6,208,405
2003	100	64,638	2,930,501	12,943,790	7,206,126
2004	100	67,076	3,077,629	16,021,410	8,176,321
2005	100	69,608	3,225,582	19,247,000	9,117,837
2006	100	72,236	3,375,687	22,622,590	10,030,180
2007	93	74,965	3,281,081	25,903,770	10,851,270
2008	0	77,799	0	25,903,770	10,851,270
2009	0	80,741	0	25,903,770	10,851,270
2010	0	83,795	0	25,903,770	10,851,270
2011	0	86,966	0	25,903,770	10,851,270
2012	7	90,259	298,341	26,202,110	10,902,080
2013	100	93,677	4,438,110	30,640,220	11,601,970
2014	100	97,227	4,632,716	35,272,930	12,278,420
2015	100	100,913	4,833,165	40,106,090	12,931,880
2016	100	104,740	5,039,968	45,146,070	13,562,810
2017	93	108,714	4,885,156	50,031,220	14,129,070
2018	0	112,840	0	50,031,220	14,129,070
2019	0	117,125	0	50,031,220	14,129,070
2020	0	121,574	0	50,031,220	14,129,070
2021	0	126,195	0	50,031,220	14,129,070
2022	0	130,993	0	50,031,220	14,129,070
2023	0	135,975	0	50,031,220	14,129,070
2024	0	141,148	0	50,031,220	14,129,070
2025	0	146,521	0	50,031,220	14,129,070

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF FEDERAL SECTOR

Year	1st User Tax Break	Developer Tax Break	Annual \$ Cash Flow	Cumulative Dollars	
				Actual	Discounted
1990	0	34,000	-184,000	-184,000	-170,370
1991	0	1,263	0	-184,000	-170,370
1992	1,566	2,165	508,902	324,902	233,613
1993	2,685	1,546	8,393,623	8,718,525	6,403,175
1994	1,918	1,105	16,017,980	24,736,510	17,304,740
1995	1,370	920	24,135,890	48,872,400	32,514,450
1996	1,141	920	32,811,130	81,683,530	51,659,420
1997	1,141	920	41,401,630	123,085,200	74,027,430
1998	1,141	0	41,705,880	164,791,000	94,890,740
1999	0	0	43,299,170	208,090,200	114,946,600
2000	0	0	44,967,370	253,057,600	134,232,300
2001	0	0	46,631,550	299,689,100	152,750,300
2002	0	0	49,096,330	348,785,500	170,803,000
2003	0	0	62,088,010	410,873,500	191,941,500
2004	0	0	74,322,910	485,196,400	215,371,100
2005	0	0	87,307,220	572,503,600	240,855,300
2006	0	0	101,182,400	673,686,000	268,201,700
2007	0	0	115,038,400	788,724,400	296,989,900
2008	0	0	117,346,500	906,070,900	324,190,500
2009	0	0	121,689,500	1,027,760,000	350,288,700
2010	0	0	126,224,300	1,153,985,000	375,364,000
2011	0	0	130,842,400	1,284,827,000	399,431,200
2012	0	0	136,685,800	1,421,513,000	422,710,800
2013	0	0	157,518,000	1,579,031,000	447,551,300
2014	0	0	177,263,800	1,756,295,000	473,435,000
2015	0	0	198,219,000	1,954,514,000	500,234,500
2016	0	0	220,598,100	2,175,112,000	527,850,400
2017	0	0	243,120,300	2,418,232,000	556,031,300
2018	0	0	249,415,000	2,667,647,000	582,800,400
2019	0	0	258,867,200	2,926,515,000	608,525,900
2020	0	0	268,747,200	3,195,262,000	633,254,900
2021	0	0	278,904,000	3,474,166,000	657,017,500
2022	0	0	289,434,700	3,763,601,000	679,850,700
2023	0	0	300,414,500	4,064,015,000	701,794,500
2024	0	0	311,845,900	4,375,861,000	722,886,000
2025	0	0	323,494,200	4,699,355,000	743,144,600

CASE SPECIFIC ECONOMIC PARAMETERS

Workpiece Temperature Analyzer by Acurex
 Raman Spectroscopy Semiconductor Industry
 OIF Improved Combustion Efficiency
 Industrial Sector SIC 28 Code per THRESH.....= 14
 Enter System Type -- Three Choices
 1 -- New Technology= 1
 Salvage Value as a % of Capital Cost -- Proposal.....= 0.00
 Salvage Value as a % of Capital Cost -- Baseline.....= 0.00
 First Year of Market Penetration.....= 1993
 Diff. Capital Equip. Cost in Base Year Dollars.....= \$30,000
 Diff. Install. Cost in Base Year Dollars.....= \$10,000
 Total Capital Cost in Base Year Dollars.....= \$0
 Front End Costs to Commercial Production.....= \$100,000
 Diff. Non-Fuel O & M Costs per Unit per Year.....= \$3,000
 Other Non-Fuel Savings or Costs/Unit/Year.....= \$193,000
 System Useful Life in Years -- Proposed.....= 10
 System Useful Life in Years -- Baseline.....= 10
 Depreciation Life in Years.....= 7
 Number of Units Sold in Initial Year.....= 7
 Maximum Market Potential (cumulative units).....= 22,000
 Market Fraction.....= 0.05
 Years of Market Acceleration.....= 5
 Market Penetration Efficiency.....= 1.000
 Market Unit Sales Limit.....= 200
 Learning Curve Factor.....= 0.90

Energy Savings per Unit per Year (Btu)
 Nat. Gas= 1.00E+09
 No. 2 Oil= 0.00E+00
 No. 6 Oil= 0.00E+00
 Coal= 0.00E+00
 Electric= 0.00E+00
 Other= 0.00E+00

First Year of Federal Investment.....= 1990
 Federal Investments in Sequence (\$000)
 Yr 1990 390

First Year of Private Investment.....= 1990
 Private Investments in Sequence (\$000)
 Yr 1990 100

GENERALLY USED FINANCIAL PARAMETERS
(costs per first of year; profits, end of year)

Finance Base Year.....	=	1990
R&D Base Year.....	=	1990
Cost of Capital -- Discount Rate.....	=	0.080
Cost of Capital -- Equity + Debt.....	=	0.200
Tax Rate.....	=	0.340
Investment Tax Credit.....	=	0.000
Capital Costs Escalator.....	=	0.040
Installation Costs Escalator.....	=	0.030
O & M Costs Escalator.....	=	0.030
Past Federal Investment Cost Escalator.....	=	0.040
Past Private Investment Cost Escalator.....	=	0.040
Future Federal Investment Discount.....	=	0.070
Future Private Investment Discount.....	=	0.080
Sellers Profit Margin (first unit).....	=	0.150
Hurdle Rate -- Corporate minimum ROR.....	=	0.200
Market Years.....	=	20

Energy Cost per Million Btus

Nat. Gas	=	3.630
No. 2 Oil	=	4.560
No. 6 Oil	=	3.320
Coal	=	1.880
Electric	=	5.690
Other	=	1.000

Energy Cost Escalators

Nat. Gas	=	0.070
No. 2 Oil	=	0.060
No. 6 Oil	=	0.060
Coal	=	0.060
Electric	=	0.050
Other	=	0.060

Project Name: Workpiece Temperature Analyzer by Acurex
 Description: Raman Spectroscopy Semiconductor Industry

ENERGY SAVINGS POTENTIAL (Btu/YR)

Fuel Type	1995	2000	Annual 2005	2010	Cumulative 2010
Nat. Gas	4.07E+11	1.10E+12	1.51E+12	2.20E+12	3.25E+13
No. 2 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
No. 6 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electric	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	4.07E+11	1.10E+12	1.51E+12	2.20E+12	3.25E+13
B/DOE*	1.90E+02	5.13E+02	7.02E+02	1.03E+03	

POTENTIAL MONETARY SAVINGS (\$/yr)
(Discounted to 1990 dollars)

Fuel Type	1995	2000	Annual 2005	2010	Cumulative 2010
Nat. Gas	1.53E+06	3.96E+06	5.17E+06	7.21E+06	1.09E+08
No. 2 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
No. 6 Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electric	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	1.53E+06	3.96E+06	5.17E+06	7.21E+06	1.09E+08

ECONOMIC ATTRACTIVENESS

End User's ROI: 326.6 %
 Payback Period: 0.3 years
 Developer's ROI: 268.3 %
 Benefits Rating: 0.2

PROGRAM EFFICIENCY

ETI: 139.1
 MEI: 77.8
 RFD (1995): 2.8
 RFD (2000): 7.1
 RFD (2005): 9.3
 RFD (2010): 13.0

* B/DOE = Barrels per Day Oil Equivalent.

DOE/OIF THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex						
Description: Raman Spectroscopy Semiconductor Industry						
Year	Annual Units	<----- Annual Cash Flow (actual \$000) ----->				
		1st User	Developer	All Users	DOE+IRS	Nation
1990	0	0	-66	0	-424	-490
1991	0	0	0	0	0	0
1992	0	0	-103	0	0	-103
1993	7	100	85	697	527	1,309
1994	200	150	4,413	21,529	17,408	43,350
1995	200	154	5,210	53,102	33,081	91,392
1996	200	158	5,634	86,370	49,726	141,729
1997	200	162	5,992	121,481	67,492	194,965
1998	200	167	6,327	158,615	86,366	251,308
1999	93	172	3,083	185,353	95,396	283,832
2000	0	176	0	196,035	97,146	293,181
2001	0	181	0	201,347	100,955	302,302
2002	0	187	0	207,058	104,662	311,720
2003	7	0	270	214,005	109,172	323,447
2004	200	0	8,063	247,791	136,811	392,665
2005	200	0	8,450	297,191	161,577	467,218
2006	200	0	8,843	349,333	187,885	546,061
2007	200	0	9,243	404,423	215,737	629,403
2008	200	0	9,654	462,544	245,267	717,465
2009	93	0	4,679	507,317	261,311	773,307
2010	0	0	0	530,452	267,684	798,137
2011	0	0	0	546,076	277,291	823,366
2012	0	0	0	562,551	286,889	849,440
2013	7	0	410	580,988	297,747	879,145
2014	200	0	12,189	635,335	340,824	988,348
2015	200	0	12,713	712,470	379,548	1,104,731
2016	200	0	13,254	793,748	420,599	1,227,601
2017	200	0	13,814	879,480	463,985	1,357,279
2018	200	0	14,393	969,801	509,906	1,494,100
2019	93	0	6,966	1,043,016	537,330	1,587,313
2020	0	0	0	1,086,973	551,842	1,638,815
2021	0	0	0	1,120,428	571,342	1,691,770
2022	0	0	0	1,155,530	591,042	1,746,572
2023	0	0	0	1,192,145	611,153	1,803,298
2024	0	0	0	1,230,132	631,896	1,862,028
2025	0	0	0	1,269,465	653,378	1,922,843

DOE/OIP THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex

Description: Raman Spectroscopy Semiconductor Industry

Year	Cumulative Units	Cash Flow (actual \$000)				
		<----- 1st User	Cumulative Developer	All Users	DOE+IRS	-----> Nation
1990	0	0	-66	0	-424	-490
1991	0	0	-66	0	-424	-490
1992	0	0	-169	0	-424	-553
1993	7	100	-84	697	103	716
1994	207	250	4,329	22,226	17,511	44,066
1995	407	403	9,538	75,328	50,592	135,458
1996	607	561	15,172	161,698	100,318	277,188
1997	807	723	21,164	283,178	167,810	472,153
1998	1,007	890	27,492	441,793	254,176	723,461
1999	1,100	1,062	30,574	627,147	349,573	1,007,293
2000	1,100	1,238	30,574	823,182	446,718	1,300,474
2001	1,100	1,420	30,574	1,024,529	547,674	1,602,777
2002	1,100	1,607	30,574	1,231,586	652,336	1,914,497
2003	1,107	1,607	30,845	1,445,591	761,508	2,237,944
2004	1,307	1,607	38,908	1,693,382	898,319	2,630,609
2005	1,507	1,607	47,358	1,990,573	1,059,896	3,097,827
2006	1,707	1,607	56,201	2,339,906	1,247,781	3,643,887
2007	1,907	1,607	65,444	2,744,329	1,463,518	4,273,290
2008	2,107	1,607	75,097	3,206,873	1,708,784	4,990,755
2009	2,200	1,607	79,777	3,714,190	1,970,095	5,764,062
2010	2,200	1,607	79,777	4,244,642	2,237,779	6,562,198
2011	2,200	1,607	79,777	4,790,718	2,515,070	7,385,564
2012	2,200	1,607	79,777	5,353,269	2,801,959	8,235,004
2013	2,207	1,607	80,186	5,934,257	3,099,706	9,114,148
2014	2,407	1,607	92,375	6,569,592	3,440,530	10,102,500
2015	2,607	1,607	105,088	7,282,062	3,820,078	11,207,230
2016	2,807	1,607	118,342	8,075,810	4,240,677	12,434,830
2017	3,007	1,607	132,156	8,955,290	4,704,662	13,792,110
2018	3,207	1,607	146,549	9,925,090	5,214,569	15,286,210
2019	3,300	1,607	153,515	10,968,110	5,751,899	16,873,520
2020	3,300	1,607	153,515	12,055,080	6,303,742	18,512,340
2021	3,300	1,607	153,515	13,175,510	6,875,084	20,204,110
2022	3,300	1,607	153,515	14,331,040	7,466,125	21,950,680
2023	3,300	1,607	153,515	15,523,180	8,077,278	23,753,980
2024	3,300	1,607	153,515	16,753,310	8,709,174	25,616,010
2025	3,300	1,607	153,515	18,022,780	9,362,552	27,538,850

February 20, 1990

Page 6

JWLarson

DOE/OIP

DOE/OIF THRESHOLD ANALYSIS MODEL -- (ECONOIP2)

Project Name: Workpiece Temperature Analyzer by Acurex						
Description: Raman Spectroscopy Semiconductor Industry						
Year	Cumulative Units	<----- 1st User	Cumulative Developer	Cash Flow (discounted \$000) All Users	-----> DOE+IRS	Nation
1990	0	0	-61	0	-393	-454
1991	0	0	-61	0	-393	-454
1992	0	0	-143	0	-393	-535
1993	7	73	-80	512	-5	427
1994	207	175	2,923	15,165	11,843	29,930
1995	407	272	6,206	48,628	32,689	87,523
1996	607	364	9,493	99,024	61,704	170,220
1997	807	452	12,730	164,656	98,168	275,554
1998	1,007	535	15,896	244,003	141,372	401,271
1999	1,100	615	17,324	329,857	185,559	532,740
2000	1,100	691	17,324	413,933	227,223	658,480
2001	1,100	763	17,324	493,891	267,314	778,528
2002	1,100	831	17,324	570,026	305,798	893,147
2003	1,107	831	17,416	642,866	342,967	1,003,268
2004	1,307	831	19,957	721,000	386,095	1,127,052
2005	1,507	831	22,424	807,747	433,258	1,263,429
2006	1,707	831	24,814	902,161	484,037	1,411,012
2007	1,907	831	27,127	1,003,367	538,025	1,568,519
2008	2,107	831	29,364	1,110,544	594,856	1,734,764
2009	2,200	831	30,368	1,219,388	650,920	1,900,676
2010	2,200	831	30,368	1,324,765	704,097	2,059,230
2011	2,200	831	30,368	1,425,210	755,102	2,210,680
2012	2,200	831	30,368	1,521,021	803,964	2,355,353
2013	2,207	831	30,432	1,612,643	850,918	2,493,993
2014	2,407	831	32,212	1,705,413	900,684	2,638,309
2015	2,607	831	33,931	1,801,740	952,000	2,787,671
2016	2,807	831	35,590	1,901,106	1,004,653	2,941,350
2017	3,007	831	37,191	2,003,050	1,058,435	3,098,677
2018	3,207	831	38,736	2,107,136	1,113,162	3,259,035
2019	3,300	831	39,428	2,210,788	1,166,561	3,416,777
2020	3,300	831	39,428	2,310,807	1,217,339	3,567,574
2021	3,300	831	39,428	2,406,267	1,266,017	3,711,713
2022	3,300	831	39,428	2,497,426	1,312,644	3,849,498
2023	3,300	831	39,428	2,584,506	1,357,286	3,981,220
2024	3,300	831	39,428	2,667,706	1,400,023	4,107,158
2025	3,300	831	39,428	2,747,205	1,440,941	4,227,575

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF FIRST USER

Year	<----- Annual Dollars ----->			Cumulative Dollars	
	Tax Break	Operations	Cash Flow	Actual	Discounted
1993	2,170	142,104	99,601	99,601	73,210
1994	3,720	146,489	150,208	249,809	175,439
1995	2,657	151,013	153,670	403,479	272,277
1996	1,898	155,683	157,580	561,060	364,224
1997	1,582	160,502	162,083	723,143	451,792
1998	1,582	165,476	167,058	890,201	535,363
1999	1,582	170,611	172,192	1,062,393	615,121
2000	0	175,911	175,911	1,238,304	690,566
2001	0	181,384	181,384	1,419,688	762,596
2002	0	187,034	187,034	1,606,721	831,368

February 20, 1990

Page 8

JWLarson

DOE/OIP

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF DEVELOPER

Year	Units Sold	Unit Cost	Annual \$ Cash Flow	Cumulative Dollars Actual	Cumulative Dollars Discounted
1990	0	0	-66,000	-66,000	-61,111
1991	0	0	0	-66,000	-61,111
1992	0	0	-102,907	-168,907	-142,802
1993	7	55,922	84,837	-84,069	-80,444
1994	200	58,049	4,412,770	4,328,700	2,922,813
1995	200	60,259	5,209,525	9,538,224	6,205,696
1996	200	62,553	5,633,790	15,172,020	9,492,957
1997	200	64,936	5,992,348	21,164,370	12,730,430
1998	200	67,410	6,327,224	27,491,590	15,895,620
1999	93	69,980	3,082,701	30,574,290	17,323,510
2000	0	72,649	0	30,574,290	17,323,510
2001	0	75,420	0	30,574,290	17,323,510
2002	0	78,299	0	30,574,290	17,323,510
2003	7	81,288	270,327	30,844,620	17,415,540
2004	200	84,393	8,063,144	38,907,760	19,957,380
2005	200	87,617	8,450,160	47,357,920	22,423,900
2006	200	90,966	8,842,624	56,200,550	24,813,790
2007	200	94,444	9,243,173	65,443,720	27,126,880
2008	200	98,057	9,653,754	75,097,480	29,363,770
2009	93	101,809	4,679,079	79,776,550	30,367,650
2010	0	105,706	0	79,776,550	30,367,650
2011	0	109,754	0	79,776,550	30,367,650
2012	0	113,958	0	79,776,550	30,367,650
2013	7	118,324	409,838	80,186,380	30,432,290
2014	200	122,860	12,188,700	92,375,080	32,212,050
2015	200	127,571	12,712,770	105,087,900	33,930,840
2016	200	132,465	13,254,110	118,342,000	35,590,070
2017	200	137,548	13,813,900	132,155,900	37,191,290
2018	200	142,827	14,393,230	146,549,100	38,736,080
2019	93	148,312	6,966,171	153,515,300	39,428,360
2020	0	154,008	0	153,515,300	39,428,360
2021	0	159,926	0	153,515,300	39,428,360
2022	0	166,073	0	153,515,300	39,428,360
2023	0	172,458	0	153,515,300	39,428,360
2024	0	179,092	0	153,515,300	39,428,360
2025	0	185,982	0	153,515,300	39,428,360

Project Name: Workpiece Temperature Analyzer by Acurex

ECONOMIC PERSPECTIVE OF FEDERAL SECTOR

Year	1st User Tax Break	Developer Tax Break	Annual \$ Cash Flow	Cumulative Dollars Actual	Discounted
1990	0	34,000	-424,000	-424,000	-392,593
1991	0	0	0	-424,000	-392,593
1992	0	5,253	0	-424,000	-392,593
1993	2,170	9,006	527,306	103,306	-5,007
1994	3,720	6,433	17,408,000	17,511,310	11,842,580
1995	2,657	4,595	33,080,710	50,592,010	32,689,030
1996	1,893	3,829	49,725,990	100,318,000	61,703,660
1997	1,582	3,829	67,492,430	167,810,400	98,167,690
1998	1,582	3,829	86,365,850	254,176,300	141,372,100
1999	1,582	0	95,395,260	349,572,600	185,559,000
2000	0	0	97,145,830	446,718,400	227,223,200
2001	0	0	100,955,300	547,673,800	267,313,900
2002	0	0	104,662,500	652,336,300	305,798,000
2003	0	0	109,171,900	761,508,100	342,966,800
2004	0	0	136,810,800	898,318,900	386,095,200
2005	0	0	161,577,200	1,059,896,000	433,258,000
2006	0	0	187,885,000	1,247,781,000	484,037,400
2007	0	0	215,736,800	1,463,518,000	538,025,200
2008	0	0	245,266,600	1,708,784,000	594,856,500
2009	0	0	261,310,500	1,970,095,000	650,920,100
2010	0	0	267,684,300	2,237,779,000	704,097,000
2011	0	0	277,290,600	2,515,070,000	755,102,000
2012	0	0	286,889,300	2,801,959,000	803,963,600
2013	0	0	297,746,600	3,099,705,000	850,917,900
2014	0	0	340,824,100	3,440,530,000	900,684,300
2015	0	0	379,548,200	3,820,078,000	951,999,800
2016	0	0	420,599,200	4,240,677,000	1,004,653,000
2017	0	0	463,985,000	4,704,662,000	1,058,435,000
2018	0	0	509,906,300	5,214,569,000	1,113,162,000
2019	0	0	537,330,400	5,751,899,000	1,166,561,000
2020	0	0	551,842,500	6,303,742,000	1,217,339,000
2021	0	0	571,342,100	6,875,084,000	1,266,017,000
2022	0	0	591,041,600	7,466,125,000	1,312,644,000
2023	0	0	611,152,800	8,077,278,000	1,357,286,000
2024	0	0	631,896,000	8,709,174,000	1,400,023,000
2025	0	0	653,378,000	9,362,552,000	1,440,941,000

APPENDIX B

IMPROVED INFRARED TEMPERATURE MEASUREMENT BY UTILIZATION OF LASER TECHNOLOGY

IMPROVED INFRARED TEMPERATURE MEASUREMENT BY UTILIZATION OF LASER TECHNOLOGY
U. Baustian, E.K. Matthews, Pyrometer Instrument Co., Northvale, NJ U.S.A.

INTRODUCTION -- Radiation pyrometers are widely used for measuring temperatures in scientific and industrial applications where it is inconvenient or impractical to utilize direct contacting sensors. Product contamination, operator safety and sensor durability justify non-contact techniques. This paper discusses an improved measurement technique using a pulsed laser to determine emissivity (ϵ), a critical variable for accurate temperature determination.

THERMAL RADIATION -- All bodies above absolute zero radiate thermal energy. The Stefan-Boltzmann law describes the rate at which a black surface emits this energy per unit area over all possible wavelengths, $W_b = \sigma T^4$ where (W_b) is the total emissive power, and (σ) the Stefan-Boltzmann constant and (T) the temperature of the surface. No perfectly black body exists in nature; non-black surfaces emit radiant energy at a lesser rate, $W = \epsilon W_b$ where (ϵ) is the total hemispherical emissivity of the surface. Emissivity is a function of temperature and various surface characteristics of the material; it is the average emissivity over all wavelengths and directions of the emitted radiant energy. Planck's distribution law describes the radiant energy emitted by a monochromatic black surface around the wavelength (λ).

$$W_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \quad (1)$$

which must be integrated over the range λ_1 to λ_2 to obtain the emitted radiant energy, which for a non-black body is

$$W = \int_{\lambda_1}^{\lambda_2} \epsilon_{\lambda} W_{b\lambda} d\lambda \quad \text{where } C_1 \text{ and } C_2 \text{ are constants.} \quad (2)$$

THE EMISSIVITY PROBLEM -- While pyrometers can detect the energy emitted from a radiating surface, the determination of surface temperature requires also a knowledge of the emissivity (ϵ). Unfortunately, emissivity varies widely for different materials, and for the same material at different temperatures and surface conditions, such as roughness. See TABLE I

<u>TABLE I EXAMPLES</u>	<u>TEMPERATURE °F</u>	<u>EMISSIVITY (ϵ)</u>	<u>EMISSIVITY (ϵ)</u>
Aluminum	338	0.05 polished	0.49 oxidized
Iron	302	0.16 polished	0.98 oxidized

Emissivity changes with temperature; for metals it generally increases and for non-metals it decreases with increasing temperature.

TABLE II	TEMPERATURE °F	EMISSION (E)	TEMPERATURE °F	EMISSION (E)
Tungsten	77	0.03	570	Glass 0.88 ----
	1830	0.16		Quartz ---- 0.90
	3632	0.30	1470	Glass 0.46 ----
	5972	0.40		Quartz ---- 0.68

It is clear that to measure surface temperature it is vital to have direct knowledge of the emissivity. Directionally, the higher the temperature and the lower the emissivity, the greater the error in temperature measurement.

THE IRRADIANCE PROBLEM -- In many applications the temperature of a material within a furnace is required where the walls of the furnace are hotter than the target. If the emissivity of the target is less than unity, then some energy from the walls will be reflected by the target to the measuring pyrometer. The pyrometer will receive more radiance than that emitted solely by the target. The temperature readings will be incorrect due to this irradiance as well as due to the surface emissivity. The error increases with temperature difference (wall minus target temperature) and with decreasing emissivity.

TABLE III Calculated Temperature Error °F Due to Irradiance and Emissivity

EMISSION	WALL TEMPERATURE MINUS TARGET TEMPERATURE °F			
	200	400	600	
0.75	71	176	300	These Errors Are For Target Temperature of 1800 °F
0.85	45	120	219	
0.95	16	46	97	
0.98	6	30	44	

The above errors are too large to be ignored in most applications and the need for an instrument to measure directly emissivity is evident.

INSTRUMENT DESCRIPTION -- The pyrometer (PYROLASER) is a 6.5 lb. battery powered (or on-line) instrument containing all components - laser, electronics, optics, and data logger.

OPTICAL SYSTEM -- The optical system is of single axis configuration with the viewing, focusing, (distance measuring) laser transmit, laser receive and radiance receive, all being coincident through objective lens. The laser transmit energy is introduced via a beam splitter and filters protect the operator from any laser energy. The field of view is 7°; the measuring cone 1/3° with measuring range 6 to 30 ft. For small targets add-on lenses are used.

LASER -- The measuring instrument uses a solid state GaAs diode stack laser with peak power of 25 W. The laser is pulsed to distinguish between reflected laser (AC-signal) and emitted radiance (DC-signal) from the target. The enormous changes of radiant laser power with ambient temperature is roughly compensated for by changing the supply voltage of the storage capacitor. The final precision is achieved by referring the laser return signal to the monitored laser output signal.

The wavelength of 865nm according to tests done by Exxon is a good window through combustion gases. However, for pyrometry this short wavelength limits the lowest measurable temperature to about 600°C. It is desirable to extend the range of the instrument to lower temperatures. Windows are available at 1.25um, 2.2um and 3.7um. Currently, there is a lack of solid state lasers at these wavelengths.

ELECTRONICS -- Besides communicating with the operator via keypad, LCD-display, in-view-finder LED-display, and/or RS232 communication line, the electronics measure the distance to the target by detecting the lens position after focussing manually, to power and fire the laser, to monitor the outgoing signal, and to detect the returning laser signal and the radiance emitted from the target, finally; to calculate from these raw data the temperature and emissivity and to store the results. Figure 1 is a block diagram of the electronics.

APPENDIX C
EQUIPMENT SPECIFICATIONS

- **LASER SPECIFICATIONS**
 - Spectra Physics DCR-11 Nd:YAG lasers
 - Continuum YG-600 Nd:YAG lasers
- **OPTOELECTRONICS**
 - Diode Array Detectors
 - 77200 1/4 m Spectrographs, Slits and Gratings
 - 77225 1/4 m Double Spectrographs
 - Data Acquisition Systems: INSTASPEC II—AT/XT
 - EG&G OMA III System
- **NBS TRACEABLE TEMPERATURE CALIBRATION SOURCES**

LASER SPECIFICATIONS

Spectra Physics DCR-11 Nd:YAG lasers

*New! High Energy
DCR-11-3*

DCR-11 Pulsed Nd:YAG Laser

An Economical and Transportable Pulsed Laser

Features:

- High Energy, High Quality Output
- Compact
- Self-contained Cooling
- Computer Controllable
- Rugged

The Quanta-Ray® DCR-11 is a unique combination of performance, convenience, and economy. It has the high energy, stability, and beam quality that are typical of the diffraction coupled resonator. It comprises three small packages designed for maximum convenience: a remote control that places all operating controls at your fingertips, a power supply so small it can be put where it belongs—out of the way, and a laser head that can be mounted wherever you need it. A computer interface links the laser with automated laboratory or factory environments, and because its cooling and cavity purge systems are self-contained, the

DCR-11 adapts easily to flying, floating, or rolling laboratories.

The DCR-11 was designed for total economy. Its utility requirements are minimal: single phase 208 V service. The stability of the diffraction coupled resonator makes it virtually maintenance free, and a conservative electronic design insures a long operating life.

The DCR-11 continues the Spectra-Physics Quanta-Ray tradition of design excellence and high performance. Indeed, it is the standard bearer for the next generation of pulsed Nd:YAG lasers.

Quanta-Ray®

DCR-11 System Description

Figure 1: In-line optical layout of the DCR-11 results in high performance and high reliability.

DCR-11 Uses the Diffraction Coupled Resonator

The Nd:YAG laser primary wavelength of 1064 nm is well placed in the optical spectrum for nonlinear conversion to both longer and shorter wavelengths. If the commonly used nonlinear processes (harmonic generation, frequency mixing, and Raman scattering) are to produce coherent outputs efficiently, the input beam must have a high degree of spatial coherence as well as high peak power.

The diffraction-coupled resonator (DCR) provides the best means of delivering these essential qualities. Herbst, Komine, and Byer¹ first adapted Siegman's unstable resonator concept to the large volume, high gain Nd:YAG medium. In 1978 Quanta-Ray brought the first commercial laser based on this concept to market. The DCR-11 is the third generation of Quanta-Ray lasers to utilize this convenient, reliable, and cost effective design.

Figure 2 is a schematic of the DCR. The output coupler has a high reflectivity dot in the center of a convex substrate. The laser beam diverges as it is reflected off the dot, and as it builds in intensity, it effectively sweeps the gain from the Nd:YAG medium. The concave high reflector collimates the beam and compensates for thermal lensing of the Nd:YAG rod. As the beam exits the resonator, the light diffracts around the edge of the dot, creating the characteristic "donut" spatial profile.

Figure 2: Diffraction Coupled Resonator

The DCR-11 is an oscillator only, designed as a compact laser that produces high power at a nominal 10 Hz repetition rate with no need for external cooling water. The system comprises three major components: the laser head, its power supply, and a control module. A flexible ten-foot umbilical, which contains all cooling, purge, and power lines connects the power supply and laser head.

