

IV. ADDITIVE COST SURVEY

A. Approach

In this portion of the study, the objective was to determine the cost of the three additives suggested for improving the flame luminosity of fuel methanol from the Task 1 Expansion, namely:

- Toluene
- Cyclopentene
- Indan.

The initial steps included reviewing chemical supplier publications and catalogs and making telephone inquiries for availability and price. Cyclopentene and indan appeared to be available in small, expensive quantities from chemical supply houses. No bulk prices were obtained by calling several chemical supply houses. Neither chemical is a commercial product available in bulk or as an intermediate material for the production of other chemicals.

Toluene is distributed widely in bulk quantities because of its use as an intermediate chemical for the production of solvents, explosives, isocyanates, and other chemicals as well as an octane booster in gasoline. Toluene is also used to make benzene by thermal dealkylation when the benzene price and demand are high. Prices for toluene as a commodity are reported in several publications. The cost for toluene was derived as a projection of the cost for the last year (January through December 1991).

The approach to develop costs for indan and cyclopentene required an estimate for the costs of making them from other starting materials because initial inquiries to major U.S. companies that produce coke and by-product chemicals from coal (possible sources of indan and cyclopentene) produced disappointing results. Those companies sold most of their by-products which contained indan and cyclopentene to other companies for internal use, and the quantities were not sufficient to supply the projected needs as a potential fuel additive.

Since no direct source of indan or cyclopentene was found, then an alternative was needed. Dicyclopentadiene (DCPD) was selected as a source of cyclopentene because DCPD is a dimer of cyclopentadiene (CPD) which could then be converted into cyclopentene. Similarly, indene is an unsaturated homolog which could be converted to indan. Both materials are included in the by-product mixtures from the high temperature carbonization (coking) of coal. The problem was to find a supplier who separates and purifies DCPD and indene. These raw materials would then be processed to saturate one olefinic bond by hydrotreating at relatively mild conditions, thus producing the desired compounds.

A library reference book indicated that large quantities of DCPD were available in the U.S. from steam cracking of hydrocarbons to make ethylene and propylene.⁽⁷⁰⁾ In addition, the quantities of DCPD from these sources were several times the amount available from coal, and a purity of over 95 percent was possible. Other starting materials were considered such as furan or thiophene for cyclopentene and benzothiophene for indan. However, these considerations were dropped because the oxygen or sulfur in the five-member rings would require processing conditions with higher severity to remove the heteroatoms. More severe conditions would result in increased costs and the possibility of more unwanted side reactions.

The distribution of products for the discussion below was assumed to be by bulk shipment in tank trucks. The destinations would be terminals where the additives would be blended into methanol or fleet operations with bulk storage to do the same thing. The third possibility would be to put a small, metered volume of additives into a tank truck before it went to a source of M100 for splash blending. The truck loading racks would be automated with card access and controls to permit driver loading.

B. Toluene

Spot prices for unleaded regular gasoline in Los Angeles and for toluene nationwide were tabulated from a weekly newsletter market report for all of 1991.⁽⁷³⁾ Trends of prices with time are shown in Figure 16. The peak prices of both products occurred at about the same time, but there was a slight downward trend for gasoline that was not as apparent for toluene.

A linear regression of the data is shown in Figure 17. The equation for the line is:

$$T = 0.7646UR + 0.4378$$

Where: T = Toluene price in \$/gal, and
UR = Unleaded regular price in \$/gal.

The correlation coefficient, R, of 0.6666 is relatively low as indicated by the scatter shown in the plot. The R-squared value, 0.4444, implies that about 44 percent of the variation in toluene price is accounted for by the unleaded regular price. This result is reasonably good considering:

- Gasoline prices were for Los Angeles
- Toluene prices were national
- Toluene price is affected by other uses in chemical markets.

Figure 18 presents the most direct representation of the 48 data points with a frequency distribution of toluene spot prices. The arithmetic average was \$0.901 per gallon, and the median value of \$0.905 per gallon was exceeded by half of the data points. The middle 50 percent of the sample fell in the range of \$0.870 to \$0.945 per gallon. A price of \$0.90 per gallon will be used in estimating the additive costs for toluene.

C. Cyclopentene Production

DCPD is available from petrochemical plants on the Gulf Coast which can meet the maximum quantities listed above. Three grades of DCPD are available for potential feedstocks to make cyclopentene. Analyses were provided of typical production and were used to estimate purity of the final product, as follows:

<u>Grade</u>	<u>DCPD/CPD In feed, Wt%</u>	<u>Cyclopentene In Product, Wt%</u>
DCPD 97	97.0	98.0
Polyester Resin	82.0	91.3
Hydrocarbon Resin	76.8	88.0

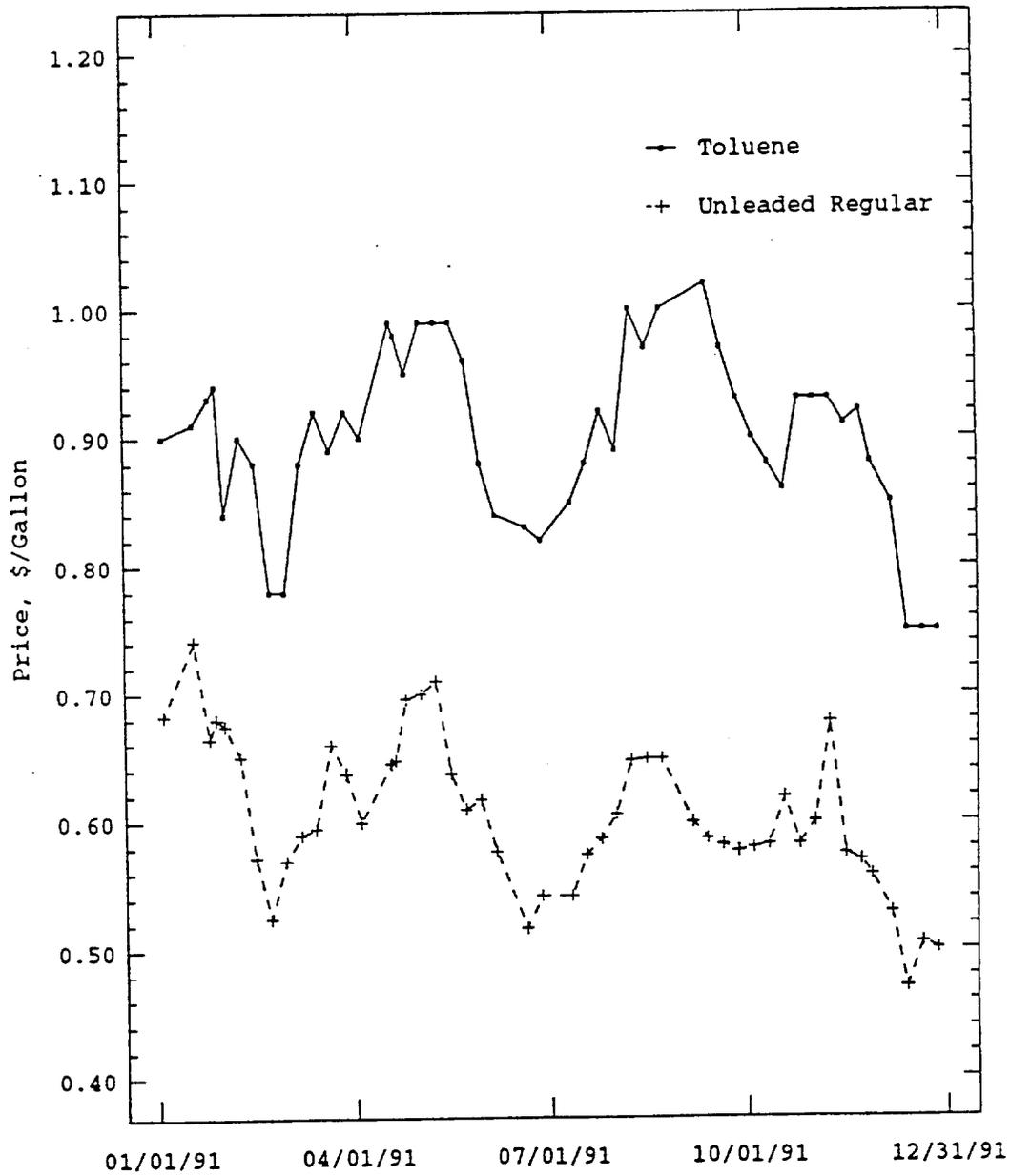


FIGURE 16. TRENDS OF TOLUENE AND UNLEADED REGULAR SPOT PRICES

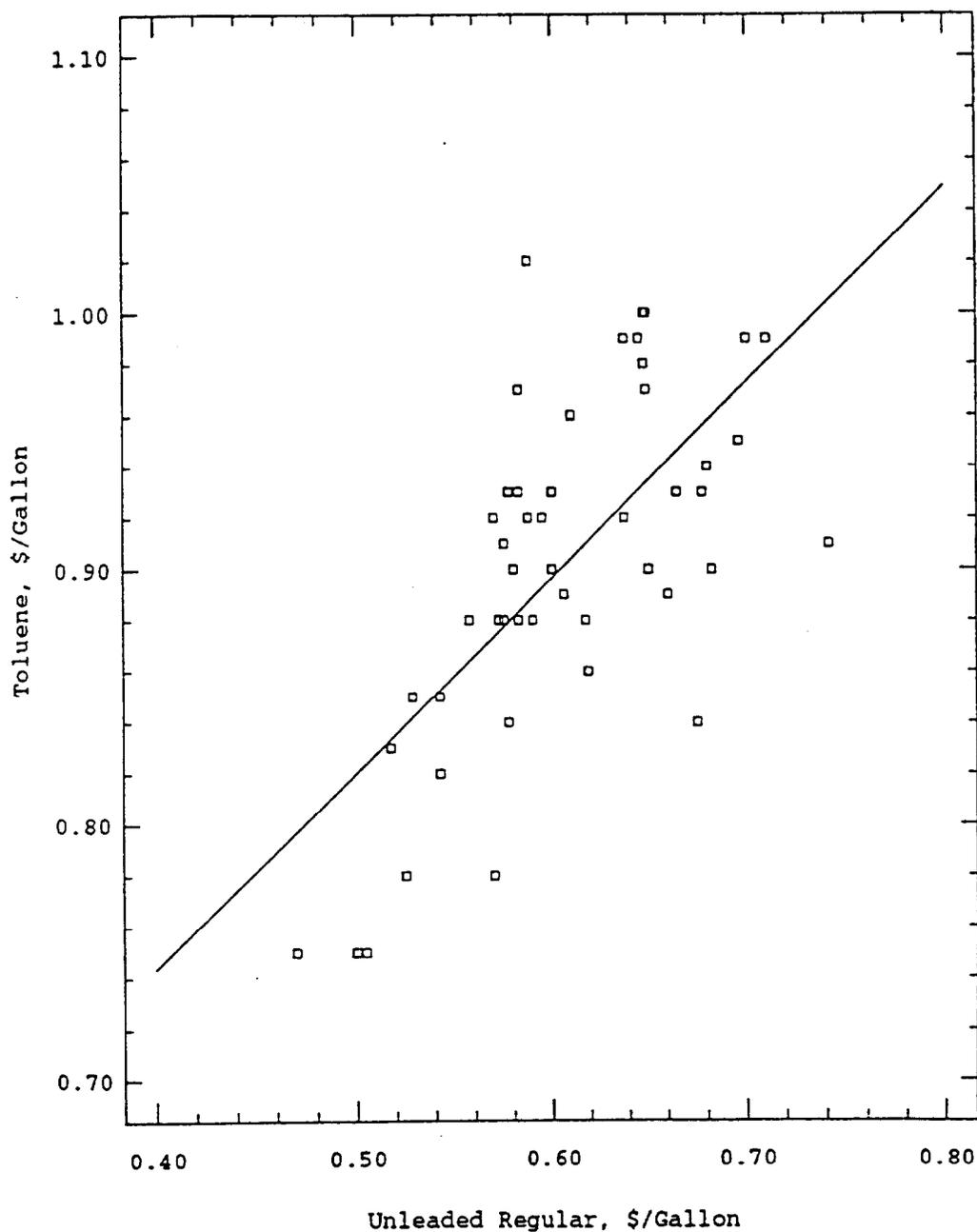


FIGURE 17. COMPARISON OF TOLUENE AND UNLEADED REGULAR SPOT PRICES - 1991

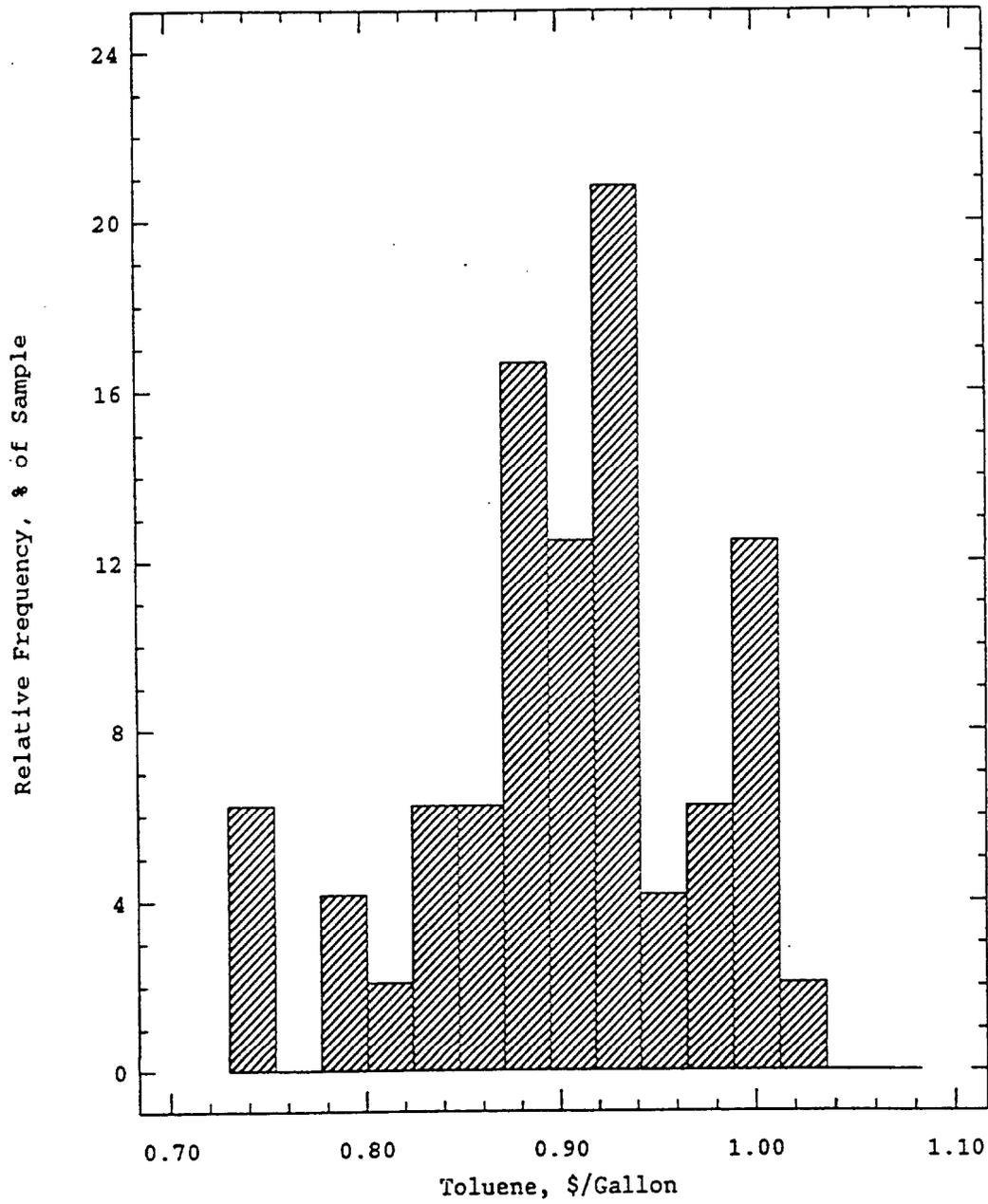


FIGURE 18. TOLUENE SPOT PRICE VARIATION FOR 1991

The product purity increased over the feed because unreactive heavy compounds were discarded to fuel with unconverted DCPD in the DCPD cracking unit. An assumption was made that C₁₀ co-dimers were 50 percent cyclopentadiene which would dissociate and be converted to product. These lower purity grades were included in the economic analysis in Section IV. F. along with the 97 percent purity feedstock. Current prices for the different feedstocks vary with purity and are listed in Table 27.

TABLE 27. CURRENT PRICES FOR DICYCLOPENTADIENE

Purity, wt %	Price Delivered to Southern California		
	Cents/Pound*	Pounds/gal	Dollars/gal
97	35	8.17	2.86
80-85	19-21	8.03	1.53-1.69
70-75	17-18	7.98	1.36-1.44

*includes transportation costs in tank cars from Gulf Coast at 3 cents/lb

The process scheme for converting DCPD to cyclopentene is shown in Figure 19, with a material balance based on actual properties of the 97 percent purity DCPD and a few assumptions of purity of other streams. The DCPD dimer would be received from tank cars and transferred to the DCPD cracking unit where the feed would be converted to essentially pure CPD monomer. A small portion of the DCPD is discarded in fuel oil to avoid high concentration of peroxides. The CPD monomer is then processed in a partial hydrogenation unit to saturate one of its two olefin bonds. A catalyst supplier verified that this hydrogenation step is feasible with a selective palladium catalyst, and provided operating conditions and catalyst cost.⁽⁷⁴⁾

It was assumed that the conversion plant would be located in or immediately adjacent to a refinery to provide access to a source of hydrogen, utilities, and other refinery support systems such as fire protection and administrative functions. The plant would consist of the processing equipment plus facilities for storage and handling of feedstock and product.

Published information on refinery construction plans was reviewed to provide a basis for estimating investment cost for the hydrotreater section. The data for nine hydrotreaters with a wide range of capacities are listed in Table 28.⁽⁷⁵⁾ These process units are located in different areas of the country, and the variation of costs for plants of similar capacity may indicate differences in processing severity or construction standards.

A regression of the data in Table 28 resulted in the following relationship:

$$\text{Ln}(\text{Cost}) = 2.025 + (5.023 \times 10^{-5}) \text{ Capacity}$$

or

$$\text{Cost} = e^{(2.025 + 5.023 \times 10^{-5} \times \text{Capacity})}$$

A plot of the regression line is shown in Figure 20 with dashed lines for the 95 percent confidence limits. The correlation coefficient is 0.9479, and the R-squared value of 0.8986 indicates that almost 90 percent of the variation in Ln(Cost) is explained by the relationship with capacity. Using the equation with the planned capacity of 3,172 barrels of DCPD per stream day gives an investment cost for the hydrotreater section of \$8.9 million.

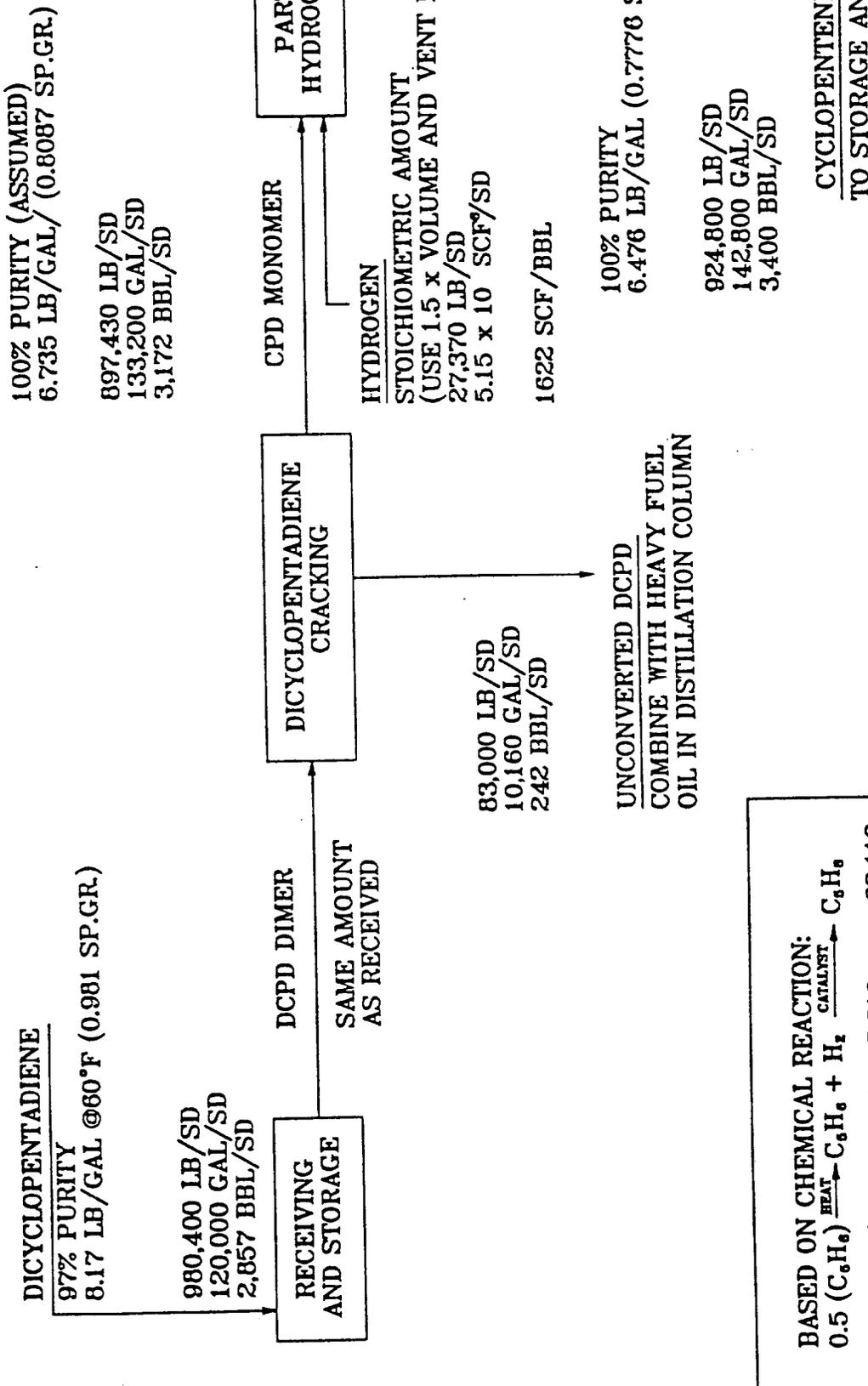


FIGURE 19. PROCESS SCHEME AND MATERIAL BALANCE FOR CONVERSION OF DICYCLOPENTADIENE TO CYCLOPENTENE

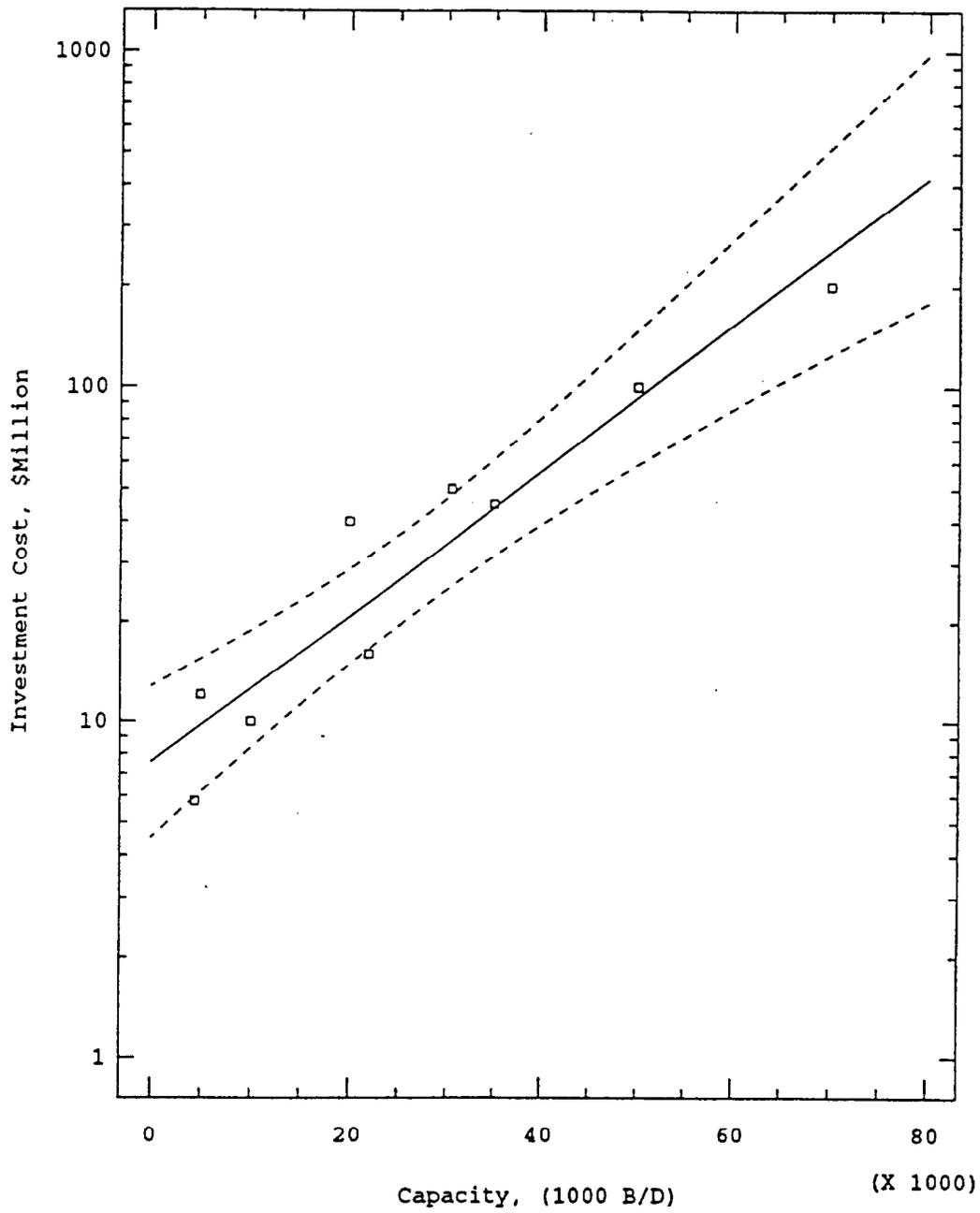


FIGURE 20. HYDROTREATER INVESTMENT COST VS. CAPACITY

TABLE 28. HYDROTREATER INVESTMENT COSTS

Hydrotreater Capacity, barrels per day	Investment Cost, \$ million
4,400	5.8
5,000	12.0
10,000	10.0
20,000	40.0
22,000	16.0
30,500	50.0
35,000	45.0
50,000	100.0
70,000	200.0

Investment costs for the total plant to convert DCPD to cyclopentene are given in Table 29. The DCPD cracking section is a relatively simple fractionation column with an overhead and a bottoms product estimated to cost \$1 million. Off-site facilities were taken as 30 percent of the processing equipment cost. Catalyst cost was added in two increments: the aluminum oxide base which can be depreciated and the palladium metal content which is ultimately recoverable at the end of the project life.