Compact Laser Head Saves Valuable Space

Because the DCR-11 laser head contains only the optical resonator, Q-switch driver electronics, and lamp start circuit, it occupies but two square feet of valuable optical benchtop. More space is available for your experiment. Figure 1 shows the laser head interior, with the optional HG-2 harmonic generator attached. This simple, in-line optical layout results in high performance and high reliability.

Unique Q-Switch Provides a Choice of Pulse Widths
The Q-switch has two pulse widths: 8 and 2.5 nsec (nominal). Changing pulse widths

is as simple as changing a single BNC cable connection on the Q-switch driver.

A Marx bank drives the Q-switch efficiently and with minimal time jitter. The DCR-11 uses a combination of a polarizer, quarter-wave plate, and Pockels cell to regulate the loss in the cavity. No voltage is applied to the Pockels cell during the build-up of the population inversion; hold-off is provided by the quarter-wave plate/polarizer combination. To form the light pulse, a high speed, high voltage waveform is applied to the Pockels cell, canceling the effect of the quarter-wave plate. Since the Pockels cell is only biased when the Q-switch is turned on, the DCR-11 is immune to Q-switch leakage caused by changes in ambient temperature; therefore, the Q-switch voltage rarely needs adjustment. Additionally, the short duty cycle of the Pockels cell prolongs the life of this critical component.

Figure 3: Q-switch Assembly and Driver

The Nd:YAG rod is optically pumped by one flash lamp in a close-coupled chamber, whose geometry produces excellent beam quality. The mechanical design of its housing makes lamp replacement quick and simple, without disturbing the optical alignment. Because the DCR-11 uses only one flash lamp, which is simmered for maximum stability and lifetime, the operating cost is greatly reduced.

Assures Clean Optical Path
The entire optical path is enclosed with stainless steel dust tubes, sealed with O-rings, and purged with filtered and dried air. This prevents contamination, eliminates the need for cleaning, and substantially increases the lifetime of the optics. The air purge system is sufficient for most environments, but connections are provided so bottled nitrogen can be used under harsh conditions.

The reliability and high performance of the DCR-11 are due to its diffraction coupled resonator, careful mechanical design, and execution using the highest quality materials. The diffraction coupled resonator extracts maximum energy from the Nd:YAG rod. By virtue of this optical design, the mode quality and energy of the output are insensitive to ordinary perturbations of the optical cavity. The superior mode quality is demonstrated by the highest harmonic conversion efficiencies in the industry.

Quanta-Ray DCR lasers have been installed and operate reliably in numerous applications, both mobile and stationary.

Under The Table
Because the power supply is only 57 cm (22.5 in.) high, it fits under most optical tables, or it can be mounted in a standard 19-inch electronics cabinet.

Figure 4: Compact Power Supply Fits Under Most Optical Tables

The electrical efficiency and well regulated output of the high frequency switching power supply are evidence of its careful design. Because it is well regulated, the stored energy delivered to the flash-lamp is stable to 0.25%.

A single control board drives the supply and monitors its performance. Control circuitry employs a ground plane to minimize inductive effects and electromagnetic interference (EMI). These features and the use of CMOS technology in the timing circuitry make the system virtually immune to noise. In addition, the control board serves as the interface for either the remote control module or a user-supplied computer.

The power supply is completely protected against inadvertent power failures. If one occurs, the system automatically shuts down, preventing damage to the laser.

Figure 5 Power Supply is Rack Mountable

Re: Herbert H. Komine and P. 1/26 1/2 2/26 1/2
~~Re: Re: Komine~~ P. 1/26 1/2 2/26 1/2
 1/26 1/2 2/26 1/2

Remote Control

Figure 6. Remote Control of All Functions

Controls at Your Fingertips for Maximum Convenience

A handy remote module controls all functions, so once the main circuit breaker is closed, you can turn your attention to the experiment. A ten-foot cable connects the module to the power supply, keeping control of lamp energy, pulse repetition rate, and Q-switch firing at your fingertips.

The DCR-11 lets you match the pulse width and timing to your experimental needs. Its controls allow you to choose the Q-switch mode, repetition rate, and whether or not to synchronize firing with external events. The Q-switch mode control allows Q-switched operation, long pulse operation without Q-switch, or external triggering in synchronism with external events. The repetition rate selector permits operation at 10 Hz, synchronous with line voltage for ultra-low electronic jitter. The variable repetition rate offers accurate triggering in synchronism to line frequency for experiments involving measurement of low-frequency signals.

The connectors for external triggering are located on the power supply cabinet. Digital input circuits require standard TTL compatible pulses and are overload protected. The high quality of synchronization outputs assure accurate triggering of external devices. System logic prevents problems caused by an improper turn on sequence.

A toggle switch on the remote control module switches the system between manual and computer control. Since the switch remains active under computer control, you can immediately restore manual control at any time.

The DCR-11 Can be Completely Computer Controlled

Complete automation of your experiment or process is now available. Once the DCR-11 is turned on, a toggle switch on the remote control module transfers control to your laboratory computer, which can then control and monitor all laser functions.

The system tests computer input for valid commands. An inadvertent computer program error will not harm the laser. If a control command is invalid, the DCR-11 sends an error message to the computer and halts optical output. Digital control commands are latched prior to lamp firing, which ensures that control parameters do not change during the firing sequence. All digital communications utilize standard TTL compatible signals and are transmitted via a parallel port for high speed data transfer. All digital input circuits are opto-isolated.

Analog strobing provides the option to sample analog control data during periods of low electrical noise and hold it for subsequent firing of the laser. Analog input circuits employ differential amplifier signal processing to suppress noise pick-up.

DCR-11 System Accessories

HG-2 Harmonic Generator

The HG-2 provides exceptionally efficient nonlinear wavelength conversion of the uniphase, diffraction-limited output beam of the DCR-11. The high energy output generates harmonics efficiently without the aid of beam focusing optics. Consequently, it is ideally suited for many research applications, particularly for pumping tunable dye lasers. In fact, it has ample pump energy to drive multiple dye cells, with sufficient fundamental and harmonic energy remaining for other experimental uses.

KD*P is the material of choice for harmonic generation because of its durability. The crystals in the HG-2, each cut to the proper phase-matching angle, are mounted in a temperature stabilized environment to prevent drifting of the output power. Simple mechanical translation of the crystals changes the wavelength of the output. A single knob adjusts the phase-matching angle for maximum power at each stage of harmonic generation. (The fourth harmonic crystal is not temperature-controlled because it is operated close to its 90 phase matching angle.)

Output beam polarization can be conveniently rotated to any desired orientation. For maximum durability and performance, the HG-2 uses no index-matching fluids. Mechanical crystal mounts prevent contamination problems. Other important HG-2 features include: hermetically sealed optics, a purge port, a dessicant chamber, controlled back reflections.

Performance specifications of the HG-2 are shown in the table on page 7.

Figure 7: HG-2 Harmonic Generator

ELN-2 Electronic Line Narrowing Accessory

The ELN-2, which is used in conjunction with the ICE-1, further reduces the linewidth of the fundamental to less than 0.02 cm^{-1} . This exceptional performance is achieved through a novel method of electro-optic control of the pre-Q-switched gain of the DCR oscillator. The result is laser oscillation confined to a spectral linewidth less than 1/50 of that of the DCR-11 alone. When the ELN-2 is used, the loss in output energy is less than 20%.

Our tests have shown that more than 50% of the output pulses from the DCR are transform limited, i.e., they have a linewidth narrower than 0.002 cm^{-1} (60 MHz). Figure 9 shows both the time and frequency spectra of such a pulse. Those pulses that are not single axial mode in character have higher frequency components that arise from intermode modulation of adjacent $c/2L$ resonator modes. Consequently, the temporal pulse shape is structured, but even these pulses are contained in the overall multiple-pulse linewidth of less than 0.02 cm^{-1} .

Figure 8: Time and Frequency Spectra of a Transform-limited Pulse

ICE-1 Temperature Controlled Intracavity Etalon

The ICE-1 reduces the linewidth of the DCR fundamental to less than 0.2 cm^{-1} . Other etalons that narrow the linewidth even further are available by special order. While the insertion loss of the etalon is less than 10%, a provision is made for easy removal from the intracavity space when your experiment requires maximum power instead of narrow linewidth.

Figure 9: ICE-1 Intracavity Etalon

Additional Quanta-Ray™ Accessories

The DCR-11 is a compatible pump source for the PDL-2 pulsed dye laser, PDA-1 pulsed dye amplifier, RS-1 Raman shifter, and the WEX-1 wavelength extender. For more information about these products, contact your Spectra-Physics sales engineer.

DCR-11 System Performance

Pulse Energy Stability

The histogram in Figure 10 demonstrates the pulse energy stability of the DCR-11 at 1064 nm. Sample data was acquired at 10 Hz over 1.5 hours. More than 58,000 pulses were measured and sorted by a gated integrator/multichannel analyzer apparatus. Over 90% of the pulses were within $\pm 1\%$ of the mean energy, and every pulse was within $\pm 2.3\%$ of the mean.

Figure 10: Histogram of Pulse Energy Stability

Variable Pulse Width

Figures 11 and 12 show the temporal waveforms of the 1064 nm laser pulses measured by a fast photodiode. The horizontal scale is 5 nsec per large division for both photos. Figure 11 depicts the output when the DCR-11 is in the *normal* Q-switched mode, 8 nsec (nominal) pulse width, giving a peak power of 30 MW. Figure 12 shows the output in the *fast* Q-switch mode. Its 2.5 nsec (nominal) pulse width yields peak powers that approach 100 MW. The fast mode is useful in time-resolved spectroscopy, and is recommended for picosecond pulse amplification.

Figure 11: Temporal Profile of Output Pulse in Normal Q-switch Mode

Figure 12: Temporal Profile of Output Pulse in Fast Q-switch Mode

Spatial Mode Pattern

Figure 13 shows the beam intensity pattern of the DCR-11 with its standard optics. The inset is a two-dimensional spatial profile of a typical pulse. The remainder of the figure is an intensity distribution of a single laser pulse. For the latter a linear diode array was precisely placed in the center of the beam one meter from the output coupler. This cross section demonstrates the smooth intensity contour produced by the Quanta-Ray™ diffraction coupled resonator.

Filled-in-beam (FIB) optics are available for applications requiring energy in the center of the beam. Quanta-Ray™ holds the patent for use of unstable resonator optics in solid-state lasers (U.S. patent number 4,310,808).

Figure 13: Spatial Characteristics of a Typical Pulse

Specifications

	1064 nm	532 nm	355 nm	266 nm
Pulse Width ² (nsec)	8-9	6-7	5-6	4-5
Pulse Energy (mJ)				
DCR-11-2	275	135	60	30
DCR-11-3	320	155	70	35
Pulse Energy Stability	±4%	±7%	±10%	±15%
Pulse Repetition Rate	10 Hz optimum, 1-14 Hz range			
Output Pulse Jitter	<0.5 nsec (rms) from sync pulse			
Spatial Mode	Diffraction coupled, uniphase, nearly diffraction limited, 6.4 mm diameter			
Linewidth	<1.0 cm ⁻¹ at 1064 nm <0.2 cm ⁻¹ at 1064 nm with optional ICE-1 <0.02 cm ⁻¹ at 1064 nm with optional ELN-2			
Flashlamp Lifetime	>10 ⁷ pulses			
Linear Polarization				
DCR-11-2	>96% at 1064 nm			
DCR-11-3	>92% at 1064 nm			
Average Power Stability	5% per 10 hr at 1064 nm, 532 nm, or 355 nm with optional HG-2			
Beam Divergence	<0.5 mrad			
Beam Pointing Stability	<0.5 mrad			
Electrical Requirements ³	208 or 220 V (nominal), single phase 10A, 50/60 Hz			
Dimensions:				
Laser Head ⁴	83.8x27.9x26.7 cm (33.00x9.00x10.51 in.)			
Laser Head with HG-2 ⁴	102.2x22.9x26.7 cm (40.25x9.00x10.51 in.)			
Power Supply	49.5x59.1x55.8 cm (19.50x23.25x21.98 in.)			
Weight:				
Laser Head	25 kg (55 lb)			
Power Supply	68 kg (150 lb)			
Umbilical Length	305 cm (10 ft)			

1 Specifications subject to change without notice. Unless stated otherwise, specifications apply to both versions.

2 Short pulse mode, included at no extra cost, reduces pulse width by a factor of about three (to 2.5 nsec at 1064 nm) and reduces pulse energy approximately 10%.

3 Input transformer has taps at 190, 208, 220, and 240 V. Once a tap is chosen, actual input voltage differing by more than ±5% from nominal voltage may affect operation of the laser.

4 Height of laser head given with adjustable feet at the middle of their range (±0.5 cm, ±0.20 in.).

Warranty

Spectra-Physics products are protected by a one-year warranty. All mechanical, electronic, and optical parts and assemblies are unconditionally warranted to be free of defects in workmanship and material for the first year following delivery. This warranty is in lieu of all other warranties, express or implied, and does not cover incidental or consequential loss.

Laser Safety

Spectra-Physics has worked closely with federal agencies to promote the safe use of lasers and has designed this product to comply with the Center for Devices and Radiological Health (CDRH) standards now in effect in the United States.

A CDRH warning logotype, similar to that shown here, appears on each laser to indicate the CDRH classification and to certify that the output power of the laser will not exceed the power level printed on the logotype.

Spectra-Physics

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LASER SPECIFICATIONS

Continuum YG-600 Nd:YAG lasers

Quantel International

YG660 Series Datasheet

(All specifications at 1064nm unless otherwise noted)

Model/rep rate YG660

Energy (mJ)

1064nm

532nm

355nm

266nm¹

Pulsewidth² (ns)

1064nm

532nm

355nm

266nm

Linewidth³(cm⁻¹)

no options

Injection Seeded SLM (SI500)

Divergence⁴ (mrads)

Rod diameter (mm)

Beam pointing stability (μrads)

Jitter⁵ (ns)

Energy stability⁶ (%)

1064nm

532nm

355nm

266nm

Power drift⁷ (%)

1064nm

532nm

355nm

266nm

Beam Spatial Profile (% fit to Gaussian⁸)

Near Field (<1m)

Far Field (∞)

Max. deviation from fitted Gaussian⁹ (±%)

Near Field (<1m)

-10Hz	-20Hz	-30Hz	-50Hz
250	225	210	200
100	80	65	60
45	35	25	20
15	10	8	6
5-7	5-7	6-8	6-8
4-6	4-6	5-7	5-7
4-6	4-6	5-7	5-7
3-5	3-5	4-6	4-6
1.0	1.0	1.0	1.0
0.006	0.006	0.005	0.005
0.5	0.5	0.5	0.6
6	6	6	6
250	250	350	400
0.5	0.5	0.6	0.6
2.5	2.5	3.0	3.0
3.5	3.5	4.5	4.5
4.0	4.0	5.0	5.0
10	10	12	12
3.0	3.0	3.0	3.0
5.0	5.0	6.0	6.0
5.0	5.0	6.0	6.0
N/A	N/A	N/A	N/A
0.70	0.70	0.70	0.70
0.95	0.95	0.90	0.90
30	30	35	35

1 With temperature phase matched quadrupling.

2 Full Width Half Maximum.

3 FWHM 1cm⁻¹=30GHz.

4 Full angle for 86% energy.

5 With respect to external trigger ± 1ns with SI500 option.

6 ± shot-to-shot for 99.9% of pulses.

7 ± from average for 8 hours.

8 A least squares fit to a Gaussian profile. A perfect fit would have a coefficient of 1.

9 At beam center.

12/88

Beam Temporal Profile

Optical Layout

- 1) Rear mirror
- 2) Pockels cell Q-switch
- 3) Quarter-wave plate
- 4) Polarizer
- 5) 6mm Nd:YAG
- 6) Gaussian mirror output coupler
- 7) Turning mirrors
- 8) Harmonic generators
- 9) Dichroic separation

Physical Layout

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Service Requirements
Power: 208V, 3 phase, 12A/phase; 220V/20A single phase
Water: 3-4GPM @ 40-60 PSI

Continuum
FORMERLY QUANTEL INTERNATIONAL

**THE YG 600 SERIES.
HIGH PERFORMANCE
ND:YAG LASERS.**

**Presenting the YG 600 Series:
our third generation of Nd:YAG lasers.**

In succeeding the YG400 and YG500, Quantel's YG600 series draws on more than a dozen years in designing, manufacturing and supporting pulsed Nd:YAG lasers for a host of high power applications.

As the world's only established company dedicated to pulsed solid-state systems, we stand uniquely suited to provide a global customer base with products and service unexcelled.

—Across the board—the highest performance specifications of any commercial Nd:YAG products

—The industry's best warranty and warranty renewal plan

—Revolutionary packaging requiring half the space of competitive products

Standard systems include oscillator only, oscillator/amplifier, and oscillator/dual amplifier systems.

Custom Nd:YAG laser systems are available: Quantel remains the most diversely capable provider of pulsed solid-state lasers in the world.

Pictured are the YG682 and the YG661 (foreground) collectively representing more than 10 man-years of solid state laser development by Quantel International.

We designed the YG 600 Series with the laser end user in mind.

The first thing you'll notice about the YG600 series lasers is their size; they are 50% smaller than competing designs. This tangible difference gives the first indication of a product line completely re-engineered to keep pace with today's changing laboratory environment.

OPTICAL ASSEMBLY

When you remove the top cover and the sealed internal covers you'll notice the absence of steel from the resonator assembly—in its place graphite—stiffer and more stable than Invar assuring unsurpassed long term stability.

The laser heads offer easy access—a quick lock releases the heads from their kinematic mounts for convenient lamp

replacement with no realignment required.

The high efficiency evidenced in our SF600 series heads allows operation at roughly half the pump level of competing products. Reducing the thermal loading on the rods promotes optimum beam quality and harmonic conversion efficiency by minimizing the thermally-induced birefringence—this at repetition rates to 50Hz.

The flashlamps are simmered ensuring

The YG600 design reflects our customers' concern for ease of operation. Easy accessibility within a modular framework results in minimal downtime for both occasional and routine maintenance.

C-20

Beam Spatial Profile

quiet, reproducible pumping with lifetimes rated at 30 million shots. It is noteworthy that our largest standard system (YG682) contains but (3) linear flashlamps while the YG661 generates more than 18 watts at 1064nm from a single xenon lamp.

Rod diameters from 6mm to 9.51 mm are standard within the YG600 series and Quantel offers the option of 12.7mm Nd:YAG amplifiers on a custom basis.

POWER SUPPLY

Notice how the power supply is sized to allow convenient storage beneath a standard optical bench, thus minimizing its encroachment on the laboratory.

The redesigned PFN features fast-switching capacitor charging units designed around industrial grade MOSFETs for high efficiency and uncompromised reliability.

Two control units are offered: one featuring microprocessor logic is fully PC compatible. The optional RB02 remote unit allows user control of all laser parameters including:

- Start/Stop
- Program number of shots in a scan
- Change laser repetition rate
- alter pulse-width
- Tune harmonic generators

These same parameters can be controlled from any PC compatible computer through the RS3232 interface.

For the high energy systems (YG681 and YG682) an electronic power attenuator

The power supply pictured is that of the largest laser within the YG600 family. Control, power, energy storage and cooling are functions of rack mounted subassemblies permitting great flexibility in system design.

allows the user convenient adjustment of the laser output with minimal effect on other laser parameters.

In designing and engineering the YG600 series we have relied heavily on input from the laser user community. Judge for yourself and see if you don't concur that user orientation results in a superior product.

Remote operation via computer is used by more than 50% of our YAG dye customers. With this in mind we provide both the hardware and software, freeing the user to concentrate on the business end of the laser.

From the performance leader, Q-switched lasers which clearly set the standards.

PULSEWIDTH/TEMPORAL PROFILE

Standard YG600 series lasers produce 5-8ns FWHM pulses (see Fig. 3 for SLM profile, see accompanying data sheets for multimode profiles). All YG600 series have the SI500 Injection Seeding system as an option. With this option we will guarantee beat-free temporal profiles on greater than 99.9% of shots. The trace shown is of a YG682-20 producing more than 600mJ at 532nm with injection seeding. The trace shows 200 consecutive pulses and supports temporal jitter of less than 1 ns relative to a trigger input.

LINEWIDTH

Standard YG600 lasers offer linewidth less than 1 cm^{-1} with no options; less than 0.05 cm^{-1} with a fixed etalon LNE option; and less than 2 times transform limited pulses when equipped with the SI500 Injection Seeding system.

SPATIAL CHARACTERISTICS

The resonator employed in all YG600 series systems produces hole-free uniform energy distribution in both the near and far field. Fig. 1 shows a 3 Dimensional portrait of the YG 660 at a range of 5 meters using Beamcode[®]. Amplified systems will exhibit near field diffraction effects as characterized in the product spreads (pages 8-12). Quantel is the only manufacturer of solid-state lasers to use this high resolution diagnostics package as a part of QA, hence we are the only supplier to attach a verifiable figure of merit to beam spatial profiles.

DIVERGENCE/POINTING STABILITY

This same diagnostics package allows us to routinely measure the intrinsic divergence which we will guarantee at less than 2 times the diffraction limit (for all models) and the beam pointing stability as $< 250 \mu \text{ rads}$.

It is noteworthy that our divergence specification is for a gaussian beam rather than an airy disc. In comparing Quantel's beam divergence with those from diffraction coupled resonators, note that the minimum spot size achievable with our systems is smaller by nearly a factor two.

ENERGY

The YG682 delivers more than 1400mJ at 1064nm, more than 750mJ at 532nm for 10 Hz operation. The short pulse-widths, low divergence and uniform near field energy distribution enable us to guarantee more than 280mJ at 355nm using standard KD*P crystals in temperature stabilized housings. All YG600 series lasers ordered with fourth harmonic generators come equipped with temperature phase-matching.

The stability histogram plots energy reproducibility for 10K consecutive shots from a YG682. Our high efficiency pump chambers, all simmered flashlamp circuitry, and Marx-bank driven Q-switches pay tangible dividends.

STABILITY

The histogram of Fig. 2 shows the reproducibility for 10000 shots to be less than $\pm 2.5\%$ for 100% of the shots. We will guarantee this level of performance for all YG600 series systems.

Our specification on drift is less than $\pm 4\%$ for the fundamental output, less than $\pm 5\%$ for the second and third harmonics.

*Beamcode is a registered trademark of Big Sky Software.

The 3-D profile shown is of a YG660 at a range of 8 meters. Demonstrably superior beam quality is indicative of our attention to detail and, moreover, of our sensitivity to the needs and expectations of the laser end user.

Fig. 1

Quantel International's unique Gaussian-coupled resonator: The no-compromise solid state solution.

The heart of any high powered Nd:YAG laser is the oscillator. Developed specifically for injection seeding and now offered as standard on all YG600 series, Quantel's V-ROC resonator has in the short time since its introduction become the standard by which all others must be compared.

Quantel's V-ROC Resonator shown with Injection Seeding

This unique design,^{*1} 2 years in development utilizes a variable reflective output coupler—the Gaussian mirror—to provide no-compromise performance:

- High energy/ High peak power
- Near diffraction limited focusability
- Uniform spatial profile near and far field
- Available with 3 linewidth options including SLM on all models

The V-ROC oscillator though geometrically unstable is made optically stable by the unique properties of the Gaussian mirror.^{*2} As the intra-cavity beam encounters Mg it is transformed upon reflection into a beam with the same TEM₀₀ spatial characteristics but with reduced size. This enables large intra-cavity mode volume therefore efficient energy extraction from what is physically a very short resonator (<50cm). The small size promotes short pulsewidths and excellent day to day stability.

Stability leads to a discussion of mechanics where our "floating" 3 bar resonator

framework has for the YG 680 series been upgraded by substituting graphite for Invar. This design allows for thermal expansion without applying mechanical constraints to the graphite rods which offer increased rigidity over their Invar counterparts.

A Marx bank drives the Pockels cell

Q-switch on all YG600 series models. This is a zero Volt DC bias trigger which assures long life-time and crisp operation with <500ps jitter for unseeded lasers, <1ns

jitter when injection seeded. Hold-off against free-running (conventional mode lasing) is provided by a quarter-wave plate in series with high contrast polarizers.

Compare ours to other designs delivering low order beams at the expense of beam spatial uniformity or uniform beams which are in fact multimode. See if you don't agree—there's no comparison to the no compromise solution. V-ROC...only from Quantel where a strong commitment to R&D combined with the company's

Fig. 3

Where other suppliers seem content with dated technology, reluctant to incorporate change—Quantel prides itself in its role as the industry leader.

clear focus on solid-state lasers gives us a decisive lead in Nd:YAG laser design.

With evermore Q-switched applications requiring narrow bandwidth and/or beat-free temporal profile, we have seen a steady increase in the percentage of lasers ordered with our SI500 injection seeding system. Quantel is by far the leading supplier of injection seeded Nd:YAGs and here our system engineering concept is clearly in evidence. The diode pumped seeder^(*3) is built into the optical head assembly on all YG600 models—not tacked on as an afterthought. The user has the option of operating SLM or multimode with the flip of a switch; when seeded the CW output is coupled into the Q-switched resonator via the polarizer protected from feedback by a permanent magnet Faraday isolator integral to the unit. With the SI500 option Quantel guarantees greater than 99.9% of shots to be single longitudinal mode. Compare this to performance levels obtained through other electronic line narrowing techniques and you'll understand why we regard "seeding" as breakthrough technology.

*1 A. E. Siegman Lasers pp. 836-837.

*2 A. Caprara, S. Butcher, R. Aubert "Injection seeding of an Nd:YAG laser utilizing a radially variable reflectivity output coupler."

*3 Quantel uses diode pumped injection seeders from Lighwave Electronics.

Throughout the YG600 series we have built on our considerable experience. Where new designs and/or new materials were chosen the selection follows extensive testing under varied operating conditions.

The YG 680 Series delivers the highest performance of any commercially available Nd:YAG laser.

To fully appreciate the YG680 performance, consider the following:

—For the last 10 years we have offered 20% more energy than the nearest rival. With the advent of the YG680 series our lead increases to nearly 50% —we guarantee $E > 750\text{mJ}$ at 532nm for the YG682 at 10 Hz.

—The YG682 at 20 Hz delivers more than 12W at 532nm—again 50% more than the closest competitor.

—Injection seeded single longitudinal mode operation is an option on every laser in the YG680 series with no derating in beam spatial profile or energy.

STANDARD FEATURES

—Quantel's exclusive V-ROC™ resonator delivering high peak power, superior beam quality and near diffraction-limited divergence.

—Quantel's SF600 series laser heads—the industry's most efficient allowing low

Pictured is a YG682 with the SI500 injection seeding option. For applications requiring even higher energy we offer 10Hz Q-switched lasers on a custom basis with guaranteed 1 J at 532nm; 400 mJ at 355nm. For higher average power systems ask your Quantel sales engineer for information on our YG1000 series of Q-switched Nd:YAGs delivering up to 30W at 532nm at repetition rates from 540-1080Hz.

energy pumping for optimum harmonic conversion

—Revolutionary packaging of both the optical head and power supply are roughly half the size of competing designs

—Electronic power attenuation

—Sealed inner covers which avoid the use of beam tubes

OPTIONAL ACCESSORIES

—Temperature stabilized second and third harmonic generators with temperature phase-matched frequency quadrupling

The profile shows the frequency doubled output of a YG682 at a range of 1 meter. Such a beam becomes purely Gaussian in the far-field.

—Motorized translation stages for automatic wavelength selection

—Beam access packages availing multiple dye laser pumping schemes

—Parallel mode-locked operation offering peak powers >1 Gigawatt

The YG 660 Series guarantees big laser performance at a small laser price.

The YG660 series represents a new dimension in high powered Nd:YAG design: single head, single flashlamp lasers with performance and features which belie their compact size and price. The optical head measures less than 34" in length and weighs less than 35 lbs. The power supply which has the option of air cooling can operate from a standard 110 volt source making the YG660-10 ideal for OEM applications. All YG660 models are single flashlamp designs minimizing the cost of extensive operation. The YG660

series feature a new mechanical design concept wherein stabilization is maintained by the optical bench assembly: honeycomb aluminum with a graphite skin. A positive airflow is maintained keeping the optical surfaces clean even outside the laboratory environment. For performance start with:

- Guaranteed energy $>300\text{mJ}$ at 532nm for 10 Hz operation
- Guaranteed average power of nearly 6 Watts at 532nm for 30Hz operation

Due to its small size, frugal power consumption and the excellent low frequency damping characteristics exhibited by the graphite bench, the YG660 is ideally suited for industrial, mobile or airborne environments.

- Injection seeded SLM performance available on all models
- Quantel's V-ROC™ resonator providing uniform uniphase beam

The YG661 guarantees the lowest cost per photon of any pulsed Nd:YAG laser available. When coupled with our TDL line of tunable dye lasers we offer to the scientific community a high power tunable package with a twist: economy.

The beam profile is of a YG660 at a range of five meters.

OPTIONAL ACCESSORIES

- Temperature stabilized second and third harmonic generators with temperature phase-matched frequency quadrupling
- High contrast dichroic separation packages
- RB02 Remote Box plus RS232 interface.

Industry leading lasers from a company known for its after-sales support.

In an industry where large faceless corporations are becoming the rule, our people keep Quantel the exception.

With any YG600 series system comes Quantel's commitment to customer satisfaction: a commitment to go the extra mile to insure a product which, beyond meeting specifications, genuinely satisfies the customer requirements.

Our team of engineers and technicians has the expertise to design, manufacture and service Nd:YAG lasers which take complete advantage of current advances in crystal growth, laser diode, electro-optic and optical coating technologies. This ability to respond quickly to the marketplace, maintaining at all times a family of products which is contemporary with the support industries is what makes Quantel unique.

From our 45,000 square foot Santa Clara facility come 100% U.S. made products assembled, tested Q'ed, and documented by our team of in-house laser professionals. It is noteworthy that in an industry often plagued by lackluster performance Quantel's growth has exceeded 25% for the last 10 consecutive years—growth directly attributable to our people and their efforts.

Whether you're a first time laser user or a seasoned laser jock, our sales engineers and product managers will work closely with you in defining the YG600 series model plus options which, while tailored to your present application, retains the flexibility to address quite different needs of research to come.

A key element to Quantel's continued success is our service commitment—a commitment which begins with the installation and continues through the lifetime of the laser—often through several generations of operators. All of our highly trained service technicians are specialists in solid-state lasers—their attention is not divided between ion or excimer technologies.

All Quantel YG600 series lasers come backed by the industry's best warranty: 1 year on the optical head assembly and 18 months on the power supply.

At Quantel we have spent 12 years developing a reputation for leading edge performance. We firmly believe the YG600 series to be the finest line of high power Nd:YAG lasers available and we invite comparisons with any commercially available products. To learn more about the YG600 family or to learn how a Q-switched Nd:YAG addresses your laser requirements, call us today. See why we've become the #1 provider of high power pulsed lasers in all the world.