In order to develop operating costs, the material balance was expanded to a heat and material balance. Process design calculations were made in enough detail to estimate utility requirements.⁽⁷⁶⁾ Major equipment items are shown in the process flow diagram (See Figure 21).

Conversion of DCPD dimer to the CPD monomer is done by thermal dissociation or cracking. The operating conditions require high pressure (HP) steam, 565 psig superheated to 650°F, to obtain 480°F at the bottom of the column and to provide the heat of reaction of 1,205 BTU per pound.⁽⁷⁰⁾ The CPD monomer distilled overhead is condensed at 100°F and then chilled to 30°F to reduce the rate of dimerization which occurs spontaneously at ambient temperature.⁽⁷⁷⁾

In the hydrogenation section, the reactor temperature was controlled by generating low pressure (LP) steam, 52 psig saturated at 300°F, to absorb the heat of reaction estimated to be 608 BTU per pound of CPD monomer. The cyclopentene product was separated from the excess hydrogen and sent to a stripper column to remove dissolved hydrogen and any hydrocarbons lighter than cyclopentene. All other heating services were done with medium pressure (MP) steam, 235 psig saturated at 400°F. Cooling water was assumed to be available at 70°F as needed for coolers and condensers. The 3,400 B/SD cyclopentane product was sent to storage at 100°F. Its boiling point of 111-112°F made it advisable to provide low pressure spherical storage tanks to reduce vapor losses and to protect against overpressure on warm days. Utility costs were derived from published data and were shown in Table 30.

Operating expenses anticipated for cyclopentene production are listed in Table 31. Two operators and a product handler were planned at the hourly rates shown plus percentage allowances for benefits and supervision.⁽⁸²⁾ The 10 percent of facilities cost for maintenance and 3 percent for taxes and insurance are customary factors for this type of estimate.⁽⁷⁹⁾ Utilities and hydrogen costs plus fuel credit for excess

TABLE 29. CYCLOPENTENE UNIT INVESTMENT COST

Dicyclopentadiene Cracking Unit	\$1,000,000
Cyclopentadiene Hydrogenation Unit	<u>8,900,000</u>
Processing Facilities	\$9,900,000
Off-Sites, 30% of Processing Facilities	<u>2,970,000</u>
Total Facilities Cost	\$12,870,000
Catalyst, Depreciable Portion of Cost	<u>104,000</u>
Depreciable Investment	\$12,974,000
Metal Content of Catalyst (Recoverable)	<u>32,300</u>
Total Investment	\$13,006,300

OFF-SITE FACILITIES INCLUDE THE FOLLOWING MAJOR ITEMS:

1. Dicyclopentadiene Receiving and Storage
 - a. Unloading Rack, 8 railroad cars each side
 - b. Two cone roof tanks, 15,000 barrels each (approximately 10 days supply of feedstock)
2. Cyclopentene Product Shipping and Storage
 - a. Loading rack, 4 trucks total
 - b. Three spheres (low pressure), 12,000 barrels each (approximately 10 days production)
3. Connections to Utilities and Other Refinery Support Systems

TABLE 31. CYCLOPENTENE UNIT OPERATING EXPENSES

<u>Operating Cost</u>	<u>Units</u>	<u>Unit Cost</u>	<u>Cost, \$/SD</u>	<u>Cost, \$/SD</u>
Operating Labor				
No. 1 Operator	24 hr	\$17/hr	408	
Boardman	24 hr	\$15/hr	360	
Shipping & Receiving	16 hr	\$12/hr	<u>192</u>	
Subtotal			960	
Supervision	20%		<u>192</u>	
Subtotal			1,152	
Benefits	30%		<u>346</u>	
Total Operating Labor				1,498
Maintenance	10% of Facilities Cost/Year*			3,677
Taxes & Insurance	3% of Facilities Cost/Year*			1,103
Utilities				
Steam	<u>lb/hr</u>	<u>\$/Mlb</u>		
HP Steam, 565 psig, 650°F	55,980	4.27	5,737	
MP Steam, 235 psig, Sat.	11,270	3.64	985	
LP Steam, 50 psig, Sat.	(24,980)	2.64	(1,583)	
Boiler Feed Water	24,980	0.31	<u>186</u>	
Sub-Total Steam			5,325	
Electric Power	720 Kw	\$0.06/Kwh	1,037	
Cooling Water Usage	13.7 MMBTU/hr	\$0.38/MMBTU	<u>124</u>	
Total Utilities				6,486
Excess DCPD to Fuel	(242 B/SD)	\$16.57/B		(4,010)
Hydrogen	<u>MSCF/hr</u>	<u>\$/MSCF</u>		
Hydrogen Supply	321.5	1.34	10,339	
Excess Hydrogen	(107.2)	0.72	<u>(1,852)</u>	
Net Hydrogen				8,487
Catalyst Consumption	\$104,000, 5-Year Life			<u>60</u>
Total Operating Cost, \$/SD				17,301
Annual Cost, 350 Days/Year				\$6,055,350
Annual Feedstock Cost, 97% Dicyclopentadiene				
\$2.86/gal × 120,000 gal/SD × 350 Days/Year =				\$120,120,000

*Facilities cost does not include cost of hydrogenation catalyst.

TABLE 30. UTILITY COSTS FROM PUBLISHED DATA

<u>UTILITY</u>	<u>COST, \$/UNIT</u>	<u>REFERENCE</u>
1. Steam		
High Pressure	4.27/Mlb	77
Medium Pressure	3.64/Mlb	77
Low Pressure	2.64/Mlb	77
Boiler Feed Water	0.31/Mlb	78
2. Electric Power	0.06/Kwh	79
3. Cooling Water	0.38/MMBTU	79
4. Plant Fuel	2.63/MMBTU	77
Barrel, Fuel Oil Equivalent (6.3 MMBTU)	16.57/BFOE	77
5. Hydrogen (NHV 274 BTU/SCF)		
Supply (1.86 × Fuel Value/BTU)	1.34/MSCF	80
Excess to Fuel (Fuel Value/BTU)	0.72/MSCF	80

DCPD were valued at unit costs from Table 30. Note that hourly rates need to be multiplied by 24 hours per day to obtain costs per stream day. Annual costs assume operating 350 stream days per year. Costs for the remaining days of the year are part of the maintenance budget. Operating costs and feedstock cost were annualized for use in economic calculations in Section IV. F.

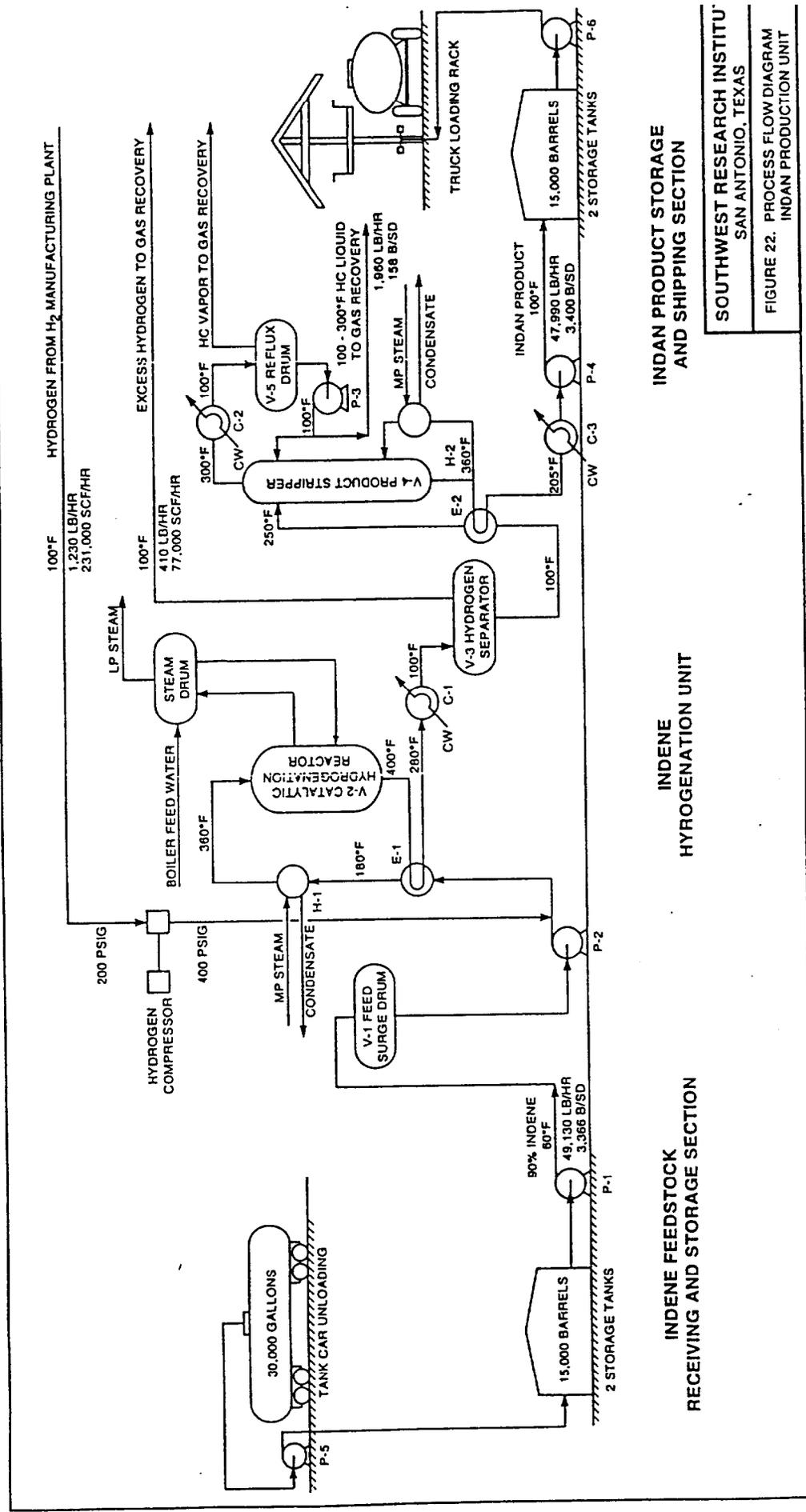
D. Indan Production

The starting material, indene, is available at 90 percent purity on the West Coast at a price of about \$2.00 per kilogram or \$0.9074 per pound. At \$0.9074 per pound and 8.340 pounds/gal,⁽⁸³⁾ indene cost would be \$7.57 per gallon.

The indene is imported from Germany, where it is recovered from liquids produced in coking of coal. The supply should be sufficient for the initial need of 4 million pounds of indene per year, but it is questionable whether the future growth to 10 times and 100 times that amount could be supplied. A domestic supplier or manufacturer has not been located in the course of this study. There is the possibility that a supplier will be found with further effort, or that an assured demand would stimulate increased production.

The process scheme would be similar to that for cyclopentene, to saturate an olefin bond with hydrogen. As with cyclopentene, processing would include hydrogenation, however, a cracking step would not be necessary. Investment costs are listed in Table 32. The 30 percent factor for off-site facilities is directionally correct because indan storage may use cone or floating roof tanks which cost less than low pressure spheres for cyclopentene.

The process flow diagram in Figure 22 shows the major equipment in the feedstock receiving, hydrogenation, and product shipping sections with flow rates and temperatures of all streams. All heating is done with medium pressure (MP) steam. The heat of reaction of 421 BTU per pound of indene for partial hydrogenation produces low pressure (LP) steam. After separating hydrogen from the hydrogenated product, the distillation column removes about 4 volume percent hydrocarbons with boiling points lower than indan. The indan product is estimated to be about 96 percent purity.



INDAN PRODUCT STORAGE AND SHIPPING SECTION

INDENE HYDROGENATION UNIT

INDENE FEEDSTOCK RECEIVING AND STORAGE SECTION

SOUTHWEST RESEARCH INSTITU
SAN ANTONIO, TEXAS

FIGURE 22. PROCESS FLOW DIAGRAM
INDAN PRODUCTION UNIT

TABLE 32. INDAN UNIT INVESTMENT COST

Indene Hydrogenation Unit	\$8,900,000
Off-Sites, 30% of Processing Facilities	<u>2,670,000</u>
Total Facilities Cost	\$11,570,000
Catalyst, Depreciable Portion of Cost	<u>104,000</u>
Depreciable Investment	\$11,674,000
Metal Content of Catalyst (Recoverable)	<u>32,300</u>
Total Investment	\$11,706,300

OFF-SITE FACILITIES INCLUDE THE FOLLOWING MAJOR ITEMS:

1. Indene receiving and storage
 - a. Unloading rack, 8 railroad cars each side
 - b. Two cone roof tanks, 15,000 barrels each (approximately 10 days supply of feedstock)
2. Indan product shipping and storage
 - a. Loading rack, 4 trucks total
 - b. Two cone roof tanks, 15,000 barrels each (approximately 10 days production)
3. Connections to utilities and other refinery support systems

The heat and material balance calculations provided utility quantities. Operating expenses for the indan unit are summarized in Table 33. These costs are lower than those for cyclopentene production because of:

- Lower investment cost
- No HP steam
- Lower utilities and hydrogen consumption.

E. Combined Plant for Both Cyclopentene and Indan Production

Because the two additives may be used in combination, a combined plant was considered for production of cyclopentene and indan. The feedstocks would not be processed together but would be run separately in blocked operation because of differences in temperatures in the reactor and product stripper. Time blocks of 12 to 15 days would be used for each product. Capacity of the process equipment would be doubled because it would be used half the time for each product. Investment cost would not double,

TABLE 33. INDAN UNIT OPERATING EXPENSES

<u>Operating Cost</u>	<u>Units</u>	<u>Unit Cost</u>	<u>Cost, \$/SD</u>	<u>Cost, \$/SD</u>
Operating Labor				
No. 1 Operator	24 hr	\$17/hr	408	
Boardman	24 hr	\$15/hr	360	
Shipping & Receiving	16 hr	\$12/hr	<u>192</u>	
Subtotal			960	
Supervision	20%		<u>192</u>	
Subtotal			1,152	
Benefits	30%		<u>346</u>	
Total Operating Labor				1,498
Maintenance	10% of Facilities Cost/Year*			3,306
Taxes & Insurance	3% of Facilities Cost/Year*			992
Utilities				
Steam	<u>lb/hr</u>	<u>\$/Mlb</u>		
MP Steam, 235 psig, Sat.	8,920	4.27	914	
LP Steam, 50 psig, Sat.	(22,740)	2.64	(1,441)	
Boiler Feed Water	22,740)	0.31	<u>169</u>	
Sub-Total Steam			(358)	
Electric Power	578 Kw	\$0.06/Kwh	832	
Cooling Water Usage	7.3 MMBTU/hr	\$0.38/MMBTU	<u>67</u>	
Total Utilities				541
Light Hydrocarbons	(158B/D)	\$24.80/B		(3,918)
Hydrogen	<u>MSCF/hr</u>	<u>\$/MSCF</u>		
Hydrogen Supply	237.0	1.34	7,429	
Excess Hydrogen	(77.0)	0.72	(1,331)	
Net Hydrogen				6,098
Catalyst Cost	\$104,000, 5 Year Life			<u>60</u>
Total Operating Cost, \$/Day				8,577
Annual Cost, 350 Days/Year				\$3,001,950
Annual Feedstock Cost, 90% Indene				
\$7.57/gallon × 141,400 gallons/SD × 350 days/year =				\$374,639,300

*Facilities cost does not include catalyst.

but would increase approximately by the ratio of capacities to the 0.6 power.⁽⁸³⁾ For example, doubling the size of the hydrogenation unit would change the investment cost as follows:

$$\begin{aligned} \text{Investment} &= \left(\frac{6,800 \text{ B/SD}}{3,400 \text{ B/SD}} \right)^{0.6} \times \$8.9 \text{ million} \\ &= 1.516 \times \$8.9 \text{ million} \\ &= \$13.5 \text{ million} \end{aligned}$$

The storage capacity for feedstocks and products would be increased to provide at least 15 days volume for all liquids. This was done by increasing off-site allowance from 30 percent to 35 percent of the original investment cost for the separate units. Table 34 shows the elements of investment cost for the combined plant.

TABLE 34. COMBINED PLANT INVESTMENT COST

Hydrogenation Unit	\$13,500,000
DCPD Cracking Unit	1,500,000
Cyclopentene Unit Off-Sites @35% of \$9,900,000	3,465,000
Indan Unit Off-sites @35% of \$8,900,000	<u>3,115,000</u>
Total Facilities Cost	\$21,580,000
Catalyst, Depreciable Portion of Cost	<u>208,000</u>
Depreciable Investment	\$21,788,000
Metal Content of Catalyst (Recoverable)	<u>64,600</u>
Total Investment	\$21,852,600

Operating expenses are listed in Table 35. These values were derived from values for the separate plants given in Tables 31 and 33. Operating labor did not increase. Maintenance and taxes plus insurance were based on the new facilities cost. Other costs for making the two additives were doubled for stream day rates and the sum was multiplied by 175 stream days per year. The investment costs and operating expenses were applied in the economic evaluation to arrive at product prices, as discussed in the following section.

F. Economic Evaluation and Product Prices

To estimate the costs of cyclopentene and indan, the economics of operating the separate and combined plants were evaluated. This method is used in industry to determine if a potential investment will be profitable or to compare investment opportunities. The discounted cash flow (DCF) concept is

TABLE 35. COMBINED PLANT OPERATING EXPENSES

<u>OPERATING COST</u>	<u>\$/SD</u>	<u>\$/Year</u>
Maintenance	10% of Facilities Cost/Year*	2,158,000
Taxes & Insurance	3% of Facilities Cost/Year*	647,400
Cyclopentene Unit, 175 days/year		
Operating Labor	1,498	
Total Utilities	12,972	
Excess DCPD to Fuel	(8020)	
Net Hydrogen	16,974	
Catalyst Cost	120	
Subtotal, Cyclopentene Unit	23,544	4,120,200
Indan Unit, 175 Days/Year		
Operating Labor	1498	
Total Utilities	1082	
Light Hydrocarbons	(7,836)	
Net Hydrogen	12,196	
Catalyst Cost	<u>120</u>	
Subtotal, Indan Unit	7,060	<u>1,235,500</u>
Total Operating Cost		8,161,100
<u>FEEDSTOCK COST</u>		
Dicyclopentadiene, 97%	686,400	120,120,000
Indene, 90%	<u>2,140,796</u>	<u>374,639,300</u>
Total Feedstock Cost	2,827,196	494,759,300

*Facilities cost does not include cost of hydrogenation catalyst.

based on the fact that the present value of future income must be reduced by compound interest factors that decrease with longer time to receipt of the income.

The customary evaluation would use estimates of income, investment cost, and operating expenses to arrive at the expected DCF rate of return. In this evaluation, the DCF rate of return was defined and the estimated costs were used to define earnings and gross income to develop the sales price of the final products.

At least 15 percent rate of return would be needed to justify the investment if there was no risk at all, and 20 to 25 percent return would be more likely to attract the funds to build the unit.⁽⁷⁸⁾ Therefore, all three rates of return were used to determine the effect on price. Typical refinery units are depreciated over 13-year life. However, higher risk petrochemical plants are allowed to use 5-year life for depreciation which will increase cash flow and earnings in the first five years of operation. Both 13-year and 5-year life were used in the calculations. Economic calculations were based on the following factors affected by project life:

<u>Depreciation Life</u>	<u>13 Years</u>	<u>5 Years</u>
Depreciation Policy:		
Double Declining Balance	First 7 Years	First 3 Years
Straight Line	Last 6 Years	Last 2 Years

Common factors for both life periods were:

Income Tax, % of Net Income	
Federal	34.0
California	<u>9.3</u>
Total	43.3

Present Worth Factors: Continuous Income and Annual Compounding

An assumption was made that earnings would be constant over project life, i.e., no change in gross income, feedstock cost, or operating expenses. A spreadsheet program simplified the calculations using pre-calculated depreciation rates. Present worth factors for continuous income and annual compounding were provided in equation form.⁽⁸⁴⁾ The reliability of the computer program was verified by a manual calculation at each life period.

Since depreciation and present worth factors vary in each year, the effects of showing these factors over the project life would be a large tabulation. Table 36 illustrates the format of the calculations for all three plants in the first year of operation for 13-year life and 20 percent DCF return rate. The computer program solved for earnings listed in the upper part of the table which indicates the amount that must be earned after costs, and before taxes and depreciation, to return the investment amount on the top line. In this example, earnings were independent of feedstock and operating costs; those costs could be changed without affecting the DCF return calculations which involved only investment, depreciation, and income tax.