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OPTOELECTRONICS SYSTEMS

- OPTOELECTRONICS
 - Diode Array Detectors
 - 77200 1/4 m Spectrographs, Slits and Gratings
 - 77225 1/4 m Double Spectrographs
 - Data Acquisition Systems: INSTASPEC II—AT/XT
 - EG&G OMA III System

Oriel InstaSpec™ II - DIODE ARRAY DETECTOR

FEATURES

- Arrays with 512 or 1024 detector elements
- Fast 5 millisecond scan time
- Captures pulsed light exposures
- Calibratable for absolute energy radiometry
- Detector attaches to a modified Nikon camera
- Full graphics capabilities

ADVANTAGES

- A day's research done in minutes
- Friendly complete software for instant use
- No problems from mechanical scanning
- Total control using standard computers
- Versatile and adaptable to many applications
- Data files compatible with Lotus 1-2-3®

77400 MultiSpec, InstaSpec™ Head and 77110 InstaSpec™ Controller.

Photodiode arrays are versatile and powerful detectors for many applications. Though the arrays are simple in concept, extensive engineering of support hardware and software is required to get the best results from these detectors. Our new InstaSpec™ II System provides both the hardware and software that's easy-to-use and adaptable, in a single economic package.

InstaSpec™ is a multi-element detector for use in spectroscopy and image analysis. InstaSpec™ simplifies many experiments and monitoring processes.

A Photodiode array with 1024 25 μ m x 2.5 mm elements.

APPLICATIONS

- Spectroradiometry, and fluorescence
- Beam profiling of pulsed or continuous sources
- Light source analysis
- Detection of ultrashort flashes
- Time resolved spectroscopy
- Interference fringe measurements
- Tracking of position, alignment and focus
- Spectrophotometric process control

A complete InstaSpec™ system consists of:

- Diode Array Detector Head
- Controller
- Optional Spectrograph (for spectroscopy)
- Interface Card
- Computer
- Graphics Card and Monitor
- Software
- Printer and Plotter
- Mounting Flange

DRIEL INSTASPEC™ II - DIODE ARRAYS

Fig. 1 Photodiode array construction.

A photodiode array is a line of silicon detectors constructed as an integrated circuit. Light generates a photocurrent and causes a charge to accumulate in the series of diodes. Switching transistors sequentially read and reset the charge from each diode element, and direct the output to a single output line. The output charges are converted to a voltage, amplified, and converted by an analog to digital converter into a series of digitized readings for computer processing. The cycle time for the scan of the diodes, along with the light intensity, governs the charge stored before it is read. The scan rate is determined by clock pulses which are fed to the array circuit by an external controller. Scan rates for spectroscopic applications are typically 5 ms to 100 ms to read an entire array.

MULTICHANNEL DEVICES

The most important advantage of diode arrays over other detectors such as photomultiplier tubes is the multichannel nature of the arrays. Many hundreds of data points (channels, wavelengths) can be recorded in one single reading. As a consequence, diode arrays are excellent for taking a series of scans of a changing optical source. A good practical example of this is in spectrophotometry, where a spectrograph/diode array combination can replace a motor-driven scanning monochromator and photomultiplier tube, and take entire spectra in a few milliseconds.

Fig. 2 Spectrum of Helium Neon plasma.

EXPOSURE TIMES

Diode arrays and photomultiplier tubes are fundamentally different in their method of light measurement. Photomultiplier tubes measure radiant flux (power), i.e. watts, while diode arrays measure radiant energy, i.e. joules. The diode elements accumulate charge generated by the arrival of photons, and the charge is proportional to the total radiant energy. For constant light sources, this is the product of the radiant flux and exposure time. In essence a diode array acts as an electronic photographic film, and the exposure time is adjusted to obtain the best signal.

SPECTRAL RESPONSE

The spectral response of a silicon diode array is that of silicon, and is from about 180 nm to 1100 nm, which is better than the majority of photomultiplier tubes. The sensitivity at 200 nm can be about 20% of the peak response, between 600 and 800 nm.

Fig. 3 Diode output charge vs. light energy.

Fig. 4 Photodiode array spectral response.

Oriel 1/4 METER MONOCHROMATOR/SPECTROGRAPH

77200 1/4 m Monochromator.

- Operates as a monochromator or spectrograph
- 0.1 nm resolution with a 1200 l/mm grating
- Wide spectral range - 200 nm to 24 μ m with interchangeable gratings
- Fast F/4.4 optics
- Selectable lateral or parallel slit configurations
- Low stray light
- Fully supported stepper drive and data acquisition options
- Low cost scanning drives
- Sturdy monolithic construction

Performance and versatility make this 1/4 meter Monochromator/Spectrograph an excellent choice for moderate resolution spectroscopy. Use it as a traditional monochromator with input and output slits, or as a spectrograph. It has a flat output plane for instruments such as InstaSpec[™], our diode array detector.

Resolution in the visible is 0.1 nm with a 1200 line/mm grating. The spectral range is 200 nm to 24 microns with interchangeable gratings.

The flanged input and output slits accept any of our 1.5 Inch Series of Accessories. This provides the 77200 with a family of detector, source and beam handling accessories. Use the 77200 with our Light Sources or Universal Monochromator Illuminator for monochromatic illumination. Choose from a range of optics, including fiber optics, to best transfer the light between the source, the 77200, and your sample. Mount the InstaSpec[™] on the output, and select from an array of gratings to capture spectra very quickly.

APPLICATIONS

- Monochromatic irradiation or illumination
- Spectroscopic studies
- Radiometry and photometry
- Transmission, reflection, and absorption
- Emission and fluorescence
- Lasers and fiber optic studies

We offer a comprehensive range of optical, mechanical, and motorized accessories to simplify the use of the 77200. In the next several pages we describe:

Single 77200 Monochromator	213
Gratings	215
Slits	216
Single Monochromator Mounting	218
Double Monochromator	219
Double Monochromator Mounting	221
Ordering Information	222

Selected Related Products:

Universal Monochromator Illuminator	167
Input Accessories	243
Focusing Lens Assemblies	244
Fiber Optic Accessories	248
Monochromator Reflectors	251
Filters for Monochromators	252
Stepper Wavelength Drives	281
Synchronous Wavelength Drives	283
Wavelength Readout	283

C-37

LATERAL OR PARALLEL CONFIGURATIONS

The 77200's design allows the input and output ports to be changed from a lateral (in-line) to a parallel (side by side) configuration. Fig. 2 shows the two configurations. Simply rotate the pair of folding mirrors (M3 and M4), and block the unused ports with the light tight caps. The two mirror positions are precisely preset. The parallel configuration can save space because input and output accessories mount side by side.

For some applications, you may wish to combine the two configurations by using a parallel port and a lateral port

FLAT FIELD FOR ARRAYS OR CAMERAS

The 77200 functions both as a monochromator and spectrograph. As with our MultiSpec[™], the optical arrangement produces a flat output field. Remove the exit slit and you have a 1.0 inch (25.4 mm) flat output plane for diode arrays, film cameras, vidicons, and IR converters.

InstaSpec[™], our diode array detector described on pages 347 to 359, fits on the parallel output port to record and display spectra in the 200 to 1100 nm range. See Fig. 1 below, for a typical wavelength scan taken in 5 milliseconds.

Fig. 1 Scan of 6035 Hg(Ar) Lamp taken with InstaSpec[™] and 77200 Spectrograph. A 1200 l/mm, 500 nm Blaze Grating was used.

OPTICAL CONFIGURATION

The 77200 utilizes an in-plane asymmetrical Czerny-Turner configuration, illustrated in Fig. 2. Placing the entrance and exit slits asymmetrically, with respect to the grating, allows the zero coma point to be located within the working wavelength range. This results in minimal aberration throughout the range.

A baffle is supplied to mask off the center of the grating to block re-entrant spectra.

HIGH EFFICIENCY

The dispersion is twice that of our 77250 1/8 meter Monochromator. For any slit/grating combination in the 1/8 meter, the 1/4 meter uses a slit twice as wide to achieve the same bandpass. The fixed slits in the 1/4 meter are 18 mm high. This large slit area results in better throughput.

See pages 230 to 233 for comments on throughput and performance data.

Fig. 2 Lateral and parallel configurations of the 77200.

STRAY LIGHT

Many factors influence the stray light at the output. The grating used, the operating wavelength and the scattering of light inside the monochromator are usually the most important. The stray light signal also depends strongly on such external factors as the intensity and spectral distribution of the input source and the detector's spectral response. The superb stray light rejection of the 77200 is shown for two modes where stray light can be a significant problem: UV measurements, and close to an intense monochromatic line.

- With a 60055 Deuterium Source, a 77345 Photomultiplier (S-5 response) and a 77231 Holographic Grating blazed at 200 nm, measurements were made with and without a glass plate in the beam. The glass blocks all radiation below 320 nm. At 250 nm, the stray light signal was only 0.14% of the unblocked signal.
- With a Helium Neon laser at 632.8 nm focused on the slit in an F/5 cone, the average of the stray radiation measurements at 612.8 nm and 652.8 nm was 0.0012% of the 632.8 reading, when using the 77231 Grating.

WAVELENGTH DRIVE AND READOUT

We use a sine bar linkage to drive the grating. The sine drive provides a linear dependence of wavelength on lead screw advance. This lead screw can be manually driven by an external hand crank, or by optional stepper motors. The hand crank is outside the path of the beam, regardless of the configuration of the slits. A convenient, five digit wavelength counter on top of the instrument displays the wavelength in nanometers when a 1200 l/mm grating is used. The first counter is marked with 0.02 nm graduations to let you read the wavelength to 0.01 nm. For gratings with different groove density multiply the reading by the appropriate wavelength dial factor found in Table 1 on page 215.

INERT GAS PURGE

These monochromators have a hose fitting to allow you to purge the housing with dry nitrogen and obtain transmission down to 175 nm. See the atmospheric transmittance curve on page 164.

Oriel SPECIFICATIONS

For 1/4 m Monochromator/Spectrograph

SPECIFICATIONS

Range:

200 nm to 24 μ m with interchangeable gratings
175 nm with dry nitrogen purge
0.1 nm with 1200 l/mm grating

Minimum Bandpass: (10 μ m slit - 1st order)

1.6 nm/mm for 2400 l/mm grating
3.2 nm/mm for 1200 l/mm grating at 500 nm

Reciprocal Dispersion:

Focal Length:

250 mm

Effective Aperture:

F/4.4

Wavelength Readout:

5 digit counter with index marks every 0.02 nm

Wavelength Dial Range:

0-1200 nm with 1200 l/mm grating

Wavelength Dial Accuracy:

1 nm with 1200 l/mm grating

Wavelength Precision:

The wavelength is resettable to 0.1 nm from either direction

Re-entrant Spectra:

None when used with supplied baffle

Dimensions:

7.3 x 10.75 x 5.75 inches
(185 x 273 x 146 mm)

Weight:

12 lb (5.5 kg)

MOTORIZED WAVELENGTH DRIVES AND ACCESSORIES

Digital Stepper Motor Drives

Two internally mounted stepper motor drives are available for bidirectional scanning or wavelength selection. See page 281 for complete details. See pages 285 to 288 for information on the 78200 Drive Controller, and pages 289 to 293 for computer interfacing.

Fixed Speed Scanning Drives

For fixed speed and unidirectional scanning, our more economical synchronous motors are an excellent choice. See page 283 for information.

Analog Wavelength Readout

The 77246 Wavelength Readout can be used with both types of wavelength drives. It puts out a precise DC signal, proportional to wavelength setting. See page 283 for details.

Fig. 3 Wavelength scan.

Fig. 4 77200 1/4 m Monochromator.

Oriel GRATINGS

For 1/4 m Monochromator/Spectrograph

The combination of grating and slits define the bandpass, spectral range, and power throughput of a monochromator. The input slit and grating are the major factors in determining the resolution of the 77200 in the spectrograph mode. An attractive feature of the 77200 is the ease with which you can insert and remove these components.

These 50 x 50 mm replicated gratings come prealigned in a protective frame. The frame has a tab so you can hold the grating without touching its surface. Simply remove the lid of the monochromator, and slip the grating into place.

Fig. 1 shows the relative efficiency of our 77232 and 77233 gratings for unpolarized light. Choose the holographic gratings for lowest stray light and where spectral ghosts could be mistaken for results!

MONOCHROMATORS

Table 1 Grating Specifications

Model No.	Blaze Wavelength	Type	Groove Spacing (l/mm)	Wavelength Dial and Bandwidth Factor	Reciprocal Dispersion (nm/mm)	Wavelength Region		Wavelength Span at 500 nm when 77200 is used as a spectrograph
						Primary	Usable	
77230	270 nm	Holographic	2400	X0.5	1.6	175-500 nm	150-600 nm	41 nm
77231	200 nm	Holographic	1200	X1	3.2	180-700 nm	180-700 nm	82 nm
77232	280 nm	Ruled	1200	X1	3.2	200-375 nm	175-700 nm	82 nm
77233	500 nm	Ruled	1200	X1	3.2	330-750 nm	300-1000 nm	82 nm
77234	1.0 μ m	Ruled	600	X2	6.4	0.67-1.5 μ m	0.6-2.0 μ m	164 nm
77235	2.0 μ m	Ruled	300	X4	12.8	1.33-3.0 μ m	1.2-4.0 μ m	N/A
77236	4.0 μ m	Ruled	150	X8	25.6	2.67-6.0 μ m	2.4-8.0 μ m	N/A
77237	8.0 μ m	Ruled	75	X16	51.2	5.33-12.0 μ m	4.8-16 μ m	N/A
77238	12.0 μ m	Ruled	50	X24	76.8	3.0-18.0 μ m	7.2-24 μ m	N/A
77239	200 nm	Ruled	600	X2	6.4	180-300 nm	175-500 nm	164 nm
77240	550 nm	Ruled	400	X3	9.6	360-600 nm	300-900 nm	246 nm
77241	730 nm	Ruled	200	X6	19.2	485-1100 nm	400-1200 nm	492 nm
77242	800 nm	Ruled	50	X8	25.6	530-1200 nm	450-1300 nm	655 nm
77243	750 nm	Ruled	600	X2	6.4	500-1125 nm	400-1500 nm	164 nm

Fig. 1 Efficiency of 1200 l/mm grating relative to aluminum coating.

C-40

Oriel 1/4 M MONOCHROMATOR/SPECTROGRAPH SLITS

We offer three types of slit assemblies:

- Variable Slits-continuously adjustable slit width.
- Multiple Fixed Slit Wheel with 8 slit widths.
- Single Fixed Slit Assembly with choice of 8 slit widths.

Each slit type has 1.5 Inch Series flanges to support our range of 1.5 Inch Series accessories, sources, and detectors.

CHOOSING A SLIT

The entrance and exit slits of a monochromator determine the throughput and bandpass. For convenience we list here the major considerations in choosing a slit.

Three of the most common applications of the 77200 are:

1. As a source monochromator.

The desired bandpass often determines the slit width. The bandpass of the transmitted light is approximated by:

Slit width X Reciprocal dispersion for an input with a continuous spectrum such as light from a xenon or QTH lamp.

Closing the slits reduces the bandpass and the power through the monochromator.

2. A detector monochromator for spectral analysis.

The most important step is deciding the largest bandpass which gives the spectral information required. Refer to Fig. 1. Work with the largest bandpass you can get away with for maximum signal. A wide slit means a large bandpass, which has the additional benefit of simpler coupling of a source into the monochromator.

3. With InstaSpec™ or other array detector.

System resolution is best with a smaller slit width, down to about twice the element width.

Fig. 1 Transmitted power for broadband and uniform source which overfills the 3.16 mm slits varies as the square of the slit width.

VARIABLE SLIT ASSEMBLY

The 77248 Variable Slit Assembly offers the most flexibility. Slit width is continuously adjustable from 20 μ m to 3.2 mm. The corresponding bandpass ranges from 0.13 nm to 10 nm when used with a 1200 l/mm grating. Multiply by the Grating Factor for other gratings. The adjustment wheel has index markings every 0.1 mm. The slit height is also adjustable. A sliding wedge aperture varies the height from 1 mm to 12 mm.

A flange on the outside of this slit assembly lets you mount any of the Oriel 1.5 inch Series accessories described on pages 155 to 157 on Oriel Detectors.

77249 Multiple Fixed Slit.

MULTIPLE FIXED SLIT

The 77249 consists of 8 fixed slits on a wheel. The slit widths are listed below. The wheel has a positive detent for exact repeatability of slit position. A sliding wedge adjusts the slit height from 1 to 12 mm.

The table below lists the approximate bandpass of these slits when used with a 1200 l/mm grating. Multiply by the Grating Factor for other gratings.

The 77249 has a flange to support any of our 1.5 Inch Series Accessories described on pages 155 to 157.

Approximate Bandpass of Multiple Fixed Slits when used with a 1200 l/mm grating.

Slit Position	Width (um)	Bandpass (nm)
1	50	0.25
2	120	0.5
3	280	1
4	600	2
5	1240	4
6	760	2.5
7	1560	5
8	3160	10

FIBER OPTIC SLIT REPLACEMENTS

We offer single fibers and fiber optic bundles with rectangular outputs that can act as Monochromator Slits. See page 248 for details.

77210 Fixed Slit Holder with Slits.

FIXED SLITS

Fixed slits are a good choice when only one or two widths are required. Eleven different precision slits, each separately mounted in a machined slide, are available for quick and repeatable insertion into the 77210 Fixed Slit Holder.

These slits cover a range from 10 um to 6.32 mm in width. The table below lists the approximate bandpass of these slits when used with a 1200 l/mm grating.

The 77210 Fixed Slit Holder accepts 1.5 Inch Series Accessories.

Approximate Bandpass of Multiple Fixed Slits when used with a 1200 l/mm grating.

Model No.	Width (um)	Height (mm)	Bandpass (nm) (at 500 nm)
77222	10	2	0.1
77220	25	3	0.15
77219	50	6	0.25
77218	120	18*	0.5
77217	280	18*	1
77216	600	18*	2
77215	760	18*	2.5
77214	1240	18*	4
77213	1560	18*	5
77212	3160	18*	10
77211	6320	18*	20

* Since these slits are 18 mm high, more throughput is available from extended sources and PhotoMax™ with higher power lamps.

INPUT SLIT FOR 77200 USED AS A SPECTROGRAPH

When using the 77200 as a spectrograph only one slit assembly is needed. Choose the type of slit assembly. Variable, Multiple Fixed, or Fixed for your application.

Oriel 1/4 M MONOCHROMATOR/SPECTROGRAPH

Mounting Information

The 77200 weighs 12 lbs. (5.5 kg). For some applications, particularly those where the critical optical components are supported off the 77200, no fastening is necessary. We supply four instrument feet with the 77200. These are for leveling and provide 0.63 inch (16 mm) height adjustment.

BOTTOM-COUPLED RAIL

The 77252 Special Table Rail may be bolted to the bottom of the monochromator to facilitate bringing light to or from the instrument. It is very convenient when the 77200 is used on a desktop or standard wooden lab bench.

The center of the rail lies under either one parallel port or the two lateral ports. Use two rails to mount accessories at both parallel ports.

The 77252 is 24.0 inches (610 mm) long. It extends outward from the monochromator so carriers can be placed on it to hold optical components in line with the ports. Order carriers and optical mounts from Volume I.

MOUNTING TO A RAIL OR BENCH

The Bottom Coupled Rail described above attaches directly to the monochromator in a fixed position, and components translate along it. To translate the monochromator along a table rail or optical bench order the 77292 Set of Adapter Bars and four 11641 Narrow Carriers. You will need two rails separated by 8 inches when using the lateral ports and 4 inches when using the parallel ports. Order carriers and rails from Volume I.

MOUNTING TO AN OPTICAL TABLE

Fixing the 77200 in place can save a lot of frustration when working with extended optical arrangements. Use the mounting holes on the monochromator base to bolt it directly to optical tables with either 1.0 inch or 25 mm hole spacing. The optical height is 4.0 inches (102 mm). For other optical heights use the precision spacers on page 211.

Fig. 1 Monochromator with 77252 Table Rail mounted along parallel port.

ROD MOUNTING

Four tapped holes in the underside of the 77200 accept Oriel Bench Rods. You should use four rods if you wish to rod mount this device. The minimum practical optical height will be about 7.0 inches (178 mm). (See Fig. 2.)

Fig. 2 Monochromator rod mounted to optical table.

MOUNTING WITH THE MONOCHROMATOR ILLUMINATOR

The 7345 Monochromator Illuminator on page 167 is a dual source illuminator. Using two sources is often necessary to extend the usable spectral range. The 77475 Mounting Kit mounts the 7345 and 77200 together. The Illuminator is matched to the 77200.

MOUNTING WITH PHOTOMAX

See pages 234-241 for performance and hardware for use of the 77200 with the efficient PhotoMax™ Lamp Housing.

Oriel 1/4 M DOUBLE MONOCHROMATOR

MONOCHROMATORS

The outstanding resolution and the low stray light of the 1/4 m monochromator are further enhanced by combining two 77200 Monochromators into a double monochromator. The stray light of the combination is negligible while the bandwidth is halved. (See Fig. 1.) For a given slit width the throughput is, of course, reduced. Usually the stray light performance is the motivation for going to the double monochromator. In this case it is often possible to compensate for the reduced throughput by increasing the slit width to admit more of the source image. Opening the slits also transmits more radiation for a source with a bandwidth wider than the instrument bandpass.

THE 77225 DOUBLE MONOCHROMATOR

The 77225 Double Monochromator consists of two 77200 Monochromators in optical tandem. A single center slit serves as the lateral exit slit of one and the lateral entrance slit of the other. The dispersions of the two monochromators are added. A mechanical assembly couples the two units without light leakage, and holds the common center slit. The wavelength drive shafts are coupled together so a single crank or motor drives both units. A common base plate holds the monochromators in alignment.

Fig. 1 Ratio of measured output signal to the peak signal as the wavelength of the 77225 Double Monochromator was changed from 617 to 648 nm with a HeNe laser at 632.8 nm both focused into the monochromator at F/5. Both monochromators were fitted with 77233 1200 l/mm gratings blazed at 500 nm. The performance is even better with 77231 holographic gratings.

Oriel 1/4 M DOUBLE MONOCHROMATOR MOUNTING

PRODUCT NUMBERS AND WHAT YOU SHOULD ORDER

The 77225 Double Monochromator consists of two 77200 1/4 Meter Monochromators aligned on a base plate with a center slit assembly. In addition to the 77225 you should order two identical gratings, two slit assemblies for the entrance and exit ports and a fixed slit for the center port. Select holographic gratings for the very best stray light performance. The center slit should be at least 0.5 mm wider than the entrance and exit slits; if you choose variable or multiple slit assemblies for the input and output, then order several fixed slits for the center.

If you already have one or two 77200s and want to set up the double monochromator, order the 77226 Conversion Kit. This has all that is required to convert two single 77200s (with identical gratings) to the 77225 except for the center slit. Order a center slit appropriate to your input and output slits.

STRAY LIGHT

The second monochromator accepts the total output of the first, including the stray light. It then passes the desired waveband and rejects the input stray light component. Any light which enters the second monochromator can, of course, be scattered and become stray light. Restrict the width of the center slit to no more than 0.5 mm larger than the other slits to minimize unwanted radiation passing into the second monochromator.

We have measured the stray light of the 77225 Double Monochromator for the two meaningful conditions described on page 213 for the 77200 Single Monochromator.

- Using 77232 Holographic Gratings, 1 nm bandpass, a 6312 Deuterium Lamp, the 77345 Photomultiplier, and a glass filter, the stray light was $5 \times 10^{-5}\%$ of the signal for the 77225. This contrasts with the 0.14% for the single 77200.
- Using 77233 Holographic Gratings, and a HeNe laser at 632.8 nm, the stray light at 622.8 and 642.8 nm was $2 \times 10^{-5}\%$ of the signal.

DOUBLE MONOCHROMATOR WITH INSTASPEC

The 77225 Double Monochromator can be used with InstaSpec™, our diode array, with significant reduction of stray light. Since the dispersion is doubled, the spectral range covered is only half that obtained with a single monochromator using the same grating.

When using the 77225 with InstaSpec™, a special center slit is required. The 77207 slit is 0.6 inches (15 mm) wide by 0.15 inches (4 mm) high.

77225 1/4 m Double Monochromator mounted to an optical table.

Dimensions in inches (mm).

Fig. 2 77225 1/4 m Double Monochromator.

You can use the model 77225 1/4 m Double Monochromator as a stand-alone unit. The four instrument feet allow the optical height to be adjusted from 0.5 to 1.13 inches (13 to 29 mm). Or, mount the 77225 directly to optical tables, TechBases, or carriers in a fixed height position.

FIXED HEIGHT MOUNTING To Optical Table or TechBase

You can fix the 77225 to optical tables with holes on 1.0 inch or 25 mm centers. The base plate has separate slots for inch and metric hole patterns. The slots allow 1.0 inch (25 mm) adjustment along the parallel ports. The optical height is 4.4 inches (112 mm) above the table surface. Use spacers from page 211 to raise the height. (See Fig. 1 below.)

Fig. 1 77225 Double Monochromator shown in lateral (in-line) configuration mounted to table with spacers.

To Optical Benches or Rails

To mount the 77225 Double Monochromator to benches or rails order the 77293 Set of Adapter Bars, two standard benches or rails (24.0 inches (610 mm) in length or longer), and four 11641 Narrow Carriers.

The two adapter bars mount to the bottom of the Double Monochromator base plate and to the carriers. They lie perpendicular to the rails, providing a sturdy square frame on which the monochromator system rests. See Fig. 2 below and photo on right.

Fig. 2 Front and side view of 77225 Double Monochromator mounted to 11522 Table Rails using the 77293 Adapter Bars and 11641 Narrow Carriers. Lateral (in-line) configuration shown.

77225 1/4 m Double Monochromator on two 11442 Table Rails using the 77293 Adapter Bars and four 11641 Narrow Carriers.

Fig. 3 Dimensions and mounting hole locations for 77225. Top view of lateral (in-line) configuration.

Oriel ORDERING INFORMATION

For 1/4 m Monochromator/Spectrograph

MONOCHROMATORS/SPECTROGRAPHS

- 77200** MONOCHROMATOR/SPECTROGRAPH HOUSING \$ 2783.00
- 77201** VIS-NIR MONOCHROMATOR \$ 3450.00
Includes 77233 Grating, and two 77217 Slits with Fixed Slit Holders.
(Range: 300-1000 nm)
- 77202** VIS-NIR MONOCHROMATOR \$ 3970.00
Includes 77233 Grating, and two 77248 Variable Slit Assemblies.
(Range: 300-1000 nm)
- 77203** VIS-NIR MONOCHROMATOR \$ 4044.00
Includes 77233 Grating, and two 77249 Multiple Fixed Slit assemblies.
(Range: 300-1000 nm)
- 77225** DOUBLE MONOCHROMATOR/SPECTROGRAPH \$ 6350.00
Includes two 77200 monochromator housings, common base, wavelength drive adapter, center fixed slit holder, and factory assembly and alignment. Order gratings, input and output slit assemblies, and center fixed slit separately.
For Double Monochromator
(a) Choose two identical grating assemblies.
(b) Choose input/output slit assemblies:
 • two variable slits
 • two multiple fixed slit wheels
 • two interchangeable fixed slit holders and two fixed slits
(c) Order a center fixed slit. The fixed slit width should be larger than the input/output slit widths, and at least 0.5 mm wide.
For Double Spectrograph.
(a) Choose two identical grating assemblies.
(b) Choose input slit assembly.
(c) Order 77207 Center Slit.
- 77226** Double Monochromator Conversion Kit \$ 446.00
Includes common base, wavelength drive adapter, and center fixed slit holder. Order center fixed slit separately.

SLIT ASSEMBLIES AND SLITS

- 77248** Variable Slit \$ 449.00
20 um to 3.2 mm variable width, 1 to 12 mm variable height
- 77249** Multiple Fixed Slit Wheel \$ 486.00
Eight Slits, 1 to 12 mm variable height
- 77210** Interchangeable Fixed Slit Holder \$ 93.00
- 77211** Fixed Slit, 6.32 mm, 18 mm high \$ 96.00
- 77212** Fixed Slit, 3.16 mm, 18 mm high \$ 96.00
- 77213** Fixed Slit, 1.56 mm, 18 mm high \$ 96.00
- 77214** Fixed Slit, 1.24 mm, 18 mm high \$ 96.00
- 77215** Fixed Slit, 760 um, 18 mm high \$ 96.00
- 77216** Fixed Slit, 600 um, 18 mm high \$ 96.00
- 77217** Fixed Slit, 280 um, 18 mm high \$ 96.00
- 77218** Fixed Slit, 120 um, 18 mm high \$ 96.00
- 77219** Fixed Slit, 50 um, 6 mm high \$ 168.00
- 77220** Fixed Slit, 25 um, 3 mm high \$ 215.00
- 77222** Fixed Slit, 10 um, 2 mm high \$ 238.00
- 77207** Center Slit for Double Spectrograph with InstaSpec[®], 0.6 x 0.15 inches \$ 96.00

GRATING ASSEMBLIES

All gratings are mounted in quick interchange holders.

- 77230** Holographic Grating \$ 415.00
175-500 nm, 2400 l/mm
- 77231** Holographic Grating \$ 415.00
180-700 nm, 1200 l/mm
- 77232** Grating, 280 nm Blaze \$ 289.00
175-700 nm, 1200 l/mm
- 77233** Grating, 500 nm Blaze \$ 289.00
300-1000 nm, 1200 l/mm
- 77234** Grating, 1.0 um Blaze \$ 289.00
0.6-2.0 um, 600 l/mm
- 77235** Grating, 2.0 um Blaze \$ 289.00
1.2-4.0 um, 300 l/mm
- 77236** Grating, 4.0 um Blaze \$ 289.00
2.4-8.0 um, 150 l/mm
- 77237** Grating, 8.0 um Blaze \$ 289.00
4.8-16.0 um, 75 l/mm
- 77238** Grating, 12.0 um Blaze \$ 289.00
7.2-24 um, 50 l/mm
- 77239** Grating, 200 nm Blaze \$ 289.00
175-500 nm, 600 l/mm
- 77240** Grating, 550 nm Blaze \$ 289.00
300-900 nm, 400 l/mm
- 77241** Grating, 730 nm Blaze \$ 289.00
400-1200 nm, 200 l/mm
- 77242** Grating, 800 nm Blaze \$ 289.00
450-1300 nm, 150 l/mm
- 77243** Grating, 750 nm Blaze \$ 289.00
400-1500 nm, 600 l/mm

MOUNTING ACCESSORIES

- 77252** Monochromator Table Rail \$ 155.00
24 inches long. Attaches to bottom of 77200.
- 77292** Set of Adapter Bars \$ 139.00
(For bench or rail mounting 77200.)
- 77293** Set of Adapter Bars \$ 139.00
(For bench or rail mounting 77225.)

See page 211 for Precision Spacer Sets and Rods and Rod Holders.

C-47

Oriel INSTASPEC™ II - SPECIFICATIONS

THE INSTASPEC™ II SYSTEM

Individual specifications of the components available from Oriel are detailed below. Some suggested completely integrated systems are listed on page 358, and itemized components on page 359.

A complete Basic InstaSpec™ II System consists of:

- Uncooled Diode Array Detector Head
- Controller
- Optional Spectrograph (for spectroscopy)
- Low Speed Interface Card
- XT Type Computer
- Hercules Graphics Card and Monitor
- Software
- Printer

A complete Advanced InstaSpec™ II System consists of:

- Thermoelectrically Cooled Diode Array Detector Head
- Controller
- Thermoelectric Cooler Control Card
- InstaCool™ Refrigerated Recirculator
- InstaDry™ Purging Unit
- Optional Spectrograph (for spectroscopy)
- High Speed Interface Card
- AT or 386 Type Computer
- EGA or VGA Color Graphics Card and Monitor
- Software
- Printer
- Plotter

A complete Diode Array Camera System consists of:

- Uncooled Camera Diode Array Detector Head
- Controller
- Camera, Mount and Lens
- Low or High Speed Interface Card
- XT, AT or 386 Type Computer
- Hercules, EGA or VGA Graphics Card and Monitor
- Software
- Printer and/or Plotter

DETECTOR HEADS

Three types of detector heads are available:

- Uncooled Detector
- Thermoelectrically Cooled Detector
- Camera Detector Head

All three types are available with either 512 or 1024 element diode arrays.

SPECIFICATIONS

	Array Size	
	512	1024
Number and size of pixels:	512 50 μ m x 2.5 mm	1024 25 μ m x 25 mm
Spectral response:	180-1100 nm	180-1100 nm
Minimum exposure time: (100 kHz interface)	6 ms	12 ms
Maximum S/N ratio:	c. 8,000	c. 8,000
Array Dynamic range:	c. 30,000	c. 30,000
Dark current (25°C):	0.5 pA typical	0.25 pA typical
Electro-optical Characteristics		
Radiant sensitivity 600 nm:	c. 350 mA/W	c. 350 mA/W
200 nm:	c. 70 mA/W	c. 70 mA/W
Light Responsivity: (per energy density at 600 nm)	c. 0.44×10^{-3} C/J/cm ²	c. 0.44×10^{-3} C/J/cm ²
Charge amplification: (at unity gain)	14×10^{11} V/J	14×10^{11} V/J
Maximum gain:	8	8
Output sensitivity:	5×10^{11} V/J	5×10^{11} V/J
Saturation charge:	10 pC	10 pC
Saturation exposure: (600 nm)	3×10^{11} J	3×10^{11} J
Dimensions		
Uncooled heads:	2 x 3.5 x 3 in. (51 x 89 x 76 mm)	2 x 3.5 x 3 in. (51 x 89 x 76 mm)
Cooled heads:	2 x 3.5 x 6 in. (51 x 89 x 152 mm)	2 x 3.5 x 6 in. (51 x 89 x 152 mm)
Camera heads:	3 x 3 x 3 in. (76 x 76 x 76 mm)	3 x 3 x 3 in. (76 x 76 x 76 mm)

THERMOELECTRIC COOLER

Cooled detector heads only. Requires the thermoelectric cooler control card for the controller.

Thermostated temperature

Under normal ambient conditions: 5°C
Minimum with InstaCool™ recirculator: -20°C

Temperature Stability

Fluctuations: ± 0.1°C
Drift: ± 0.5°C/°C

INSTACOOL REFRIGERATED RECIRCULATOR

This unit is used to pump refrigerated liquid through the detector head to lower the temperature of the diode array to as low as -20°C. Provision is also made for cooling the purging gas from InstaDry™, or some other source of dried gas.

Temperature range: 50°C to -15°C
Temperature stability: ± 0.1°C
Maximum pumping height: 10 ft. (3 m)

CONTROLLER

The controller provides power and timing signals to the detector head. It also sets the exposure time and coordinates the synchronizing signals to and from other instruments. The thermoelectric cooler control card is required for cooled detector heads.

Exposure time range: 6 ms to 10 min, and line synchronized
Diode array read rate: 12.5, 25, 50 and 100 kHz
Dynamic range: 12 bit

BNC (TTL) Outputs

External synch: Video signal
Video trigger
Gate/Camera trigger

BNC (TTL) Inputs

Trigger Input: Remote trigger

COMPUTER AND MONITOR SPECIFICATIONS

Computer:

- XT (8086) compatible, with 8087 coprocessor
- AT (80286) compatible, with 80287 coprocessor
- 386 (80386) compatible, with 80387 coprocessor
- IBM™ PS/2 computer with appropriate coprocessor

640 kbytes of memory

Hard disk recommended

Other computers will be supported at a later date.

Graphics Cards and Monitors:

- Hercules card and monochrome 720 x 348 resolution monitor
- Enhanced Graphics Adapter (EGA) with color 640 x 350 monitor
- Video Graphics Adapter (VGA) with color 640 x 480 monitor

HARD COPY SUPPORT

- Printers and Laser Printers
- Hewlett-Packard Plotters

INTERFACES

Low speed: 25 kHz 12 bit A/D board (XT computers only)
Medium speed: 50 kHz 12 bit A/D board (AT & 386 computers only)
50 kHz 12 bit A/D board (PS/2 computers only)
High speed: 100 kHz 12 bit A/D board (AT & 386 computers only)

Other interface cards will be available at a later date.

SOFTWARE

- InstaSpec™ Program
Included with InstaSpec™ system.
Stand alone executable program
Not copy protected
Operating manual included
- Programmer's Kit
Interfacing manual
Array drivers, subprograms and source code

CAMERA SHUTTER

This is a modified Nikon camera body for use as a fast mechanical shutter, and for imaging light sources onto a diode array detector. This permits the use of a wide variety of high quality 35 mm Nikon lenses. Only uncooled camera detector heads can be attached to the camera body. The InstaSpec™ Mounting Adapter, model 77150, is required to accurately attach these heads to the camera body.

Camera type: Nikon, 35 mm single-lens reflex
Lens mount: Nikon bayonet mount
Lenses: More than 70 Nikkor™ and Nikon series E lenses
Shutter speeds: Stepless from 1 s to 0.5 ms
Manual and electronic (B setting)

Oriel INSTASPEC™ II - ORDERING INFORMATION

COMPLETE INSTASPEC™ SYSTEMS

All the InstaSpec™ detectors will work any of the computers specified on the next page. The systems below represent well balanced combinations of various diode array detectors, interfaces, and computers. The computers used by ORIEL have been carefully evaluated for their superior performance and quality.

Detectors can be purchased separately by those who already possess a computer system, and/or the combinations can merely be considered as a guide for ordering individual components from the itemized list at the end of this section.

THE INSTASPEC™ XT SYSTEM

This is the basic low cost InstaSpec™ system for imaging or spectroscopy. An additional spectrograph is required for spectroscopic measurements.

77160 InstaSpec™ XT Detector

- Uncooled 512 Element Diode Array Detector Head
- Controller
- InstaSpec™ Software and Manual
- Low Speed Interface Card
- InstaSpec™ Mounting Flange

77170 XT 10 MHz Computer

- 640 kbyte RAM
- 8087 Coprocessor
- 5 1/4 inch 360 kbyte Floppy Disk Drive
- 20 Mbyte Hard Disk
- Hercules Monochrome Graphics Card and Monitor
- Parallel and Serial Ports
- 9 Pin Printer

THE INSTASPEC™ AT SYSTEM

This is the high speed, high resolution InstaSpec™ system for imaging or spectroscopy. An additional spectrograph is required for spectroscopic measurements.

77161 InstaSpec™ AT Detector

- Uncooled 1024 Element Diode Array Detector Head
- Controller
- InstaSpec™ Software and Manual
- Medium Speed Interface Card
- InstaSpec™ Mounting Flange

77171 AT/286 10 MHz Computer

- 1 Mbyte RAM
- 80287 Coprocessor
- 5 1/4 inch 1.2 Mbyte Floppy Disk Drive
- 40 Mbyte Hard Disk
- EGA Graphics Card and Monitor
- Parallel and Serial Ports
- 24 Pin Printer
- Hewlett-Packard Color Pro Plotter

THE INSTASPEC™ ET SYSTEM

This combines high speed and long integration times using a cooled InstaSpec™ system for imaging or spectroscopy. An additional spectrograph is required for spectroscopic measurements.

77162 InstaSpec™ ET Detector

- Cooled 512 Element Diode Array Detector Head
- Controller
- InstaSpec™ Software and Manual
- Cooler Control Card
- Medium Speed Interface Card
- InstaSpec™ Mounting Flange
- InstaDry™ Purging Unit

77171 AT/286 10 MHz Computer

- (See InstaSpec™ AT System)

THE INSTASPEC™ GT SYSTEM

This is the top performing InstaSpec™ system. It combines very high acquisition speed, high resolution, and long integration times, with excellent graphics display. This uses a cooled InstaSpec™ system for imaging or spectroscopy. An additional spectrograph is required for spectroscopic measurements.

77163 InstaSpec™ GT Detector

- Cooled 1024 Element Diode Array Detector Head
- Controller
- InstaSpec™ Software and Manual
- Cooler Control Card
- High Speed Interface Card
- InstaSpec™ Mounting Flange
- InstaCool™ Recirculator
- InstaDry™ Purging Unit

77172 286 20 MHz Computer:

- 1 Mbyte RAM
- 80287 Coprocessor
- 3 1/2 inch 1.4 Mbyte Floppy Disk Drive
- 40 Mbyte Hard Disk
- VGA Graphics Card and Monitor
- Parallel and Serial Ports
- 24 Pin Printer
- Hewlett-Packard Color Pro Plotter

THE INSTASPEC™ IT SYSTEM

This is a high speed InstaSpec™ system for linear imaging using the Nikon camera shutter and Nikon lenses.

77164 InstaSpec™ IT Detector

- Uncooled 512 Element Camera Diode Array Detector Head
- Controller
- InstaSpec™ Software and Manual
- Medium Speed Interface Card
- Camera Shutter
- InstaSpec™ Mounting Accessory
- 105 mm VIS Lens Kit

77171 AT/286 10 MHz Computer

- 1 Mbyte RAM
- 80287 Coprocessor
- 5 1/4 inch 1.2 Mbyte Floppy Disk Drive
- 40 Mbyte Hard Disk
- EGA Graphics Card and Monitor
- Parallel and Serial Ports
- 24 Pin Printer
- Hewlett-Packard Color Pro Plotter

OMA[®] III

The Total Solution For All Your Spectroscopy Investigations

EG&G PRINCETON APPLIED RESEARCH

C-51

What Is The OMA[®] III?

• Measure Multiple Wavelengths from the Near-Infrared to the X-Ray Region

OMA III, the state-of-the-art Optical Multichannel Analyzer system from EG&G Princeton Applied Research Corporation, consists of an integrated family of multiple element light detectors and signal processing equipment. The OMA III can rapidly collect and analyze full spectrum data containing wavelengths from the near-infrared to the x-ray region.

The basic OMA III system consists of a Model 1460 System Processor or a Model 1461 Detector Interface, along with a diode array or Vidicon Detector and a Detector Controller module. The detector at the front end of most OMA systems is attached to a spectrograph. The OMA detector can be considered to operate like "electronic film" that replaces the single element detector of pre-OMA systems.

The Model 1461 OMA system requires an external computer. It should be your choice if you need to attach an OMA to an existing lab computer without sacrificing essential OMA power. The Model 1461 brochure describes that system more fully.

The Model 1460 OMA described in this brochure is a self-contained system that you can literally unpack, set up, and run. It requires neither programming knowledge, nor external hardware or software to be able to acquire and fully process spectral data. The desktop-sized Model 1460 System Processor is the most prominent component of the system. It features Motorola 68000-based high speed signal processing, two double-sided, double-density floppy disk drives (one of which can be replaced by a 20 Mbyte hard disk), as well as a high resolution, touch-sensitive screen, an external keyboard, and front panel buttons for flexibility of control. All OMA III systems include schematic diagrams and a comprehensive operating manual.

With the OMA III, you won't have to compromise your experiment to match the requirements of our instruments. Through the 1460's friendly system of menus, you can easily change the system's setup and data acquisition parameters to meet your needs. In fact, it is so easy to learn to use our 1460-based OMA that you should find few occasions when you will find it necessary to refer to the manual before running experiments.

*OMA is a registered trademark of Princeton Applied Research Corporation

What Are The Benefits Of Using An OMA?

3

● Acquire a Full Spectrum from a Single Pulsed Event

The ability of the detector's diode array to store signals until sampled allows the OMA to capture a full spectrum of data from a single event. The duration of such events can range from CW to pulses in the femtosecond range. The OMA is therefore the ideal instrument for experiments involving pulsed lasers, flash lamps, explosives, Tokamaks, etc.

Compared to systems that require a light pulse for each wavelength of data to be collected, the OMA lowers the consumption of sample materials and it also lessens sample degradation due to exposure to high intensity light sources, both of which can save researchers both time and money. In the same way, the OMA also overcomes problems such as Shot-to-Shot Variance, which makes it difficult to exactly correlate separate wavelengths in mechanically scanned systems.

● Rapid Scanning Yields Kinetic Information

Since OMA detectors are electronically scanned, they can collect a spectrum much faster than most mechanically scanned systems. Depending on experimental conditions, such as spectral resolution and the number of data points, a continuously scanning OMA III can acquire a 75 point spectrum in as little as 2 ms.

Its large memory capacity, along with its powerful post processing software, makes the OMA ideal for stopped-flow, liquid chromatography, and other time-varying experiments.

● Optical Shuttering for Time Resolution and Background Rejection

OMA detectors with gated intensifiers capable of being shuttered at nanosecond speeds are ideally suited for investigations such as time resolved fluorescence or absorbance. Such intensifiers are able to extract very narrow "time slices" of the (time-varying) spectra associated with such experiments.

During data acquisition, high speed gating can also be used to reject background signals. This is accomplished by controlling the detector so that it only collects data during the time pulses are being received. With this feature, it is possible to carry out investigations that would otherwise prove to be very difficult, such as analyzing the Raman spectra of particles or gases in flames and studying water pollution via pulsed fluorescence experiments conducted in daylight.

● Rapid Collection of Weak Signal Spectra

Researchers conducting low light level experi-

ments involving Raman scattering, Fluorescence, Phosphorescence, Luminescence, etc. can benefit greatly from the multi-element design of OMA detectors. Because all of the detector's elements are exposed simultaneously, an entire spectrum can be acquired in the time it normally takes a mechanically scanned system to reach the desired signal-to-noise ratio for any one wavelength. With weak signals, this time savings allows more spectra to be collected in a given time period. The result is increased information throughput for your system. In addition, the OMA speed also alleviates much of the deterioration that many materials undergo as they are exposed to light sources with high excitation powers or long exposure times.

● Greater Signal-To-Noise Ratio During Fixed-Time Experiments

Unlike a single element detector, which can obtain data from a single wavelength interval of the desired spectrum during only a fraction of the total experiment time, every OMA element detects light during the entire time an experiment is being run. Therefore, for a given time period, OMAs will have better detectivity, as well as increased (full spectrum) S/N ratio. These OMA advantages are effective over the complete range of the instrument, which covers data acquisition times from CW to nanoseconds.

● Rapid, Reproducible Data Acquisition in Industrial Applications

Many industrial processes involving light require very rapid testing. The OMA III is the ideal tool for this work since it only takes seconds for an OMA to measure a coating thickness or to verify the performance of such devices as filters, light sources, and mirrors. The high reproducibility of OMA III data allows test results to be expressed in calibrated radiometric units. Finally, the 1460's multiple wavelength capability, along with its speed and powerful Y.T. software, makes the OMA III the perfect choice to monitor the dynamics of the semiconductor industry's plasma etching chambers.

VME standard cards

How Does The OMA III Make Your Work Easier?

• Flexible And Easy To Learn

Based on state-of-the-art signal acquisition techniques, the heart of the OMA III is really its menu-driven software. The 1460's menus are very easy to use because they are designed to present only pertinent choices at each stage of your experiment. In addition, the flexibility of being able to operate the instrument under programmed control, as well to control it manually through either the touchscreen or the keyboard, makes the OMA III easily adaptable to all experiments.

OPTIMIZE THE DATA ACQUISITION PROCESS TO YOUR EXPERIMENT

• Control Detector Scanning to Increase Sensitivity and/or Speed

OMA III systems that include the Model 1463 Detector Controller module allow you to mix normal scanning with "grouped" and/or "fast" scan patterns (Fig. 1). During grouped scanning, the OMA combines the outputs of contiguous elements of the detector's diode array in order to improve sensitivity and memory utilization. Fast scanning, on the other hand, allows you to decrease the total scanning time of the instrument by selectively ignoring data from portions of the array that are not expected to collect useful information. It does this while retaining wavelength calibration.

Besides being able to select from a broad range of detectors with various sensitivities, you can also change an OMA's sensitivity by setting exposure times ranging from milli-seconds to hours. In addition, our gated detectors allow you to time resolve high speed events with gate times as fast as 5 ns

• Collect Data in Hostile Environments

If you plan to collect data in a hostile environment or an inaccessible location, you can set up the 1460 to remotely control an optional Model 1461 Detector Interface (and its accompanying detector), at distances up to 100 feet from the OMA's System Processor

• Optional Programmable Pulser for Full Control

The Model 1303 Gate Pulse Interface option is a programmable TTL pulse generator whose delay can be automatically incremented during data acquisition. When the Model 1304 Pulse Amplifier option is included with the system, you can also set the width of the gate pulse. The combination of the 1303 and a pulse generator allows you to set up the system for automatic acquisition of time-resolved spectra. It even permits you to view

changing intensities of stopped flow, plasma chemistries, and fluorescence in real time

POWERFUL DATA ACQUISITION MODES

• Display Spectra in Real Time or Select from 17 Preprogrammed Data Acquisition Modes

The OMA III includes 17 preprogrammed Data Acquisition Modes that have proven valuable to researchers over the years. These flexible modes allow you to meet the requirements of nearly every experiment by selecting data acquisition operations (Fig. 2) ranging from simple averaging to complex kinetics routines and multimemory sequences.

Several Data Acquisition Modes even allow you to automatically subtract data pairs and/or ignore a number of scans between each data acquisition. In addition, many modes allow you to select trigger inputs and outputs to best match your experiment.

Data Acquisition Mode Examples:

The following functional descriptions of Data Acquisition Modes 2, 7, and 12 illustrate some of the flexibility and power of OMA III data acquisition. In these examples, the user specifies integer values for 'J', 'I', and 'K'. The variable, 'J', is the number of separate memory buffers into which data will be stored, while 'I' is the number of scans per data acquisition, and 'K' is the number of scans to be ignored during each data acquisition.

Data Acquisition Mode #2

```
FORM = L TO J
  TRIGGER OUT
  ON TRIGGER
  FOR S = 1 TO I
    ADD L SCAN
    FOR G = 1 TO K
      IGNORE L SCAN
    NEXT G
  NEXT S
NEXT J
```

Explanation: 'J' sets of scans take place, with 'I' scans summed into each set. Each set of scans is preceded by a TRIGGER OUT. The system then scans, waiting to receive an 'ON TRIGGER' instead of instantly proceeding. Immediately after each 'ON TRIGGER', a complete set of 'I' scans is accumulated and the results from each set are ADDED into separate memories. This mode allows you to IGNORE 'K' scans after each added scan ('K' can equal 0). (In Mode #2, all data is ADDED with 32 bit precision.)

Figure 1. Setting Up Mixed Mode Scanning

Figure 2. Data Acquisition Mode Setup Screen

Note that Data Acquisition Mode #1 is nearly identical to Mode #2, with the only difference being that Mode #1 does not wait to receive an ON TRIGGER pulse before taking data.

Comment: With 'J' set to 1 and 'K' set to 0, Mode #2 is a very frequently used data acquisition mode. If 'J' is set to an integer greater than 1, a series of experiments can be run. Setting 'K' > 0 allows the system to wait a predetermined interval for each event such as the recharging of a laser's power supply.

Data Acquisition Mode #7

```

TRIGGER OUT
FOR M = 1 TO J
  STORE 1 SCAN
  FOR G = 1 TO K
    IGNORE 1 SCAN
  NEXT G
NEXT M

```

Explanation: Following a single TRIGGER OUT pulse, 'J' scans occur. The result of each is STORED in a different memory. This mode allows you the option to IGNORE 'K' scans after each STORED scan.

Comment: In this Kinetics mode, the STORE command uses two bytes to store each data point, thus allowing twice as many curves to be stored. The instrument's sampling rate can be slowed down by setting 'K' > 0.

Data Acquisition Mode #12

```

FOR M = 1 TO J
  TRIGGER OUT
  STORE 1 SCAN
  SUBTRACT 1 SCAN
  FOR G = 1 TO K
    IGNORE 1 SCAN
  NEXT G
NEXT M

```

Explanation: This mode STORES 'J' scan pairs, with each pair occupying a unique memory. Following a TRIGGER OUT, the first scan of each pair is STORED in a memory and the second scan is then SUBTRACTED from the one just stored. This process is repeated for each of 'J' memories. Mode #12 allows you to IGNORE 'K' scans after each subtracted scan.

Comment: Mode #12 is ideal for applications involving pulsed experiments with dynamic optical backgrounds. The subtraction of the scan that follows the "hot" scan allows the most accurate background correction possible. It also combines into a single run what used to require two separate experiments.

Setting 'K' > 0 allows you to prevent detector saturation by performing low duty cycle experiments with short exposure times. This minimizes the need to water-cool the detector to reduce "dark current."

CUSTOM DESIGN YOUR OWN DATA ACQUISITION MODES

Users with unusual data acquisition requirements can custom design their own Data Acquisition Modes, using our unique DAD (Data Acquisition Design) software.

DAD allows you to design data acquisition modes in which you can mix the ADD, SUBTRACT, IGNORE, STORE, TRIGGER OUT, and ON TRIGGER commands in virtually limitless combinations, using a range of memories that you specify. DAD will control TTL outputs with logical tests conducted on a scan-by-scan basis (such as IF ... THEN ... ELSE ...). It even reads and interprets TTL inputs.

The total flexibility provided by DAD will maximize OMA performance for experiments not covered by the standard set of data acquisition modes. Thus, your OMA III system will grow to run experiments that have yet to be defined. There is not enough room in this brochure to describe the full potential of our DAD software. Please feel free to ask your EG&G PARC representative for more complete information on this unique OMA III feature.

DATA MANIPULATION AND DISPLAY FEATURES To Meet the Requirements of Virtually Every Experiment

● Calibrate Both Spectral Axes

With a standard spectral line source, you can quickly calibrate the OMA's X-axis in units of wavelength (nm) or wavenumbers (cm^{-1}), using a linear or third order polynomial fit. In addition, you can calibrate the amplitude of the curve data in terms of radiometric units (Fig. 3).

You can even select from three automatic scaling options for data displays, as well as expand displays horizontally or vertically by pressing the appropriate front panel keys.

● Process Spectral Data with an Extensive Set of Math Functions

The OMA's built-in full curve computation capabilities include such functions as logarithms, square roots, and many other features found in advanced scientific calculators. The 1460 allows you to solve equations that operate on real numbers, as well as on user-defined variables. One of the most convenient math features in the OMA allows you to solve equations using entire files in a single entry, as in:

$$F9 = F7 \cdot F2$$

This adds the contents of each data point in file F7 to the corresponding points in file F2. The results are stored in file F9. Each of these files can contain thousands of data points! No more do you have to manipulate files with clumsy techniques, such as FOR I = 1 TO 1024, ... , NEXT I.

Figure 3.
Radiometric
Calibration Screen

Figure 4.
A Multimemory X:Y
Plot With "Hidden"
Lines Removed

Figure 5. Disk
Operating System
Control Screen

Figure 6. Sample
Plotter Output

The data being manipulated can be located in Live memory, in disk files, or in "RAM buffers", which are special sections of memory that are used as high speed virtual disks. In addition, the 1460 allows you to smooth data curves, as well as to display their first five derivatives using a Savitzky-Golay algorithm.

• Display Multiple Curves and Multiple Memories

The 1460 System Processor allows you to simultaneously display up to four curves on the same set of axes. These curves can include real-time data, as well as information stored in disk files. When data is stored in sequential memories, the OMA III can display the data in a "waterfall" format (Fig. 4), or it can graph all the memories on a single axis. With the waterfall format, you have the option to display the memories in forward or reverse order. You can elect to "hide" overlapping portions of the curves and you can vary the angle of the "z" axis to improve readability.

• Choose from a Variety of Powerful Background Subtraction Methods to Meet YOUR Experimental Requirements

The spectral data collected by the detector is normally mixed with unwanted background data resulting from dark current in the detector and from ambient light in the laboratory. The OMA offers several methods which you can use to display and store data that has been compensated for such background effects.

• Automatic Source Compensation Modes

Excitation energy variations during data acquisition can often affect experimental results. The

OMA's source compensation hardware and software allow you to correct data being stored for variations in the intensity of experimental light sources.

PRODUCE PUBLICATION-QUALITY HARDCOPY With Powerful Plotting and Printing Software

The OMA III is easily interfaced to a wide selection of plotters and printers. Our powerful plotting software allows you to manipulate data sets by selecting not only the source of the data, but also the range and order of the memories to be plotted and the ranges of their X and Y axes. Before plotting, you can set up all parameters and observe the results on the screen. The plotting software supports multiple character sizes, plot sizes, line types, plotting speeds and pen colors. It even allows you to place comments or labels anywhere on the paper. This results in publication quality hardcopy that is very clear and easy to interpret (Fig. 6).

The OMA allows you to print data stored in memory, including curve values stored in user-accessible memory registers. You can even print OMA graphics displays, including data curves and entire system screens on an Epson FX-80, FX-85, or FX-100 dot matrix printer.

POWERFUL DISK OPERATING SYSTEM SOFTWARE For Easy Manipulation of OMA files

In addition to allowing you to label, store and retrieve data files at will, the OMA III's custom disk operating system software (Fig. 5) automatically stores all instrument parameters to disk. You can then use a single command to reset the system to the stored settings. This feature allows you to rapidly change from one experimental setup to another while saving you the pain of having to repeat an experiment if you forget to record a parameter.

The key element to the 1460's DOS, as with all OMA III features, is flexibility. You decide what you want to do and the system makes it easy for you to do it. You will find that the OMA III imposes very few constraints on your experiments.

ADVANCED TIME RESOLVED SPECTROSCOPY

- Compare How Spectral Regions Change with Time
- Control External Devices Through "Y:T" Analysis

Another powerful OMA feature is its ability to display the relationship of spectral areas to time

The 1460's advanced Y:T software allows you to see how up to 8 areas (or 8 user-defined equations based on up to 24 spectral regions) change with respect to time. The OMA can simultaneously plot up to eight of these functions while data is being acquired (Fig. 7). In fact, you can set up the OMA to continuously test these functions and to use the system's TTL ports to switch external equipment ON or OFF based on the results of these tests. One very useful Y:T operation allows you to use complex mathematical operations to post-process multimemory data that is already stored on disk. These are only some of the features of our Y:T software that make the OMA III unique in the field.

EASILY PROGRAMMABLE FOR UNATTENDED OPERATION

• ... Through Keystroke Programming

There are three ways to set up the OMA to automatically collect data. The first is to enter a "Keystroke Program" in memory in much the same manner as you would enter a series of keystrokes into a programmable calculator (Fig. 8). Even though it doesn't require elaborate computer programming, this feature allows you to automatically execute frequently used data acquisition and processing sequences, as well as make decisions that cause automatic branching. (For more details, please request our Keystroke Programming Application Note.)

• ... Through Rear Panel Control

The second method that allows unattended operation is to control data acquisition by means of an external computer connected to the standard RS232C or GPIB interfaces on the 1460's rear panel. Data from the OMA can then be sent to or from another computer, where it can be further analyzed and stored.

• ... Through BASIC

BASIC Language Option Adds the Capabilities of a Powerful Microcomputer to the OMA'S Instrumentation

The third way to automatically run the 1460 is to program the system in BASIC, using our optional Hemenway Operating System software. Through a BASIC program running on the 1460, you can set the OMA's data acquisition parameters, collect and analyze data, and display the resulting curves, never leaving the BASIC program. You can even design your own touch screens as a final touch to customize your experiment.

A system that includes our BASIC software gives your OMA III the unmatched power and flexibility of a high-speed BASIC computer and the industry's most powerful data acquisition system, all combined into one convenient package.

A VARIETY OF INTERFACES Increases the Number of Potential OMA III Applications

The flexibility of the OMA III is enhanced by its RS232C and GPIB interfaces. Each of these interfaces can be assigned as a Rear Panel Control port for an external computer, or as a plotter or printer port, or an I/O link. Note that the optional I/O-B module includes a second RS232C interface and a Centronics™ port that can be used to drive a parallel printer.

RELIABILITY AND REPRODUCIBILITY

The solid construction of all OMA III components, combined with the rigid quality control and inspection procedures at EG&G PARC, makes this system by far the most reliable optical analyzer in today's marketplace. All OMA III systems include software updates and a two year warranty.

OMA III Hardware Options

• Choose from a Growing Family of System Options, Including More than 19 Diode Array Detectors

EG&G PARC offers a wide selection of both standard and high performance detectors. The 1412, 1420, 1421, and 1422 series of high performance detectors is designed for the Model 1463 Detector Controller, while the 1452, 1453, and 1454 series of detectors are used with the Model 1462 controller. The following pages describe the OMA III's required components, as well as several optional accessories.