Feedstock and operating costs were used in this example to calculate product sales price. First, they were added to the earnings to obtain gross income from sales. This amount was moved to the sales price calculation in the lower part of Table 36 where it was divided by the product volume to obtain the sales price. The \$2.599 and \$7.623 per gallon prices for cyclopentene and indan, respectively, in the first two columns agreed with the computer results. In the combined plant, the computer produced an average

TABLE 36. EXAMPLE OF ANNUAL CASH FLOW AND PRODUCT PRICE CALCULATION

BASIS: FIRST YEAR OF OPERATION, 13-YEAR LIFE, 20% DCF RETURN

<u>Cash Flow Calculation</u>	<u>Algebraic Symbols</u>	<u>Cyclopentene Plant</u>	<u>Indan Plant</u>	<u>Combined Plant</u>
Depreciable Investment	I	12,974,000	11,674,000	21,788,000
Gross Income from Sales	G	129,881,545	380,976,083	509,144,431
Less Costs				
Feedstock Cost	F	120,120,000	374,639,300	494,759,300
Operating Expense	O	<u>6,055,350</u>	<u>3,001,950</u>	<u>8,161,100</u>
	F+O	126,175,350	377,641,250	502,920,400
Earnings	E	3,706,195	3,334,833	6,224,031
Less Depreciation, $D = 0.0769$	<u>DI</u>	<u>997,700</u>	<u>897,730</u>	<u>1,675,497</u>
Taxable Income	E-DI	2,708,495	2,437,103	4,548,534
Less Taxes, 43.3%	<u>$0.433 \times (E-DI)$</u>	<u>1,172,778</u>	<u>1,055,266</u>	<u>1,969,515</u>
Net Income	$0.567 \times (E-DI)$	1,535,717	1,381,837	2,579,019
Add Depreciation	<u>DI</u>	<u>997,700</u>	<u>897,730</u>	<u>1,675,497</u>
Cash Flow	$0.567E + 0.433DI$	2,533,417	2,279,567	4,254,516
<u>Sales Price Calculation</u>				
Gross Income from Sales	G			509,144,431*
Cyclopentene		129,881,545		128,919,051
Indan			380,976,083	380,225,380
Sales Volume, Gallons/Yr	V			
Cyclopentene		49,980,000		49,980,000
Indan			49,980,000	49,980,000
Sales Price, \$/Gallon	G/V			
Cyclopentene		2.599		2.579
Indan			7.623	7.608

*Distributed in proportion to earnings in separate plants.

price of \$5.094 per gallon. Earnings were apportioned to the two products in proportion to the earnings in the individual plants. Adding the feedstock and operating costs, the prices were calculated at \$2.579 per gallon for cyclopentene and \$7.608 per gallon for indan. These prices were about \$0.02 per gallon less than in the separate plants.

Comparing the magnitude of the numbers in Table 36 shows that feedstock costs far overshadow the amounts of earnings and operating expenses that must be recovered in gross income. As a result, feedstock costs are the major factor in determining product price. Table 37 presents the product prices as the rate of return was varied from 15 to 25 percent. In comparison with the feedstock prices listed in Table 36, product prices are the same order of magnitude. The differences between feedstock and prices include not only the economic factors, but also the difference in densities and production of by-products in processing. Lower densities for products resulted in larger volumes than feedstocks. The volumes used in the economic calculations are identical to the material balance by weight used in the process flow diagrams.

Examination of Table 37 shows that for each increment of 5 percent DCF return at 13-year life, product price changed \$0.012 to \$0.016 per gallon. At 5-year life, the increment for 5 percent DCF return varied from \$0.009 to \$0.012 per gallon. These increments would not be altered by a change in feedstock cost; only the magnitude of the product price would change. This effect shows up in the cyclopentene made from lower purity feedstocks. The medium purity feed was \$1.17 per gallon less than high purity, and reduced the product prices about \$0.99 per gallon. A second increment of \$0.25 per gallon to the low purity feed had a similar reduction of about \$0.21 per gallon of product. These lower purity products offer considerable additive cost savings and may work nearly as well in modifying flame luminosity. Product prices did not include distribution costs for transport of the additive to terminals or other point of usage.

Table 38 presents the annual earnings for each product at each rate of return. For the cyclopentene plant, lower price feedstocks did not affect the amount of earnings. The earnings required for the indan plant are slightly lower than the cyclopentene plant because of lower investment and operating costs. Earnings for the 5-year depreciation schedule were higher than the 13-year schedule; this effect caused the slightly higher prices observed in Table 37 for 5-year life.

TABLE 37. PRODUCT PRICES AT VARYING RATES OF RETURN IN DOLLARS/GAL

<u>13-Year Plant Life</u>	<u>Feedstock Price, \$/Gallon</u>	<u>Rate of Return</u>		
		<u>15%</u>	<u>20%</u>	<u>25%</u>
Cyclopentene Plant				
High Purity	2.86	2.584	2.599	2.614
Medium Purity	1.69	1.594	1.610	1.625
Low Purity	1.44	1.381	1.396	1.412
Indan Plant				
Indan	7.57	7.609	7.623	7.637
Combined Plant				
Cyclopentene	2.86	2.566	2.579	2.593
Indan	7.57	7.596	7.608	7.620
<u>5-Year Plant Life</u>				
Cyclopentene Plant				
High Purity	2.86	2.611	2.623	2.635
Medium Purity	1.69	1.622	1.633	1.645
Low Purity	1.44	1.408	1.420	1.432
Indan Plant				
Indan	7.57	7.633	7.644	7.655
Combined Plant				
Cyclopentene	2.86	2.590	2.601	2.611
Indan	7.57	7.617	7.627	7.636

TABLE 38. EFFECT OF RATE OF RETURN ON ANNUAL EARNINGS, \$1,000 (ROUNDED)

<u>13-Year Plant Life</u>	<u>DCF Rate of Return</u>		
	<u>15%</u>	<u>20%</u>	<u>25%</u>
Cyclopentene Plant			
High Purity	2,951	3,706	4,484
Medium Purity	2,951	3,706	4,484
Low Purity	2,951	3,706	4,484
Indan Plant	2,655	3,335	3,776
Combined Plant	4,955	6,224	7,530
<u>5-Year Plant Life</u>			
Cyclopentene Plant			
High Purity	4,303	4,987	5,497
Medium Purity	4,303	4,897	5,497
Low Purity	4,303	4,897	5,497
Indan Plant	3,872	4,406	4,946
Combined Plant	7,226	8,223	9,232

V. DISCUSSION

Potential additive candidates were screened individually and then in combination to determine the concentration of the additive required to reach the desired effect. This experimentation determined the extent of improvement in the properties in relation to the original objectives of the program. One key limitation for the first task was a total additive concentration less than 5 percent by volume. Table 39 lists the nominees and the suggested concentration ranges for each additive based on the criteria in Task 1 - Literature Search and Additive Evaluation. The coded additive MO was included in this list because this compound improved the flame luminosity toward the latter part of the burn; however, MO also left a residue in the bottom of the Petri dish which caused some concern for future applications in a vehicle. The residue may cause plugged injectors or excessive wear in an engine.

TABLE 39. ADDITIVE PACKAGE NOMINEES AND SUGGESTED CONCENTRATION RANGES FOR TASK 1

Property	Additive	Concentration Range
Flammability	Butane	2.2-2.5 Vol%
Flammability	Butene	2.2-2.5 Vol%
Luminosity	Toluene	2.8-5.0 Vol%
Luminosity	MO coded sample ^a	0.75-1.0 Wt%
Luminosity	Ethanol	10-20 Vol%
Lubricity ^b	DCI-4A, OS85798, OS86453, OS86454, OS86455, OS86456, OS86457, OS86458, OS86460, VX3181, VX3182, Metacor 704, Unicor J, IPC 44210	0.12 Wt%
Taste	Bitrex	0.0012 Wt%
Color	Alcohol-soluble Dye	0.00013-0.013 Wt%
Odor	Various	0.007 Wt%
^a This additive formed a residue after burning ^b These corrosion-inhibitor/lubricity improvement additives are considered to be interchangeable as regards their compatibility with other additive package constituents at the nominated low level of concentration.		

In the Task 1 Expansion, the 5 volume percent limitation was lifted and replaced by a limit on the total cost of the additive package not to exceed 125 percent of the gasoline component cost in M85. The leading candidates for luminosity improvement were:

- Toluene
- Cyclopentene

- Indan
- Benzaldehyde

Trimethyl borate improved the flame luminosity at a low concentration with a characteristic green flame, but the residue left behind after the burn caused some concern about possible engine wear. Two compounds at slightly higher concentrations, methylcyclopentane (early in the burn) and mesitylene (late in the burn), improved the luminosity above the minimum threshold visibility. MO and ethanol, recommended in Task 1, were not included in the Task 1 Expansion because ethanol was required at much higher concentrations to enhance flame luminosity and MO left a residue after burning.

A. Lubricity

For lubricity, the mechanism operating with methanol fuel involved the washing away of the lubricant and subsequent corrosion caused by the formation of acids and other oxidizing agents from the fuel. The additives identified for methanol lubricity should handle both lubrication and corrosion. In general, the two most successful classes of compounds included the fatty acids and organic amine salts. Several proprietary lubricity/corrosion additives from this class of compounds were equally effective in improving the lubricity. These compounds compared favorably to M85 for a reduction in wear and showed significant improvement in the lubricity of M100.

B. Flammability

For flammability, the addition of butane or butene lowered the flammability limit to below -18°C at a concentration of about 3 volume percent. The addition of toluene increased the rich flammability limit of the mixture when blended with butane or butene. When the total additive concentration was held to 5 volume percent with combinations of 2 percent butane or butene, 3 percent toluene, and a balance of methanol, the rich flammability limit was about 0°C . With 15 volume percent ethanol and 6 volume percent of the toluene and butane, the rich flammability limit was about -25°C . These rich flammability limits were well below normal ambient temperatures and below the typical daily temperatures in California except in mountainous areas or on extremely cold days. In addition, the RVP was sufficient to provide good fuel volatility. Therefore, the flammability of saturated fuel vapors in underground and vehicle storage tanks can be lowered below typical ambient temperatures with sufficient volatility to provide good cold-starting and warm-up performance to -18°C (0°F). Fuel weathering was not considered in this program.

C. Flame Luminosity

Flame luminosity was improved for fuel methanol through the addition of compounds which burned with visible flames. The luminosity depends on a number of factors:

- Type of fire (pool, spill, or container)
- Path length and size of flame
- Surface where burning takes place (porous or non-porous)
- Background of the flame in relation to the observer
- Lighting conditions (dark, twilight, or bright sunshine)

- Concentration, volatility, and luminosity of additives
- Flame color.

Since the luminosity of neat methanol is poor, the addition of any soot-forming material improves the flame luminosity.

1. Single Component Additives

Ethanol was chosen as the luminosity standard for the experimental procedure, and M85 was the standard of comparison. For M85, the luminosity varied throughout the burn. Through the initial and final portions of the burn, M85 produced 70 to 90 percent of the luminosity of ethanol. During the middle portion of the burn, M85 yielded only a 15 percent increase in luminosity over M100.

Boron compounds produced a green flame when burned. Trimethyl borate achieved the minimum threshold visibility for about 50 percent of the burn at the 5 percent concentration by volume; however, a white residue remained in the Petri dish after burning probably due to boric acid. These compounds showed some promise as luminosity enhancers, but some concern arose about the residue left behind after burning. This residue may cause excessive wear or other problems in the engine or fuel handling system of an actual vehicle. The increase in visibility with respect to luminosity from boron compounds was probably due to the higher sensitivity of the human eye to wavelengths in the green to yellow portion of the spectrum.

Three additives were investigated for their effect on flame luminosity based on their low Carter MIR; pentamethylbenzene, benzaldehyde, and pentamethylbenzaldehyde. Pentamethylbenzene and pentamethylbenzaldehyde resulted in a small increase in the flame luminosity compared to methanol. Benzaldehyde is unique in that it has a negative MIR; however, benzaldehyde is an irritant and considered toxic. If benzaldehyde passes through the combustion process unburned, a lower or negative potential for ozone formation may occur. Benzaldehyde increased the flame luminosity above the minimum threshold visibility toward the latter part of the burn at the 5 percent by volume concentration. This compound was unique among oxygen-containing compounds because it yielded a higher flame luminosity than the homologous compounds without oxygen. In combination with toluene or cyclopentene, benzaldehyde should result in a visible flame throughout the majority of the burn and may contribute to lower ozone formation of the exhaust.

The best combinations for improving flame luminosity were those with unsaturation, cyclization, and aromaticity. Chemicals with unsaturation, cyclization, and aromaticity resulted in molecules with lower hydrogen/carbon number ratios, and lower hydrogen/carbon number ratios tend to improve the flame luminosity more than homologous compounds. Carbon chain branching also increased the luminosity; but in combination with methanol, higher concentrations were required. Unsaturated, branched-chain, and cyclic hydrocarbons typically increased the flame luminosity in the initial part of the burn more than straight chain hydrocarbons; however, many of these compounds required concentrations above 10 volume percent to raise the luminosity to the level of the minimum threshold visibility (0.2 foot-candles). Aromatics and certain substituted cyclic hydrocarbons improved the flame luminosity in the latter part of the burn.

The differences between compounds which enhanced the luminosity at the beginning of the burn and those that improved the luminosity near the end of the burn were related to the volatility of the compounds and the ability to form azeotropes with methanol. Compounds with a carbon number of 5 or 6 yielded the highest luminosity in the early part of the burn. Above and below carbon numbers of 5 and 6, the luminosity during the early part of the burn dropped off dramatically. Compounds with a

hydrogen/carbon number ratio between 1.5 and 2.5 (olefins and paraffins) produced the highest luminosity in the early part of the burn, while compounds with a hydrogen/carbon number ratio less than 1.5 (aromatics) exhibited higher luminosity in the latter part of the burn.

Toluene and cyclopentene provided the highest flame luminosity at the lowest concentration during the initial part of the burn, while indan produced good luminosity at a low concentration in the latter part of the burn. Indan met the minimum threshold visibility at a concentration of approximately 1 percent by volume for a short time near the end of the burn. Alcohols and ethers provided limited improvements in the luminosity except at very high concentrations. One exception was cyclohexanol, but even this compound had a lower luminosity than its homologous cyclic hydrocarbon, cyclohexane.

When toluene was added to methanol at 8 volume percent, the luminosity exceeded ethanol. With 6 volume percent toluene, the luminosity surpassed M85 for the initial part of the burn. At a concentration of 2.8 volume percent, toluene was sufficient to provide luminosity above the estimated minimum threshold visibility of 0.2 foot-candles for the initial portion of the burn. Other compounds such as coded sample MO provided a luminosity improvement during the final portion of the burn, but left a residue in the bottom of the Petri dish. The luminosity of methanol can be improved through the use of additives other than gasoline, but the degree of improvement is dependent on the concentration of the additive, the portion of the burn considered, and the degree of improvement required.

2. Multiple Component Additives

To reach the minimum threshold visibility throughout the burn, multiple component blends were required. Many multiple component mixtures were tried to take advantage of the different volatilities of various compounds which demonstrated good luminosity as single component blends. These combinations included:

- Ethanol + TBA
- Ethanol + MTBE
- Indan + cyclopentene
- Indan + methylcyclopentane
- Toluene + indan
- Toluene + ethyl ether
- Toluene + n-propyl benzene
- Toluene + tetralin
- Ferrocene + cyclopentene + indan
- Feedstocks and commercial products
- Cycloalkane/olefin blends

- Olefin blends
- Various grades of DCPD
- DP5-160.

Several blends were found to be equivalent to or better than M85 in terms of a visible flame duration above the minimum threshold visibility. A blend of ferrocene, cyclopentene, and indan also produced a flame with a good flame duration, but concern over residue left after the burn precluded additional investigation of this blend. The best blends with the lowest additive concentration by volume were 5 percent indan + 5 percent cyclopentene and 4 percent toluene plus 2 percent indan. Experimentation with these two blends was continued through outdoor luminosity studies and emission testing in a dual fuel vehicle.

D. Outdoor Burns

A set of experiments was designed to compare the laboratory results to real world situations. These experiments were conducted outdoors with larger quantities of fuel on a variety of surfaces to simulate real world conditions. Two of the best multiple component additive combinations from the laboratory investigation were selected for continued investigation. The effect of five different liquids:

- 100% methanol
- 100% ethanol
- M85
- 4% toluene + 2% indan in methanol
- 5% indan + 5% cyclopentene in methanol

on each of five surfaces:

- Concrete
- Asphalt
- Sheet metal
- Grass
- Soil

was determined to make these comparisons. A panel of eight to nine observers watched the burns, rated the visibility, and answered questions about the lighting conditions, flame color, flame luminosity, flame height, background, and other distinguishing features. All burns were performed during bright sunlight or partly cloudy conditions. In general, the additive blends performed as well as or better than ethanol and M85 on most surfaces, and the additive blends were significantly better than M100 in all cases. These results, while limited to a small number of observers, indicated that the flame visibility of methanol can be improved through the use of selected additives.

E. Emission Measurements

Emission testing was performed on two different vehicles with different additive blends. The measured emissions included a complete hydrocarbon speciation (C₁ - C₃ hydrocarbons plus benzene and toluene, C₄ hydrocarbons including 1,3-butadiene, and C₅ - C₁₀ hydrocarbons), aldehydes, and methanol. All exhaust emissions were measured on a bag by bag basis and compared for their ozone formation potential based on the most current Carter MIRs.

A 1986 Toyota Camry (dedicated M85 vehicle) was tested with an SwRI methanol blend and with an actual commercial blend of M85 fuel obtained from California. The SwRI methanol blend was made from M100 blended to contain the following additives:

- 6 volume percent toluene
- 2.5 volume percent butane
- 0.12 weight percent DCI-4A (Dupont)
- 0.0001 weight percent Bitrex (denatonium benzoate)
- 0.007 weight percent odorant.

In a separate set of tests, a 1989 dual-fuel Volkswagen Jetta was tested with five fuels:

- M100
- 4% toluene + 2% indan blended with M100
- 5% indan + 5% cyclopentene blended with M100
- Auto/Oil industry average gasoline (RF-A)
- M85 blended from RF-A

Both vehicles were tested with different additive blends, but the results from these tests were similar in many ways even though the engines and emission control systems were different on each vehicle. In general, the hydrocarbons in the exhaust were analogous to the hydrocarbons in the fuel. For example, when toluene was added to the fuel, higher concentrations of toluene were detected in the exhaust. Some other comparisons for both vehicles were:

- Cold-start emissions contributed to the majority of the exhaust emissions from both vehicles.
- Methanol was the major organic constituent in the exhaust when present in the fuel.
- Speciated hydrocarbons in the exhaust reflected the additives in the fuel.
- Regulated emissions from the Jetta with the two fuel additives had minimal emissions impact when compared to M100.

- Ozone formation potential from both vehicles was lower for the additive blends when compared to M85, but the criterion for no more than 50 percent of the exhaust reactive hydrocarbon emissions for the blend compared to M85 was not met.
- Toxic emissions from the Jetta were variable compared to M100; the additive with T&I had more toxic emissions, and the additive with I&C had less toxic emissions.
- Toxic emissions from the Camry with the methanol additive package were lower when compared to M85, but higher than M85 with the Jetta; the total additive package concentration was also greater with the Jetta.
- When the additive blends were compared to gasoline, the total and NMOG hydrocarbons were greater, but the toxics were less.

In general, the additive blends performed well when compared to M85 and M100. Minimal emissions impact was observed for the regulated emissions, but the criterion for no more than 50 percent of the exhaust reactive hydrocarbons as compared to M85 without the additive was not met. It should be noted that even M100 did not meet this criterion. The toxic emissions found to be more dependent on the additive package.

F. Cost

One consideration in the selection of potential additives was the cost to achieve the desired effect. The additional costs depended on the specific additives and concentration of each additive in the package. In Task 1 - Literature Search and Additive Evaluation, an additive package was proposed to meet the safety and performance criteria for the initial part of the program. Table 40 lists the costs for the individual additive package nominees based on their suggested concentrations from Table 39. As an example, the fuel cost increase for an additive package which would address each of the fuel properties may include the following:

- 2.2 volume percent butane (1 cent/gal)
- 2.8 volume percent toluene (3 cents/gal)
- 0.12 weight percent of a lubricity additive (1 cent/gal)
- 0.0012 weight percent Bitrex (2 cents/gal)
- 0.007 weight percent odorant (0.04 cent/gal)
- Dye for coloration (0.2 cent/gal).

With the cost of methanol at 37 cents/gal based on an average of the spot market prices from January to May 1992⁽⁸⁶⁾, the total cost of the fuel with the example additive package listed above would be about 42 cents/gal. If ethanol were included in the blend at a concentration of 20 percent with the same additive package listed above, the fuel cost was about 58 cents/gal. It should be noted that these costs do not include blending and other related costs such as transportation and handling since some of these costs would be similar for any fuel. The costs for the additive package in methanol are within an acceptable range to improve the properties of the fuel without pricing the fuel out of the market.

TABLE 40. ADDITIVE COSTS FOR TASK 1 ADDITIVE COMBINATIONS(86,87)

Additive	Bulk Price	Cost Increase, \$/Gal Fuel*
Methanol	\$0.37/gal	--
Butane	\$17.50/bbl	\$0.01
Toluene	\$0.90/gal	\$0.02 - \$0.045
Butene	\$2.50/gal	\$0.055 - \$0.063
Ethanol	\$1.17/gal	\$0.12 - \$0.23
MO	\$4.00/lb	\$0.20-\$0.26
DCI-4A	\$0.84/lb	\$0.01
Bitrex	\$14.00/oz	\$0.02
Odorant	\$1.00/lb	\$0.0004
Colorant (dye)	\$19.00/lb	\$0.002 - \$0.02

*Cost increase based on suggested concentration ranges in Table 38 and price per gallon of the additive without transportation costs.

In the Task 1 Expansion, efforts continued to find alternative luminosity additives with the additive cost not to exceed 125 percent of the gasoline cost in M85. The additive package above was successful in improving all of the fuel properties except flame luminosity. To achieve a luminous flame throughout the majority of the burn, higher concentrations of the luminosity additives must be used. Two combinations were found which provided adequate luminosity throughout the burn. These combination were plus 5 percent indan + 5% cyclopentene and 4 percent toluene plus 2 percent indan. Table 41 lists the individual estimated additive costs for these two combinations, and the associated costs increases for each additive concentration.

TABLE 41. ADDITIVE COST FOR TOLUENE, CYCLOPENTENE, AND INDAN ADDITIVE COMBINATIONS (TASK 1 EXPANSION)

Additive	Bulk Price, \$/gal	Cost Increase, \$/gal Fuel*
4% Toluene	0.90	0.036
2% Indan	7.62	0.152
5% Cyclopentene	1.61	0.081
5% Indan	7.62	0.381

*Cost increase based on percentage of suggested concentration range and price per gallon of the additive without transportation costs.

To compute the additive costs, the spot price for toluene was reviewed for calendar year 1991 and compared with gasoline in Section IV. B. Toluene prices tend to follow the gasoline price, but it is also affected by demand as a chemical intermediate. The average price was \$0.901 per gallon, and the median value was \$0.905 per gallon. A price of \$0.90 per gallon was used in the estimation of additive cost.

Cyclopentene and indan were not available as bulk chemicals, so the approach to developing costs was to estimate the cost of production from other available materials. DCPD was available in the desired quantities as a starting material to make cyclopentene by partial hydrogenation of CPD monomer. Estimates of investment cost, operating expenses, and economic evaluation in Section IV. C. indicate that cyclopentene can be made in California for \$1.38 to \$2.58 per gallon depending on the purity. Slightly higher prices of \$1.41 to \$2.61 per gallon may be needed to encourage construction of a plant. A cost of \$1.61 for medium purity based on a 20 percent rate of return and a 13 year plant life was used in estimating the additive cost for cyclopentene.

Indene was selected as the starting material to produce indan, but no bulk producer of indene was found in the United States. Indene was available in bulk quantities in Europe, but at a high price which may not meet the long term needs as a fuel additive. A plant to make indan would be similar to the cyclopentene plant in size and design. Economic evaluation in Section IV. D. indicates that indan could be produced in California for \$7.62 per gallon. This value was used to calculate the cost of adding indan to methanol.

To estimate the additive package price in comparison to the gasoline in M85, the current cost of gasoline added to M85 was determined. The average cost of the premium unleaded wholesale rack prices from January to May 1992 was 74.9 cents/gal.⁽⁸⁶⁾ With M85, the gasoline contribution to the total cost equated to 11.2 cent/gal based on 15 percent of the average premium unleaded cost per gallon. At the pump in California, the average retail price for M85 is currently about 80 cents/gal, and ranges from 71.9 to 93.9 cents/gal depending on the transportation costs and mark up involved with the particular station.⁽⁸⁸⁾ If 85 percent of the spot market price for methanol (31.5 cents/gal) was subtracted from the average retail price for M85, then the costs yielded an increase for the gasoline, transportation, and station margin costs of between 40 and 62 cents/gal with an average of 48.5 cents/gal. By subtracting the gasoline contribution cost (11.2 cents/gal) from the remainder, the transportation costs plus station margin were 37.3 cents/gal of the average price for M85 in California. (Note: Since the transportation costs and the station margin should be similar for any fuel, no attempt was made to separate these two figures.)

To meet the criterion for the flame luminosity additive costs of less than 125 percent of the gasoline portion of M85 (11.2 cents/gal), the cost increase for the additive packages should be less than about 14 cents/gal. Neither of the two additives were capable of meeting this criterion because the raw material costs for indan were too high (See Table 40). If a substitute for indan or a lower priced feedstock could be found, then the additive package might meet the cost requirement proposed for this program. The additive package with 4 percent toluene plus 2 percent indan was the closest to meeting the cost criterion. This blend yielded a cost increase of 18.8 cents/gal, which equated to a 168 percent increase over the gasoline contribution to M85. With the 4 percent toluene plus 2 percent indan flame luminosity additive package, the average cost of the fuel at the pump would be about 91 cents/gal, including the transportation costs and the station margin calculated above. This fuel cost equates to a total cost increase of about 14 percent more than the average pump price for M85.

If the additives for flammability limit, fuel lubricity, taste, odor, and color were also added to the fuel cost for the luminosity additive, then the price at the pump would be about 94 cents/gal for an increase of about 18 percent more than the pump price of M85. On this basis, the total cost increase of

a complete additive package in the fuel was less than 125 percent of the total cost at the pump, but not less than 125 percent of the gasoline portion in M85.

A similar exercise could be performed with the 5 percent indan plus 5 percent cyclopentene flame luminosity additive. With the flame luminosity additive alone, the average cost of the fuel at the pump, including transportation costs and station margin, would be about \$1.17/gal. This cost was 46 percent more the average pump price of M85. If the additives for flammability limit, fuel lubricity, taste, odor, and color were added to the fuel cost for the luminosity additive, then the price at the pump would be about \$1.20/gal for an increase of about 50 percent more than the M85 pump price.

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GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS

AO - Coded alcohol-soluble dye

B/SD - Barrels per stream day

bbf - Barrel, 42 U.S. gal

BFOE - Barrel, fuel oil equivalent (6.3 MM BTU)

BOCLE - Ball-on-Cylinder Lubricity Evaluator

CARB - California Air Resources Board

Carter Maximum Incremental Reactivity (MIR) - Used to predict relative levels of ozone formation based on the individual hydrocarbon components in the exhaust

CEC - California Energy Commission

CO - Carbon monoxide

CPD - Cyclopentadiene monomer

DCF - Discounted cash flow

DCPD - Dicyclopentadiene dimer

DER - Department of Emissions Research at Southwest Research Institute

DME - Dimethyl ether

F - Coded alcohol-soluble dye

Foot-candle - Unit of illuminance on a surface that is everywhere one foot from a uniform point source of light of one candle

FTP - Federal Test Procedure

Gray-body radiation - Carbonaceous particles heated by a flame and emit light in the visible region of the spectrum

HP - High pressure (steam)

I&C - 5 percent indan plus 5 percent cyclopentene

Kw - Kilowatt or kilowatt hours per hour

Kwh - Kilowatt hour

GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS (CONT'D)

Lean flammability limit - Temperature where the gases in the vapor space of a closed container are too lean (insufficient fuel) to ignite; occurs at lower temperatures

LP - Low pressure (steam)

M - Thousand

M100 - neat methanol; 100 percent methanol fuel with no additives or blending components

Minimum threshold visibility - Based on a subjective consensus as the lowest level that a luminous flame would be detected under lighted conditions as measured with the instrumentation described above (about 0.2 foot-candles)

M85 - Mixture of 85 percent methanol with 15 percent gasoline

MIR - Maximum incremental reactivity

MM - Million

MMBTU/hr - Million BTU per hour

MO - Coded alcohol-soluble dye

MP - Medium pressure (steam)

MSCF/hr - Thousand standard cubic feet per hour

MTBE - Methyl t-butyl ether

NMOG - Non-methane organic gases

NO_x - Oxides of nitrogen

Ozone formation potential - Relative estimation of the contribution of the exhaust constituents to produce ozone; obtained by dividing the mass of ozone formed from hydrocarbon components in the exhaust based on the Carter MIR by the mass of NMOG

PFI - Port Fuel Injector Deposit test

RF-A - Auto/Oil industry average gasoline

Rich flammability limit - Temperature where the gases in the vapor space of a closed container are too rich (insufficient oxygen) to ignite; occurs at higher temperatures

RVP - Reid Vapor Pressure

SCAQMD - South Coast Air Quality Management District

GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS (CONT'D)

SD - Stream day or operating day

SwRI - Southwest Research Institute

T&I - 4 percent toluene plus 2 percent indan

TBA - t-butyl alcohol

Toxic emissions - Summation of benzene, 1,3-butadiene, the three isomers of xylene, formaldehyde, acrolein, and acetaldehyde based on CARB list of known and suspected toxic air contaminants

UDDS - Urban Dynamometer Driving Schedule

WSD - Wear Scar Diameter

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APPENDIX A

LUMINOSITY MEASUREMENT DATA AND LUMINOSITY CURVES

APPENDIX A

LUMINOSITY MEASUREMENT DATA AND LUMINOSITY CURVES

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**TABLE A-1. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE METHANOL FORMULATIONS (TASK 1)**

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles,^a</u>	<u>Burn Time, Sec.</u>
Ethanol (reference)	1.0	60
Regular unleaded gasoline	2.5-3.0	60
M85	0.90/0.15/0.70 ^a	60
M88	0.50/0.02/0.35	56
M90	0.35/0.01/0.20	56
M92	0.15/0.005/0.10	56
M95	0.03/0.001/0.10	58
M100	0.001	60
<u>Hydrocarbon Mixtures</u>		
5% 90 RON Reformate	0.005	54
5% H229 ^b	0.08	54
5% H400 ^c	0.10	56
5% Light hydrocrackate	0.15/0.001	56
5% Jet A	0.001	60
5% Refined peanut oil	0.001	60
<u>Aromatics</u>		
1% Toluene	0.001	60
2% Toluene	0.008	58
4% Toluene	0.20	60
5% Toluene	0.25	54
6% Toluene	0.65	60
10% Toluene	1.3	58
5% Ethyl benzene	0.001/0.1	60
5% n-Propyl benzene	0.001/0.3	58
5% n-Buryl benzene	0.001/0.25	56
5% n-Pentyl benzene	0.001/0.1	60
5% n-Hexyl benzene	0.001	60
5% Pyridine	0.001	60
5% Naphthalene	0.001	58
5% Methyl naphthalene	0.001	60
5% Decalin	0.005	60
5% Tetralin	0.005	60
<u>Aliphatics and Olefins</u>		
5% Butane	0.005	56
5% 1-Butene	0.005	54
5% 1,3-Butadiene	0.5/0.005	54
5% Pentane	0.001	56
5% Isooctane	0.01 (first 1/3 burn)	60
5% Dicyclopentadiene	0.001/0.25	54
5% 7-trans-7-Tetradecene	0.001	60

TABLE A-1 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE METHANOL FORMULATIONS (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles,^a</u>	<u>Burn Time, Sec.</u>
<u>Ethers</u>		
5% Ethyl ether	0.001	54
5% Dimethyl ether	0.003	56
5% Ethylene glycol monomethyl ether	0.003	60
5% MTBE	0.001	60
5% ETBE	0.001	60
5% Polyphenyl ether	0.005	60
5% m-Butyl acetate	0.001	60
<u>Metal Organic Salts</u>		
5% Sodium acetate	0.001	60
5% Isoamyl acetate	0.001	60
2% Lithium acetate	0.001	60
2% Calcium acetate	0.001	60
2% Aluminum acetate	0.001	60
2% Iron stearate	0.001	60
2% Sodium stearate	0.001	60
2% Zinc stearate	0.001	60
5 Vol% VX 3174 ^d	0.001	58
5 Vol% VX 3181 ^d	0.001	56
5 Vol% VX 3182 ^d	0.001	60
5 Vol% VX 3194 ^d	0.001	58
5 Vol% VX 3195 ^d	0.001	60
5 Vol% OS 85800 ^d	0.001	56
5 Vol% OS 85801 ^d	0.001	58
5 Vol% OS 85802 ^d	0.001	56
5 Vol% OS 85803 ^d	0.001	60
<u>Alcohol Soluble Dyes</u>		
5% Methyl orange dye	0.001	60
5% Acid yellow dye No. 38	0.001	60
5% Mordant Brown No. 4	0.001	60
5% Rhodamine B dye	0.001	60
5% Pylam blue dye	0.001	60
5% Pylam bright red dye	0.001	60
5% Pylam orange dye	0.001	60
5% Pylam lemon yellow dye	0.001	60
5% Nigrosine	0.001	50
<u>Proprietary Formulations</u>		
0.1% MO ^d	0.05	60
0.5% MO ^d	0.25 (last 1/4 burn)	58

TABLE A-1 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE METHANOL FORMULATIONS (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles,^a</u>	<u>Burn Time, Sec.</u>
1.0% MO ^d	0.3 (last 1/4 burn)	60
0.1% AB ^d	0.05	60
0.5% AB ^d	0.05	60
1.0% AB ^d	0.05	58
0.1% AO ^d	0.05	60
0.5% AO ^d	0.10 (last 1/4 burn)	60
1.0% AO ^d	0.25 (last 1/4 burn)	60
0.1% BBR ^d	0.05	60
0.5% BBR ^d	0.05	56
1.0% BBR ^d	0.05	58
0.1% DB7 ^d	0.05	60
0.5% DB7 ^d	0.05	60
1.0% DB7 ^d	0.05	56
0.1% F ^d	0.05	60
0.5% F ^d	0.07	58
1.0% F ^d	0.10	60
0.1% PBVF ^d	0.05	58
0.5% PBVF ^d	0.05	58
1.0% PBVF ^d	0.05	60
5% G1280X ^e	0.001	60
5% D1280X ^e	0.001	60
<u>Alcohols</u>		
5% Ethyl alcohol	0.001	60
10% Ethyl alcohol	0.001	60
20% Ethyl alcohol	0.05	60
5% n-Butanol	0.001	58
10% n-Butanol	0.001	58
15% n-Butanol	0.08 (last 1/3 burn)	56
5% Tertiary butyl alcohol	0.001	60
10% Tertiary butyl alcohol	0.001	58
15% Tertiary butyl alcohol	0.18 (last 1/3 burn)	58
5% Isopropyl alcohol	0.001	60
5% Cyclohexanol	0.001	60
5% Tridecylalcohol	0.001	60
5% Decyl alcohol	0.001	60

^aNOTE: Multiple numbers listed under average luminosity indicates changes from beginning, middle and end of burn.

^bH229: C₇ - C₉ hydrocarbon mix (Naphtha solvent) boiling range 240 - 360°F.

^cH400: Middle distillate solvent C₁₀-C₁₃ aromatics boiling range 340 - 490°F.

^dCoded sample.

^eAdditive provided by Omstar.

TABLE A-2. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR ADDITIVE COMBINATION IN METHANOL (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles,^a</u>	<u>Burn Time, Sec.</u>
1% Toluene + 4% Tetralin	0.001/0.01	58
3% Toluene + 2% Tetralin	0.02	60
4% Toluene + 1% Tetralin	0.08	54
4% Toluene + 1% 1-Pentene	0.20	58
3% Toluene + 2% n-Propyl benzene	0.10	60
4% Toluene + 1% n-Propyl benzene	0.30	56
3% Toluene + 2% n-Butyl benzene	0.05	60
4% Toluene + 1% n-Butyl benzene	0.20	58
3% Toluene + 2% Butene	0.10	56
4% Toluene + 1% Butene	0.30	58
3% Toluene + 2% Butane	0.05	58
3% Toluene + 3% Butane	0.04 (1/2 burn)	60
3.5% Toluene + 2.5% Butane	0.08 (1/2 burn)	60
4% Toluene + 1% Butane	0.20	56
4% Toluene + 2% Butane	0.10 (2/3 burn)	60
5% Toluene + 1% Butane	0.30 (2/3 burn)	58
2% Toluene + 1% Butane + 2% H400	0.03	58
2% Toluene + 2% Butane + 1% H400	0.001	56
2% Toluene + 1% Butane + 1% H229	0.05	60
2% Toluene + 2% Butane + 1% H229	0.001	58
2.5% Toluene + 2.5% H229	0.15	56
2.4% Toluene + 2.5% H400	0.04	56
4% Toluene + 4% H400	0.4	54
3% Toluene + 3% H400	0.09	58
1.67% Toluene + 1.67% H229 + 1.67% H400	0.04	56
2% Toluene + 2% H229 + 2% H400	0.15	58
3% Toluene + 1% H229 + 1% H400	0.08	54
6% Toluene + 2% H229 + 2% H400	1.2	54
2.5% H229 + 2.5% H400	0.001/0.20	56
4% H229 + 4% H400	0.5	56
2.5% Toluene + 2.5% Dicyclopentadiene	0.05	54
3% Toluene + 3% Dicyclopentadiene	0.2	54

TABLE A-2 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR ADDITIVE COMBINATION IN METHANOL (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles.^a</u>	<u>Burn Time, Sec.</u>
1% Toluene + 4% Ethyl Ether	0.002	56
2% Toluene + 3% Ethyl Ether	0.005	56
2% Toluene + 8% Ethyl Ether	0.06	56
3% Toluene + 2% Ethyl Ether	0.01	56
4% Toluene + 1% Ethyl Ether	0.1	56
4% Toluene + 6% Ethyl Ether	0.24	54
6% Toluene + 4% Ethyl Ether	0.90	54
8% Toluene + 2% Ethyl Ether	1.2	56
0.8 Toluene + 2.5% Ethyl Ether + 1.7% HSR Naphtha	0.001	54
1.3% Toluene + 4% Ethyl Ether + 2.7% HSR Naphtha	0.04/0.001	54
2% Toluene + 6% Ethyl Ether + 4% HSR Naphtha	0.35/0.08	54
1% Toluene + 1% Ethyl Ether + 3% 90 RON Reformate	0.01	54
2% Toluene + 2% Ethyl Ether + 6% 90 RON Reformate	0.4	54
4% Toluene + 6% 90 RON Reformate	1.1	58
5% EtOH + 5% TBA	0.001	60
10% EtOH + 5% TBA	0.001	60
2% Toluene + 10% EtOH + 10% TBA	0.05 (7/10 burn)	60
4% Toluene + 10% EtOH + 10% TBA	0.40 (7/10 burn)	60
6% Toluene + 15% EtOH	0.80 (9/10 burn)	60
5% Toluene + 15% EtOH	0.60 (9/10 burn)	58
4% Toluene + 15% EtOH + 2% Butane	0.30 (9/10 burn)	60
3% Toluene + 15% EtOH + 2.5% Butane	0.30 (9/10 burn)	60
3% Toluene + 15% EtOH + 3% Butane	0.10 (3/4 burn)	60
2% Toluene + 1% Butene + 2% H400	0.005	58
2% Toluene + 2% Butene + 1% H400	0.001	58
3% Toluene + 1% Butene + 1% H400	0.04	56
2% Toluene + 1% Butene + 1% H229	0.001	60
2% Toluene + 1% Butene + 2% H229	0.06	58
3% Toluene + 1% Butene + 1% H229	0.10	58

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Ethanol(reference)	1.0	53	NA	NA
5% Ethanol	0.004	57	--	--
10% Ethanol	0.005	48	--	--
20% Ethanol	0.006	48	--	--
30% Ethanol	0.004	51	--	--
50% Ethanol	0.004/0.008	54	--	--
75% Ethanol	0.08	51	--	--
90% Ethanol	0.12/0.38	54	32	59
100% Isopropanol	13.5	57	NA	NA
5% Isopropanol	0.005	48	--	--
10% Isopropanol	0.006	48	--	--
20% Isopropanol	0.007	52	--	--
100% t-Butyl alcohol	14.3	61	NA	NA
5% t-Butyl alcohol	0.004	48	--	--
10% t-Butyl alcohol	0.004/0.02	49	--	--
20% t-Butyl alcohol	0.005/0.2/0.09	58	10	17
30% t-Butyl alcohol	0.35	71	27	38
50% t-Butyl alcohol	4/1.0/0.1	108	75	69
75% t-Butyl alcohol	11.8/1.0	89	83	93
100% t-Amyl alcohol	13.8	68	NA	NA
5% t-Amyl alcohol	0.004/0.009	51	--	--
10% t-Amyl alcohol	0.003/0.008	72	--	--
20% t-Amyl alcohol	0.005/0.03/0.1	125	--	--
100% Cyclohexanol	would not ignite	--	NA	NA
5% Cyclohexanol	0.002	52	--	--
10% Cyclohexanol	0.005/0.13	92	25	27
15% Cyclohexanol	0.005/0.35	86	25	29
20% Cyclohexanol	0.005/1.1	98	40	41
100% Phenol	would not ignite	--	NA	NA
5% Phenol	0.004	45	--	--
10% Phenol	0.005	46	--	--
20% Phenol	0.005/1.7/1.1	98	55	56
100% Diethanolamine	would not ignite	--	NA	NA
5% Diethanolamine	0.005	45	--	--
10% Diethanolamine	0.006	43	--	--
20% Diethanolamine	0.005	39	--	--
100% 1-Propanol	6	73	NA	NA
5% 1-Propanol	0.004	50	--	--
10% 1-Propanol	0.004	53	--	--
20% 1-Propanol	0.004	87	--	--
100% n-Butanol	6.6	104	NA	NA
5% n-Butanol	0.004	72	--	--
10% n-Butanol	0.004/0.001	93	--	--
20% n-Butanol	0.002/0.012	124	--	--

TABLE. A-4. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ALDEHYDES, KETONES, ACIDS,
AND ESTERS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Acetone	13	38	NA	NA
5% Acetone	0.006	50	--	--
10% Acetone	0.005*	78	--	--
20% Acetone	0.008	45	--	--
5% Ethyl acetoacetate	0.002	50	--	--
10% Ethyl acetoacetate	0.004/0.03	74	--	--
20% Ethyl acetoacetate	0.003/0.4	104	25	24
100% Ethyl acetate	5.5	54	NA	NA
5% Ethyl acetate	0.004	49	--	--
10% Ethyl acetate	0.004	47	--	--
20% Ethyl acetate	0.004	47	--	--
5% Pyrrolidinone	0.004	47	--	--
10% Pyrrolidinone	0.004	46	--	--
20% Pyrrolidinone	0.004	43	--	--
5% 1-Indanone	0.004	49	--	--
10% 1-Indanone	0.004	47	--	--
20% 1-Indanone	0.004	50	--	--
5% Methacrylic acid	0.005/0.001	62	--	--
10% Methacrylic acid	0.004/0.16	99	--	--
20% Methacrylic acid	0.004/0.001/0.6	101	30	30
5% Methacrylic anhydride	0.004	48	--	--
10% Methacrylic anhydride	0.004	48	--	--
20% Methacrylic anhydride	0.004/0.45	114	48	42
100% Ethyl formate	1/1.6	46	NA	NA
5% Ethyl formate	0.005	50	--	--
10% Ethyl formate	0.005	47	--	--
20% Ethyl formate	0.005	46	--	--
0.006 wt % trans-Cinnamic acid	0.004	48	--	--
0.013 wt % trans-Cinnamic acid	0.004	47	--	--
100% 2,4-Pentanedione	12.5	65	NA	NA
5% 2,4-Pentanedione	0.004	48	--	--
10% 2,4-Pentanedione	0.005	54	--	--
20% 2,4-Pentanedione	0.004/0.18	74	5	7

TABLE A-4 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALDEHYDES, KETONES, ACIDS, AND ESTERS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
0.001 wt% Pentamethylbenzaldehyde	0.004	52	--b	--
0.003 wt% Pentamethylbenzaldehyde	0.005	51	--	--
0.006 wt% Pentamethylbenzaldehyde	0.005	53	--	--
100% Benzaldehyde	5	83	83	NA
5% Benzaldehyde	0.004/0.5	61	17	28
10% Benzaldehyde	0.5	88	71	81
20% Benzaldehyde	1	95	86	91
0.001 wt% Benzoic acid	0.001	57	--	--
0.003 wt% Benzoic acid	0.001	53	--	--
0.006 wt% Benzoic acid	0.001	49	--	--

TABLE A-5. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALICYCLIC COMPOUNDS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Cyclohexene	10	113	NA	NA
5% Cyclohexene	0.006	48	--	--
10% Cyclohexene	0.005	47	--	--
20% Cyclohexene	0.005/0.88	74	35	47
100% Cyclohexane	17.8	63	NA	NA
5% Cyclohexane	0.002	46	--	--
10% Cyclohexane	1.2/0.002	47	10	21
20% Cyclohexane	4/0.1/0.002	46	12	26
100% Cyclohexanol	would not ignite	--	NA	NA
5% Cyclohexanol	0.002	52	--	--
10% Cyclohexanol	0.005/0.13	92	25	27
15% Cyclohexanol	0.005/0.35	86	25	29
20% Cyclohexanol	0.005/1.1	98	40	41
100% Cyclopentane	21.3	42	NA	NA
5% Cyclopentane	0.2/0.004	48	3	6
10% Cyclopentane	1.0/0.03/0.003	44	10	23
20% Cyclopentane	20/0.13/0.004	42	15	36
100% Methylcyclopentane	19.3	44	NA	NA
5% Methylcyclopentane	1.0/0.2/0.004	44	5	11
10% Methylcyclopentane	2.2/1.1/0.004	45	15	33
20% Methylcyclopentane	14.5/0.25/0.004	45	20	44
100% Phenylcyclohexane	would not ignite	--	NA	NA
5% Phenylcyclohexane	0.005	46	--	--
10% Phenylcyclohexane	0.045	45	--	--
20% Phenylcyclohexane	0.005/0.22	43	3	7
100% Cyclopentene	10/19.5	30	NA	NA
5% Cyclopentene	1/0.005	47	12	26
10% Cyclopentene	2/0.005	44	10	23
20% Cyclopentene	2.5/0.005	39	10	26
5% Decahydronaphthalene	0.005	48	--	--
10% Decahydronaphthalene	0.009/0.2	75	10	13
20% Decahydronaphthalene	0.005/2.2	87	47	54
100% Cyclooctane	16.5	87	NA	NA
5% Cyclooctane	0.005	48	--	--
10% Cyclooctane	0.008	47	--	--
20% Cyclooctane	0.025/2.3	83	40	48

TABLE A-5 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALICYCLIC COMPOUNDS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
5% Dicyclohexylamine	0.004	41	--	--
10% Dicyclohexylamine	0.004	48	--	--
20% Dicyclohexylamine	0.004/0.87/2.1	148	88	59
5% Tetrahydronaphthalene	0.005/0.03	50	--	--
10% Tetrahydronaphthalene	0.005/0.1	50	--	--
20% Tetrahydronaphthalene	0.005/0.03/0.4	40	5	13
100% Dicyclopentadiene	2	59	52	88
5% Dicyclopentadiene	0.003/0.2	48	8	17
10% Dicyclopentadiene	1/0.3	84	29	35
20% Dicyclopentadiene	1.5/0.4	100	82	82