DETECTOR CONTROLLER MODULES

• Model 1463 Detection Systems—The Ultimate for Performance and Control

The Model 1463 Detector Controller is a three-card module based on a 14-bit Analog-to-Digital converter. It supports normal scanning, as well as fast access, grouped, and mixed mode scan sequences. The 1463 includes Trigger input and Output connectors, a Scan Sync input connector, X, Y, and Z outputs for monitor scopes, clock phase adjustments, and a video output port. In addition, an Analog Input with a bias adjustment is accessible for integrated or sampled Source Compensation, both of which can be used to normalize

Figure 7. Y:T Plot Of Four Equations

```

11: REM PROGRAM TO RUN A FILE ACQUIRED EXPERIMENT.
12: REM BACKGROUND IS STORED IN A1 AFTER SHUTTER IS CLOSED.
13: REM LASER DELAY IS INCREMENTED A SET AMOUNT FOR EACH
14: REM LASER SHOT. DATA IS STORED ON DISK IN SEQUENTIAL FILES.
15: REM
16: REM
17: REM INPUT THESE WIDTHS: VISO, WIDTH VISO,
18: REM INPUT INITIAL LASER DELAY, VISO DELAY VISO
19: REM INPUT LASER DELAY INCREMENT, VISO
20: REM INPUT # OF INCREMENTS, VISO
21: REM INPUT DISK FILE, VISO
22: REM
23: REM
24: REM P1A: SET 11
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Figure 8. Sample Keystroke Program

spectral curves for the effects of fluctuations in exciting light sources. Detectors using the 1463 controller have their Exposure Times and Peltier Coolers adjusted through software.

● **Model 1462 Detection Systems—For Cost Effective, Reliable and Accurate Data Acquisition**

The Model 1462 Detector Controller resides on a single VME card. It includes a 12-bit Analog-to-Digital converter, and it has the Model 1462/99 14-bit A/D converter card available as an option. The Model 1462 can acquire a spectrum of 512 elements in 15 ms, or one with 1024 elements in 30 ms. The 14-bit A/D option decreases the scan time to 10 and 20 ms, respectively. The 14-bit A/D option also increases the detector's dynamic range four times (from 4095 to 16383).

In addition, the Model 1462 has a 0-10 V video output port available for a real-time display on an oscilloscope. The 1462 provides BNC connectors for Trigger Input and Trigger Output signals and it also includes a Source Compensation input connector. The 1462 Detector Controller does not support mixed-mode scanning, but it does allow you to adjust the temperature by means of an easily accessible trimpot.

● **Model 1216 Vidicon Detection Systems—For Two-Dimensional Data Acquisition**

The 1460-based Vidicon system is a two dimensional data acquisition system with excellent sensitivity and a high dynamic range. It allows you to specify the detector's scan pattern in single or multiple tracks. Thus the detector can be adjusted for optimum data collection.

The Model 1216 Detector Controller services the scanning, power and signal processing requirements for all EG&G PARC OMA III Vidicon-based detectors. The Model 1216 may be operated with the Model 1460 System Processor via the High Speed Serial port on the 1460's DMA card. Note

that the 1216 can also be operated as a computer peripheral through its own 16-bit Parallel Interface.

**HIGH PERFORMANCE DETECTORS
(for the 1463 Controller)**

The high performance detectors described in the following paragraphs offer fast readout time combined with sophisticated scan patterns.

The Model 1412 is a 1024-element silicon photodiode array detector that has the highest sensitivity of our unintensified detectors. The 1412 incorporates a Peltier cooler for normal operation at -20°C. (This temperature can be brought even lower with supplemental cooling.) Such low temperatures make possible extended integration directly on the photodiodes. The spectral response of the 1412 is from below 200 nm to 1100 nm.

The Model 1412F detector is identical to the Model 1412, with the exception that it has been designed for direct coupling to fiber optic bundles, such as those at the end of special image intensifiers. It therefore has a fiber optic faceplate in place of the quartz window. It can be used with experiments that employ specially designed intensifiers or other fiber optic inputs. Since the 1412F can be evacuated, it is ideal for x-ray and VUV measurements when coated with appropriate scintillators.

The Model 1412XR is an x-ray sensitive version of the Model 1412 detector. This detector is the ideal instrument for the detection of pulsed or CW x-rays in the 1 - 20 keV range. Based on a diode array, the M1412XR features 950, 2 mm x 25 μ m elements, each of which has a sensitivity of approximately 0.8 count per 8 keV-photon.

The Model 1420/1421 series of detectors consists of a set of 12 intensified diode array detectors based on a proximity- focused microchannel plate (MCP) intensifier. These detectors offer a sensitivity of one A/D converter count per detected photon. The individual detectors in the 1420/1421 series differ with respect to their cathode types, the number of detector elements, and their gating abilities. All 1420/1421 detectors feature low geometric distortion and the ability to cool the diode array to -35°C so that long integration times can be used.

The Model 1422 is an intensified, low cost detector based on an electrostatically focused MCP intensifier. It features 1000 elements and one count per detected photon. This detector is ideal for applications that do not require gating or UV sensitivity. Although the Model 1422 has some geometric distortion, both the normal and fast phosphor versions have excellent line spread (resolution) and they can be cooled to -35°C

OMA[®] III Detectors

STANDARD DETECTORS (for the 1462 Controller)

The Models 1452A and 1453A are 512 and 1024 element versions, respectively, of the same detector. Both are unintensified detectors based on a Reticon linear photodiode array. Each has a broad wavelength response of 180 to 1100 nm. These detectors include Peltier coolers to maintain a normal operating temperature of -5°C , although they can be set as low as -35°C .

The Model 1454A is the most sensitive of the 145x series of detectors. It features an electrostatically focused intensifier in front of a 512 element diode array and it provides detection levels of approximately 100 photons per A/D converter count. The detector's temperature is normally maintained at -5°C by a Peltier cooler, although it can be set as low as -35° . Like the other 145x series detectors, the 1454A is capable of low temperature operation using a water flow block to assist the Peltier cooler. The wavelength response of this detector is limited to approximately 365 to 900 nm by the glass input of the intensifier and by its cathode, respectively. An optional UV scintillator extends the blue response to below 200 nm.

VIDICON DETECTORS (for the 1216 Controller)

Vidicon Detectors provide two-dimensional light sensing capabilities with a virtually limitless number of possible scan patterns.

The Model 1252 series of Vidicon detectors are optimized for various spectral ranges by controlling the target thickness and by the proper selection of window materials. Anti-reflective coatings reduce spurious (moiré) effects at wavelengths longer than 800 nm, which is where silicon target materials begin to become transmissive.

The Model 1254 and 1254E Vidicon Detectors have peak sensitivities of 14 photons per count, and they can be gated by the Model 1211 Gate Pulse Generator to provide time resolution down to 40 ns. The Model 1254E is the same as the 1254, with the exception that it has an extended red photocathode response.

SPECTROGRAPHS

EG&G PARC has a large selection of gratings available for the Models 1231, 1232, and 1234 spectrographs. These gratings allow you to optimize your spectrograph to the wavelength and dispersion ranges required for your experiment. (The gratings are fully described in the specification sheets for the individual spectrographs.)

We also have three lengths of quartz bundles available for our spectrographs. The 1.0 m, 1.9 m,

and 2.9 m kits for the Model 1232, and 1234 spectrographs are Fiber Optic Kit Models K0219, K0218, and K0217, respectively. The corresponding kits for the Model 1231 spectrograph are Models K0222, K0221, and K0220.

The Model 1231 is a 32.0 cm focal length ($f/5.4$), low stray light Czerny-Turner spectrograph designed to accommodate all OMA detectors. Because of its vertically and horizontally flat focal plane, the Model 1231 is particularly well suited for area detectors including Vidicons.

The Model 1232 is a 15.6 cm focal length ($f/3.8$), compact cross-beam Czerny-Turner spectrograph with a 90° exit/entrance relationship. It is designed specifically for linear focal plane array detectors.

The Model 1234 is a 27.5 cm ($f/3.8$), cross-beam Czerny-Turner spectrograph designed to be used with all diode-array detectors from EG&G PARC. This spectrograph features a turret mount that can hold up to three gratings, each of which can have unique blaze and groove frequencies.

PULSE GENERATORS

• Control Gated Detectors with EG&G PARC Pulse Generators

The Model 1303 Gate Pulse Interface resides on a single VME card. It generates pulses with delays that can be auto-incremented through software. The Model 1303 can increment delays up to 13 ms in 1 ns steps and it includes on-board optical and electrical trigger inputs. The 1303 also provides a software-controlled pulse width. When its output is amplified by the Model 1304 Pulse Amplifier, the pulse width can be varied from 100 ns to 10 ms.

The Model 1304 Pulse Amplifier, combined with the Model 1303 pulser or a user-supplied pulse generator, is designed to turn gated detectors ON and OFF by supplying high voltage gate

NOTE: The /OI lines indicate detectors with chemical scintillator applied. The response of scintillated detectors is approximate.

Figure 9.
Typical Detector
Response Curves

Spectrographs and
Accessories

pulses in the 100 ns to 10 ms range. The Model 1304 also includes monitor outputs that can prove very useful while an experiment is being set up and tested.

The Model 1302 High Speed Gate Pulse Generator has an adjustable delay. This triggered pulser is used to supply gate pulses of 5, 10, or 20 ns width to gated 1420 series detectors. Its delay time is adjustable from 0 to 256 ns with a propagation delay ≥ 40 ns. Like the Model 1304, it also includes monitor outputs that can be very useful while an experiment is being set up.

The Model 1211 Gate Pulse Generator is used to gate the Model 1254 series of SIT Vidicon detectors. The Model 1211 has an adjustable Pulse Width of 40 ns to 999 μ s and a adjustable Delay Time of 100 ns to 999 ms. The pulse amplitude is adjustable from -500V to -1500V, with a Repetition Rate of 10 kHz continuous (100 kHz burst). The 1211 is remotely programmable with a Model 1211/99 interface. If the 1211/80 Terminator Box is used, the 1211 will also work with 1420/21 detectors.

The Model 1301 Optical Trigger Detector uses a fiber optic input to an avalanche photodiode to produce a 100 μ s TTL pulse from a 20 ns light pulse as small as 3pJ (at 650 nm). During data acquisition, the Model 1301 can be used to optically trigger a pulse generator or the system's detector controller.

ADDITIONAL OPTIONS

• The I/O-B Module—an Extremely Useful, Cost-Effective Option

The I/O-B Module (Model 1008/92 to 1008/99) is a VME plug-in card that includes a real-time clock with battery backup that is used to stamp

data files with the date and time they were saved to disk. The I/O-B also includes a Centronics printer port, a second RS232C serial port, analog recorder outputs, a 1 8-bit programmable bidirectional I/O port (usable by BASIC), and an optional 512K bytes of additional memory.

The CE0091 Extended Memory VME board adds 256K bytes per card to the OMA's memory.

The CE0113 Extended Memory VME board adds 2 Mbytes of extra memory to the OMA III.

• Hemenway BASIC—A Major Increase in OMA Power for a Modest Investment

The Model 1460/89 Hemenway BASIC software option turns your OMA into an integrated system consisting of the best light detection and analysis system in today's marketplace, combined with a powerful BASIC microcomputer. The instrument and computer software work together to acquire and analyze data without user intervention. The main features of the BASIC software are:

- Complete software control of all instrumentation parameters
- Support of all OMA interfaces (with redirectable I/O ports)
- Versatile set of powerful math functions
- Graphics support including scaling, axes, etc.
- Touch Screen Design
- Multitasking operation with touchscreen or keyboard control

The Model 1460/98, 20 Mbyte Hard Disk option replaces the lower floppy disk drive in the Model 1460. The hard disk is an ideal OMA III accessory if you are storing a large number of data files or if you plan to do much BASIC or Keystroke Programming.

Digital Plotters supplied by EG&G PARC include the following: the Houston Instruments, Inc. DMP 40 (the RS232C version is PARC Model RE0093 and the GPIB version is Model RE0100) and the DMP 29 (PARC Model RE0146), and the Hewlett Packard, Inc. Model HP7440A GPIB plotter (PARC Model Number RE0144). (The OMA III software also supports the HP7470, HP7472, HP7475, and HP7550 plotters.)

The Model RD0033 Dot Matrix Printer, which is the serial version of the Epson FX-85 printer, is fully graphics-compatible with the OMA III. The printer can be driven by the CPU or I/O-B serial port.

The Model C0217 Extender Cable, allows you to place a 1412 or 142x series detector up to 25 feet from the Model 1463 Detector Controller card. (If you wish to substitute the 25 foot cable

OMA • III Pulsers

for the standard cable normally shipped with a new system, order the Model No. 1463/99 cable.) Note that the extended cable results in a slight signal-to-noise ratio degradation when compared to the standard 6 foot cable

● **Collect Data in Hostile Environments by Using the OMA to Remotely Control an Optional Model 1461 Detector Interface**

The Model 1461 Detector Interface, when

combined with the Model SC0071 Extender Cable, allows you to remotely collect spectra in hostile (or inaccessible) environments up to 100 feet from the 1460 System Processor. After you connect a Model 1461 to your 1460 system, you will be able to control the OMA just as you always did; the 1461 is virtually "invisible" to the user. The Model 1461 can also be used without a Model 1460 if it is properly interfaced to an external computer.

Specifications For The Model 1460 System Processor

Soft-Touch Screen: 9 inch diagonal, high resolution, raster scan (656 × 356 pixels), with 60 active touch-sensitive regions (10 × 6). Screen has adjustable tilt +15° to -10°, and brightness is software controlled.

Disk Drives: Two 5-1/4 inch double-sided, double-density floppy drives are standard. Each stores 385K bytes of data under the control of file management software.

Front Panel Keys: Thirteen keys on the front of the System Processor perform such operations as moving the cursor, expanding, contracting, and autoscaling displays, as well as stopping and resuming the drawing of curves.

External Keyboard: Containing a numeric keypad, as well as cursor control and function keys, the keyboard is used as an alternate means of command entry. It is also used to enter Keystroke and BASIC programs into the OMA.

CPU: VME card with 68000 microprocessor, 512K bytes of RAM, an RS232C port, and access to a RESET switch for rebooting. (RAM is expandable with additional memory boards.)

I/O-A: VME card with IEEE-488 GPIB port and EG&G PARC parallel interface.

CRT Controller: VME card with BNC connectors for a monochrome video output signal, for horizontal, vertical, and composite sync signals, as well as for the blanking pulse.

1460 DMA: Intelligent Direct Memory Access VME card with 68000 microprocessor that can perform extremely sophisticated data acquisitions, including asynchronous accumulation using both addition and subtraction of data. The 1460 DMA also includes a 16-bit programmable I/O, a reset switch, and a proprietary High Speed Serial Interface to communicate with a Model 1461 Detector Interface or a Model 1216 Detector Controller.

Power Requirements:

Selected Voltage	Range (V rms)	Fuse Rating
115	100-130	3.0 A S.B.
230	200-260	1.5 A S.B.
48-62 Hz 260 VA Maximum		250 V S.B.

Dimensions: 11-1/4" High × 18-1/2" Wide × 20" Deep (28.6 cm × 47 cm × 50.8 cm)

Weight: 65 lbs (30 kg)

The Future

The innovative engineering behind the OMA III system has produced a Model 1460 System Processor that is truly the OMA console of the future. The Model 1460 has been designed to control all present and future EG&G PARC detectors. In fact, Model 1215 OMA II system processors now in the field can already be replaced by the much more powerful Model 1460. Very soon, a single 1460 System Processor will be able to control several detectors simultaneously, with each detector connected to its own Model 1461 Detector Interface.

- **Diskette-Based Software and Modular Design Provide for Easy Upgrading and Expansion**

Because the 1460 is a disk-based system, software improvements are easily integrated into existing instruments. In addition, since the system was designed with the universally accepted VME-bus configuration, hardware enhancements usually require little more than simply adding one or more VME cards. Because the OMA III is so easily upgraded, it can never become obsolete.

- **Software Updates**

Our policy of assuring that our customers always have the latest version of the OMA's software means that the system's performance will grow during the life of the instrument. Indeed, many user-suggested improvements are included in the current release of the software.

Warranty

- **2 Year Warranty**

We back up the OMA III with a 24 month warranty on all hardware components except detectors. For a small additional charge, detectors can also be warranted for 24 months. Prompt and courteous service is available at EG&G PARC facilities around the world.

A Final Word

- **Enjoy Easy Access to Our Professional Customer Support Staff**

At EG&G PARC, we have earned our reputation not only by supplying the scientific community with instruments of unsurpassed quality since 1961, but also by our readiness to stand behind our products with a truly professional and accessible customer support staff. Please feel free to contact the factory or your local representative if you have any questions about the OMA III system, its accessories, or any of our other products.

EG&G PRINCETON APPLIED RESEARCH
Scientific Instruments Division

P.O. BOX 2565 • PRINCETON, NJ 08543-2565, USA • 609/452-2111 • TELEX: 843409

OMA[®] III

MODEL 1461

**DETECTOR
INTERFACE**

EG&G PRINCETON APPLIED RESEARCH

The OMA III family of instruments is designed to do simultaneous, multiple resolution element spectroscopy. The Model 1460 System Processor and the Model 1461 Buffered Detector Controller are the major computer options in the family. If you need a state-of-the-art OMA system with full software and hardware that you unpack and use, the Model 1460 is your choice. The Model 1460 brochure describes this flexible system more fully.

The Model 1461 is your choice if you:

- already have a computer and need a cost effective OMA without sacrificing any essential OMA power;
- have a large amount of hardware and software invested in a computer controlled experiment that needs an OMA;
- require multiple OMA's connected to a central computer;
- need an OMA but have unique software requirements or computing power not supplied by the M1460.

OMA technology has been evolving at EG&G Princeton Applied Research since 1972. The M1461 is a superior instrument that reflects all of the lessons of past experience. Some of the major features of this instrument are:

- control of any detector from the growing family of more than 17 linear diode array based detectors;
- acquisition of data using one of more than 16 preprogrammed Data Acquisition Modes;
- a non-standard data acquisition mode can be designed for the few cases where your experiment doesn't match the preprogrammed modes (this OMA will never limit your future experiments);
- storage of data until transmission to a host computer;
- preprocessing of the data, such as background subtraction which lessens the time it takes to transmit an experiment result to the host computer;

- interaction with an experiment through programmable, TTL I/O bits, input triggers, and output triggers;
- modular design allows easy upgrades or changes as new experimental requirements turn up;
- standard RS232 and IEEE interface communication links (optional high speed DMA transfer to DEC computers);
- 2-year warranty;
- no charge software update policy.

||||

The Model 1461 Software has been designed to provide most of the common data acquisition modes of optical multichannel analyzers and also to permit user programming for special requirements. For example, setting the exposure time (the time the light is allowed to integrate on the detector elements) is as simple as sending the command ET and the desired value over the computer interface. Other commands such as a Total Scans, Trigger Out, Trigger In and Store in a Memory have similar command mnemonics. Once the setup commands have been sent, the RUN command tells the Detector Interface to acquire the spectrum.

Several different data acquisition modes are preprogrammed and others may be created with the user programming mode. Normal scan reads and digitizes each detector element and stores the data in a memory. Fast scan skips over individual elements in $.5 \mu s$ and allows the user to improve the time resolution by only storing the elements of interest. Grouping combines adjacent pixels into one data point, giving the advantages of improved sensitivity and faster data collection. The mixed mode permits all of the above scan modes to be combined in one scan of the detector. For instance, you can skip the first 100 channels, group the next 100 into 50 data points, and scan the rest in normal mode. This complex scan pattern will be executed every time the RUN command is sent from the host computer.

Once the detector scan pattern is defined, the timing of the data acquisition must be established. Most experimental setups can be classified into one of two groups. The data collection can be initiated by the Detector Interface through the Trigger Out or the experiment can initiate the acquisition through the Trigger In connector. The Model 1461 with the Model 1463 Detector Module has two different trigger outputs, the first occurs at the end of every scan or every nth scan. The second is a pretrigger and can be set to occur at any channel to allow for timing synchronization in pulsed experiments.

Another important part of experimental timing and data acquisition is the storage of the individual scans in memory. The Model 1461, unlike previous simple buffer boxes, can store and perform calculations on the spectra before transmission to the host computer. This has several important implications. First and foremost the host computer is not tied to the data acquisition process. Once the Detector Interface has been given the scan and timing parameters and the RUN command is sent, the host computer can ignore the Model 1461 until it is time to transfer the data. Second, the host computer is not burdened with having to retrieve each scan and background subtract it or sum it into its memory. Since data transfer over RS232C even at high baud rates can take a significant amount of time, there is a net increase in data throughput by preprocessing the data before it is sent.

The Model 1461 Detector Interface has over sixteen built-in data acquisition modes plus one mode that is user definable. These data acquisition modes are designed for the maximum flexibility in accumulating spectra and are divided into two major groups. First, the Model 1461 can sum scans into one memory where each data point is 32 bits wide and from 1 to 30,000 scans can be added.

In addition, an output trigger can be sent before each scan or only at the beginning of the first scan. Likewise, an input trigger can be required before each scan or only at the beginning of the first scan. It is also possible to interleave the input and output triggers such that an output trigger is sent at the beginning and an input trigger is required for each scan. Any memory can be designated as a background that can be subtracted from the accumulated data before the spectrum is transmitted to the host computer.

The second major group of data acquisition modes are concerned with storing one scan or summed scans into sequential memories. Here the experimenter can sum into one memory a number of double-precision curves before automatically moving to the next memory and repeating the data accumulation. The built-in routines allow trigger outputs to be sent and input triggers to be required. Background subtraction of each of the accumulated spectra is easily performed.

These two major groups of data acquisition modes were designed to provide common methods of data collection. Realizing that unique measurement requirements arise, a high level language of over twenty commands has been included. It gives absolute control over the sequence of data collection, including output trigger, input trigger, memory used, and number of scans taken. Any number of data acquisition modes may be created for the Model 1461 and loaded from the host computer.

The Model 1461 Detector Interface can be equipped with a High Speed Serial/Parallel Card, which allows it to be connected to the Model 1460 System Processor. This configuration allows the detector to operate remote (up to 100 feet) from the Model 1460 System Processor and still have all the advantages of our exclusive OMA® III software. Real-time spectra are displayed on the Model 1460 Soft-touch screen and later stored on the floppy disk. This card can also be used to transfer data to another computer, using 16-bit parallel transmission.

Model 1461 Hardware. The Model 1461 Detector interface is based on a sophisticated Motorola 68000 microprocessor. The VME standard bus structure is used for all expansion modules. This basic system consists of the CPU card with 128K of ROM and 32K of RAM storage. Also included on the CPU board are the two computer interfaces, IEEE-488 GPIB and RS232C, and a PIA parallel interface adapter. This configuration will allow six double precision (32 bits/point) 1024-element curves to be stored or as many as 24 single-precision 512-element curves. The standard memory is expandable with the addition of optional 256K byte or 2MEG byte memory cards.

The Detector Interface requires one detector controller module to complete a basic system. The Model 1462 Detector Module is a single-card module designed to control any of the 145X series detectors. It has a 12-bit ADC and can acquire a spectrum of 512

elements in 15 ms. A 1024-element detector can be read in 30 ms and stored in memory. In addition, the Model 1462 has a video output for a real-time display on any oscilloscope and both Trigger Out and Trigger In. A Source Compensation input is provided to normalize the spectrum against the fluctuations of a light source. An optional 14-bit ADC is available as a plug-in card and decreases the scan time to 20 ms per 1024-element detector and 10 ms per 512-element detector.

The Model 1463 Detector Module is a three-card module designed to control Models 1412, 1412F, and 1420 Detectors. Based on a 14-bit ADC, it can digitize data at 16 μ s/channel. It supports fast access, grouping, and mixed mode scan patterns. Trigger Input and two Trigger Outputs are provided, as well as X, Y, Z outputs for monitor scopes. In addition, an Analog input with a bias adjustment is accessible from the rear panel for Source Compensation.

Computer Interfacing. The Model 1461 Detector Interface comes with both RS232C and IEEE-488 GPIB as standard. A high speed serial port (HSS) for connection to the Model 1460 System Processor and a DEC 16-bit parallel DRV11-B interface are available as a separate card.

The RS232C interface can be set from 150 baud up to 19.2K baud. It supports 7 or 8 data bits, 1 or 2 stop bits, odd, even or no parity checking, hardware handshaking and XON-XOFF software handshaking. The software can detect and configure the interface to accept carriage returns or carriage return-line feeds as a terminator. The RS232C offers one advantage over other computer interfaces available; it can be used where a long distance between the host computer and the Detector Interface is necessary.

The IEEE-488 GPIB also has some distinct advantages over the older methods of transmitting data and commands. The GPIB can provide data at $\sim 12 \mu\text{s}/\text{byte}$ in Binary Dump Mode. Thus a full 1024 point curve can be output in 60 ms (start overhead time included). It can also be used in a star configuration or a daisy-chain configuration. This means one host computer can be connected to more than one Detector Interface or, alternatively, one Detector Interface and several other GPIB compatible instruments, such as plotters, printers and motor-driven spectrographs, could be connected.

The Model 1461 is a truly intelligent Detector Interface. It is the ideal solution to low cost, high speed parallel detection of optical spectra and yet, can be expanded to meet the most demanding of future needs.

Detectors. Several different photodiode array detectors, each with its own unique advantages, are available. The individual detectors in the OMA[®] III family are explained more fully in their specification sheets.

Models 1452 and 1453 Detectors. The Model 1452 is a 512-element unintensified detector based on a Reticon linear photodiode array. The Model 1453 is a 1024-element version of the same detector. Each has a broad wavelength response of 200 nm to 1100 nm. Individual photodiodes are $25 \mu\text{m}$ wide by 2.5 mm high and the length is 12.5 mm for the 512 array and 25 mm for the 1024 array. They include a Peltier cooler to maintain a normal operating temperature of $+5^\circ\text{C}$ and can be set to a user selectable temperature (-19°C limit) under software control. A

water flow block to remove heat at the lower setting and a N_2 purge port to prevent moisture build up are provided.

Model 1454 Detector. The most sensitive of the 145X series of detectors is the Model 1454—a 512-element intensified diode array providing detection levels of approximately 100 photons per ADC count. The array dimensions are $25 \mu\text{m}$ by 2.5 mm by 12.5 mm long and temperature is maintained at $+5^\circ\text{C}$ by a Peltier cooler. Like the other detectors of this series, low temperature operation, N_2 purge, and water flow block are standard. The wavelength response of the 1454 is limited by the intensifier to the range of 365 nm to 800 nm. An optional UV scintillator extends the blue response to 200 nm.

The rear panel of the Model 1461 shows the plug-in VME bus modules. The top module is the CPU with RS232C, GPIB and PIA. Next down is the Model 1463 Detector Module (3-card set) with connectors for Triggers and other control signals. Last is a 256K byte RAM module. There are three empty slots behind the bottom blank panels.

High Performance Detectors.

Model 1412 and 1412F

Detectors

The Model 1412 is a 1024-element silicon photodiode array detector that incorporates a Peltier cooler for normal operation down to -20°C and even lower with supplemental liquid cooling. Extended integration directly on the photodiodes is therefore possible. The spectral response is from 200 to 1100 nm and it has the highest sensitivity of any unintensified detector. The Model 1412F detector has been designed for direct coupling to fiber optic outputs and has a fiber optic faceplate in place of the quartz window. It can be used wherever the experimenter requires a special design intensifier or other input optics.

Model 1420-1421 Detectors. This family of 12 intensified diode array detectors offers a sensitivity of one ADC count per detected photon. Selection of a cathode type, number of detector elements, and gating ability allows the user cost-effective matching of the detector to the experiment. The whole family features low geometric distortion and the ability to cool the array to -40°C for long integration times.

The **Model 1422 Detector** features 1000 elements and one count per detected photon performance at a low cost. The detector is ideal for applications that do not require gating or UV sensitivity. Although this detector has some geometric distortion, it has excellent line spread (resolution). The M1422 can be cooled to -40°C .

Data Acquisition Mode Power. The following three Data Acquisition Modes are listed to present typical examples of the *Acquisition Power* of the M1461.

```
ACQUISITION MODE #2
FOR M = MEM TO MEM + J
  TRIGGER OUT
  ON TRIGGER
  FOR S = 1 TO I
    ADD
  FOR G = 1 TO K (K can equal 0)
    IGNORE
  NEXT G
  NEXT S
  NEXT M
```

EXPLANATION: 'J' sets of scans occur with 'I' scans in each set. Each set of scans is preceded by a TRIGGER OUT and an ON TRIGGER. A complete set of 'I' scans is taken after each ON TRIGGER and the results from each set are ADDED into separate memories. There is provision for ignoring 'K' scans after each ADDED scan.

Mode (2) is identical to Mode (1), except that the instrument must wait for an incoming ON TRIGGER signal before beginning each set of scans.

COMMENT: DA2 with J = 1 and K = 0 is a classic data acquisition mode. With J > 1, a series of experiments can be run. Setting K > 0 can be used for such timing convenience as allowing a laser's supply to recharge.

```
ACQUISITION MODE #7
  TRIGGER OUT
  FOR M = MEM TO MEM + J
    STORE
  FOR G = 1 TO K (K can equal 0)
    IGNORE
  NEXT G
  NEXT M
```

EXPLANATION: Following a single TRIGGER OUT, 'J' scans occur. The result of each is STORED in a different memory. There is provision for ignoring 'K' scans after each STORED scan.

COMMENT: In DA7 the STORE command uses 2 bytes to store a data point, allowing better utilization of memory in this *kinetics* mode.

K > 0 can be used to slow down the sampling rate in the basic time units of detector scans for a kinetics experiment.