TABLE A-6. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ALKENES AND ALKYNES IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visiblity Duration, Sec.	Percent Luminous Flame
100% Cyclohexene	10	113	NA	NA
5% Cyclohexene	0.006	48	--	--
10% Cyclohexene	0.005	47	--	--
20% Cyclohexene	0.005/0.88	74	35	47
5% 2-methyl-2-pentene	0.006	52	--	--
10% 2-methyl-2-pentene	0.004/0.008	85	--	--
20% 2-methyl-2-pentene	0.005/0.17	100	20	20
5% 2-methyl-1-butene	0.004	47	--	--
10% 2-methyl-1-butene	0.05/0.006	48	--	--
20% 2-methyl-1-butene	11.2/0.006	42	10	24
100% 2,4,4-Trimethyl-1-pentene	15/3/0.5	124	NA	NA
5% 2,4,4-Trimethyl-1-pentene	0.005	52	--	--
10% 2,4,4-Trimethyl-1-pentene	0.01/0.005	53	--	--
20% 2,4,4-Trimethyl-1-pentene	1.2/0.005/0.02	80	15	19
100% 4-Methyl-2-pentene	18	33	NA	NA
5% 4-Methyl-2-pentene	0.006	48	--	--
10% 4-Methyl-2-pentene	1.2/0.005	44	6	14
20% 4-Methyl-2-pentene	18/0.005	40	10	25
100% 1-Pentene	35	24	NA	NA
5% 1-Pentene	0.005	45	--	--
10% 1-Pentene	0.005	46	--	--
20% 1-Pentene	0.25/0.005	42	3	7
100% Cyclopentene	10/19.5	30	NA	NA
5% Cyclopentene	1/0.005	47	12	26
10% Cyclopentene	2/0.005	44	10	23
20% Cyclopentene	2.5/0.005	39	10	26
5% Methacrylic acid	0.005/0.001	62	--	--
10% Methacrylic acid	0.004/0.16	99	--	--
20% Methacrylic acid	0.004/0.001/0.6	101	30	30
5% Methacrylic anhydride	0.004	48	--	--
10% Methacrylic anhydride	0.004	48	--	--
20% Methacrylic anhydride	0.004/0.45	114	48	42
100% 2-Methyl-1-pentene	27/1.25/0.01	81	--	NA
5% 2-Methyl-1-pentene	0.004	52	--	--
10% 2-Methyl-1-pentene	0.22/0.008	50	10	20
20% 2-Methyl-1-pentene	6.8/0.008	50	18	36
100% 2-Methyl-2-butene	27	31	NA	NA
5% 2-Methyl-2-butene	0.2/0.005	48	2	4
10% 2-Methyl-2-butene	0.75/0.005	49	3	6
20% 2-Methyl-2-butene	10/0.006	46	14	30
100% cis-2-Pentene	27.5	36	NA	NA
5% cis-2-Pentene	0.004	56	--	--
10% cis-2-Pentene	0.35/0.004	54	5	9
20% cis-2-Pentene	0.8/0.004	52	13	25
trans-Cinnamic acid	0.004	48	--	--
trans-Cinnamic acid	0.004	47	--	--

FOR SINGLE-ADDITIVE AROMATICS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Indan	would not ignite	—	NA	NA
1% Indan	0.005/0.18	47	3	6
2% Indan	0.008/1.1	48	8	17
3% Indan	0.005/1.2	49	15	31
4% Indan	0.005/1.6	51	18	35
5% Indan	0.02/1.6	48	23	48
6% Indan	0.02/2.1	47	25	53
7% Indan	0.02/2.0	48	25	52
10% Indan	1.6	60	42	70
20% Indan	1.8	73	65	89
100% Phenol	would not ignite	—	NA	NA
5% Phenol	0.004	45	—	—
10% Phenol	0.005	46	—	—
20% Phenol	0.005/1.7/1.1	98	55	56
0.003 wt.% Ferrocene	0.02/0.2	50	8	16
0.005 wt.% Ferrocene	0.02/0.25	49	10	20
0.013 wt.% Ferrocene	0.21/0.3	51	23	45
Saturated ferrocene	0.3	48	20	42
100% Pyridine	14	55	NA	NA
5% Pyridine	0.002/0.14	53	—	—
10% Pyridine	0.006/0.25	60	8	13
20% Pyridine	0.005/5.5/0.25	70	35	50
5% Naphthalene	0.015	58	—	—
5% <i>s</i> -Butylbenzene	0.005/0.25	49	5	10
10% <i>s</i> -Butylbenzene	0.005/4.0	54	18	33
20% <i>s</i> -Butylbenzene	0.005/0.25/4.5/1.6	61	37	61
100% 1-Phenyl octane	would not ignite	—	NA	NA
5% 1-Phenyl octane	0.005	48	—	—
10% 1-Phenyl octane	0.005	48	—	—
20% 1-Phenyl octane	0.005	43	—	—
100% Phenylcyclohexane	would not ignite	—	NA	NA
5% Phenylcyclohexane	0.005	46	—	—
10% Phenylcyclohexane	0.045	45	—	—
20% Phenylcyclohexane	0.005/0.22	43	3	7
100% Dimethylnaphthalene	would not ignite	—	NA	NA
5% Dimethylnaphthalene	0.005	47	—	—
10% Dimethylnaphthalene	0.005	45	—	—
20% Dimethylnaphthalene	0.005	43	—	—
100% 4- <i>t</i> -Butylpyridine	would not ignite	—	NA	NA
5% 4- <i>t</i> -Butylpyridine	0.005	48	—	—
10% 4- <i>t</i> -Butylpyridine	0.005/1.8	74	25	33
20% 4- <i>t</i> -Butylpyridine	0.005/1.8	118	70	59
0.003 wt.% Acetylferrocene	0.015	48	NA	NA
0.005 wt.% Acetylferrocene	0.012	48	—	—
0.013 wt.% Acetylferrocene	0.015	48	—	—

TABLE A-7 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE AROMATICS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
0.013 wt.% Benzoylpyridine	0.005	47	--	--
0.025 wt.% Benzoylpyridine	0.005	48	--	--
0.013 wt.% Benzophenone	0.003	50	--	--
0.025 wt.% Benzophenone	0.004	48	--	--
Saturated carbazole	0.012/0.04/0.008	56	--	--
0.013 wt.% 1,2,4,5-Benzenetetracarboxylic acid	0.004/0.006	48	--	--
0.025 wt.% 1,2,4,5-Benzenetetracarboxylic acid	0.005/0.02/0.006	50	--	--
100% Toluene	6.1/8.8	40	NA	NA
5% Toluene	0.35/0.004	46	25	54
10% Toluene	5.5/0.004	45	37	82
20% Toluene	14	46	40 (Yellow)	87
5% Pyrrole	0.006/0.02	50	2	4
10% Pyrrole	0.01/1.7	60	8	13
20% Pyrrole	0.012/9	73	25	34
5% Aniline	0.005	48	--	--
10% Aniline	0.005	46	--	--
20% Aniline	0.006	44	--	--
1-Indanone	0.004	49	--	--
1-Indanone	0.004	47	--	--
1-Indanone	0.004	50	--	--
1% Mesitylene	0.004	52	--	--
2% Mesitylene	0.004/0.02	50	--	--
3% Mesitylene	0.004/0.2	49	5	10
4% Mesitylene	0.004/0.45	52	12	23
5% Mesitylene	0.004/0.95	48	20	42
10% Mesitylene	0.05/2	52	38	73
20% Mesitylene	2.2	81	73	90
5% 1-Methylnaphthalene	0.004/0.008	46	--	--
10% 1-Methylnaphthalene	0.006	45	--	--
20% 1-Methylnaphthalene	0.005/0.015	40	--	--
trans-Cinnamic acid	0.004	48	--	--
trans-Cinnamic acid	0.004	47	--	--
5% Tetrahydronaphthalene	0.005/0.03	50	--	--
10% Tetrahydronaphthalene	0.005/0.1	50	--	--
20% Tetrahydronaphthalene	0.005/0.03/0.4	40	5	13
5% Indene	0.001/1.2	51	22	43
10% Indene	2	65	48	74
20% Indene	4	66	56	85
0.001 wt% Pentamethylbenzaldehyde	0.004	52	-- ^b	--
0.003 wt% Pentamethylbenzaldehyde	0.005	51	--	--
0.006 wt% Pentamethylbenzaldehyde	0.005	53	--	--
0.001 wt% Pentamethylbenzene	0.001	52	--	--
0.003 wt% Pentamethylbenzene	0.001	52	--	--
0.006 wt% Pentamethylbenzene	0.003	58	--	--

FOR SINGLE-ADDITIVE AROMATICS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
0.001 wt% Benzoic acid	0.001	57	--	--
0.003 wt% Benzoic acid	0.001	53	--	--
0.006 wt% Benzoic acid	0.001	49	--	--
100% Borane-pyridine complex	3	55	49	89
5% Borane-pyridine complex	0.05/0.002	82	--	--
10% Borane-pyridine complex	0.2/0.02/0.5	63	13/8	33
20% Borane-pyridine complex	0.3/2	47	42	89
100% Nitrobenzene	0.8/2	59	59	NA
5% Nitrobenzene	0.003	43	--	--
10% Nitrobenzene	0.003	45	--	--
20% Nitrobenzene	0.003/0.6	77	28	36
100% Benzaldehyde	5	83	83	NA
5% Benzaldehyde	0.004/0.5	61	17	28
10% Benzaldehyde	0.5	88	71	81
20% Benzaldehyde	1	95	86	91

**TABLE A-8 LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ETHERS IN METHANOL**

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
5% Methyl-t-butyl ether	0.005	47	--	NA
10% Methyl-t-butyl ether	0.008	46	--	--
15% Methyl-t-butyl ether	0.11/0.005	48	--	--
20% Methyl-t-butyl ether	0.33/0.006	44	15	34
5% t-Amyl methyl ether	0.005	47	--	--
10% t-Amyl methyl ether	0.005	47	--	--
20% t-Amyl methyl ether	0.05/0.02	44	--	--
5% Diethyl ether	0.005	49	--	--
10% Diethyl ether	0.006	47	--	--
20% Diethyl ether	0.025/0.006	46	--	--
100% Dimethoxytetraethylene glycol	would not ignite	--	NA	NA
5% Dimethoxytetraethylene glycol	0.005	47	--	--
10% Dimethoxytetraethylene glycol	0.005	47	--	--
20% Dimethoxytetraethylene glycol	0.004	52	--	--
100% Tetrahydrofuran	22	47	NA	NA
5% Tetrahydrofuran	0.008	48	--	--
10% Tetrahydrofuran	0.005	48	--	--
20% Tetrahydrofuran	0.008	46	--	--
100% Butylethyl ether	18	51	NA	NA
5% Butylethyl ether	0.005	50	--	--
10% Butylethyl ether	0.005	49	--	--
20% Butylethyl ether	0.008	48	--	--
5% t-Butylethyl ether	0.005	50	--	--
10% t-Butylethyl ether	0.006	49	--	--
20% t-Butylethyl ether	0.35/0.012	48	18	38
100% Buryl ether	15	74	NA	NA
5% Buryl ether	0.004	48	--	--
10% Buryl ether	0.004/0.001	69	--	--
20% Buryl ether	0.004/0.001/0.005	88	--	--
100% Dimethoxymethane	0.02	43	NA	NA
5% Dimethoxymethane	0.004	49	--	--
10% Dimethoxymethane	0.004	49	--	--
20% Dimethoxymethane	0.005	45	--	--
100% Furan	20	29	NA	NA
5% Furan	0.005	51	--	--
10% Furan	0.15/0.005	47	1	2
20% Furan	10.5/0.5/0.005	44	22	50

TABLE A-9. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE HETEROCYCLIC COMPOUNDS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Pyridine	14	55	NA	NA
5% Pyridine	0.002/0.14	53	--	--
10% Pyridine	0.006/0.25	60	8	13
20% Pyridine	0.005/5.5/0.25	70	35	50
100% 4-t-Butylpyridine	would not ignite	--	NA	NA
5% 4-t-Butylpyridine	0.005	48	--	--
10% 4-t-Butylpyridine	0.005/1.8	74	25	34
20% 4-t-Butylpyridine	0.005/1.8	118	70	59
0.013 wt.% Benzoylpyridine	0.005	47	--	--
0.025 wt.% Benzoylpyridine	0.005	48	--	--
Saturated carbazole	0.012/0.04/0.008	56	--	--
100% Tetrahydrofuran	22	47	NA	NA
5% Tetrahydrofuran	0.008	48	--	--
10% Tetrahydrofuran	0.005	48	--	--
20% Tetrahydrofuran	0.008	46	--	--
5% Pyrrole	0.006/0.02	50	2	4
10% Pyrrole	0.01/1.7	60	8	13
20% Pyrrole	0.012/9	73	25	34
5% Furfurylamine	0.005	47	--	--
10% Furfurylamine	0.005/0.32	88	8	9
20% Furfurylamine	0.006/2.4	101	35	35
100% Pyrrolidine	33	69	NA	NA
5% Pyrrolidine	0.005	51	--	--
10% Pyrrolidine	0.006/0.02/0.002	76	--	--
20% Pyrrolidine	0.009/0.2/0.003	79	5	6
100% Piperidine	16	70	NA	NA
5% Piperidine	0.005	53	--	--
10% Piperidine	0.005/0.001	88	--	--
20% Piperidine	0.006/0.045	85	--	--
5% Pyrrolidinone	0.004	47	--	--
10% Pyrrolidinone	0.004	46	--	--
20% Pyrrolidinone	0.004	43	--	--
100% Furan	20	29	NA	NA
5% Furan	0.005	51	--	--
10% Furan	0.15/0.005	47	1	2
20% Furan	10.5/0.5/0.005	44	22	50
100% Borane-pyridine complex	3	55	49	89
5% Borane-pyridine complex	0.05/0.002	82	--	--
10% Borane-pyridine complex	0.02/0.02/0.5	63	13/8	33
20% Borane-pyridine complex	0.3/2	47	42	89

TABLE A-10. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALKANES IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
5% 2,2-Dimethylbutane	0.008	47	--	--
10% 2,2-Dimethylbutane	0.2/0.006	44	3	7
20% 2,2-Dimethylbutane	7.5/0.1/0.006	43	5	12
100% Heptane	25	52	NA	NA
5% Heptane	0.004	48	--	--
10% Heptane	0.02/0.004	46	--	--
20% Heptane	0.7/0.005	42	15	36
100% Octane	19	79	NA	NA
5% Octane	0.006	49	--	--
10% Octane	0.006	46	--	--
20% Octane	0.16/0.006	46	3	7
100% 1-Phenyl octane	would not ignite	--	NA	NA
5% 1-Phenyl octane	0.005	48	--	--
10% 1-Phenyl octane	0.005	48	--	--
20% 1-Phenyl octane	0.005	43	--	--
100% Isooctane	20	55	NA	NA
5% Isooctane	0.005	50	--	--
10% Isooctane	0.7/0.005	45	8	18
20% Isooctane	4/0.005	42	20	48
100% Cyclohexane	17.8	63	NA	NA
5% Cyclohexane	0.002	46	--	--
10% Cyclohexane	1.2/0.002	47	10	21
20% Cyclohexane	4/0.1/0.002	46	12	29
100% Phenylcyclohexane	would not ignite	--	NA	NA
5% Phenylcyclohexane	0.005	46	--	--
10% Phenylcyclohexane	0.045	45	--	--
20% Phenylcyclohexane	0.005/0.22	43	3	7
100% Pentane	28	43	NA	NA
5% Pentane	0.005	45	--	--
10% Pentane	0.005	46	--	--
20% Pentane	0.8/0.005	43	4	9
100% 3-Methylpentane	38	46	NA	NA
5% 3-Methylpentane	0.005	45	--	--
10% 3-Methylpentane	0.06/0.005	45	1	2
20% 3-Methylpentane	7.5/0.005	42	8	19
100% Isopentane	30	38	NA	NA
5% Isopentane	0.005	47	--	--
10% Isopentane	0.005	46	--	--
20% Isopentane	0.4/0.005	41	8	20
5% 4-Methyloctane	0.005	57	--	--
10% 4-Methyloctane	0.01	58	--	--
20% 4-Methyloctane	0.04	57	--	--
100% Hexane	22.5	67	NA	NA
5% Hexane	0.004	49	--	--
10% Hexane	0.012/0.004	46	--	--
20% Hexane	2.7/0.004	45	18	40

TABLE A-11. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ALKENES AND ALKYNES IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% 1-Pentyne	16.5	25	NA	NA
5% 1-Pentyne	0.012/0.005	47	--	--
10% 1-Pentyne	3.4/0.005	47	7	15
20% 1-Pentyne	16.5/0.005	44	12	27
100% 1-Hexyne	14.2	30	NA	NA
5% 1-Hexyne	0.005	49	--	--
10% 1-Hexyne	2.2/0.005	48	15	31
20% 1-Hexyne	13/0.005	41	22	54
5% Indene	0.001/1.2	51	22	43
10% Indene	2	65	48	74
20% Indene	4	66	56	85

TABLE A-12. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR ADDITIVE COMBINATIONS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
15% Gasoline (California M-85)	0.8/0.15/0.25	46	34	74
5% Ethanol + 5% TBA	0.005	53	-a	-
5% Ethanol + 10% TBA	0.005/0.02	52	--	--
10% Ethanol + 5% TBA	0.006	53	--	--
10% Ethanol + 10% TBA	0.004/0.025	51	--	--
10% Ethanol + 20% TBA	0.005/0.20	60	8	13
20% Ethanol + 10% TBA	0.005/0.13	50	--	--
20% Ethanol + 20% TBA	0.005/0.6	61	15	25
5% Ethanol + 5% MTBE	0.005	49	--	--
10% Ethanol + 10% MTBE	0.006	47	--	--
20% Ethanol + 20% MTBE	0.65/0.008	49	17	35
5% Cyclopentene + 1% Indan	0.6/0.01/0.5	46	10	22
5% Cyclopentene + 2% Indan	1.4/0.02/1.3	47	20	43
5% Cyclopentene + 3% Indan	1.3/0.05/1.6	48	25	52
5% Cyclopentene + 5% Indan	2.2/0.15/2	46	36	78
6% Cyclopentene + 3% Indan	2.1/0.05/1.6	49	25	51
6% Cyclopentene + 4% Indan	2/0.12/1.6	46	30	65
6% Cyclopentene + 5% Indan	2.1/0.15/1.6	48	40	83
5% Methylcyclopentane + 1% Indan	0.08/0.025/0.12	48	--	--
5% Methylcyclopentane + 2% Indan	0.12/0.006/0.9	47	10	21
5% Methylcyclopentane + 3% Indan	0.18/0.006/1.3	47	20	43
5% Methylcyclopentane + 4% Indan	0.2/0.04/1.9	45	25	56
5% Methylcyclopentane + 5% Indan	0.15/2.1	46	25	54
6% Methylcyclopentane + 2% Indan	0.2/0.006/1.2	47	10	21
6% Methylcyclopentane + 3% Indan	0.2/0.05/1.3	47	18	38
6% Methylcyclopentane + 4% Indan	0.5/0.1/1.4	47	30	64
7% Methylcyclopentane + 3% Indan	0.21/0.08/1.5	49	25	51

TABLE A-12 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR ADDITIVE COMBINATIONS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
1% Toluene + 1% Indan	0.005/0.15	48	--	--
2% Toluene + 2% Indan	0.25/0.04/1.2	49	11	22
3% Toluene + 3% Indan	0.5/1.7	50	35	70
4% Toluene + 2% Indan	0.15/0.5/1.3	48	39	81
4% Toluene + 4% Indan	0.7/2.8	48	42	88
100% Cycloalkane/olefin mix ^b	13.8	93	--	--
5% Cycloalkane/olefin mix	0.004	51	--	--
10% Cycloalkane/olefin mix	0.2/0.004	51	--	--
20% Cycloalkane/olefin mix	0.88/0.35	49	33	67
100% Olefin mix ^c	15.5/11/5.5	99	--	--
5% Olefin mix	0.004	53	--	--
10% Olefin mix	0.015/0.005	50	--	--
20% Olefin mix	1/0.2/0.005	48	15	31
5% Chevron α -olefins (C ₉ -C ₁₁)	0.005	50	--	--
10% Chevron α -olefins (C ₉ -C ₁₁)	0.005/0.01	51	--	--
20% Chevron α -olefins (C ₉ -C ₁₁)	0.005/0.62	76	25	33
5% C ₅ -C ₆ mix ^d	0.005	53	--	--
10% C ₅ -C ₆ mix	0.11/0.005	50	--	--
20% C ₅ -C ₆ mix	1.8/0.005	80	12	15
0.006 wt% Ferrocene + 5% Cyclopentene + 5% Indan	0.75/0.17/1.2	49	38	78
2% Cyclopentene + 2% Toluene + 2% Indan	0.1/0.04/1	49	12	24
100% Hydrocarbon grade DCPD ^e	8	58	57	98
5% Hydrocarbon grade DCPD	0.002/0.1	50	4	8
10% Hydrocarbon grade DCPD	0.2/1	59	30	51
20% Hydrocarbon grade DCPD	0.3/2	66	44	67
100% Polyester grade DCPD ^f	3	63	62	98
5% Polyester grade DCPD	0.002/0.1	103	5	5
10% Polyester grade DCPD	0.003/1	67	31	46
20% Polyester grade DCPD	2/0.7/0.3	131	102	78

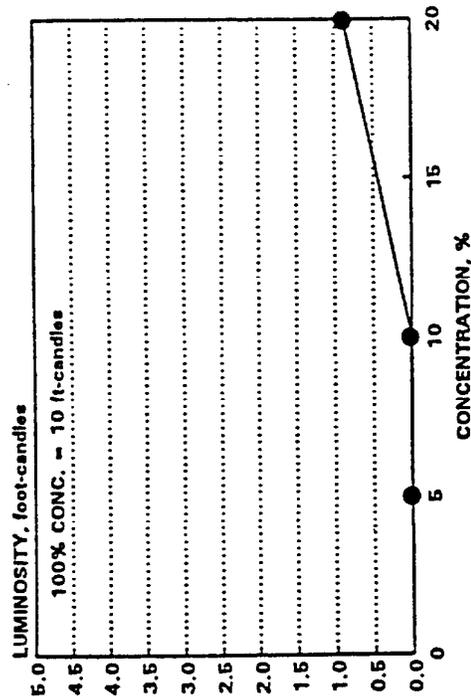
TABLE A-12 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR ADDITIVE COMBINATIONS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Dicyclopentadiene 97 ^z	3	57	50	88
5% Dicyclopentadiene 97	0.003/0.1	84	1	1
10% Dicyclopentadiene 97	0.003/1	73	26	36
20% Dicyclopentadiene 97	0.05/1.5/0.3	101	80	79
100% DP5-160 ^b	2	81	78	96
5% DP5-160	0.003/0.03	44	--	--
10% DP5-160	0.005/0.6	79	36	46
20% DP5-160	0.05/1	77	42	55
100% DP6-46 ⁱ	6	72	71	99
5% DP6-46	0.02/0.1	47	--	--
10% DP6-46	0.1/1.5	52	24	46
20% DP6-46	0.5/5	66	61	92

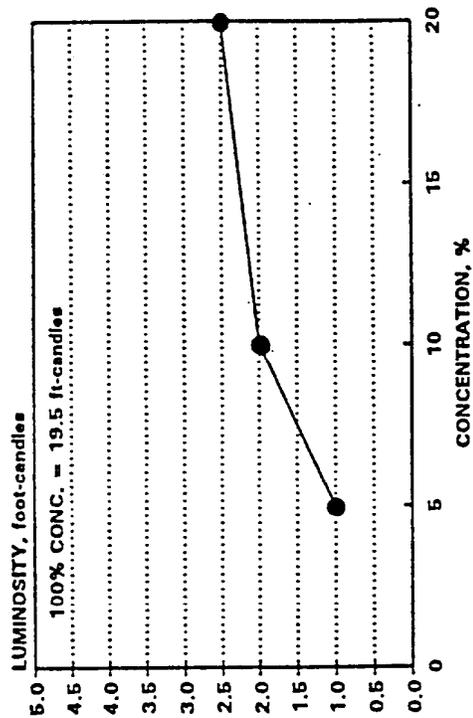
^zIndicate luminosity did not reach minimum threshold visibility (0.2 foot-candles)
^b40% hexane, 11% cycloheptane, 10% cyclopentene, 10% cis-1,2-dimethylcyclopentane, 10% 1,1,3-trimethylcyclohexane, 10% n-propylcyclohexane, 4% cis-1,2-dimethylcyclohexane, 4% cyclooctane, and 1% 4-methylcyclohexene
^c15% hexane, 10% 1-pentene, 10% cis-2-pentene, 10% 4-methylpentene, 10% cyclohexene, 5% 1-hexene, 5% 1-octene, 2.5% 2-heptene, 1.5% cycloheptene, 1% 2-methyl-2-butene, 1% 3,3-dimethyl-1-butene, 1% (cis & trans) 4-methyl-2-pentene, 1% 2-methyl-1-pentene, 1% 2-methyl-2-pentene, 1% (cis & trans) 4-methylcyclohexene, and 25% combination of 1-nonene, 1-decene, and 1-undecene
^d30% 2-methyl-2-butene, 15% (cis & trans) 4-methyl-2-pentene, 10% pentane, 10% hexane, 10% 2-methyl-1-butene, 10% cis-2-pentene, 10% 2-methyl-2-pentene, and 5% 2-methyl-1-pentene
^e76.0% DCPD, 15.8% C₁₀ codimers, 4.8% C₁₁ codimers, 2.1% C₉ codimers, 0.8% cyclopentadiene, and 0.4% C₅ and C₆ hydrocarbons
^f81.6% DCPD, 12.5% C₁₀ codimers, 3.9% C₁₁ codimers, 1.6% C₉ codimers, and 0.3% cyclopentene
^g95% DCPD, 2% cyclopentadiene, 1.5% C₅ acyclic dienes, and 1.5% cyclic diene and trimers
^h40% C₁₀ hydrocarbons, 25% methyl and dimethyl indenenes, 17% C₉ aromatics, 16% indene, and 2% C₈ aromatics
ⁱ61.8% DCPD, 8.1% cyclopentane plus 2-methylcyclopentane, 1.9% cyclopentene, and 1.1% cis-piperylene; the balance had less than 1% each of trans-piperylene, n-pentane, isoprene, 1-pentene, 2-methyl-1-butene, 2-methyl-2-butene, benzene, other C₆ hydrocarbons, and about 25% other undetermined compounds

FIGURE A-13. LUMINOSITY CURVES FOR CYCLOHEXENE, CYCLOPENTENE, DICYCLOPENTADIENE, AND PHENYL CYCLOHEXANE

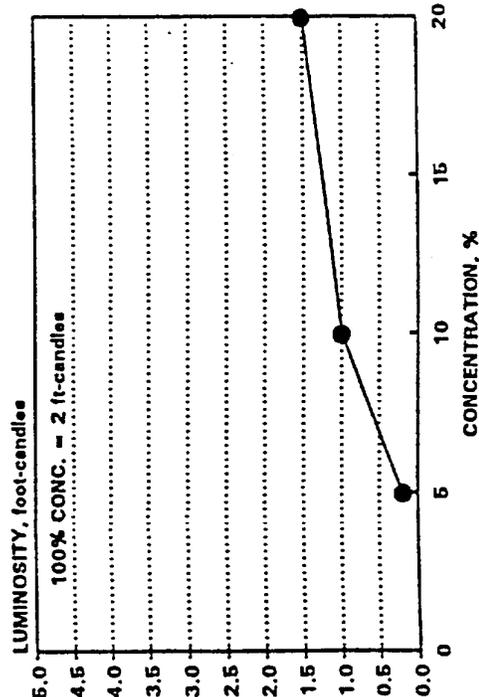
CYCLOHEXENE



CYCLOPENTENE



DICYCLOPENTADIENE



PHENYL-CYCLOHEXANE

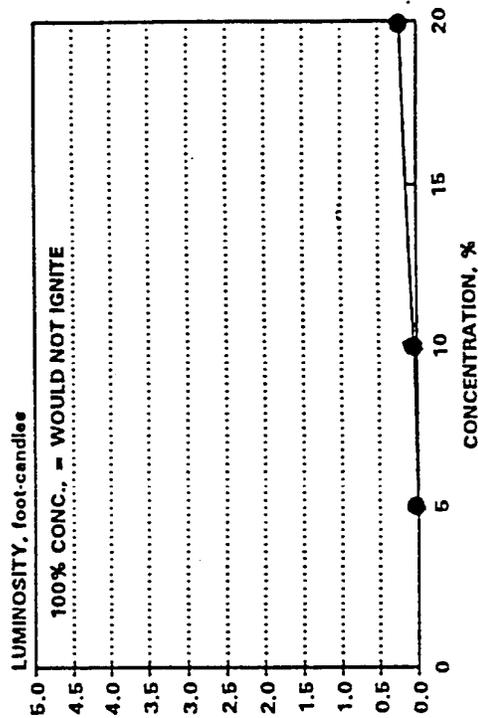
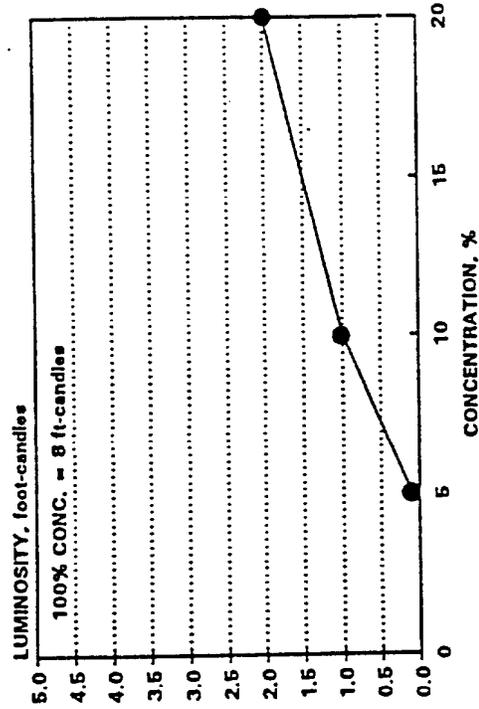
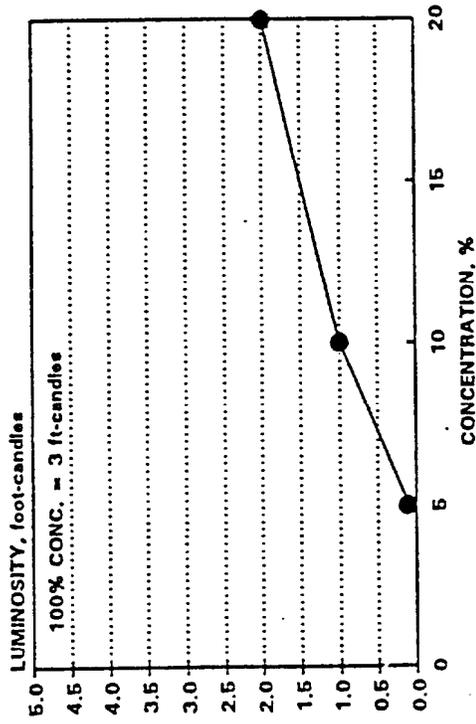


FIGURE A-14. LUMINOSITY CURVES FOR HYDROCARBON GRADE DCPD, POLYESTER GRADE DCPD, POLYESTER GRADE DCPD, DICYCLOPENTADIENE 97, AND DP6-46

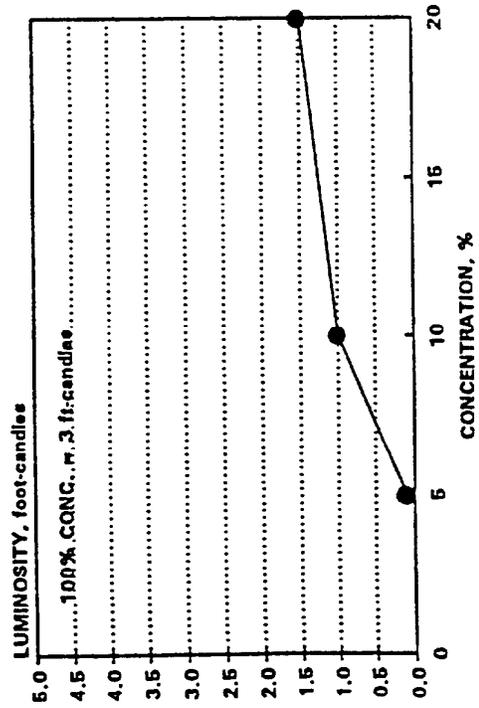
HYDROCARBON GRADE DCPD



POLYESTER GRADE DCPD



DICYCLOPENTADIENE 97



DP6-46

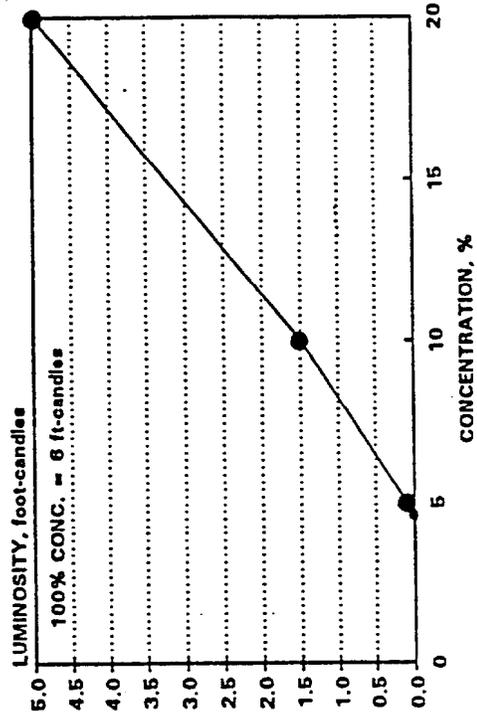


FIGURE A-15. LUMINOSITY CURVES FOR INDAN, INDENE, 1-INDANONE, AND DP5-160

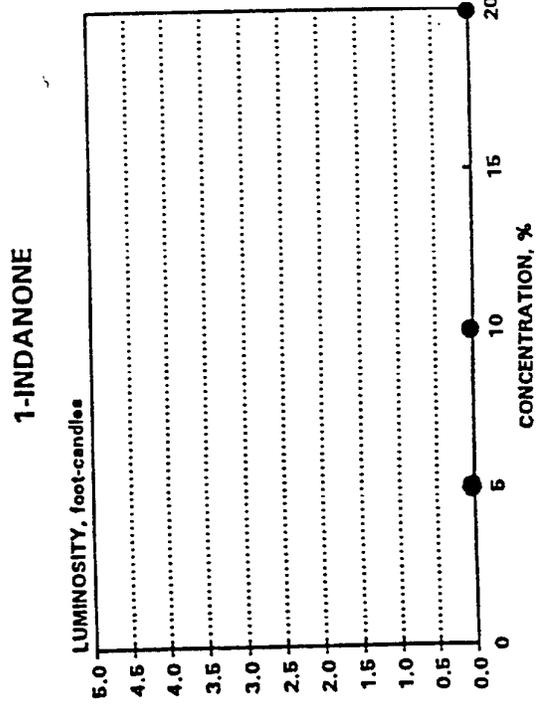
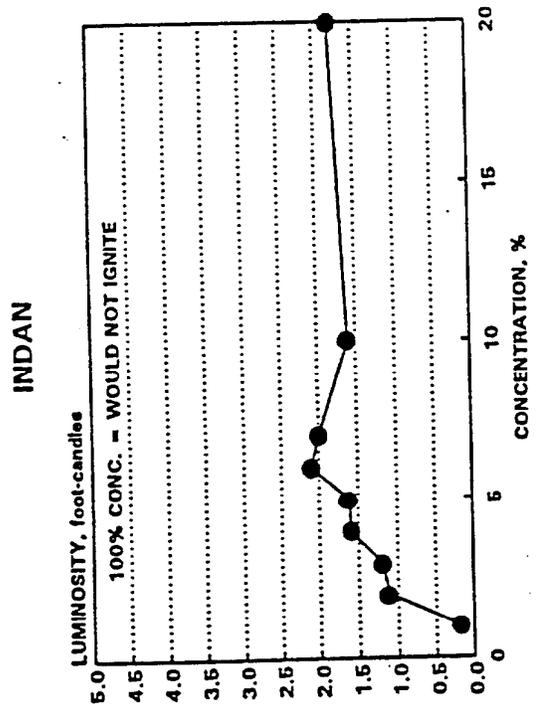
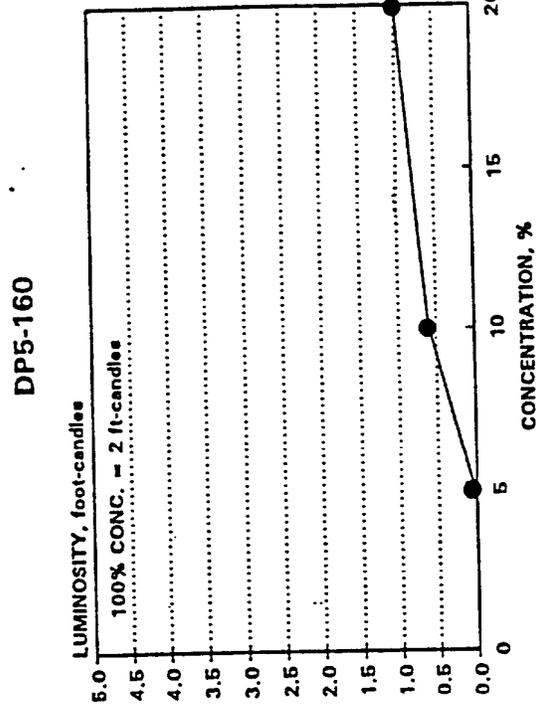
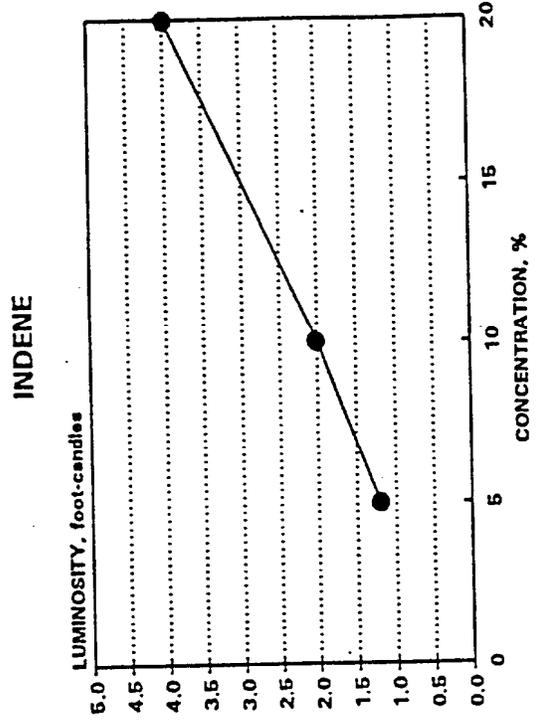


FIGURE A-16. LUMINOSITY CURVES FOR TOLUENE, MESITYLENE, *s*-BUTYL BENZENE, AND PENTAMETHYLBENZENE

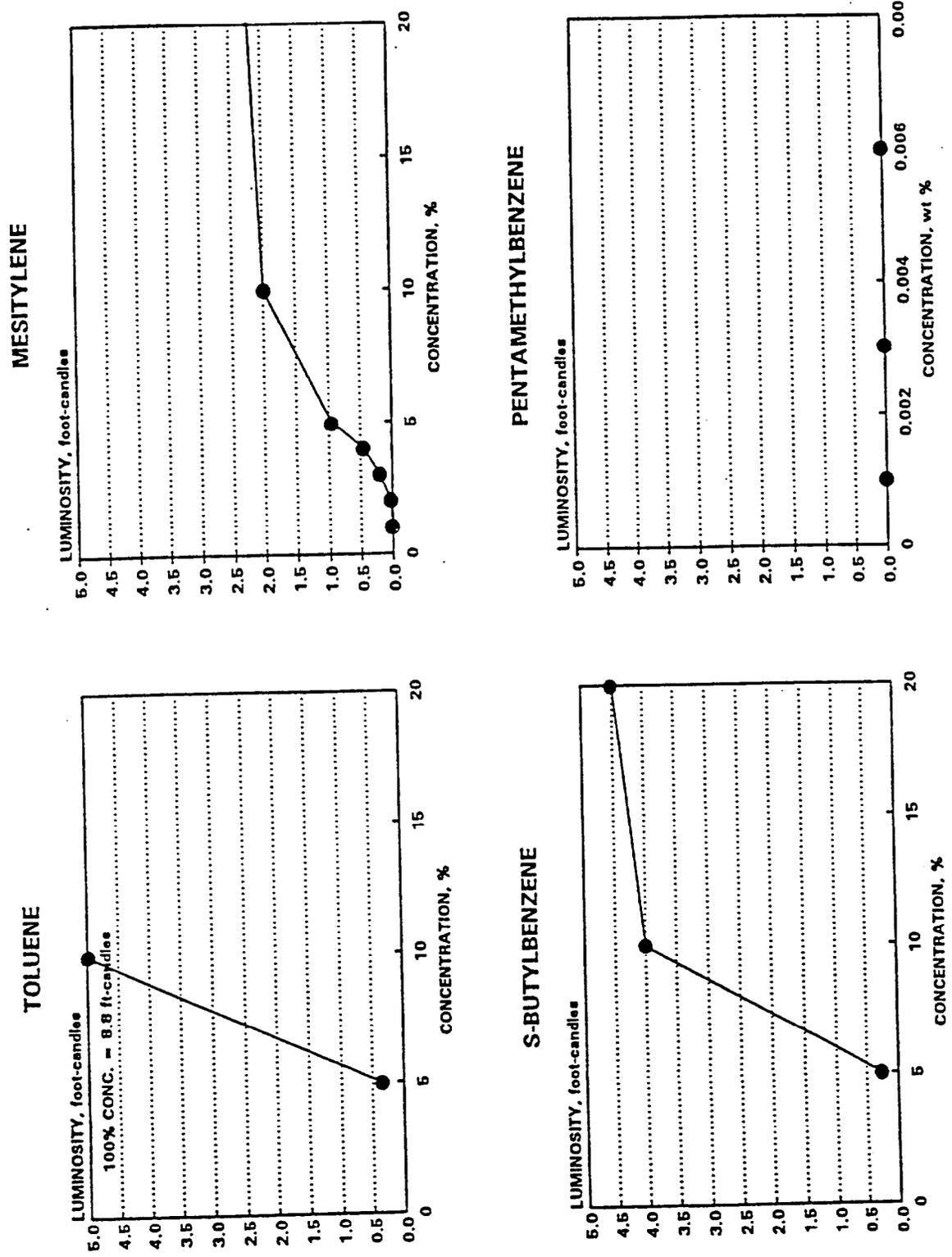
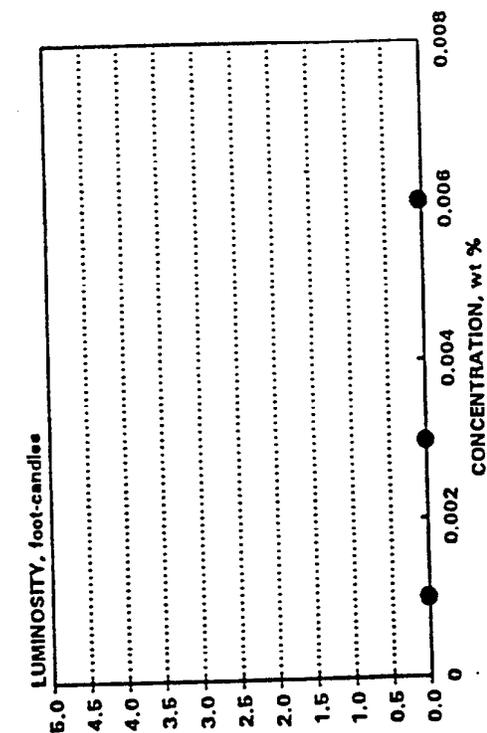
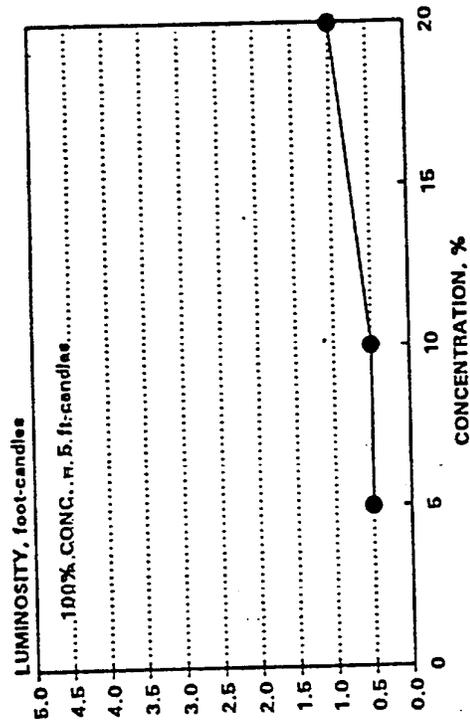


FIGURE A-17. LUMINOSITY CURVES FOR PENTAMETHYLBENZALDEHYDE,
 BENZALDEHYDE, BENZOIC ACID, 1,2,4,5-BENZENETETRCARBOXYLIC ACID

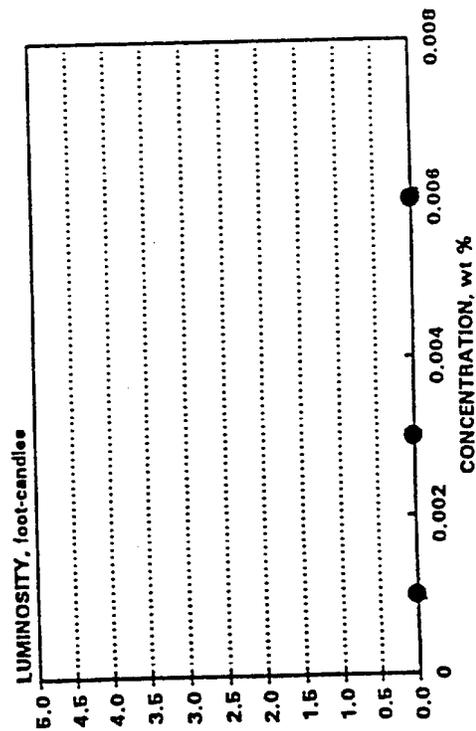
PENTAMETHYLBENZALDEHYDE



BENZALDEHYDE



BENZOIC ACID



1,2,4,5-BENZENETETRCARBOXYLIC ACID

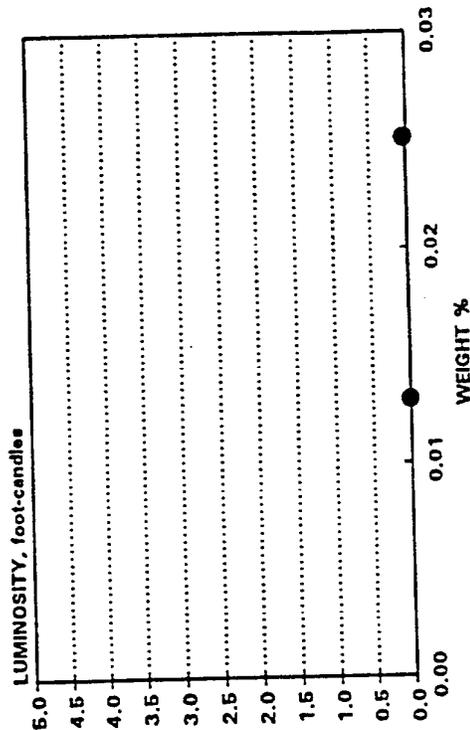
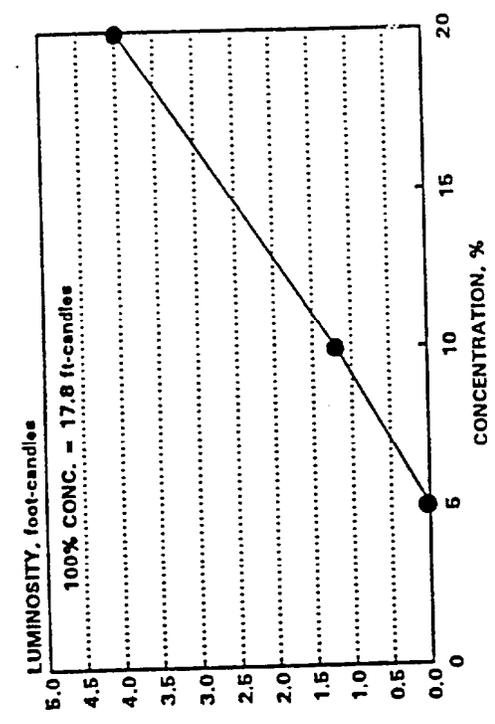
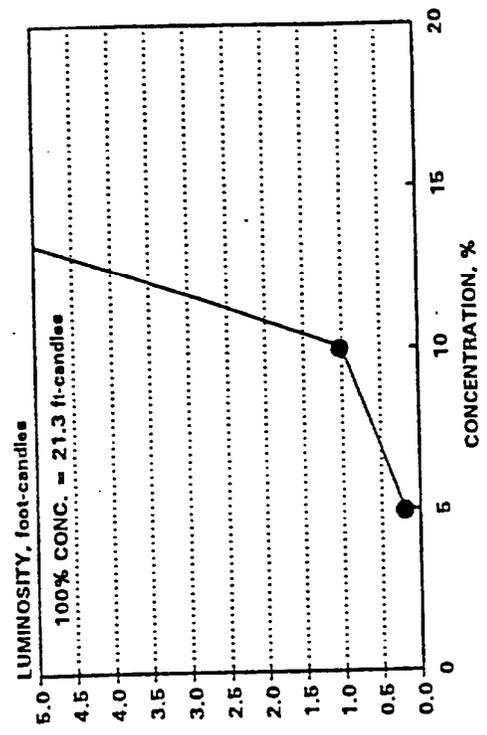