```
ACQUISITION MODE #12
FOR MEM = MEM TO MEM + J
  TRIGGER OUT
  STORE
  SUBTRACT
  FOR G = 1 TO K (K can equal 0)
    IGNORE
  NEXT G
  NEXT M
```

EXPLANATION: There are 'J' scan pairs, with each pair using a different memory. Each is preceded by a TRIGGER OUT. The first scan of each pair is STORED in memory. The second scan of each pair is SUBTRACTED from the one just STORED. There is provision for ignoring 'K' scans after each SUBTRACTED scan.

COMMENT: Mode DA12 is ideal for application to pulsed experiments that are taken in dynamic optical backgrounds. The subtraction of the scan immediately after the "hot" scan allows the most accurate possible background correction. It also combines what used to be two experiments into one.

The IGNORE feature of this mode allows the user to do low duty cycle experiments with short detector exposure times. Thus minimizing dark current or the need to add water cooling to the peltier.

DA X: The ability to mix ADD, SUB, IGNORE, STORE, TRIG OUT, ON TRIG, PIA commands etc. in virtually limitless combinations allows total flexibility to maximize OMA performance for experiments not covered by the standard set of DA modes. This feature means that the M1461 will be able to grow into as yet undefined experiments.

All DA modes have corresponding modes with no output triggers. This feature allows the user complete freedom to take experimental backgrounds without the need to disconnect BNC cables. (Just one example of the attention to experimental detail gained through 14 years of OMA design.)

Sample Commands for M1461. To help understand the ease of programming a M1461, a small sample of the high level commands is listed below.

A ":" is the command delimiter, an "n" indicates a numerical input, and a "d" indicates a default condition. An "r/s" denotes a command that functions as an input when an "n" is present or a status poll when no "n" is present. The large number of "r/s" commands are especially useful during program design. Also a string of commands may be stored and executed by a single command.

STATUS COMMANDS

CL:	Reply is a 1 if peltier cooler is temperature-locked at set point. Reply is 0 if peltier cooler is still moving toward lock.
DLEN:	Reads the detector length (512 or 1024)
ERR:	Responds with error codes.
MIN ET:	Tells programmer the minimum allowed exposure time based upon the current detector setup and size.
MAX.MEM:	Tells programmer the maximum number of available memories.

DETECTOR CONTROLLER SETUP COMMANDS

DT n: r/s	Detector temperature in °C.
ET n: r/s	Exposure time in seconds (i.e., 3.02)
TRIG.ON:	Turns main trigger on
TRIG.OFF: d	Turns main trigger off
LS:	Sets the detector controller to line-synchronized scans
DDRA n:	Sets the direction of data register A
PORT.A n: r/s	Sets or reads the data register A.

DATA ACQUISITION COMMANDS

DA n: r/s	Selects one of the preprogrammed data acquisition modes
I n: r/s	Selects the number of detector scans added into a memory during a data acquisition
J n: r/s	Selects the number of memories to be filled during a data acquisition
K n: r/s	Selects the number of detector scans that are ignored during a data acquisition
RUN:	Begins data acquisition. All memories set to receive data will be cleared before operation

CURVE CALCULATION COMMANDS

CLR n:	Sets memory, n, to zero
CLR ALL:	Sets all memories to zero.
MEM n: r/s	Sets current memory to, n, or tells program the current memory numbers
SUB n1, n2	Subtracts the contents of memory, n1, from memory, n2, leaving the result in memory, n2
DP:	Responds with data precision of currently-selected Data Acquisition Mode.

SAMPLE PROGRAM

The following string of commands are all that is needed to execute an externally triggered experiment.

CL:	Is the cooler locked?
ET 1:	Set exposure time to 100 ms
DA 2:	Select one of the externally triggered acquisition modes
I 1:	One detector scan will be stored
J 1	One trigger out/in sequence will be stored
K 0:	There will be no ignored scans
RUN:	The experiment is executed
BD 1, 1, 1024:	Data is sent to the host computer

Other System Components. ECG&G Princeton Applied Research Corporation

offers many other instruments to complement the OMA* III family. Individual specification sheets are available on the Model 1228, Model 1229, and Model 1233 Spectrographs

The *Model 1303 Gate Pulse Interface* is a VME card that provides software-controlled delays for all pulses and software-controlled width for the Model 1304. Major features are the ability to increment delays up to 13 ms in 1 ns steps, an electrical trigger, and an on-board optical trigger.

There are two gate pulse generators used to gate detectors on and off. The Model 1304 Pulse Amplifier combined with the Model 1303 or a user-supplied pulse generator supplies gate pulses in the 100 ns-10 ms range. The Model 1302 supplies gate pulses in the 5-20 ns range.

Warranty. All hardware carries a 24-month warranty. For a small added charge, all detectors can be warranted for 24 months.

Model 1461 Specifications

FRONT PANEL LEDS:

- Cooler Lock
- Interface Status
- Remote
- Talk
- Listen
- Service Request
- Error

REAR PANEL: 8 VME Standard Card Slots

INCLUDED CARDS: CPU—1 slot

CHOICE OF DETECTOR MODULES:

1462 Detector Module (145X series)—1 slot

1463 Detector Module (1412 and 1420)—3 slots

OPTIONAL CARDS:

1461/98 HSS/PAR—1 slot

1462/99 14-bit ADC—1 slot

2000-0091 Extended Memory, 256K byte—1 slot each

2000-0113 Extended Memory, 2Meg byte—1 slot

1303 Gate Pulse Interface—1 slot

CPU Module Specifications

MICROPROCESSOR: Motorola 68000, 16 bits

MEMORY: 12bK ROM, 32K RAM (expandable with VME bus RAM Cards)

MEMORY CAPACITY (STANDARD): 6 double-precision (32 bits)
1024-element curves: 24 single-precision 512-element curves

COMPUTER INTERFACE:

RS232C 25-pin (DB-25S) connector

IEEE-488 GPIB connector

PIA 25-pin (DB-25S), 16-bit user-programmable I/O port

Reset Switch

DIMENSIONS: 18.75" (47 cm) wide x 7.5" (19 cm) high x 15" (38 cm) deep

WEIGHT: 37.5 lbs (17 kg)

SHIPPING WEIGHT: 45 lbs (20.5 kg)

POWER: 120/240 V, 50/60 Hz

ACCESSORIES: Rack Mount Ears, Cables (depending on configuration)

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OMA[®] III

MODEL 1422

INTENSIFIED DIODE ARRAY DETECTORS

DESCRIPTION

The 1422R-1024-N-F and the M1422-1024-N utilize an image inverting, electrostatically focused image intensifier fiber optically coupled to a diode array. The difference between the two detectors indicated by the -F (Fast) designation is the speed of the phosphor in the intensifier. This high gain detector is an excellent choice for experiments in the 350 to 900nm wavelength region that do not require gating. Although there is a small amount of geometric distortion due to the electrostatic image section, the line spread of this detector is excellent when compared to a proximity focused MCP intensified detector.

The M1422 uses an S-20R photocathode behind a glass fiber optic input. The sensitivity is very high in the visible and red with the characteristic glass cut off around 350nm. UV sensitivity can be gained with the deposition of a chemical scintillator (M1422/01

option) onto the fiber optic input of the detector. As shown by the typical curve, the scintillator does degrade performance in the visible. Therefore, the scintillator should be selected only if absolutely required.

These detectors are controlled by the M1463 detector controller, a VME card set that is fully compatible with either the M1460 or M1461. Some features of the M1463 are mixed scan of the diode array, digital control of temperature and exposure time, source compensation, and full compatibility with all DA modes.

Some applications of the M1422 are:

- Raman
- Fluorescence
- Phosphorescence
- Plasma Monitoring
- Emission Spectroscopy
- Low Level Absorbance or Transmittance

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C-71

SPECIFICATIONS

1422R-1024-N 1422R-1024-N-F

25mm Intensifier
S-20R behind glass
fiberoptic

1024 Element
Diode Array

Cannot Be Gated

Fast Phosphor

DETECTOR TYPE: Inverting, electrostatically focused, MCP intensified, Diode Array

PHOTOSENSITIVE MATERIAL: S20R behind glass fiberoptic

WAVELENGTH RANGE (NM): 350-900
(< 200-900 with/01 scintillator)

QUANTUM EFFICIENCY:

	550nm	800nm	850nm
Minimum	.05	.023	.015
Typical	.07	.05	.038

SENSITIVITY (PHOTON/COUNT):

	550nm	800nm	850nm
Minimum	20	43	67
Typical	15	20	27

GAIN (COUNT/PHOTOELECTRON):
> 1

DYNAMIC RANGE W/M1463
CONTROLLER: 16383

DEVIATION FROM LINEAR
RESPONSE: < 1%

UNIFORMITY OF RESPONSE
ACROSS DETECTOR:

± 10% Typical ± 20% Maximum

GEOMETRIC DISTORTION: 5% *

OF ACTIVE ELEMENTS: Size of
Elements 1000 Typical 990 Minimum
25um x 2.5mm

SYSTEM NOISE (COUNTS/√SCAN):
@ 20 ms, 5°C ≤ 1

DARK CURRENT: 1 sec @ 5°C,
typical 1000 cts.

LINE WIDTH # of Channels FWHM: 3

PHOSPHOR PERSISTENCE: (mSec)
After removal of CW illumination

Detector	10%	1%
-N	200	1000
-N-F	3	25

* Measured using

$$\left[\frac{\text{Magnification (11mm)} - \text{Magnification (center)}}{\text{Magnification (center)}} \right] \times 100\%$$

using 2mm image feature

Wavelength error can be corrected by software in M1460

OMA III

MODEL 1420, 1421

INTENSIFIED DIODE ARRAY DETECTORS

Fast Gate (G) and High Quantum Efficiency (HQ) Options

DESCRIPTION

The 1420/21 detector family features a proximity focused, microchannel plate (MCP), image intensifier coupled via fiber optic bundles to a linear diode array. Detector electronics have been carefully optimized to assure optimum exposure time, sensitivity, and intensifier life.

These detectors, controlled by the M1463 detector controller (VME card set), are fully compatible with all the data acquisition power of the 1460 or 1461. A major 1420/21-1463 system feature is the ability to "mix mode scan". "Fast Accessed" pixels can be rapidly scanned in order to lessen the number of data points and increase the scan rate. Contiguous pixels can be "Grouped" into single data points to increase detectivity, increase scan rate, and lessen the number of data points. Fast Accessed and Grouped pixels can then be combined with Normally scanned pixels in virtually limitless combinations.

Some important detector features are:

- High Sensitivity—MCP amplification generates more than one ADC count for each detected photon. Standard gain is 1.3 counts/photo-electron to ensure a true 10,000:1 dynamic range. If needed, gain can be adjusted up or down.
- Low Noise
- Low Distortion—Proximity focusing causes minimal image distortion, especially when compared to electrostatically focused intensifiers.

- Broad Wavelength Coverage

- Large ON/OFF Ratio—When the intensifier is off, light leakage through the intensifiers is so low as to be virtually immeasurable.

The M1420 and M1421 detectors use 18mm and 25mm diameter intensifiers respectively. Photocathode response is specified as blue (B) or red (R) enhanced. The detectors may be ordered in a fast gate (G) or high quantum efficiency (HQ) configuration. The number of elements in the diode array is either 512 or 1024. The above options are combined into a "1420B-512-G" format (18 mm, Red enhanced, 512 element, Fast Gated).

The M1420 and M1421 are used in any application that requires high sensitivity over the whole UV-VIS range, fast time resolution, or rejection of background light. A partial list of applications are:

- RAMAN
- Fluorescence, Luminescence
- Phosphorescence
- Pulsed Laser Spectroscopy
- Picosecond Spectroscopy
- Laser Diagnostics

Special order, non-standard versions of the 1420 and 1421 are available. Examples are Solar blind intensifiers (Cs-Te), BR intensifiers, and intensifiers with lower priced, sub-spec cathodes for high light, time-resolved applications.

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SPECIFICATIONS

DETECTOR TYPE: Proximity focused,
MCP intensified diode array

PHOTOCATHODE: Multi-alkali on
S1-UV-A fused silica faceplate

INTENSIFIER DIAMETER: M1420-18 mm
M1421- 25 mm

SIZE OF DETECTOR ELEMENTS:
25 μ m (x), 2.5 mm (y)

Of Active Elements: 1420— 512, 512
Minimum 1420—1024, 700
1421—1024, 990

WAVELENGTH RANGE: 180–900 nm

GAIN (counts/photoelectron)²: > 1

DEVIATION FROM LINEAR
RESPONSE: < 1%

DYNAMIC RANGE W/1463: 16383

UNIFORMITY OF GAIN ACROSS FACE
OF DETECTOR³: $\pm 25\%$, $\pm 10\%$ typical

GEOMETRIC DISTORTION: < 1 channel

LINE WIDTH⁴: 3 channels FWHM

DARK CURRENT⁵ (counts):

	1024 element	512 element
.8 sec, +5°C Max.	2970	1980
.8 sec, +5°C Typical	350	560
1.0 sec, +5°C Typical	440	700
1.0 sec, -20°C Typical	35	60

TEMPERATURE RANGE W/M1463:
5° to -40°C

EBI⁶: 3×10^{-11} LM/CM²

SYSTEM NOISE⁷: < 1
counts/(scans)^{1/2}

ON/OFF RATIO: > 10⁴

GATE WIDTH⁸ Minimum:

1420..... G, 1421..... G	5 ns
1420R.... HQ	50 ns
1420B.... HQ, 1421R.... HQ	100 ns
1421B.... HQ	150 ns

QUANTUM EFFICIENCY: listed in % and (mA/Watt)¹:

		300 nm		550 nm		830 nm	
		-G	-HQ	-G	-HQ	-G	-HQ
1420B	Minimum	12.4 (30.0)	17.6 (42.5)	6.76 (30.0)	11.3 (50.0)	X	X
	Typical	13.6 (33.0)	24.8 (60.1)	10.2 (45.3)	15.0 (66.2)	1.0 (7.0)	1.2 (7.9)
1420R	Minimum	X	X	6.76 (30.0)	11.3 (50.0)	1.5 (10.0)	2.65 (17.5)
	Typical	7.8 (18.9)	8.4 (20.3)	10.5 (46.4)	15.7 (69.7)	2.5 (16.7)	3.3 (21.9)
1421B	Minimum	10.3 (25.0)	17.6 (42.5)	6.76 (30.0)	11.3 (50.0)	X	X
	Typical	10.9 (26.4)	21.3 (51.5)	9.1 (40.3)	13.7 (60.8)	.88 (5.9)	1.34 (9.0)
1421R	Minimum	X	X	6.76 (30.0)	11.3 (50.0)	1.5 (10.0)	2.65 (17.5)
	Typical	4.9 (11.9)	6.5 (15.7)	9.4 (41.5)	14.4 (64.0)	1.9 (12.8)	3.8 (25.3)

145X

DIODE ARRAY DETECTORS

1452A and 1453A

FEATURES

- *Compact Size*
- *High Reliability*
- *15 Bit Dynamic Range*
- *Optimized Mechanical Design*
- *Single Window Design*

APPLICATIONS

- *Plasma Monitoring*
- *Radiometry and Colorimetry*
- *Light Source Diagnostics*
- *Absorbance and Transmittance Measurements*
- *Optical Component Testing*
- *Laser Scattering*

1455A and 1456A

FEATURES

- *High Sensitivity*
- *Improved Minimum Detectable Flux*
- *Low Distortion*
- *Broad Wavelength Coverage*
- *Large ON/OFF Ratio*
- *Large Choice of Intensifiers*
- *15 Bit Dynamic Range*

APPLICATIONS

- *Raman*
- *Fluorescence*
- *Phosphorescence*
- *Luminescence*
- *Pulsed Laser Spectroscopy*
- *Picosecond Spectroscopy*
- *Laser Diagnostics*

OVERVIEW

The M145XA series is a family of *cost effective* linear diode array based detectors for the M1471A and M1461 detector interfaces and the M1470A and M1460 detector consoles. These high-performance detectors are designed to cover the entire experimental range of time resolutions (pico-seconds to hours) and light levels. These detectors provide 15 bits of dynamic range when used with the M1470A or M1471A. Detector control when used with the M1460 or M1461 is supported via the M1462 detector controller interface (VME card set) which has a standard 12 bit ADC. A 14 bit ADC UPGRADE is available as the M1462/99 option.

All four M145XA detectors are fully compatible with the NEW DAD (Data Acquisition Design) software and the present data acquisition power of any of the controllers.

The M145X series detectors are divided into two SENSITIVITY groups: non-intensified (1452A,1453A) and microchannel plate (MCP) intensified (1455A,1456A).

1452A and 1453A

These unintensified detectors are based on 512 and 1024 element EG&G Reticon linear photodiode arrays and respond over the wavelength range of 180 to 1100 nm.

Some important features:

Compact size

High reliability

Operating temperature as low as -40°C with cooling liquid assist. This allows long light integration times to improve minimum detectable flux.

Optimized mechanical design minimizes light scatter and eliminates vignetting at the input.

The M1452A and M1453A utilize the diode array's fused silica window as the only window in front of the silicon detector. This **single window design** eliminates the light loss and scatter caused by the second window in many detector designs. Condensation on the diode array's window (due to cold operation) is eliminated by the controlled exhausting of required dry purge gas.

1455A and 1456A

These detectors are variable gain gatable (nanoseconds) proximity focused, micro-channel plate (MCP), image intensifier coupled via fiber optic bundles to a linear diode array. They differ only in respect to the overall diameter of the intensifiers—M1455A 18mm or M1456A 25mm. Both are ideal detectors for applications that require high sensitivity over the entire UV-VIS range, fast time resolution or rejection of ambient background light.

Some important features:

High Sensitivity- MCP amplification generates more than one ADC count for each detected photon. In standard units, the gain is adjusted to 1.3 counts/photo-electron to ensure a true 10,000:1 dynamic range. If needed, gain can be adjusted up or down through a Precision MCP Variable Gain Control. Reproducibility for the different gain settings are maintained through a precision counter-dial.

Improved Minimum Detectable Flux (MDF)¹- The M1455A and M1456A employ a new exclusive PARC feature that optimizes cooling of the MCP intensifier's pho-

1455A and 1456A (continued)

tocathode. This feature, called COOL CATH™, not only improves the signal averaging of weak signals but also eliminates any condensation build-up on the intensifier's faceplate.

Low Distortion- Proximity focussing causes minimal image distortion, especially when compared to electrostatically focussed intensifiers.

Broad Wavelength Coverage- Multi-alkali photocathodes behind S1-UVA grade Fused Silica face plates yield maximum coverage.

Large ON/OFF Ratio- Gating the intensifiers allows time resolved measurements of low level signals that are buried in an intense background.

Large choice of intensifiers- Eight different intensifiers, each with its own unique advantages, are available for the M1455A and the M1456A. Although not listed in the tables two "BR" enhanced intensifiers are also available.

The M1455A can be supplied with either a 512 element or a 1024 element silicon diode array. The M1456A is supplied with a 1024 element array. Photocathode response is specified as blue enhanced (B) or red enhanced (R). Overall intensifier sensitivity are designated by (G) for fast GATE version or (HQ) for high quantum efficiency. The above options are combined into a "1455R-512-G" format (18 mm, Red photocathode enhanced, 512 element, Gated).

DETECTOR SENSITIVITY

Typical Sensitivity curves are presented in Fig 1.

Figure 1. Sensitivity Curves

TABLE 1

Quantum Efficiency: listed in % and (mA/Watt)²

	300nm		550nm		830nm	
	G	HQ	G	HQ	G	HQ
1455B						
minimum	12.4(30)	17.6(42.5)	6.76(30)	11.3(50)	X	X
typical	13.6(33.0)	24.8(60.1)	10.2(45.3)	15.0(66.2)	1.0(7.0)	1.2 (7.9)
1455R						
minimum	X	X	6.76(30)	11.3(50)	1.5(10)	2.65(17.5)
typical	7.8(18.9)	8.4(20.3)	10.5(46.4)	15.7(69.7)	2.5(16.7)	3.2(21)
1456B						
minimum	10.3(25)	17.6(42.5)	6.76(30)	11.3(50)	X	X
typical	10.9(26.4)	21.3(51.5)	9.1(40.3)	13.7(60.8)	.88(5.9)	1.34(9.0)
1456R						
minimum	X		6.76(30)	11.3(50)	1.5(10)	2.65(17.5)
typical	4.9(11.9)	6.5(15.7)	9.4(41.5)	14.4(64.0)	1.9(12.8)	3.2(21)

TABLE 2

Typical photons/count: G/HQ detector

With Model 1470A and 1471A:

nm	200	252	300	404	550	830
1455B	2.9/2.0	3.0/1.6	3.1/1.7	2.8/1.8	4.1/2.8	41.4/34.5
G/HQ						
1455R	X/X	5.2/4.5	5.3/4.9	4.8/5.3	3.9/2.7	16.6/13.0
G/HQ						
1456B	2.4/1.9	4.2/2.3	3.8/2.0	3.2/2.0	4.6/3.0	46.8/30.9
G/HQ						
1456R	X/X	11.5/6.0	8.4/6.4	7.8/5.6	4.4/2.9	21.7/13.0
G/HQ						

With Model 1460 and 1461:

nm	200	252	300	404	550	830
1455B	6.9/4.8	7.3/3.9	7.4/4.0	6.8/4.3	9.8/6.7	100.0/83.3
G/HQ						
1455R	X/X	12.5/10.8	12.8/11.9	11.7/12.7	9.5/6.4	40.0/31.3
G/HQ						
1456B	5.7/4.6	10.1/5.6	9.2/4.7	7.8/4.7	11.0/7.3	113.0/74.6
G/HQ						
1456R	X/X	27.8/14.5	20.3/15.4	18.8/13.6	10.6/6.9	52.3/31.3
G/HQ						

145X DIODE ARRAY DETECTOR SPECIFICATIONS

	M1452A	M1453A	M1455A/M1456A	
Detector type	Silicon Diode Array	Silicon Diode Array	Proximity focussed MCP intensified diode array	
Photosensitive material	Silicon behind fused silica face plate	Silicon behind fused silica face plate	Multi-alkali photocathode on S1-UV-A fused silica faceplates	
Intensifier Diameter	NA	NA	M1455-18 mm; 1456-25 mm	
# Of Active Elements: all 25 μm x 2.5 mm	512	1024	1455-512 512 1455-700 700 1456-990 990	
Wavelength Range (nm)	180-1100	180-1100	180-900	
Quantum Efficiency	.7 @ 650 nm	7 @ 650 nm	.12 see table 1 for details	
Typical Sensitivity @ 550 nm (photon/count)				
w/1470A-1471A	1160	1960	see table 2	
w/1460/1461	2800	4500	8 see table 2 for details	
GAIN(photoelectrons/count)				
w/1470A-1471A	830	1350	NA	
w/1460-1461	2000	3100	NA	
Variable Gain	NA	NA	.1 ct/pe to 4 ct/pe ¹	
Deviation from Linear response	<1%	<1%	<1%	
Dynamic Range w/1470A-1471A	32768	32768	32768	
w/1462	4095	4095	4095	
w/1462/99	16383	16383	16383	
Uniformity of response across detector	5%	5%	$\pm 25\%$ $\pm 10\%$ typical ⁴	
Geometric Distortion	<1 channel	<1 channel	<1 channel	
Line Width	2 channels FWHM ⁵	2 channels FWHM ⁵	3 channels FWHM ⁵	
Dark Current in counts ⁴			512 element	1024 element
800 ms @ 5° C Maximum	2850	2500	2850	2500
Typical	1160	910	1160	910
1 sec @ 5° C Typical	1430	1120	1430	1120
1 sec @ -20° C Typical	120	100	120	100
Temperature Range	-40° C to 18° C	-40° C to 18° C	-40° C to 18° C	
EBI ⁷	NA	NA	3×10^{-11} LM/CM ²	
System Noise(counts $\sqrt{\text{scan}}$) ²	<1.5	<1.5	<1.5	
On/Off Ratio	NA	NA	>10 ⁶	
Gate Width ⁶ , Minimum	NA	NA	1455G, 1456G	5 ns
			1455R-HQ	50 ns
			1455B-HQ,	
			1456R-HQ	100 ns
			1456B-HQ	150 ns

1 Minimum Detectable Flux (MDF) is the amount of light signal (photon/sec) required by a detection element to produce an A/D count that is twice the system noise level. Thus, a signal equal to the MDF would provide a signal-to-noise ratio of two

2 Detectors are delivered with actual QE data at 10 wavelengths between 200 and 900 nm. The typical numbers above are an average of 15 detectors received just before this table was constructed. Because photocathode manufacture is still not a science, the typical values can change up or down. The minimum #'s at the three specified wavelengths are always guaranteed. The red response @ 830 nm can vary greatly because of the sharpness of the drop on the red side of the response curve.

3 Set to 1.3 counts/photoelectron at factory as optimum point for dynamic range, detectivity, and intensifier life. It can be set higher if needed. Measured by flood illuminating with a known photon/(CM² • SEC) flux and integrating total "light-dark" counts over the center 960 pixels for 1456, center 660 pixels for 1455-700, and center 490 pixels for the 1455-512.

4 Value is maximum difference from mean for array in regions specified in note 2 when exposed to uniform illumination

5 Measured by focussing 25 μm wide line onto detector

6 Measured by subtracting .8 sec dark signal from 1.6 sec dark signal. Some arrays have a few pixels with dark currents that rise above the normally smooth baseline. As long as the dark pattern is stable and the highest point is below the specification, the array is allowed. Dark current decreases about a factor of 2 for every 7° C drop in temperature.

7 When combined with luminous gain in mA/Lm and converted for pixel size of 6.25×10^{-4} CM², typical performance is 5 photoelectrons/(pixel • sec) or 6.5 counts/(pixel • sec) for "B" detectors and 10 photo-electrons/(pixel • sec) or 13 counts/(pixel • sec) for "R" detectors. Performance improves when cooling water and cooled dry nitrogen gas is supplied to the detector

8 Measured by subtracting the results of two, 50 scan dark signal accumulations (5° C and 20 ms/scan,) and then dividing by 10

9 Numbers are measured at the FWHM of the gate pulse applied.

DETECTOR OUTLINE DRAWINGS

Figure 2. Outline Drawing of 1452A and 1453A

Figure 3. Outline Drawing of 1455A and 1456A

EG&G PRINCETON APPLIED RESEARCH

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FRANCE 1/60/779366 • JAPAN 03-638-150

2000 OMA[®] SPEC

General Purpose OMA Spectroscopy Software

Preliminary
Data Sheet

Features

- Supports all PARC solid state detectors via the Model 1461, including CCD, NIR, Diode Array, Intensified Diode Array
- Large data storage capacity for CCDs (32K spectra at 64K points per spectrum)
- Automated data acquisition modes
- Method storage
- Eight curve windows
- Context-sensitive Help
- 3-D plots with variable offset angles and hidden line removal
- Selectable IEEE address for easy peripheral control
- Near-real-time screen updates
- File conversion utilities
- Live DA mode operation
- Spectrometer control
- Macro capability
- Intensity-versus-time processing
- Multiple detector support

Description

The OMA[®]SPEC 2000 from Princeton Applied Research represents a complete redesign of our OMA software, both technically and in look-and-feel. This new package, written in Microsoft C, is equipped to run on all IBM ATs, IBM PS/2s and 100% IBM-compatibles with a 80286, 80386, or 80486 processor.

The software operates with all PARC solid state detectors, including our new CCD and NIR detectors and our wide range of intensified and unintensified diode array detectors. And it supports our exclusive Data Acquisition Modes for both Diode Arrays and CCDs. We've reworked the screens to make it easier than ever for you to set up and run experiments and perform related tasks like retrieving data or making calculations.

What does this redesign mean to you? For one thing, it gives you the best available OMA spectroscopy software in the world. For another, it gives you a solid foundation for future growth. The OMA SPEC 2000's comprehensive detector support lets you take advantage of PARC's full line of detectors, which in turn gives you the applications flexibility you need for future expansion.

Future Enhancements

Our development efforts don't end with the rich set of features already installed. Here's a list of features on the drawing board:

• Foreground/Background data acquisition mode	• Auto calibration
• Auto autoscale!	• Y-axis calibration
• Auto exposure control	• Curve separation
	• Applications packages

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Oriel SPECTRAL DATA ACQUISITION SYSTEMS

PC Based

- Designed for IBM PCs and compatibles
- Complete scan control - customize your own scan
- Complete hardware and software
- Support many types of detector
- Software for radiometry, absorption, fluorescence
- Single or double beam

If you are considering setting up spectroscopy equipment which involves scanning a monochromator and taking data, then the hardware and software described on the next few pages can save you a lot of time and effort. You can quickly put together a versatile and powerful system for spectroscopy based on an IBM PC compatible computer; spectroscopy anywhere from the ultraviolet to the infrared. You can choose scan parameters to suit your application.

We describe two boards which plug into the slots inside the computer. Both boards are supported by software to operate our monochromators (with appropriate drive hardware) and take signals from detectors.

- The **78350 Autoranging Radiometry Board** is for detectors which behave like current sources; photomultipliers and photodiodes. This board has built-in autoranging for very wide dynamic range without operator intervention.
- The **78250 Voltage Radiometry Board** is for any detection system where the final output is in volts proportional to signal. This includes many infrared detection systems employing beam chopping where the signal is recovered by our 70707 Lock-in amplifier. The 7070 Photomultiplier Detector System and 70701 Readout also have suitable outputs.

DETECTION EQUIPMENT

Fig. 1 (a) to (d) show the spectral distribution of a semiconductor diode laser as the current is increased. The spectrum shifts to longer wavelengths as different modes compete for gain. Even at high current, (c), low level spectral features are apparent. You can examine these using the different plot scaling capability. The spectra were recorded using a 77344 Photomultiplier, the 78350 Autoranging Radiometer Board, 77200 1/4 m Monochromator with 77233 grating and 10 μ m slits. The 78350 commanded the 20025 Stepper Interface to operate the 77245 Dual Ratio Wavelength Drive in the high resolution mode (0.01 nm steps). This took full advantage of the high resolution of the 77200. The resolution is shown clearly in the expanded view of spectrum (b). The log plot of the expanded view also shows the plotting capability of the 78350.

Fig. 2 (a) Near Infrared Hemispherical Total Reflectance (8°) of an anodized aluminum surface. (Total reflectance is specular plus diffuse). The data was recorded and ratioed with the 78350. We used a 7182 Silicon Photodiode in the 71920 Detector Head on the 70491 Reflectance/Transmittance Sphere. The input beam was from a 77250 1/8 m Monochromator illuminated by the 60065 Series Q Source and a 6199 Secondary Focusing Lens (150 mm F.L.). A 51520 Long Pass Filter removed the second order radiation. We recollimated the beam with a 100 mm F.L. lens and apertured it to 15 mm diameter before entering the sphere. The reflectance value was derived by ratioing the data file for the anodized sample in the sample holder to the file recorded with the Oriel Certified Standards of Diffuse Reflectance (page 366). (b) shows the total reflectance of a glass plate for comparison.

78350 AUTORANGING RADIOMETRY BOARD

- Integrates Detector Input and Monochromator stepper motor driver into one package
- Seven decades of autoranging and 12-bit A/D converter allow nine decades of dynamic range
- Includes software
- Operation of up to two Monochromator Stepper Motors
- Supports two photocurrent inputs (picoamps to milliamps) for double beam mode or matrix scans
- Occupies single slot of IBM PC bus

The 78350 Autoranging Radiometry Board is a hybrid analog/digital card that plugs directly into the IBM PC Bus, to provide photodetector input and monochromator control. It is designed for, and supported by, spectrophotometry and spectroscopy software. The 78350 records photocurrent from photomultipliers and photodiodes. The 78250 is the version for input voltage.

PLUG-IN CARD

The physical card occupies a single slot in a PC-XT. It draws approximately 5 watts of power and has two BNC connectors and one DB-15 connector at the rear of the computer. The calibrated, high-gain analog circuitry is mounted in a shielded can off the surface of the motherboard for optimum electrical isolation. Shielded coaxial cable, isolated from the main motherboard, runs the signal from the BNC connectors into the analog front end (shielded can).

INPUTS

The 78350 card has a transimpedance amplifier input with software switched gain, a fixed gain stage, and a 12 bit A/D converter. Input bandwidth is 35 Hz. Maximum resolution is 0.24 picoamperes and maximum photocurrent is 1 milliamperere. No single photodetector can use the full range but you can cover the linear range of different detectors. See the following page for practical resolution and range with our photodetectors.

INPUTS

The two inputs are protected to 2000 volts DC across the input and current limited with an input impedance of 2 megohms. The amplifier is based around an ultralow noise FET precision op amp with switchable ranges of amplification. Each individual range is factory calibrated and directly controlled by software. The output from the analog circuitry is routed into a 12-bit A/D converter and ported through the PC Bus. The 78300 software controls the electronics, performing autoranging and signal processing of the input.

OUTPUTS

Two I/O output ports are for monochromator control. The output is routed through the DB-15 connector for interface to an Oriel 20030 or 20025 Stepper Interface (The 20025 Stepper Interface is for a single monochromator.) See Fig. 1.

The TTL outputs are decoded through address ports on the PC Bus and drive the 20030 (or 20025), capable of driving monochromators at step rates of 4000 steps per minute. (With a 1200 line grating this is 400 nm/min.)

Often a single monochromator is adequate. Both ports are used with dual monochromator arrangements for performing matrix fluorescence scans where both excitation and emission measurements are required.

Our Double Monochromator Systems (coupled mechanically) use a single Stepper Drive and therefore count as one monochromator.

DETECTION

Fig. 1 78350 Autoranging Radiometry Board

C-84

Oriel 78350 AUTORANGING RADIOMETRY BOARD

PHOTODETECTORS USED WITH THE 78350

Oriel carries a complete line of photodetectors which produce a photocurrent proportional to incident light intensity, with spectral sensitivities from the UV to the IR.

Silicon photodiodes come in a variety of sizes and packages, depending on the application, and offer high sensitivities, especially in the near IR. Germanium and Indium Arsenide photodiodes extend the range into the infrared. Photomultipliers have the greatest sensitivity in the visible and ultraviolet, (usually 2 orders of magnitude greater than silicon photodiodes) and produce a photocurrent that is proportional to light intensity over 6 to 8 orders of magnitude. However, they require a separate high voltage power supply (such as the 70705) to operate. Fig. 1 shows the computer reading against photocurrent over more than 8 orders of magnitude. (Photodetector linearity may not match this range.)

Fig. 1 The computer reading against photocurrent over more than 8 orders of magnitude. (Photodetector linearity and stray light usually limit the useful range.)

Dark Current

All photodetectors produce a small amount of quiescent current in the absence of light, commonly referred to as 'dark current.' The 78350 Software allows you to take a dark current reading which is then subtracted from all subsequent signal measurements.

REAL PERFORMANCE WITH PHOTODETECTORS

The principal detectors used with the 78350 are photomultipliers and photodiodes without bias.

Photomultipliers

These detectors are linear over a wide range if the dynodes are properly supplied and when the output is into a transimpedance amplifier. (The 78350 input is designed in this way). The maximum photocurrent is specified on page 218. For precision radiometry we recommend that the anode current be 10-100 times less than specified maximum. Avoid using currents of more than 1 μ A. Do not focus light on the photocathode as this will lead to local saturation. And in order to compare signals accurately they must be distributed equivalently over the sensitive area.

Dark currents can be 10-500 pA depending on tube, voltage and recent history. (Tubes exposed to high light levels have temporarily high dark currents). Dark current is not a fundamental limitation as it is subtracted out but dark current noise may limit the detectable signal level.

Fig. 2 shows a scan of a steeply rising spectral feature and demonstrates the wide dynamic range of the 78350. The scan was taken with a 77257 Double Monochromator with a 77345 photomultiplier tube, operated at 600 volts. The 78350 subtracted out the 10 pA dark current. Averaging time was 0.5 s. The low level signal below 610 nm is due to photomultiplier dark current noise on a stray light background.

Fig. 2 Spectral scan of a steeply rising feature taken with a 77345 Photomultiplier and 77257 Double Monochromator.

Photodiodes

Photodiodes have wider spectral range of response than most photomultipliers and have sensitivity and linear behavior over many decades. Our larger area diodes have linear response over as many as 8 decades.

Unbiased photodiodes have low dark current and dark current noise and are preferred for dynamic range over biased versions. The larger diodes such as the 7182 have higher maximum linear currents (ca. 1 mA) and the large area captures much of the output from a monochromator without the necessity for auxiliary optics.

Fig. 3 is similar to Fig. 2 but shows the wide ranging performance with the 7182 Silicon Photodiode.

Fig. 3 A scan of a narrow laser line recorded with the 7182 Silicon Photodiode on the 77257 Double Monochromator with two 77298 gratings.

ORIEL 78250 VOLTAGE RADIOMETRY BOARD

77200 1/4 m Monochromator
and 20025 Stepper Interface.
Computer shows 78250
Menu Screen.

- For detectors, Lock-in Amplifiers or Readouts which produce a voltage signal proportional to radiant flux.
- Designed to interface IBM PC's and light detection equipment
- Comprehensive software
- Integration of Voltage A/D converter and monochromator control into one package
- Operation of one or two monochromators
- Supports two voltage inputs with jumper selectable gains (0-100 mV, 0-1 V, 0-10 V)
- 12-bit A/D converter allows three decades of dynamic range with selectable voltage range
- Voltage Radiometry Board occupies only a single slot of any IBM PC/XT/AT or Compatible

The 78250 Voltage Radiometry Board is a hybrid analog digital board that plugs directly into the IBM PC Bus. It has full software support for radiometry, fluorescence or absorbance measurements. The hardware and software provide monochromator control and measure voltage signals.

PLUG-IN BOARD

The physical board occupies a single slot in a PC-XT or AT draws approximately 5 watts of power and presents two BNC connectors and one DB-15 connector to the rear of the computer. The calibrated, selectable-gain analog circuitry is mounted to the rear of the board for noise isolation and is protected from overvoltage input. Shielded BNC connectors, isolated from the main trace layout, connect directly into the analog front end. A grounded plane serves to isolate transients in the computer switching power supply from the detector inputs.

INPUT RANGES

The 78250 Board has three jumper pin selectable ranges.

Range (V)	Resolution (mV)
0 - 0.1	0.025
0 - 1	0.25
0 - 10	2.5

The two channels can be set to different ranges. The two inputs are over-voltage protected to ± 100 volts DC across the input to ground and current limited with an input impedance of 200 k ohms.

The input amplifier is based around a bipolar ultralow offset op-amp. The jumper pins select the ranges of amplification. Each individual range is factory calibrated. You select the range to match the voltage source before inserting the board into the computer.

Fig. 1 78250 Voltage Radiometry Board.

Oriel 78250 VOLTAGE RADIOMETRY BOARD

Fig. 2 Arrangement for infrared fluorescence measurements on crystals. The 78250 is used in a dual beam mode. A biased photodiode monitors the source and acts as reference, while the chopper, Lock-in Amplifier and PbS detector monitors the infrared fluorescence.

12 BIT ANALOG TO DIGITAL CONVERTER

The output from the analog pre-amp and surge suppresser circuitry is routed into a 12-bit A/D converter and ported through the PC-Bus Interface. The 78250 Software controls the electronics, and signal processing of the digitized signal.

Outputs

The 78250 controls one or two monochromators through two I/O outputs (DB-15 connector). The output connects to a 20030 Stepper Interface. (The 20025 Stepper Interface will run one monochromator.) The TTL outputs are decoded through address ports on the PC-Bus Interface and drive the 20030. The 20030 provides the pulses for monochromators at step rates of 4000 steps per minute. This is 400 nm per minute for a 1200 line/mm grating. The software drives two monochromators for matrix fluorescence scans where both excitation and emission wavelengths are scanned.

COMPATIBLE DETECTION EQUIPMENT

Any of our detectors or detection systems with a **voltage output** are compatible with the 78250. The signal source may be as simple as a biased photodiode in our 71925 Detector Housing, or as complex as two 70707 Lock-in Amplifiers which recover signal by phase sensitive detection of chopper modulated radiation. You can use the 70710 Current Pre-amplifier to convert current from photomultipliers or unbiased photodiodes, to voltage signals for the 78250. (If these are the only detectors you intend to use, you should consider the 78350 Autoranging Radiometry System described on page 373.)

Using one of our Readouts to accept the signal from the detector and provide output to the 78250 has advantages.

- You can see the signal level and optimize alignment etc.
- You can condition the signal for best match to the 78250. This involves setting the range on Readouts such as the 7070, or 7080, or adjusting the gain and offset on the 70701. You can also set the time constant on several of these instruments for best S/N performance.

THE 78250 AND 70707 LOCK-IN AMPLIFIER

Pyroelectric Detectors respond only to chopped light, and other detectors (such as PbS or PbSe) benefit from operation at higher frequencies. You can use these devices with our choppers and the 70707 Lock-in Amplifier and take the output of the Lock-in to the 78250. This combines the advantages of phase sensitive detection with those of the computer; control, data storage and processing.

78250 Menu Screen.

Fig. 3 The 78250 used with a photomultiplier and biased indium arsenide photodiode. With the optional 70701 Readout (not shown) you can easily 'condition' the photodiode voltage for best utilization of the range of the 78250.

Oriel Spectroscopy Radiometric Software

- Controls monochromator and measurement of photocurrent
- Stores, processes, and plots data
- Completely menu driven - No programming experience required
- Presents data in standard Absorbance, Fluorescence, or Radiometric format
- Supports single and dual ratioed beam modes
- Controls up to two monochromators for emission, excitation, and synchronous wavelength scans for fluorescence measurements
- Linear or Log-Linear Plotting of data to Screen, Printer, or Hewlett Packard Pen Plotter

This software consists of three separate programs tailored for specific applications: absorbance, fluorescence, and spectroradiometry. All programs are written for the IBM PC-XT/AT as part of the 78350 Auto ranging Radiometry Board and 78250 Voltage Radiometry Board.

There are two slightly different versions of the software, one for the 78350 and one for the 78250. The description which follows covers both versions.

The software is written in efficient fast C (Turbo C) and each program is about 200 kB. The three programs are variations on a common base. Radiometry has functions specifically for absolute radiometric measurements. Absorbance has explicit emphasis on ratioed measurements and fluorescence has provision for excitation and emission monochromators.

COMPUTER HARDWARE

The software is shipped on 5.25" 360 kilobyte and 3.5" 1.44 Megabyte media. A minimum of 512 kilobytes RAM is required and graphic display adapters supported by the program include EGA, CGA, and Hercules Graphics Card (HGC or MCGA). The system can work with either a hard disk or a floppy based system. A numerical coprocessor is utilized if one is present.

TWO MAIN MENUS

There are two operational information screens: the **Scan Screen** displays wavelength and photocurrent readings as well as operational parameters; the **Graphing Screen** has graph set-up information and information on dumping graphs to plotters or printers.

SCAN SCREEN

In this screen, shown above, a horizontal menu of sub-menus runs across the top of the screen. The remainder of the screen displays key information on the scan, wavelength and signal level.

You activate any submenu by using either the key corresponding to the first letter of the item or using the left or right cursor keys. Every submenu of the top horizontal menu brings a pop-up menu onto the screen. You can select the pop-up menu items with either the item's first letter or by using the up and down cursor keys. The escape key returns you to the top horizontal menu or selects default items.