FIGURE A-18. LUMINOSITY CURVES FOR CYCLOHEXANE, CYCLOPENTANE, METHYLCYCLOPENTANE, AND CYCLOOCTANE

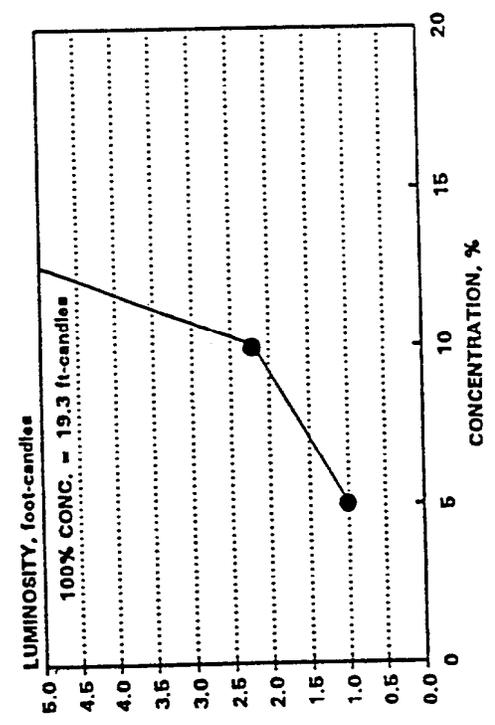
CYCLOHEXANE



CYCLOPENTANE



METHYLCYCLOPENTANE



CYCLOOCTANE

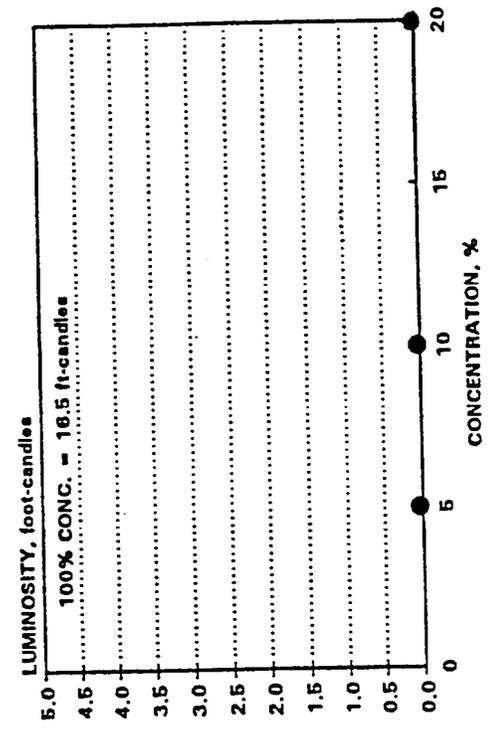
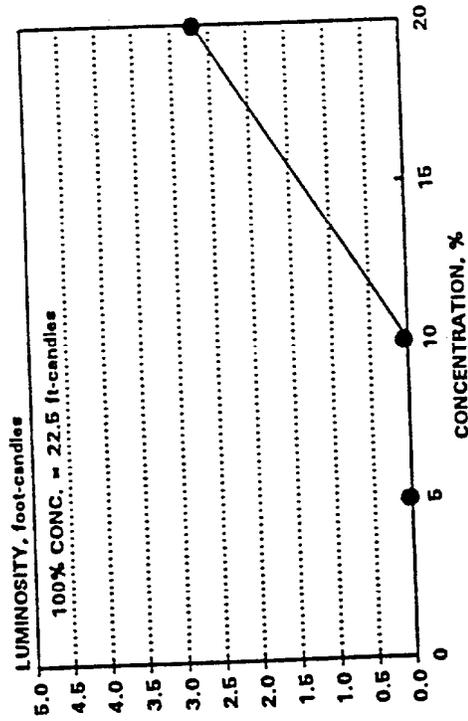
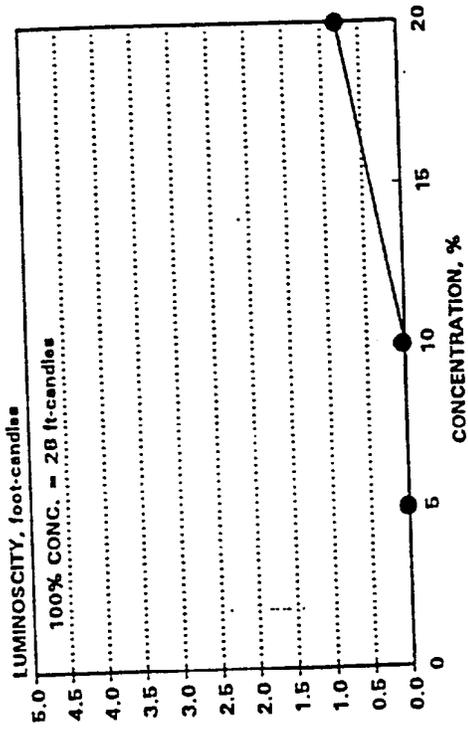


FIGURE A-19. LUMINOSITY CURVES FOR HEXANE, PENTANE, HEPTANE, AND OCTANE

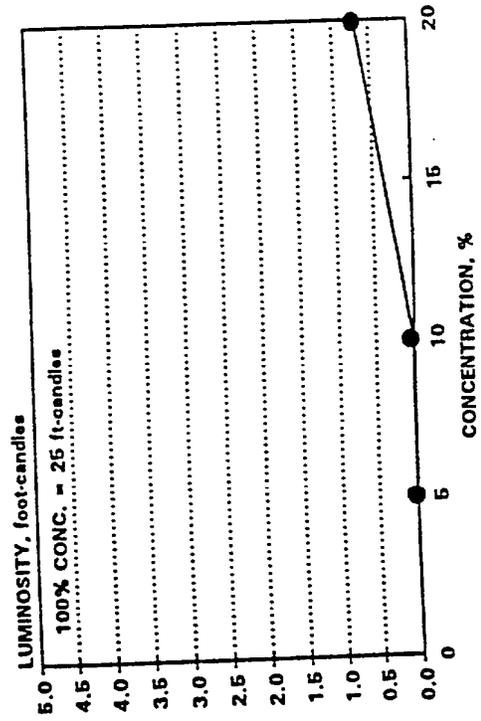
HEXANE



PENTANE



HEPTANE



OCTANE

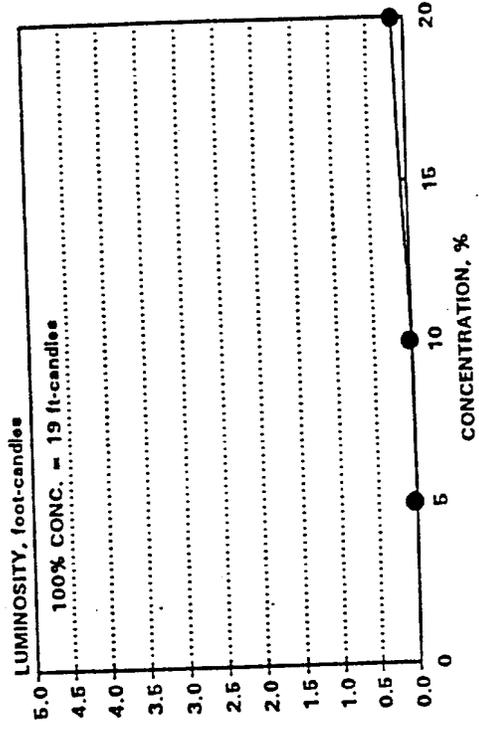
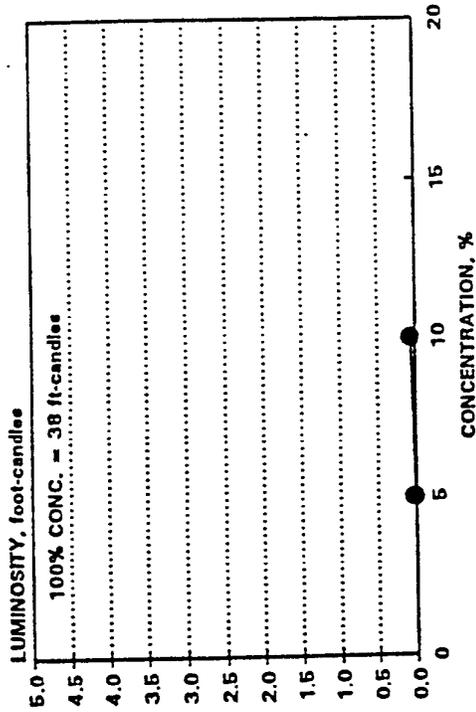
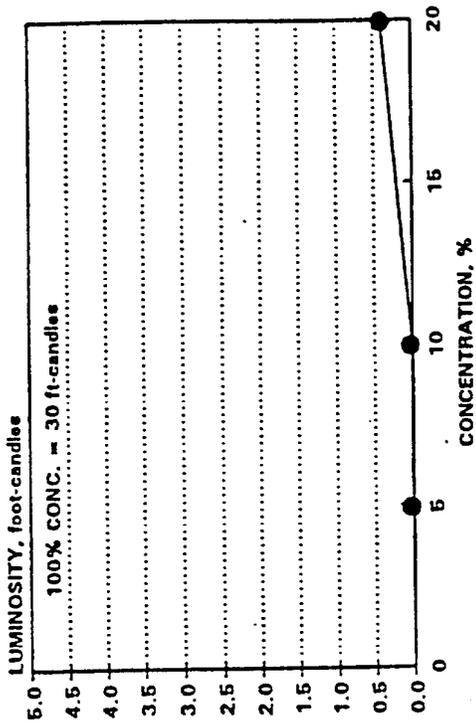


FIGURE A-20. LUMINOSITY CURVES FOR 3-METHYLPENTANE, ISOPENTANE, 2,2-DIMETHYLBUTANE, AND ISOCTANE

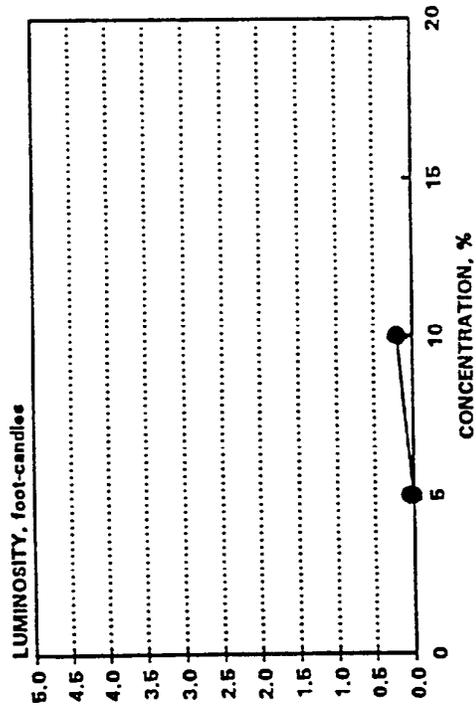
3-METHYLPENTANE



ISOPENTANE



2,2-DIMETHYLBUTANE



ISOCTANE

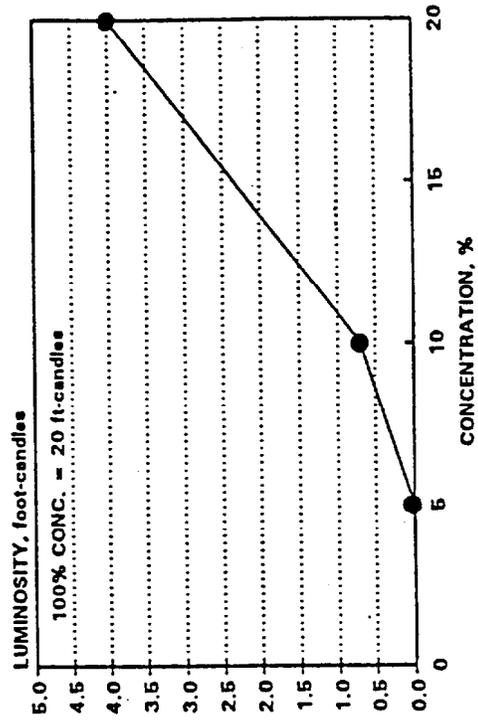
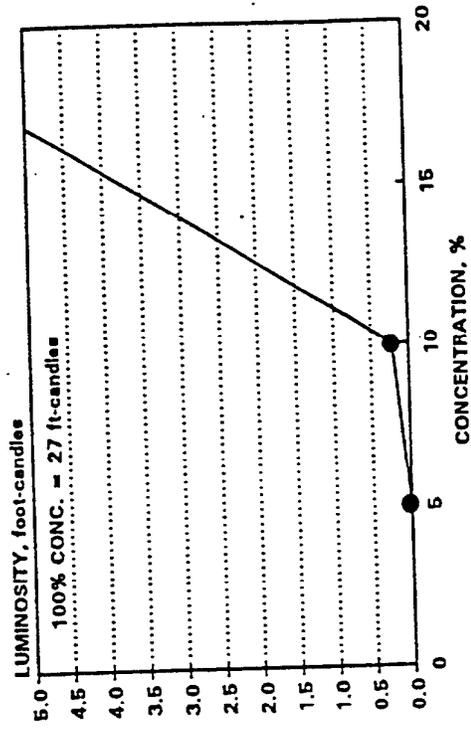
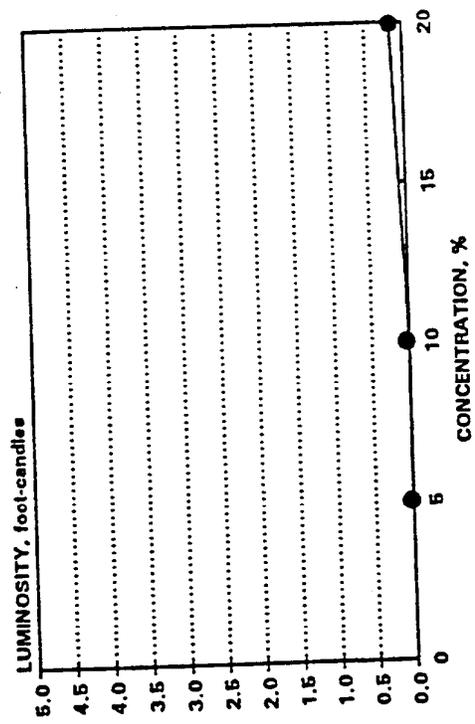


FIGURE A-21. LUMINOSITY CURVES FOR 2-METHYL-2-PENTENE,
2-METHYL-1-PENTENE, 4-METHYL-2-PENTENE, AND *cis*-2-PENTENE

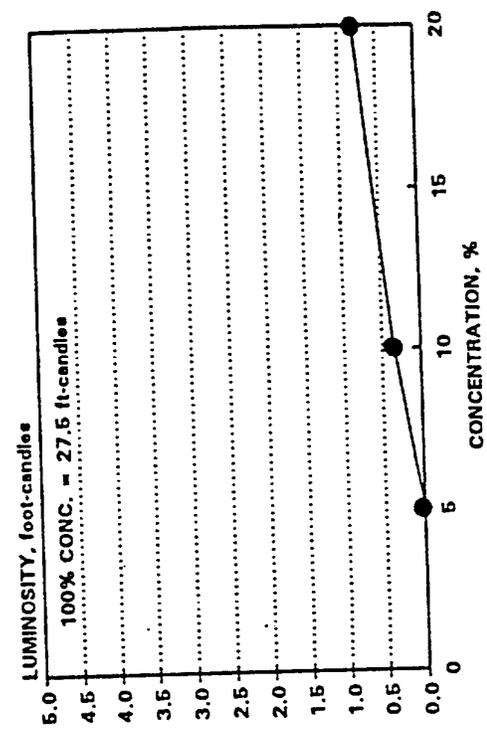
2-METHYL-1-PENTENE



2-METHYL-2-PENTENE



CIS-2-PENTENE



4-METHYL-2-PENTENE

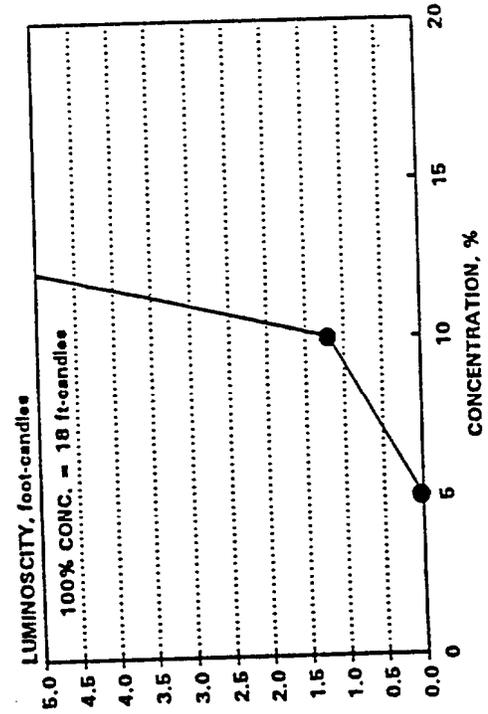
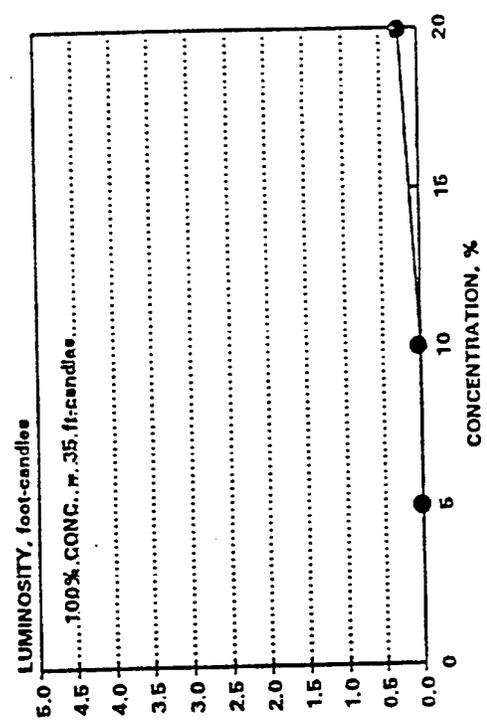
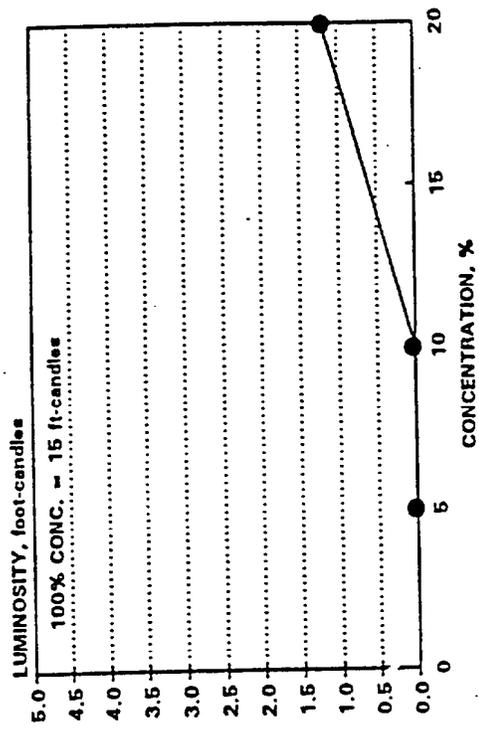


FIGURE A-22. LUMINOSITY CURVES FOR 1-PENTENE, 2,4,4-TRIMETHYL-1-PENTANE,
2-METHYL-1-BUTENE, AND 2-METHYL-2-BUTENE

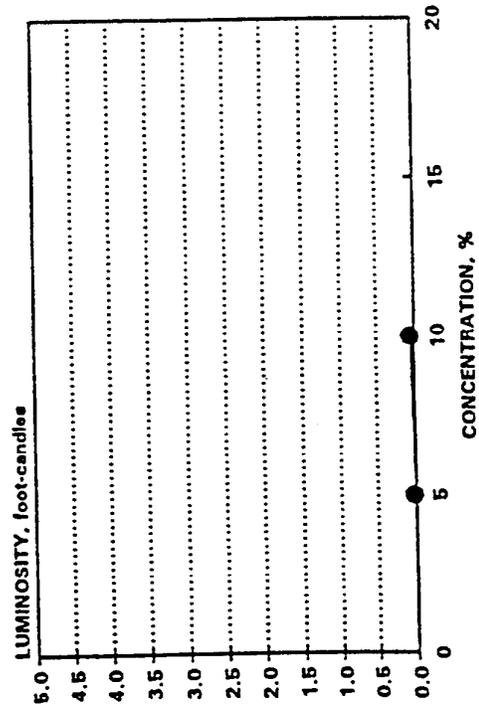
1-PENTENE



2,4,4-TRIMETHYL-1-PENTANE



2-METHYL-1-BUTENE



2-METHYL-2-BUTENE

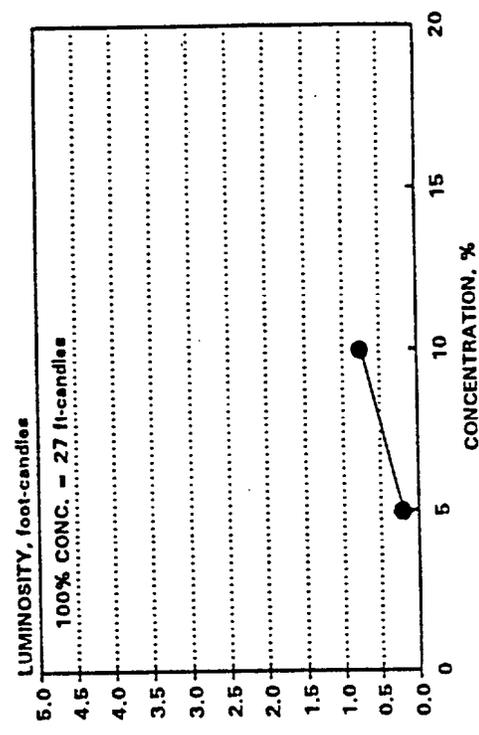
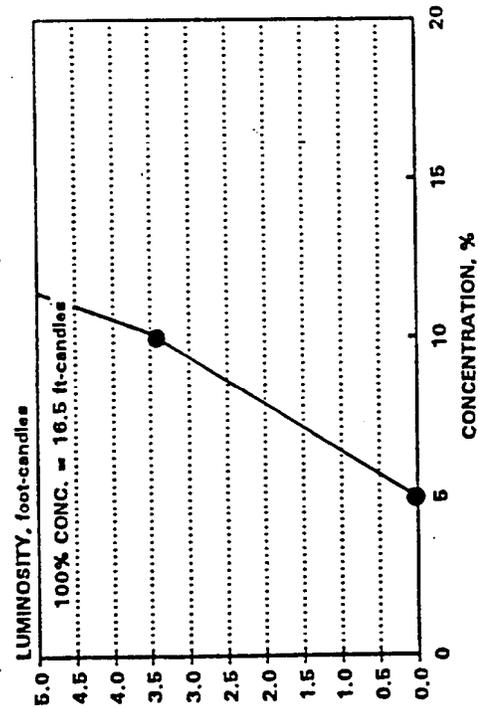
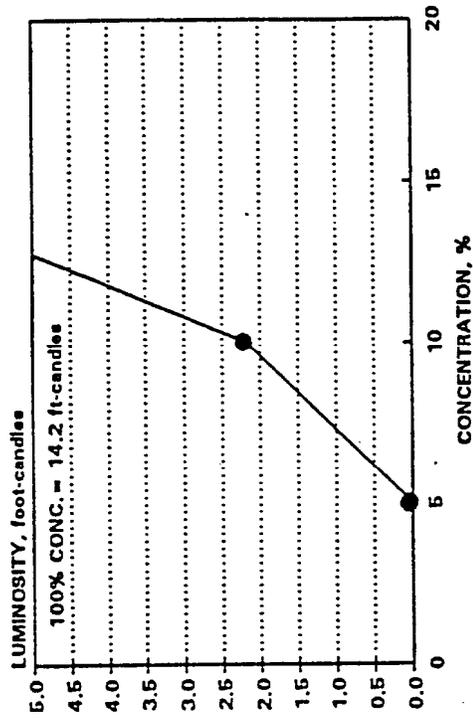