```

File  Scan  Parameters  Zero  Manual  Wavelength  Graph

-----
LAST DATA FILE
-----
Wavelength: 100.00 nm  Photocurrent: 1.00e-007 A  Ratio: UNDEFINED

-----
PARAMETERS
-----
STARTING WAVELENGTH : 300.00 nm  LIGHT SOURCE : Oriel Photonax
ENDING WAVELENGTH  : 550.00 nm
READ TIME           : 1.0 sec    FILTER       : HOYA 307-A
WAIT TIME           : 0.5 sec    GRATING      : 1200
INCREMENT           : 1.00 nm    DETECTOR     : Si Photodiode
MODE                : Single Beam SLIT WIDTH    : 50 Microns
SCAN TYPE           : Detector

-----
MESSAGES
-----

```

Scan Screen of the 78350 Software.

DETECTION

Oriel SPECTROSCOPIC/RADIOMETRIC SOFTWARE

File

This allows you to list the files on the various computer drives and to exit the program, automatically saving the parameters set you have been using, including the last wavelength.

Scan Sub Menu

This menu allows you to start a scan, save or recall a scan from disk, and display the scan which you have just completed or one you recalled to memory, as a plot. You can also display the scan values to screen and quickly move through to the specific screen of readings around the one of interest. Or you can send the list of values to your printer.

The radiometry program includes a 'Type' option in this submenu. This allows you to choose between scans recording the photocurrent, standard lamp scans, and radiometric scans of the unknown.

Parameters Sub Menu

You select your operating and scan parameters from this submenu. These include grating density (lines/mm), wavelength increment, beginning and ending wavelengths of a scan, and read time. The scanning parameters have error checking routines built in and incorrect parameters are required to be re-entered. The computer uses the grating density entered to check the validity of the scan data.

You can set the read time in increments of 0.1 second. Readings are taken at a rate of about 100 per second (depending on processor speed), and averaged. As you increase read time, the signal to noise ratio improves, but the scan takes longer. For many scans using a photomultiplier detector we use a read time of 0.3 seconds.

If you are using the 78250 Voltage Radiometer System, you should set the 'Input Voltage Range', to match the jumper selectable range on the board.

Zero Routine

This option prompts you to shutter the beam so the computer records the dark current. Dark current measurements are then automatically subtracted (in software) from each reading.

Wavelength Entry

You must enter the wavelength setting of the monochromator. The program then keeps track of the wavelength. On exiting, the wavelength setting is stored for automatic recall.

Manual Mode

Selecting this allows you to toggle or slew the monochromator from the keyboard. Manual mode simplifies peak finding for monochromator calibration or spectral analysis. You also have the option to slew to a specific wavelength. This, like all the wavelength changes controlled by the program includes an anti-backlash routine.

Scan Sub-menu screen.

Parameters Sub-menu Screen.

Manual Sub-menu Screen.

Graphical Display

The second screen controls the graphical display of wavelength/photocurrent data taken with the system.

Define Plot

Here you enter the file you want to plot and how you want it plotted. The sophisticated graphing routine allows arithmetic operations on files. You can multiply or divide a file by a constant, or add, subtract, multiply or divide matching files. (You cannot multiply or divide files with different spectral ranges or increments. The utility program allows you to interpolate files with the same spectral range so that you can operate on them.)

You can then store the result as a new file and perform further operations on it. You can use this technique to convert radiometric data to photometric. (See page 16 for procedure.) To do this you can create a file of the $V(\lambda)$ values using your wordprocessor or the utility program. Similarly you can create files for optical filters and multiply these by light source spectra.

Fig. 1 You can add a wavelength offset to a file should you discover that you had not calibrated the monochromator accurately. You can graph the data using linear-linear format, or for data with no zero or negative values, log-linear format. The horizontal and vertical axis can each be automatically scaled to fit the data or you can choose your own scale ranges. Defined scaling allows you to plot small regions of the scan as shown.

Screen display of two overlaid scans showing raw spectrum and spectrum of radiation transmitted through a sample.

Graphing Screen.

The graphing screen displays the value of the integrated signal over the graphing range. By choosing the range, you can find the integral over any spectral region of interest.

Section of a mercury lamp spectrum.

Data can be plotted on a linear-linear or log-linear plotting scale. A crosshair controlled by the cursor keys can be positioned anywhere on the graph for accurate determination of spectral features or lines.

Oriel SPECTROSCOPIC/RADIOMETRIC SOFTWARE

Printer

This submenu allows you to select a printer. Over a hundred printers are supported for graphical plotting, including a number of laser printers for high resolution plots, although the greatest resolution is displayed with the HP Pen Plotter.

Screen

Here you can name the plot, label the axes, and choose whether you want a grid.

View Plot

You can overlay multiple plots on a single graph for comparison and contrast. The graph which quickly appears on the monitor, can also be dumped to a printer or to a Hewlett-Packard Pen Plotter (or any pen plotter supporting HPGL commands).

Hard Copy

If you want the file values or information file printed out you use this submenu.

UTILITIES

We supply two useful programs for use with the software: the first allows you to create a file from wavelength and value list. When using the Radiometry Software, you must use this to enter the calibration data supplied with your standard lamp. You can also create a file of transmittance for a filter, or the $V(\lambda)$ curve on page 18.

The second program uses a polynomial interpolation routine to match scan increments. This allows you to generate a file without entering many points. When entering data for a cut-on filter for example, you need only enter closely spaced points at the knee of the curve. This program will interpolate between widely spaced points of almost constant transmittance above the cut-on.

SCAN AND OVERLAY CAPABILITY

Memory limitations and the program structure limit the maximum scan to 2000 points. The overlay capability in the graphing routine is also limited to a total of 2000 points. You can overlay 3 scans of 600 points or two scans of 800 points, but not two scans of 1200 points. You can subdivide large scans for multiple overlay.

FILE EXPORT

The files are in standard ASCII format. You can export a file to programs such as Lotus 1-2-3®, Asyst®, or Labtech Notebook® for display, further processing, or inclusion in a report.

COMPUTER COMPATIBILITY

Idiosyncrasies in IBM compatibles sometimes prevent the proper operation of programs or plug-in boards. If a computer is fully IBM compatible, then our program will work. (We cannot predict compatibility with other plug-in hardware.) We have tested this program on the following computers:

- IBM PC XT (4 MHz), IBM PC AT (8 MHz)
- Compaq DeskPro (XT equivalent, 8MHz)
- Leading Edge Model D (XT equivalent, 8 MHz)
- AST Premium (AT equivalent, 10 MHz)
- Micro Express (AT equivalent, 12 MHz)

The graphics routine will not work with original IBM PC monochrome cards (pre-1983).

The sampling time for a reading depends on the processor speed. For the slowest processor found in these computers (4 MHz) the rate is 80 samples/s.

Oriel COMPUTERIZED SPECTROSCOPY SYSTEMS

SYSTEM EXAMPLES

Versatility is a major advantage of Oriel Spectroscopy Systems. You can select a system for a particular application and later change the configuration or add pieces for other applications. On these two pages we illustrate some configurations.

SINGLE OR DOUBLE BEAM?

Many spectroscopic determinations involve two scans and simultaneous or subsequent comparison of the data sets. If the overall system is stable and repeatable to the required degree you can take one scan at a time and compare (ratio) the files afterwards. The single beam approach is particularly attractive when the alternative is two complex and expensive detection systems. The 68850 Photofeedback System can greatly improve the performance of some single beam arrangements.

For highest precision you can take the two scans simultaneously with the 78350 or 78250 in dual beam mode. (Fig. 1) You must pay considerable attention that the signal and reference optical paths react in the same fashion over the wavelength range of the scan to any spatial or polarization changes in the source. Calibrating with absorbance standards helps establish confidence.

The Absorbance program displays and stores the ratio of the two inputs as you scan.

Fig. 1 The components of a double beam system for absorbance measurements. For absorbances above ~ 4, we recommend that you use a double monochromator, and take particular care with the source spectrum and detector spectral response, to reduce error due to stray light.

Ratioing with the 70707 Lock-in Amplifier

If chopping and phase sensitive detection has an advantage, as it frequently does for infrared detection, then you can ratio the signal from two optical detectors with a single 70707 Lock-in Amplifier and the optional Ratio Unit described on page 344. (The signal from the reference detector must be unmodulated.) The output of the Lock-in is a measure of the ratio. Fig. 2 shows one arrangement.

The type of detection arrangement shown in Fig. 2 is very useful to remove the effects of source variation, but does not remove the effects of ambient light or background radiation. For this you need to modulate both light paths. Fig. 3 shows a powerful set-up using a chopper and the 78250 to ratio the two channels.

Fig. 2 Measuring near infrared fluorescence using the 79426 Diode Laser System as source, and ratioing the fluorescence signal to the excitation intensity.

Fig. 3 Computer controlled spectral measurement of optical fiber transmission. Two 70707 Lock-in Amplifiers, one for the signal path and one for the reference beam, remove ambient background.

Oriel COMPUTERIZED SPECTROSCOPY SYSTEMS

RADIOMETRIC SYSTEM

Fig. 4 shows a simple but effective radiometer system. The diffuser input to the monochromator is chosen for the particular application.

Fig. 4 A radiometer based on the 78350 system uses a single 77250 Monochromator and photomultiplier detector for high sensitivity in the ultraviolet.

In radiometry or photometry of light sources, the first step is to record a reference or calibration scan. This measures the system response against a known light source. (See page 62 for suitable standard sources). A scan of the unknown light source follows. Both sources should produce similar values of detector signal to remove any uncertainty about system linearity over a wide dynamic range.

Our radiometry program is designed so you do not have to run scans and divide them afterwards. The program allows you to run a 'Standard' scan of the calibrated lamp. You must supply a file of the calibration values for this lamp. Then by running subsequent scans as Radiometric, the program displays the name of the calibrated lamp file and the number of spectral points which match scan points. Calibration values are interpolated for other points. (If you have too few matching points, then the basis of the radiometric values may be suspect.) Data are recorded and plotted as radiometric, as distinct from detector signal, values.

A complete scanning system consists of the following components:

1. A customized modular scanning system with components selected for the application. Components include:
 - Light Source (tungsten halogen or laser)
 - Monochromator(s) with Stepper Drive(s) (found only on larger models)
 - Stepper Interface (found on larger models)
 - Detector(s) (found on larger models)

Contact Oriel Sales Engineers for help in selecting the components.

2. A 78250 Voltage Radiometry Board or Autoranging Radiometry Board, each of which includes a plug-in card, software and cables.
3. An IBM PC XT AT or full compatible with a minimum of 512 kilobytes of memory and a hard disk (HGA or EGA graphics display screen and optional peripheral graphic plotting devices such as a compact plotter or Hewlett Packard Plot Panel).

Contact Oriel Sales Engineers for recommended computers or if you wish to order a computer through Oriel.

You can find block diagrams of several systems on pages 373 to 382. These do not show details of light sources, gratings, order sorting filters, or particular photodetectors, you should choose these carefully for the spectral range and application of interest.

Contact our Sales Engineers for advice.

ORDERING INFORMATION

78350	Autoranging Radiometry Board Monitors photocurrents from pA to mA, includes plug-in board, software for radiometry, fluorescence and absorbance, and cabling to Stepper Interface	\$ 2895.00
78250	Voltage Radiometry Board Monitors voltages from 0 to 10V, includes plug-in board, software for radiometry, fluorescence and absorbance, and cabling to Stepper interface	\$ 2285.00

IBM Compatible Computer and the 78250 and 78350 Radiometry Boards.

UNIVERSITY MICROFILMS

DRIEL FIBER OPTICS

Fiber optics add a new dimension to Light Research. Their flexibility lets you bend and carry light to inaccessible places. Special configurations allow you to reshape beams to match monochromator slits and samples. Multi branch models serve as beam splitters or combiners, or as dual source illuminators.

The varied uses of fiber optics demands a line of support equipment, from simple holders to precision positioners and multi element imaging lens probes. You will find the most comprehensive line of fiber bundles, liquid light guides and support equipment on pages 396 to 415.

The photograph shows one example of the optical paths you can create with just one light source and two bifurcated fiber bundles. Integrating spheres add repeatability and meaning to many fiber optic projects. A sphere based measuring system is insensitive to fiber output pattern.

PC Based

- Designed for IBM PCs and compatibles
- Complete scan control - customize your own scan
- Complete hardware and software
- Support many types of detector
- Software for radiometry, absorption, fluorescence
- Single or double beam

If you are considering setting up spectroscopy equipment which involves scanning a monochromator and taking data, then the hardware and software described on the next few pages can save you a lot of time and effort. You can quickly put together a versatile and powerful system for spectroscopy based on an IBM PC compatible computer; spectroscopy anywhere from the ultraviolet to the infrared. You can choose scan parameters to suit your application.

We describe two boards which plug into the slots inside the computer. Both boards are supported by software to operate our monochromators (with appropriate drive hardware) and take signals from detectors.

- The **78350 Autoranging Radiometry Board** is for detectors which behave like current sources; photomultipliers and photodiodes. This board has built-in autoranging for very wide dynamic range without operator intervention.
- The **78250 Voltage Radiometry Board** is for any detection system where the final output is in volts proportional to signal. This includes many infrared detection systems employing beam chopping where the signal is recovered by our 70707 Lock-in amplifier. The 7070 Photomultiplier Detector System and 70701 Readout also have suitable outputs.

DETECTION EQUIPMENT

Fig. 1 (a) to (d) show the spectral distribution of a semiconductor diode laser as the current is increased. The spectrum shifts to longer wavelengths as different modes compete for gain. Even at high current, (c), low level spectral features are apparent. You can examine these using the different plot scaling capability. The spectra were recorded using a 77344 Photomultiplier, the 78350 Autoranging Radiometer Board, 77200 1/4 m Monochromator with 77233 grating and 10 μ m slits. The 78350 commanded the 20025 Stepper Interface to operate the 77245 Dual Ratio Wavelength Drive in the high resolution mode (0.01 nm steps). This took full advantage of the high resolution of the 77200. The resolution is shown clearly in the expanded view of spectrum (b). The log plot of the expanded view also shows the plotting capability of the 78350.

Fig. 2 (a) Near Infrared Hemispherical Total Reflectance (R) of an anodized aluminum surface. (Total reflectance is specular plus diffuse). The data was recorded and ratioed with the 78350. We used a 7182 Silicon Photodiode in the 71920 Detector Head on the 70491 Reflectance/ Transmittance Sphere. The input beam was from a 77250 1/8 m Monochromator illuminated by the 60065 Series Q Source and a 6199 Secondary Focusing Lens (150 mm F.L.). A 51520 Long Pass Filter removed the second order radiation. We recollimated the beam with a 100 mm F.L. lens and apertured it to 15 mm diameter before entering the sphere. The reflectance value was derived by ratioing the data file for the anodized sample in the sample holder to the file recorded with the Oriel Certified Standards of Diffuse Reflectance (page 366). (b) shows the total reflectance of a glass plate for comparison.

Integrates Detector Input and Monochromator stepper motor driver into one package

Seven decades of autoranging and 12-bit A/D converter allow nine decades of dynamic range

Includes software

Operation of up to two Monochromator Stepper Motors

Supports two photocurrent inputs (picoamps to milliamps) for double beam mode or matrix scans

1 Occupies single slot of IBM PC bus

The 78350 Autoranging Radiometry Board is a hybrid analog/digital card that plugs directly into the IBM PC Bus, to provide photodetector input and monochromator control. It is designed for, and supported by, spectrophotometry and spectroscopy software. The 78350 records photocurrent from photomultipliers and photodiodes. The 78250 is the version for input voltage.

PLUG-IN CARD

The physical card occupies a single slot in a PC-XT. It draws approximately 5 watts of power and has two BNC connectors and one DB-15 connector at the rear of the computer. The calibrated, high-gain analog circuitry is mounted in a shielded can off the surface of the mothercard for optimum electrical isolation. Shielded coaxial cable, isolated from the main mothercard, runs the signal from the BNC connectors into the analog front end (shielded can).

The 78350 card has a transimpedance amplifier input with software switched gain, a fixed gain stage, and a 12 bit A/D converter. Input bandwidth is 35 Hz. Maximum resolution is 0.24 picoamperes and maximum photocurrent is 1 milliamperere. No single photodetector can use the full range but you can cover the linear range of different detectors. See the following page for practical resolution and range with our photodetectors.

The two inputs are protected to 2000 volts DC across the input and current limited with an input impedance of 2 megohms. The amplifier is based around an ultralow noise FET precision op amp with switchable ranges of amplification. Each individual range is factory calibrated and directly controlled by software. The output from the analog circuitry is routed into a 12-bit A/D converter and ported through the PC Bus. The 78300 software controls the electronics, performing autoranging and signal processing of the input.

OUTPUTS

Two I/O output ports are for monochromator control. The output is routed through the DB-15 connector for interface to an Oriel 20030 or 20025 Stepper Interface. (The 20025 Stepper Interface is for a single monochromator.) See Fig. 1.

The TTL outputs are decoded through address ports on the PC Bus and drive the 20030 (or 20025), capable of driving monochromators at step rates of 4000 steps per minute. (With a 1200 line grating this is 400 nm/min.)

Often a single monochromator is adequate. Both ports are used with dual monochromator arrangements for performing matrix fluorescence scans where both excitation and emission measurements are required.

Our Double Monochromator Systems (coupled mechanically) use a single Stepper Drive and therefore count as one monochromator.

DETECTION
EQUIPMENT

Fig. 1 78350 Autoranging Radiometry Board

Oriel carries a complete line of photodetectors which produce a photocurrent proportional to incident light intensity, with spectral sensitivities from the UV to the IR.

Silicon photodiodes come in a variety of sizes and packages, depending on the application, and offer high sensitivities, especially in the near IR. Germanium and Indium Arsenide photodiodes extend the range into the infrared. Photomultipliers have the greatest sensitivity in the visible and ultraviolet, (usually 2 orders of magnitude greater than silicon photodiodes) and produce a photocurrent that is proportional to light intensity over 6 to 8 orders of magnitude. However, they require a separate high voltage power supply (such as the 70705) to operate. Fig. 1 shows the computer reading against photocurrent into the 78350 board over more than 8 orders of magnitude. (Photodetector linearity may not match this range.)

Fig. 1 The computer reading against photocurrent over more than 8 orders of magnitude. (Photodetector linearity and stray light usually limit the useful range.)

Dark Current

All photodetectors produce a small amount of quiescent current in the absence of light, commonly referred to as 'dark current.' The 78350 Software allows you to take a dark current reading which is then subtracted from all subsequent signal measurements.

REAL PERFORMANCE WITH PHOTODETECTORS

The principal detectors used with the 78350 are photomultipliers and photodiodes without bias.

Photomultipliers

These detectors are linear over a wide range if the dynodes are properly supplied and when the output is into a transimpedance amplifier. (The 78350 input is designed in this way). The maximum photocurrent is specified on page 218. For precision radiometry we recommend that the anode current be 10-100 times less than specified maximum. Avoid using currents of more than 1 μ A. Do not focus light on the photocathode as this will lead to local saturation. And in order to compare signals accurately they must be distributed equivalently over the sensitive area.

Dark currents can be 10-500 pA depending on tube, voltage and recent history. (Tubes exposed to high light levels have temporarily high dark currents). Dark current is not a fundamental limitation as it is subtracted out but dark current noise may limit the detectable signal level.

Fig. 2 shows a scan of a steeply rising spectral feature and demonstrates the wide dynamic range of the 78350. The scan was taken with a 77257 Double Monochromator with a 77345 photomultiplier tube, operated at 600 volts. The 78350 subtracted out the 10 pA dark current. Averaging time was 0.5 s. The low level signal below 610 nm is due to photomultiplier dark current noise on a stray light background.

Fig. 2 Spectral scan of a steeply rising feature taken with a 77345 Photomultiplier and 77257 Double Monochromator.

Photodiodes

Photodiodes have wider spectral range of response than most photomultipliers and have sensitivity and linear behavior over many decades. Our larger area diodes have linear response over as many as 8 decades.

Unbiased photodiodes have low dark current and dark current noise and are preferred for dynamic range over biased versions. The larger diodes such as the 7182 have higher maximum linear currents (ca. 1 mA) and the large area captures much of the output from a monochromator without the necessity for auxiliary optics.

Fig. 3 is similar to Fig. 2 but shows the wide ranging performance with the 7182 Silicon Photodiode.

Fig. 3 A scan of a narrow laser line recorded with the 7182 Silicon Photodiode on the 77257 Double Monochromator with two 77298 gratings.

77200 1/4 m Monochromator
and 20025 Stepper Interface.
Computer shows 78250
Menu Screen.

- For detectors, Lock-in Amplifiers or Readouts which produce a voltage signal proportional to radiant flux.
- Designed to interface IBM PC's and light detection equipment
- Comprehensive software
- Integration of Voltage A/D converter and monochromator control into one package
- Operation of one or two monochromators
- Supports two voltage inputs with jumper selectable gains (0-100 mV, 0-1 V, 0-10 V)
- 12-bit A/D converter allows three decades of dynamic range with selectable voltage range
- Voltage Radiometry Board occupies only a single slot of any IBM PC/XT/AT or Compatible

The 78250 Voltage Radiometry Board is a hybrid analog/digital board that plugs directly into the IBM PC Bus. It has full software support for radiometry, fluorescence or absorbance measurements. The hardware and software provide monochromator control and measure voltage signals.

The physical board occupies a single slot in a PC-XT or AT, draws approximately 5 watts of power and presents two BNC connectors and one DB-15 connector to the rear of the computer. The calibrated, selectable-gain analog circuitry is mounted to the rear of the board for noise isolation and is protected from overvoltage input. Shielded BNC connectors, isolated from the main trace layout, connect directly into the analog front end. A grounded plane serves to isolate transients in the computer switching power supply from the detector inputs.

SELECTABLE RANGES

The 78250 Board has three jumper pin selectable ranges

Range (V)	Resolution (mV)
0 - 0.1	0.025
0 - 1	0.25
0 - 10	2.5

The two channels can be set to different ranges. The two inputs are over-voltage protected to ± 100 volts DC across the input to ground and current limited with an input impedance of 200 k ohms.

The input amplifier is based around a bipolar ultralow offset op-amp. The jumper pins select the ranges of amplification. Each individual range is factory calibrated. You select the range to match the voltage source before inserting the board into the computer.

DETECTION
EQUIPMENT

Fig. 1 78250 Voltage Radiometry Board.

Fig. 2 Arrangement for infrared fluorescence measurements on crystals. The 78250 is used in a dual beam mode. A biased photodiode monitors the source and acts as reference, while the chopper, Lock-in Amplifier and PbS detector monitors the infrared fluorescence.

12 BIT ANALOG TO DIGITAL CONVERTER

The output from the analog pre-amp and surge suppresser circuitry is routed into a 12-bit A/D converter and ported through the PC-Bus Interface. The 78250 Software controls the electronics, and signal processing of the digitized signal.

Outputs

The 78250 controls one or two monochromators through two I/O outputs (DB-15 connector). The output connects to a 20030 Stepper Interface. (The 20025 Stepper Interface will run one monochromator.) The TTL outputs are decoded through address ports on the PC-Bus Interface and drive the 20030. The 20030 provides the pulses for monochromators at step rates of 4000 steps per minute. This is 400 nm per minute for a 1200 line/mm grating. The software drives two monochromators for matrix fluorescence scans where both excitation and emission wavelengths are scanned.

COMPATIBLE DETECTION EQUIPMENT

Any of our detectors or detection systems with a **voltage output** are compatible with the 78250. The signal source may be as simple as a biased photodiode in our 71925 Detector Housing, or as complex as two 70707 Lock-in Amplifiers which recover signal by phase sensitive detection of chopper modulated radiation. You can use the 70710 Current Pre-amplifier to convert current from photomultipliers or unbiased photodiodes, to voltage signals for the 78250. (If these are the only detectors you intend to use, you should consider the 78350 Autoranging Radiometry System described on page 373.)

Using one of our Readouts to accept the signal from the detector and provide output to the 78250 has advantages.

- You can see the signal level and optimize alignment etc.
- You can condition the signal for best match to the 78250. This involves setting the range on Readouts such as the 7070, or 7080, or adjusting the gain and offset on the 70701. You can also set the time constant on several of these instruments for best S/N performance.

Pyrce et al. Detectors respond only to chopped light, and other detectors (such as PbS or PbSe) benefit from operation at higher frequencies. You can use these devices with our choppers and the 70707 Lock-in Amplifier and take the output of the Lock-in to the 78250. This combines the advantages of phase sensitive detection with those of the computer control, data storage and processing.

78250 Voltage Radiometry Board being plugged in.

78250 Menu Screen.

Fig. 3 The 78250 used with a photomultiplier and biased indium arsenide photodiode. With the optional 70701 Readout (not shown) you can easily condition the photodiode voltage for best utilization of the range of the 78250.

Controls monochromator and measurement of photocurrent
 Stores, processes, and plots data
 Completely menu driven - No programming experience required
 Presents data in standard Absorbance, Fluorescence, or Radiometric format
 Supports single and dual/ratioed beam modes
 Controls up to two monochromators for emission, excitation, and synchronous wavelength scans for fluorescence measurements
 Linear or Log-Linear Plotting of data to Screen, Printer, or Hewlett Packard Pen Plotter

The software is shipped on 5.25" 360 kilobyte and 3.5" 1.44 Megabyte media. A minimum of 512 kilobytes RAM is required and graphic display adapters supported by the program include EGA, CGA, and Hercules Graphics Card (HGC or MCGA). The system can work with either a hard disk or a floppy based system. A numerical coprocessor is utilized if one is present.

There are two operational information screens; the **Scan Screen** displays wavelength and photocurrent readings as well as operational parameters; the **Graphing Screen** has graph set-up information and information on dumping graphs to plotters or printers.

SCAN SCREEN

In this screen, shown above, a horizontal menu of sub-menus runs across the top of the screen. The remainder of the screen displays key information on the scan, wavelength and signal level.

You activate any submenu by using either the key corresponding to the first letter of the item or using the left or right cursor keys. Every submenu of the top horizontal menu brings a pop-up menu onto the screen. You can select the pop-up menu items with either the item's first letter or by using the up and down cursor keys. The escape key returns you to the top horizontal menu or selects default items.

DETECTION EQUIPMENT

WAVELENGTH	PHOTOCURRENT	RATIO
100.00 nm	3.00e-009 A	UNDEFINED

PARAMETERS

STARTING WAVELENGTH : 300.00 nm LIGHT SOURCE : Oriel Photonax
 ENDING WAVELENGTH : 550.00 nm FILTER : HOYA 307-A
 READ TIME : 1.0 sec GRATING : 1200
 WAIT TIME : 0.5 sec DETECTOR : Si Photodiode
 INCREMENT : 1.00 nm SLIT WIDTH : 50 Microns
 MODE : Single Beam
 SCAN TYPE : Detector

MESSAGES

Scan Screen of the 78350 Software.

File

This allows you to list the files on the various computer drives and to exit the program, automatically saving the parameters set you have been using, including the last wavelength.

Scan Sub Menu

This menu allows you to start a scan, save or recall a scan from disk, and display the scan which you have just completed or one you recalled to memory, as a plot. You can also display the scan values to screen and quickly move through to the specific screen of readings around the one of interest. Or you can send the list of values to your printer.

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If you are using the 78250 Voltage Radiometer System, you should set the 'Input Voltage Range', to match the jumper selectable range on the board.

Zero Routine

This option prompts you to shutter the beam so the computer records the dark current. Dark current measurements are then automatically subtracted (in software) from each reading.

Wavelength Entry

You must enter the wavelength setting of the monochromator. The program then keeps track of the wavelength. On exiting, the wavelength setting is stored for automatic recall.

Manual Mode

Selecting this allows you to toggle or slew the monochromator from the keyboard. Manual mode simplifies peak finding for monochromator calibration or spectral analysis. You also have the option to slew to a specific wavelength. This, like all the wavelength changes controlled by the program includes an anti-backlash routine.

Scan Sub-menu screen.

Parameters Sub-menu Screen.

Manual Sub-menu Screen.

The second screen controls the graphical display of wavelength/photocurrent data taken with the system.

Define Plot

Here you enter the file you want to plot and how you want it plotted. The sophisticated graphing routine allows arithmetic operations on files. You can multiply or divide a file by a constant, or add, subtract, multiply or divide matching files. (You cannot multiply or divide files with different spectral ranges or increments. The utility program allows you to interpolate files with the same spectral range so that you can operate on them.)

You can then store the result as a new file and perform further operations on it. You can use this technique to convert radiometric data to photometric. (See page 16 for procedure.) To do this you can create a file of the $V(\lambda)$ values using your wordprocessor or the utility program. Similarly you can create files for optical filters and multiply these by light source spectra.

Fig. 1 You can add a wavelength offset to a file should you discover that you had not calibrated the monochromator accurately. You can graph the data using linear-linear format, or for data with no zero or negative values, log-linear format. The horizontal and vertical axis can each be automatically scaled to fit the data or you can choose your own scale ranges. Defined scaling allows you to plot small regions of the scan as shown.

Screen display of two overlaid scans showing raw spectrum and spectrum of radiation transmitted through a sample.

Define-Plot DESCRIPTION: spec112 OUTPUT FILE: SCALE: linear-linear Y RANGE: AUTOMATIC X RANGE: AUTOMATIC X OFFSET: 0.00 nm		PLOT DATA # OF POINTS: 221 MINIMUM: 5.05e-009 MAXIMUM: 5.51e-007 AVERAGE: 3.42e-007 INTEGRAL: 7.53e-005
PRINTER PRINTER TYPE: 0 DIRECTION: Horizontal # OF COPIES: 1	SCREEN TITLE: Spectral Plate X AXIS LABEL: WAVELENGTH (nm) Y AXIS LABEL: Spectral Rad. GRID LINES: ON	

Graphing Screen.

The graphing screen displays the value of the integrated signal over the graphing range. By choosing the range, you can find the integral over any spectral region of interest.

Section of a mercury lamp spectrum.

Data can be plotted on a linear-linear or log-linear plotting scale. A crosshair controlled by the cursor keys can be positioned anywhere on the graph for accurate determination of spectral features or lines.

DETECTION EQUIPMENT

VISA

Printer

This submenu allows you to select a printer. Over a hundred printers are supported for graphical plotting, including a number of laser printers for high resolution plots, although the greatest resolution is displayed with the HP Pen Plotter.

Screen

Here you can name the plot, label the axes, and choose whether you want a grid.

View Plot

You can overlay multiple plots on a single graph for comparison and contrast. The graph which quickly appears on the monitor, can also be dumped to a printer or to a Hewlett-Packard Pen Plotter (or any pen plotter supporting HPGL commands).

Hard Copy

If you want the file values or information file printed out you use this submenu.

UTILITIES

We supply two useful programs for use with the software: the first allows you to create a file from wavelength and value list. When using the Radiometry Software, you must use this to enter the calibration data supplied with your standard lamp. You can also create a file of transmittance for a filter, or the $V(\lambda)$ curve on page 18.

The second program uses a polynomial interpolation routine to match scan increments. This allows you to generate a file without entering many points. When entering data for a cut-on filter for example, you need only enter closely spaced points at the knee of the curve. This program will interpolate between widely spaced points of almost constant transmittance above the cut-on.

SCAN AND OVERLAY CAPABILITY

Memory limitations and the program structure limit the maximum scan to 2000 points. The overlay capability in the graphing routine is also limited to a total of 2000 points. You can overlay 3 scans of 600 points or two scans of 800 points, but not two scans of 1200 points. You can subdivide large scans for multiple overlay.

The files are in standard ASCII format. You can export a file to programs such as Lotus 1-2-3*, Asyst*, or Labtech Notebook* for display, further processing, or inclusion in a report.

Idiosyncrasies in IBM compatibles sometimes prevent the proper operation of programs or plug-in boards. If a computer is fully IBM compatible, then our program will work. (We cannot predict compatibility with other plug-in hardware.) We have tested this program on the following computers:

- IBM PC XT (4 MHz), IBM PC AT (8 MHz)
- Compaq DeskPro (XT equivalent, 8MHz)
- Leading Edge Model D (XT equivalent, 8 MHz)
- AST Premium (AT equivalent, 10 MHz)
- Micro Express (AT equivalent, 12 MHz)

The graphics routine will not work with original IBM PC monochrome cards (pre-1983).

The sampling time for a reading depends on the processor speed. For the slowest processor found in these computers (4 MHz) the rate is 80 samples/s.

Versatility is a major advantage of Oriel Spectroscopy Systems. You can select a system for a particular application and later change the configuration or add pieces for other applications. On these two pages we illustrate some configurations.

SINGLE OR DOUBLE BEAM?

Many spectroscopic determinations involve two scans and simultaneous or subsequent comparison of the data sets. If the overall system is stable and repeatable to the required degree you can take one scan at a time and compare (ratio) the files afterwards. The single beam approach is particularly attractive when the alternative is two complex and expensive detection systems. The 68850 Photofeedback System can greatly improve the performance of some single beam arrangements.

For highest precision you can take the two scans simultaneously with the 78350 or 78250 in dual beam mode. (Fig. 1) You must pay considerable attention that the signal and reference optical paths react in the same fashion over the wavelength range of the scan to any spatial or polarization changes in the source. Calibrating with absorbance standards helps establish confidence.

The Absorbance program displays and stores the ratio of the two inputs as you scan.

Fig. 1 The components of a double beam system for absorbance measurements. For absorbances above ~ 4 , we recommend that you use a double monochromator, and take particular care with the source spectrum and detector spectral response, to reduce error due to stray light.

Ratioing with the 70707 Lock-in Amplifier

If chopping and phase sensitive detection has an advantage, as it frequently does for infrared detection, then you can ratio the signal from two optical detectors with a single 70707 Lock-in Amplifier and the optional Ratio Unit described on page 344. (The signal from the reference detector must be unmodulated.) The output of the Lock-in is a measure of the ratio. Fig. 2 shows one arrangement.

The type of detection arrangement shown in Fig. 2 is very useful to remove the effects of source variation, but does not remove the effects of ambient light or background radiation. For this you need to modulate both light paths. Fig. 3 shows a powerful set-up using a chopper and the 78250 to ratio the two channels.

Fig. 2 Measuring near infrared fluorescence using the 79426 Diode Laser System as source, and ratioing the fluorescence signal to the excitation intensity.

Fig. 3 Computer controlled spectral measurement of optical fiber transmission. Two 70707 Lock-in Amplifiers, one for the signal path and one for the reference beam, remove ambient background.

DETECTION
EQUIPMENT

A complete scanning system consists of three main components.

1. A customized modular spectroscopy system with components selected for the application. Key components include
 - **Light Source** (found on pages 14-105)
 - **Monochromator(s) with Stepper Drive(s)** (found on pages 186-282)
 - **Stepper Interface** (found on page 293)
 - **Detector(s)** (found on pages 296-346)

Contact Oriel Sales Engineers for help in selecting the components.

2. A 78250 Voltage Radiometry Board or 78350 Autoranging Radiometry Board, each of which includes a plug-in card, software and cables.
3. An IBM PC/XT/AT or full compatible with a minimum of 512 kilobytes of memory and a Hercules, CGA, or EGA graphics display screen and optional peripheral graphic plotting devices such as a conventional printer or Hewlett Packard Pen Plotter.

Contact Oriel Sales Engineers for recommended computers or if you wish to order a computer through Oriel.

You can find block diagrams of several systems on pages 373 to 382. These do not show details of light sources, gratings, order sorting filters, or particular photodetectors. You should choose these carefully for the spectral range and application of interest.

Contact our Sales Engineers for advice.

ORDERING INFORMATION

78350	Autoranging Radiometry Board	\$ 2895.00
	Monitors photocurrents from pA to mA, includes plug-in board, software for radiometry, fluorescence and absorbance, and cabling to Stepper Interface	
78250	Voltage Radiometry Board	\$ 2285.00
	Monitors voltages from 0 to 10V, includes plug-in board, software for radiometry, fluorescence and absorbance, and cabling to Stepper Interface.

IBM Compatible Computer and the 78250 and 78350 Radiometry Boards.

DETECTION
EQUIPMENT

For further information on any product in this catalog CALL (203) 377-8282

Fiber optics add a new dimension to Light Research. Their flexibility lets you bend and carry light to inaccessible places. Special configurations allow you to reshape beams to match monochromator slits and samples. Multi branch models serve as beam splitters or combiners, or as dual source illuminators.

The varied uses of fiber optics demands a line of support equipment, from simple holders to precision positioners and multi element imaging lens probes. You will find the most comprehensive line of fiber bundles, liquid light guides and support equipment on pages 396 to 415.

The photograph shows one example of the optical paths you can create with just one light source and two bifurcated fiber bundles. Integrating spheres add repeatability and meaning to many fiber optic projects. A sphere based measuring system is insensitive to fiber output pattern.

NBS TRACEABLE TEMPERATURE CALIBRATION SOURCES

MIKRON 300 SERIES

Blackbody Radiation Calibration Sources

From -20°C to 3000°C traceable to NIST

For Precision Calibration of:

- Infrared thermometers
- Optical pyrometers
- Emissivity/reflectivity determination
- Thermal imaging equipment
- Spectral radiometers
- Radiant heat flux meters

Pictured above are several models from the Mikron family of blackbody calibration sources.

Mikron Blackbody Radiation Calibration Sources

Mikron has been making blackbody calibration sources since 1970. A tradition of innovation and a wealth of engineering know-how have helped to make Mikron a distinguished name in the field.

The blackbody sources described in this brochure were designed to meet the most demanding calibration standards. They are ideal for checking the accuracy of infrared temperature sensors, spectral radiometers, infrared thermal imaging equipment, heat flux meters, etc. These units cover temperature ranges from sub-zero to 3000°C and are suitable for calibration requirements in such industries as: ceramic, chemical, petrochemical, environmental control, food, glass, metals, plastics, semiconductor, textile, pharmaceutical, medical, biological and aerospace.

Quality Assurance:

Reliability is *never* taken for granted at Mikron. After final assembly, every blackbody source is tested and burned-in for a period of several days and rigorously subjected to thermal cycling and vibration to verify calibration stability before shipment. Every blackbody source has a history file that includes calibration data, production and service information.

MIKRON 340

The M340 is a portable blackbody calibration source covering the range from sub-zero to 100°C. The thermoelectric heating/cooling mechanism is utilized to achieve a compact and easy-to-use blackbody source. The M340 has unusually high temperature stability and a stabilization time of only 10 minutes. Source temperature is closely controlled by a self-tuning PID controller which displays temperature in a digital readout.

Specifications:

Temperature Range: -20 to 100°C
and -14.0 to 199.9°F
Accuracy: $\pm 0.2^\circ\text{C}$
Resolution: 0.1°C
Stability: 0.1°C per 8 hour period
Aperture Diameter: 51mm (2.0")
Source Non-uniformity: $\pm 0.1^\circ\text{C}$
Emissivity: $0.99 \pm 0.005 - 0.000$
Temperature Sensor: Platinum RTD

Method of Control: Digital self-tuning
PID controller

Stabilization Time: 10 minutes

Operating Ambient Temperature: 5 to 40°C
(40 to 104°F)

Power Requirements: 115VAC $\pm 10\%$ 50/60Hz
300w max. (220VAC optional)

Dimensions: 519mm H x 305mm W x 336mm D

Weight: 6.5kg (14.5 lbs.)

Optional Features:

Built-in platinum resistance thermometer standard:

Resistance: 100 ohms

Accuracy: $\pm 0.1\%$

RS485 serial communication output

MIKRON 310

The M310 is a highly compact portable blackbody calibration source with a built-in digital indicating controller that can be set at any temperature between ambient and 300°C. Once set, the source temperature is controlled to within $\pm 0.3^\circ\text{C}$ by an internal RTD sensor. The unit has an emissivity of +0.99.

The M310 is ideal for field maintenance applications since it consumes little power and can be operated from an automotive battery inverter or AC line voltage.

For applications requiring higher accuracy, the M310 can be supplied with a separate platinum RTD assembly with calibration certificate traceable to NIST.

Specifications:

Temperature Range: (Ambient $+15^\circ\text{C}$) to
300°C or 570°F

Accuracy: 0.25% of reading ± 1 digit

Stability: 0.3°C per 8 hour period

Aperture Diameter: 76mm (3.0")

Emissivity: $0.99 \pm 0.005 - 0.000$

Temperature Sensor: Platinum RTD

Method of Control: Digital PID controller

Warm-up Time: 30 minutes

Operating Ambient Temperature: 0 to 44°C
(30 to 110°F)

Power Requirements: 115VAC $\pm 10\%$ 50/60Hz
150w max. (220VAC optional)

Dimensions: 178mm H x 276mm W x 178mm D

Weight: 4.3kg (9.5 lbs.)

Optional Accessories:

Platinum resistance thermometer standard

MIKRON 300

This blackbody calibration source features a unique uniformly heated spherical cavity with a near ideal emissivity of 0.999 or better. The M300 will deliver any temperature between 100°C and 1200°C. A convenient microprocessor-based, self-tuning digital PID controller holds the selected temperature to within 1°C assuring high accuracy calibration of infrared thermometers, thermal imaging equipment, etc. The controller has dual 4-digit display with the lower display indicating the desired set point and the upper display indicating the actual blackbody source temperature.

Cavity Heater Life:

Under average usage normally encountered in industry or in the laboratory, cavity heater life is measured in years. A replacement spherical cavity, which is available from stock, can be installed in less than 2 hours. No need to disturb the insulation material since the spherical cavity is pre-assembled inside a stainless enclosure. Supplied complete and ready to operate, the M300 table-top units are easy and convenient to operate. An internal fan keeps the cabinet surfaces at a safe, comfortable temperature.

Specifications:

Temperature Range: 100 to 1200°C
and 210 to 2190°F
Accuracy: $\pm 0.25\%$ of reading ± 1 digit
Resolution: 1°C or 1°F
Stability: 0.5°C per 8 hour period
Heated Cavity Shape: Spherical
Aperture Diameter: 51mm (2.0")
Emissivity: 0.999 ± 0.0005
Method of Control: Digital self-tuning
PID controller
Warm-up Time: 1 hour
Operating Ambient Temperature: 0 to 44°C
(32 to 110°F)

Cooling: Fan cooled, air inlet on back panel
Power Requirements: 220VAC $\pm 10\%$ 50/60Hz
1.5kw max. (115VAC optional)
Dimensions: 69cm H x 53cm W x 58cm D
Weight: 80kg (175 lbs.)

Optional Features:

RS422 serial communication output
Remote analog set point control: 0 to 5VDC input

Optional Accessories:

Platinum thermocouple standard — type PT-10
Universal mounting flange
Cold aperture wheel assembly

MIKRON 305

The M305 blackbody calibration source design achieves significant weight and size reduction over the M300 with only minor sacrifices in specification and performance, making it an ideal unit where portability is required or space is limited. The spherical cavity yields an emissivity of 0.995 over the temperature range of 100 to 1000°C with an aperture of 25mm. An integrally mounted PID controller completes this versatile calibrator.

Specifications:

Temperature Range: 100 to 1000°C
and 210 to 1830°F
Accuracy: $\pm 0.25\%$ of reading ± 1 digit
Resolution: 1°C or 1°F
Stability: 1°C per 8 hour period
Aperture Diameter: 25mm (1.0")
Heated Cavity Shape: Spherical
Emissivity: 0.995 ± 0.0005 - .0000
Sensor: Precision platinum thermocouple
Method of Control: Digital self-tuning
PID controller
Warm-up Time: 15 minutes
Operating Ambient Temperature: 0 to 44°C
(32 to 110°F)
Cooling: Fan cooled, air inlet on back panel
Power Requirements: 115VAC $\pm 10\%$ 50/60Hz
1.0kw max. (220VAC optional)
Dimensions: 270mm H x 430mm W x 370mm D
Weight: 25kg (55 lbs.)

Optional Features:

RS422 serial communication output
Remote analog set point control: 0 to 5VDC input

Optional Accessories:

Platinum thermocouple standard — type PT-10
Universal mounting flange

MIKRON 360

The M360 blackbody calibration source uniquely combines portability with wide temperature range, high emissivity and remarkable resolution. The source and the controller are housed in separate modules which allows the source to be positioned in a location remote from the controller such as in an environmental test chamber, or to be used in tests which involve long path lengths. Each module is fitted with a carrying handle and can be comfortably carried to manufacturing plant or field research locations.

The source is a spherical cavity with a 25mm (1.0") dia. aperture. It operates over the 50 to 1100°C range with an emissivity of 0.999 ± 0.0005 and resolution of 0.1°. The controller is an advanced design with automatic tuning to minimize source stabilization time. It has an optional RS422 communication port for data acquisition and automatic programming of source temperatures by a computer.

Specifications:

Temperature Range: Model M360: 50 to 1100°C and 200 to 2000°F; Model M360A: 50 to 750°C and 120 to 1400°F

Accuracy: Model M360: $\pm 0.2\%$ of reading ± 1 digit; Model M360A: $\pm 0.05\%$ of reading $\pm 0.1^\circ\text{C}$

Resolution: Model M360: 1°C or 1°F ; Model M360A: 0.1°C or 0.1°F

Stability: Model M360: 0.5°C per 8 hour period; Model M360A: 0.1°C per 8 hour period

Heated Cavity Shape: Spherical

Aperture Diameter: 25mm (1.0")

Aperture Solid Angle: 20°

Emissivity: 0.999 ± 0.0005

Uniformity of Temperature: To within $\pm 0.1\%$ of controller setting

Temperature Sensor: Model M360: Thermocouple type S, NIST traceable; Model M360A: Platinum RTD, NIST traceable

Method of Control: Digital self-tuning PID controller

Slew Rate: $10^\circ\text{C}/\text{minute}$; **Cooling:** Fan cooled

Stabilization Time: 10 minutes to within rated accuracy

Operating Ambient Temperature: 0 to 44°C (32 to 110°F)

Power Requirements: 115VAC 50/60Hz 1.0kw max. (220VAC optional)

Dimensions: Blackbody source: 305mm H x 273mm W x 368mm D; Controller: 210mm H x

210mm W x 280mm D

Weight: Blackbody source: 15kg (33 lbs.);

Controller: 5.0kg (11 lbs.)

Optional Features:

RS422 serial communication output

Remote analog set point control: 0 to 5VDC input

Optional Accessories:

Platinum thermocouple standard

— type PT-10 for M360

Platinum resistance thermometer standard for M360A

Universal mounting flange

Cold aperture wheel assembly

MIKRON 330

The M330 blackbody calibration source can deliver any temperature between 100 and 1700°C . A closed end tube with a 25mm aperture diameter is heated by Molybdenum Disilicide elements which provide excellent uniformity and a quick heat-up time of only 50 minutes to reach 1700°C . A self-tuning digital PID controller with adjustable set point holds the temperature to within 1°C at 1700°C , assuring high accuracy calibration. An independent over temperature alarm and cutout system prevents heating element burnout. An internal fan keeps the cabinet surface at a safe, comfortable temperature.

Specifications:

Temperature Range: 300 to 1700°C and 572 to 3100°F

Accuracy: $\pm 0.25\%$ of reading ± 1 digit (for temperatures above 600°C)

Resolution: 1°C or 1°F

Stability: 1°C per 8 hour period

Aperture Diameter: 25mm (1.0")

Emissivity: 0.99 ± 0.005

Cavity: Closed end tube 25mm ID x 300mm long with 125mm heated length

Sensor: Platinum thermocouple — type B

Method of Control: Digital self-tuning PID controller

Warm-up Time: To 1700°C approx. 50 min.

Operating Ambient Temperature: 0 to 44°C (32 to 110°F)

Power Requirements: 220VAC $\pm 10\%$ 50/60Hz 2.0kw max. (115VAC optional)

Cooling: Fan cooled, air inlet on back panel

Dimensions: 69cm H x 53cm W x 58cm D

Weight: 80kg (175 lbs.)

Optional Features:

RS422 serial communication output.

Remote analog set point control: 0 to 5VDC input.

Optional Accessories:

Platinum thermocouple standard — type PT-10

Universal mounting flange

Cold aperture wheel assembly

MIKRON 370

The M370 tungsten lamp calibration source features an NIST traceable pyrex enveloped strip lamp and precision DC current source with rate of change limiting controller to protect filament life. This source will deliver any temperature from 800°C to 2300°C in 1°C steps. Pre-aligned apertures provide effortless aiming at the 3 x 3mm active filament area. A micro-processor-based electronic module has memorized the relationship between current and temperature. The emitted radiance intensity of the filament is compensated for the emissivity of the tungsten filament and lamp envelope. This feature eliminates the need for a conversion table. A digital display indicates the lamp absolute temperature.

This convenient source is useful for calibrating two-color infrared thermometers and other single-color thermometers or pyrometers that require small target sizes and high temperatures. The lamp is replaceable in minutes. An internal fan keeps the cabinet surfaces at a safe, comfortable temperature.

Specifications:

Temperature Range: 800 to 2300°C
and 1420 to 4170°F

Accuracy: $\pm 4^\circ\text{C}$ at 2300°C, $\pm 2^\circ\text{C}$ at 800°C

Resolution: 1°C

Stability: 1°C per 8 hour period

Source Type: Tungsten filament approximately
33mm long and 3mm wide with small notch in
side of filament

Method of Control: 4 1/2 digit PID controller

Operating Ambient Temperature: 0 to 44°C
(32 to 110°F)

Power Requirements: 115VAC $\pm 10\%$
50/60Hz (1200w) max. (220VAC optional)

Dimensions: 69cm H x 53cm W x 58cm D

Weight: 86kg (190 lbs.)

MIKRON 390

The M390 high temperature blackbody calibrator is without parallel in its capability to produce very high temperature, high emissivity targets and at the same time stabilize at the required temperature within a few minutes of switch-on. The graphite tube target has a 16mm diameter, optionally 25mm (1.00") aperture and an emissivity of 0.995. Target temperature is sensed by a rapid response Mikron infrared fiber optic thermometer which drives a PID controller to regulate the target temperature precisely to the desired value. The controller can be located up to 7.5m from the calibration source with the connecting cable supplied and remote set point setting is achieved via an RS422 communication port.

Specifications:

Temperature Range: 600 to 3000°C and
1110 to 5430°F

Accuracy: 0.25% of reading ± 1 digit

Cavity: Closed end graphite tube 150mm (6.0")
long with 64mm (2.50") heated length

Source Diameter: 16mm (.625") dia.;
25mm (1.00") optional

Emissivity: 0.995 $\pm$.003

Cooling: Water cooled, hose connections on rear,
12 lpm (3 gpm)

Heating Element Type: Graphite tube nitrogen
gas purge, 80 lph (3cfh)

Temperature Sensor: Mikron "Infraducer"

Method of Control: Digital PID controller

Remote Set Point: RS422 serial
communication output

Warm-up Time: Room to 2500°C
approx. 5 minutes

Interconnecting Cable: 7.5m (25') long

Operating Ambient Temperature: 0 to 44°C
(32 to 110°F)

Power Requirements: 240VAC, 12kw

Dimensions: 1143mm H x 559mm W x 622mm D
Weight: Approx. 182kg (400 lbs.)

Description of Optional Accessories:

Platinum Thermocouple Standard: The Mikron verification thermocouple standard is a platinum vs. platinum 10% rhodium (PT-10) thermocouple conforming closely to NIST RP1080. This thermocouple assembly can be inserted into the spherical cavity through a special opening at the top of the M300 or through opening of other models. It contains exceptional measuring accuracy, following the published IPTS-68 curve to within $\pm 0.1\%$ of reading. In addition, an individual calibration certificate with 100°C incremental data traceable to NIST is supplied. The thermocouple assembly is approximately 33cm (13") long with an immersion length of 25cm (10"). For storage, an attractive yet sturdy wooden box with a hinged cover and foam packing will protect the thermocouple from damage and contamination. To order specify PN 12341.

Resistance Thermometer Standard: The Mikron resistance thermometer is a PT-100 conforming to NIST and DIN 43760. It has exceptional accuracy ($\pm 0.2^\circ\text{C}$) and stability. The four internal leads are fine gold and the protective tube is nickel. The four external lead wires are hermetically sealed from the inner chamber of the thermometer. To order specify PN 14192.

Cold Aperture Wheel Assembly: Frequently used in application requiring smaller radiating apertures or verifying field of view of infrared thermometers, radiometers or infrared imaging equipment.

Water or gas cooling capabilities of this assembly ensure minimum contribution of background radiation. Precision machining of aperture wheel allows perfect optical alignment.

To order specify

PN 14002

Aperture Size

50mm, 25mm, 13mm, 6mm, 3mm, and 2mm

PN 14002-1

25mm, 13mm, 10mm, 8mm, 5mm, and 3mm

Universal Mounting Flange: This flange has been machined with numerous mounting holes to accept virtually all manufacturers' sensor heads. Three stand-offs provide a safe clearance between the sensor head and the radiation aperture. To order specify PN 11668

CUSTOM MODELS

The blackbody calibrator specifications in this catalog describe standard, production instruments used routinely in industrial process, medical and research environments. However, with the increasing application of infrared measurement technology in the electronics, aerospace and other demanding fields, the need for special blackbody sources has grown commensurately. Mikron has been able to respond to even the most esoteric requirements, including airborne systems, large area sources, ultra-high resolution calibrators and systems to operate in a vacuum. A selection of these non-standard instruments is illustrated here and we will be pleased to receive your specifications with a view to offering a proposal to meet your special requirements.

Dual large area low temperature blackbody source

Ultra precision dual independent cavity blackbody source; 0.01°C resolution and stability, 0.02°C absolute accuracy; temperature range: 0 to 100°C .

Vacuum blackbody source

Warranty:

Every blackbody source is covered for all defective material and workmanship for one full year after shipment. Heating elements are excluded from this warranty.

Made in U.S.A.

The 300 Series is designed and built by Mikron, the leading innovator in infrared thermometry. Manufacturing facility is located in Wyckoff, New Jersey.

MIKRON

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