FIGURE A-23. LUMINOSITY CURVES FOR 1-PENTYNE, 1-HEXYNE, ACETONITRILE,
AND DIETHANOLAMINE

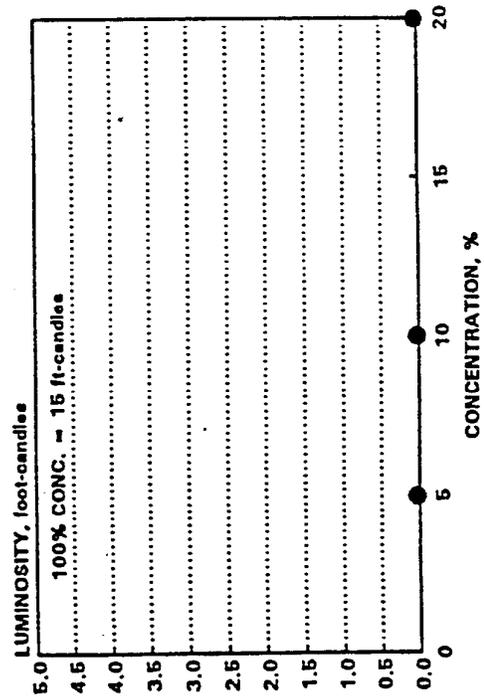
1-PENTYNE



1-HEXYNE



ACETONITRILE



DIETHANOLAMINE

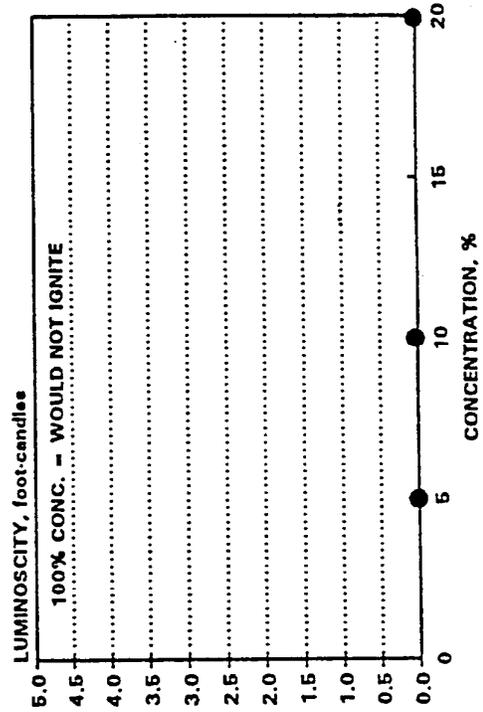
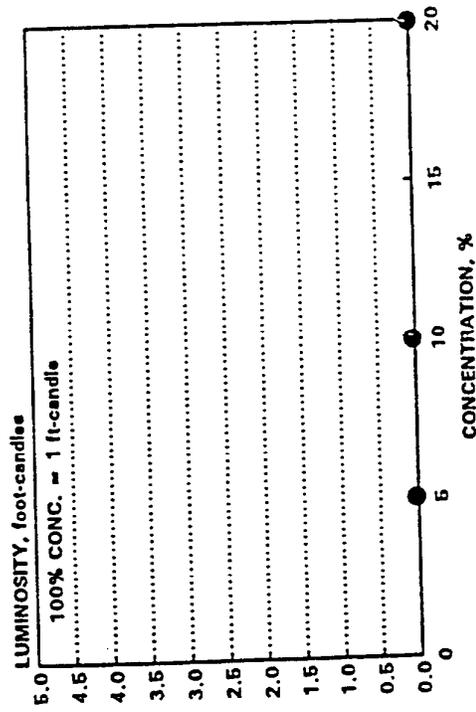
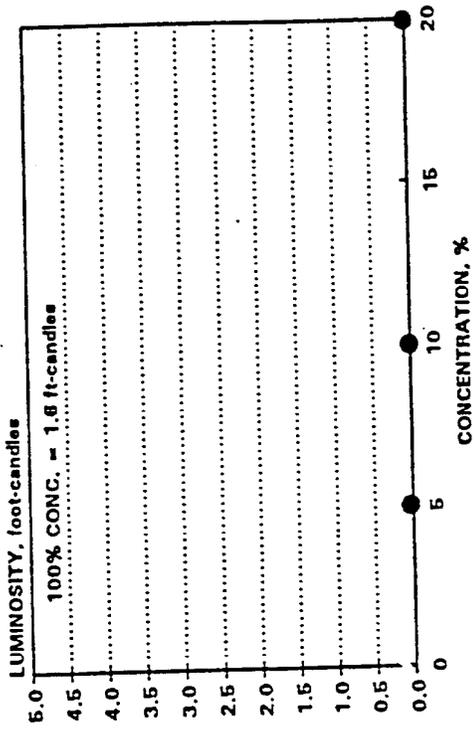


FIGURE A-24. LUMINOSITY CURVES FOR ETHANOL, ETHYL FORMATE, ETHYL ACETOACETATE, AND ETHYL ACETATE

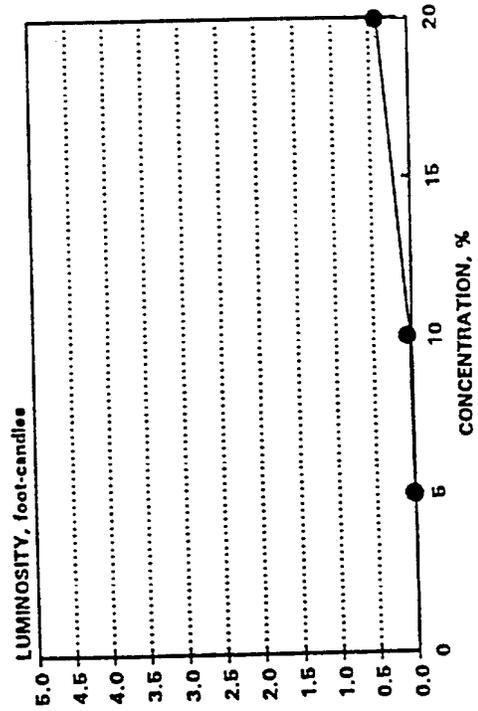
ETHANOL



ETHYL FORMATE



ETHYL ACETOACETATE



ETHYL ACETATE

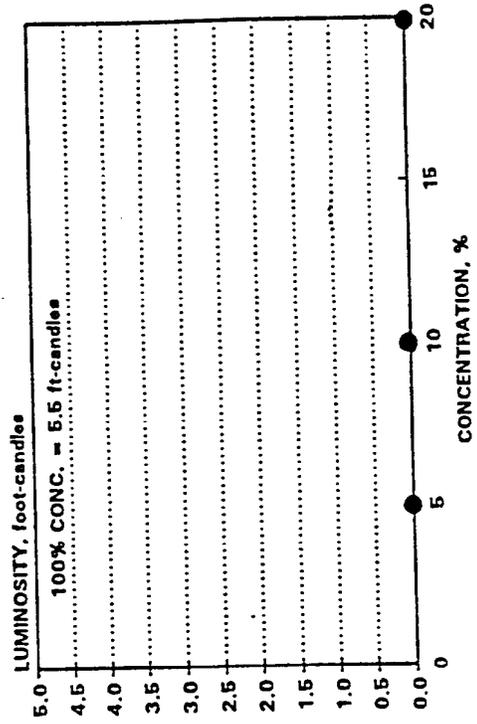
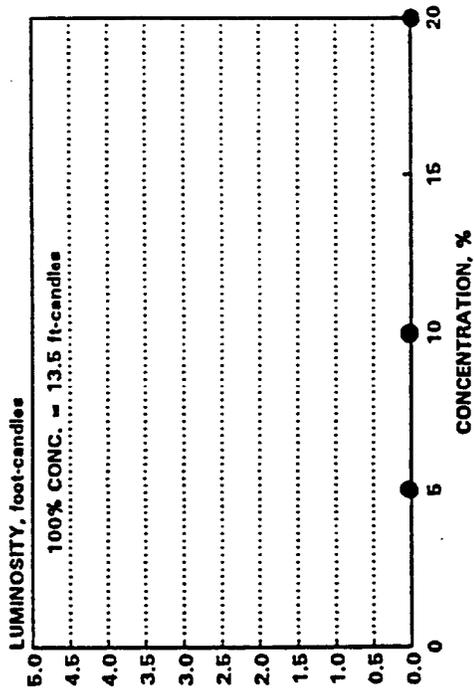
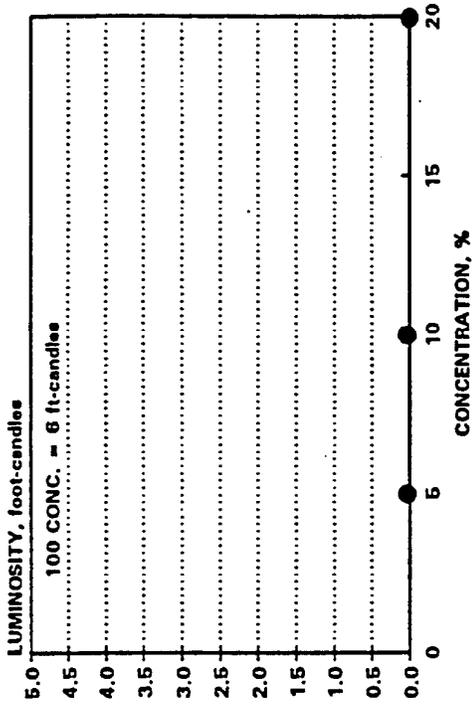


FIGURE A-25. LUMINOSITY CURVES FOR ISOPROPANOL, 1-PROPANOL, t-BUTYL ALCOHOL, AND n-BUTANOL

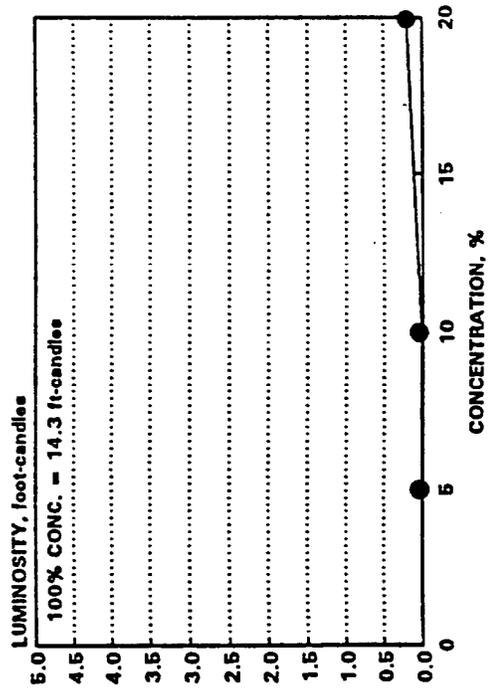
ISOPROPANOL



1-PROPANOL



T-BUTYL ALCOHOL



n-BUTANOL

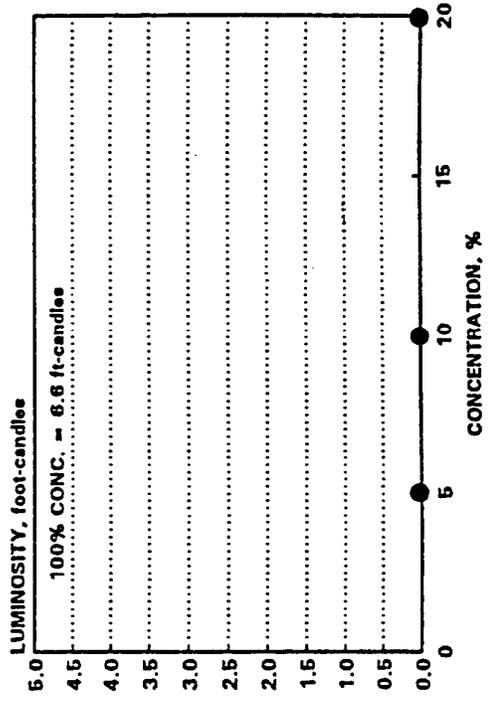
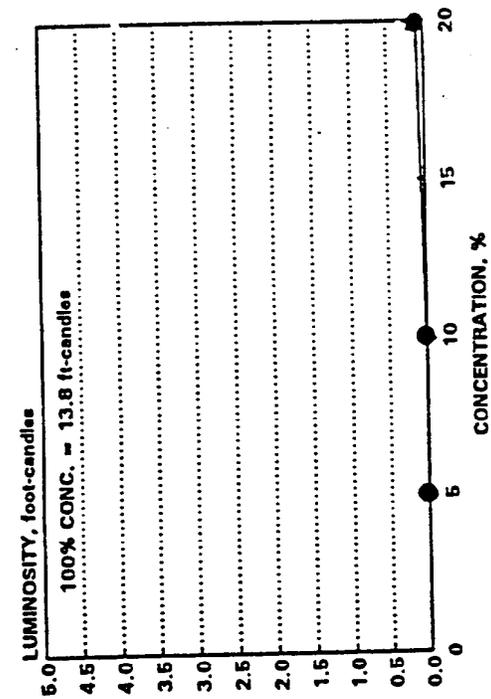
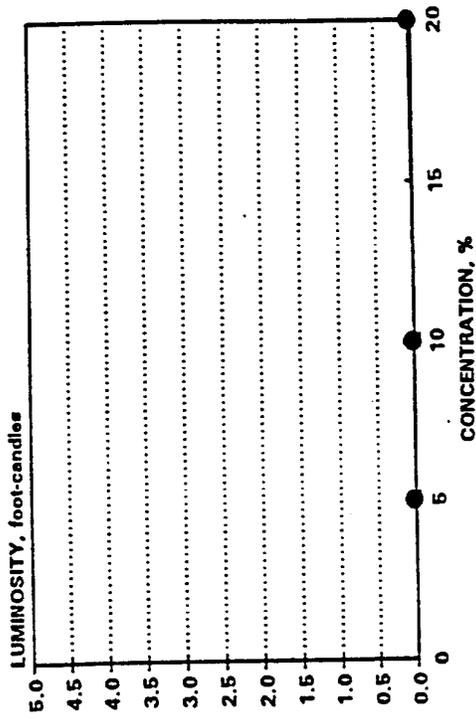


FIGURE A-26. LUMINOSITY CURVES FOR t-AMYL ALCOHOL, t-AMYL METHYL ETHER, DIETHYL ETHER, AND ACETONE

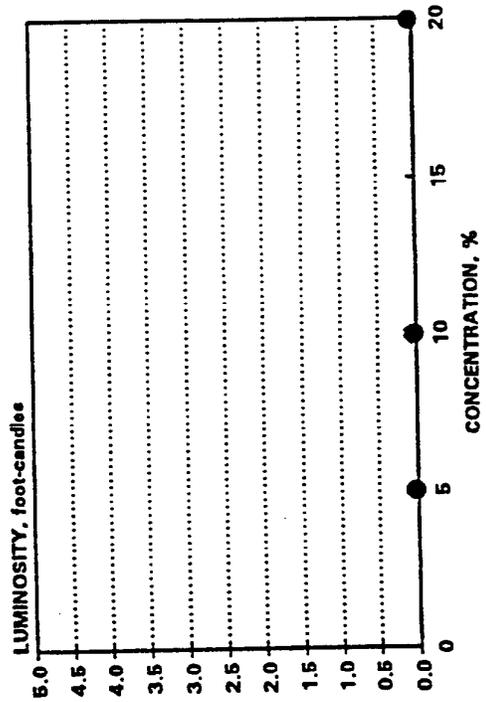
T-AMYL ALCOHOL



T-AMYL METHYL ETHER



DIETHYL ETHER



ACETONE

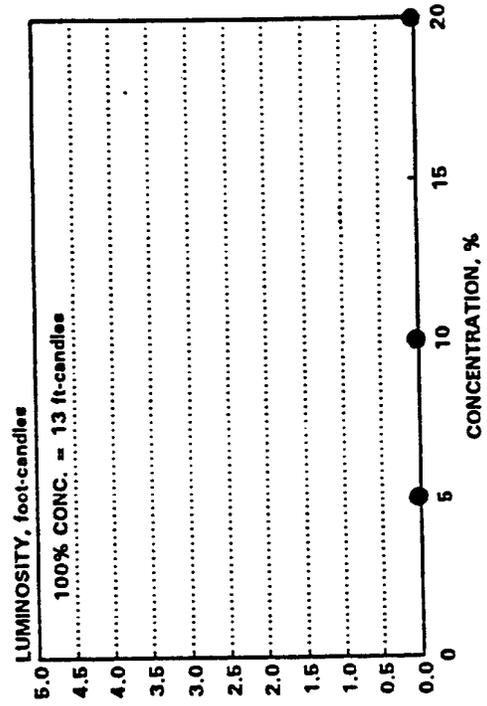
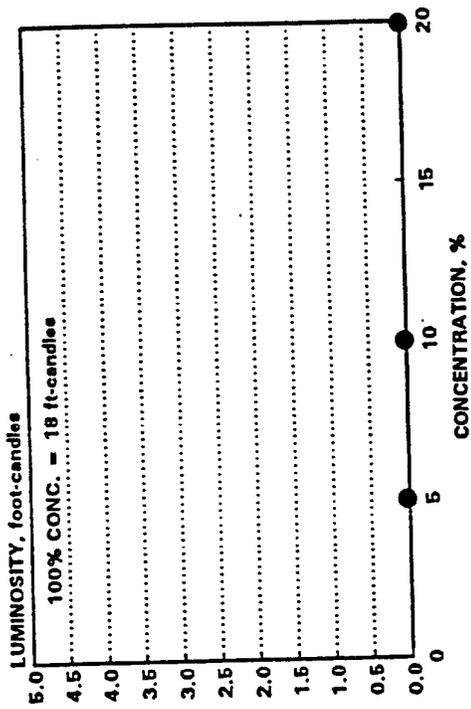
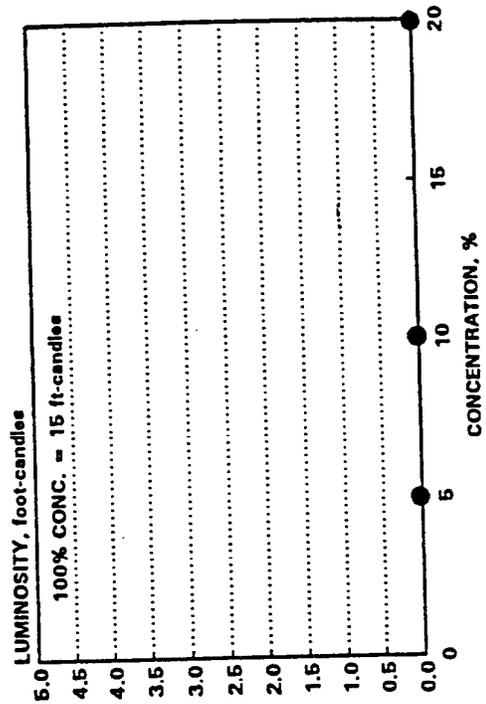


FIGURE A-27. LUMINOSITY CURVES FOR METHYL-t-BUTYL ETHER, BUTYLETHYL ETHER, t-BUTYLETHYL ETHER, AND BUTHYL ETHER

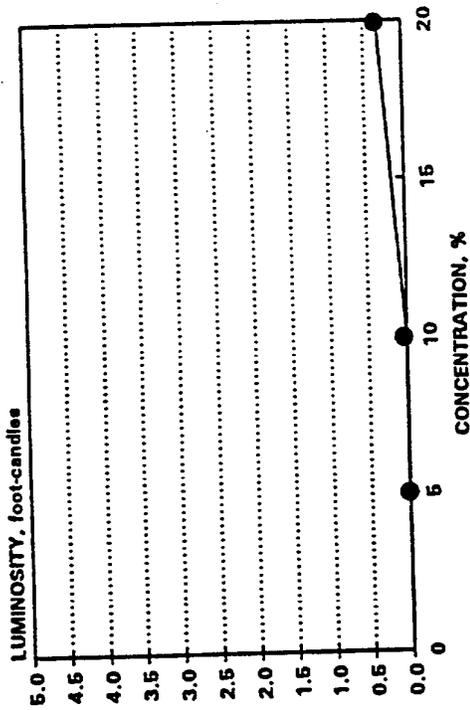
BUTYLETHYL ETHER



BUTYL ETHER



METHYL-T-BUTYL-ETHER



t-BUTYLETHYL ETHER

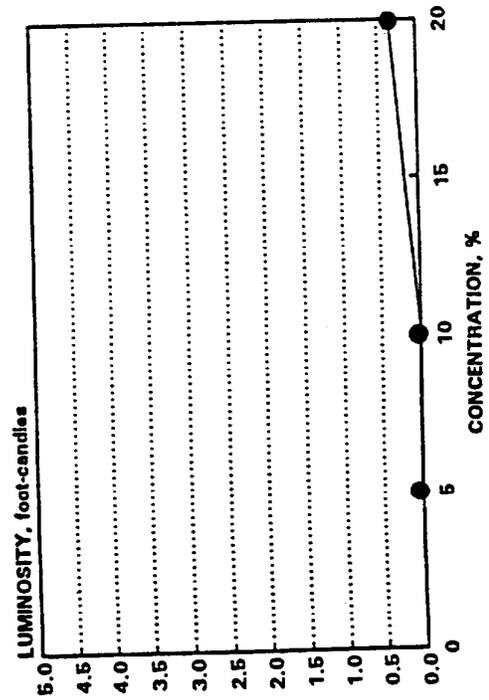
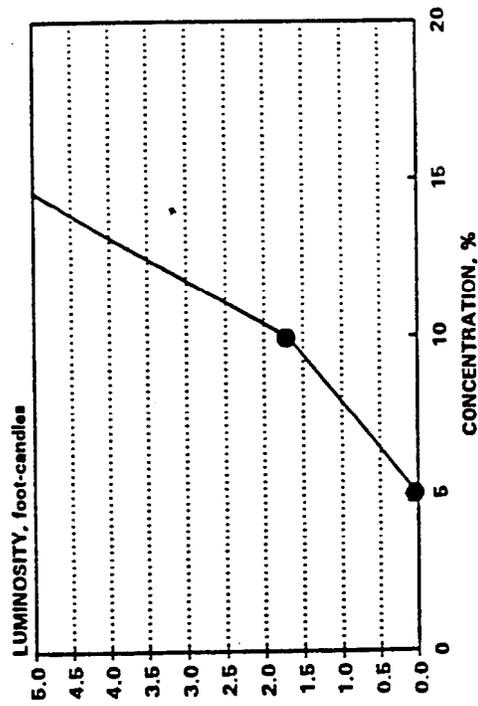
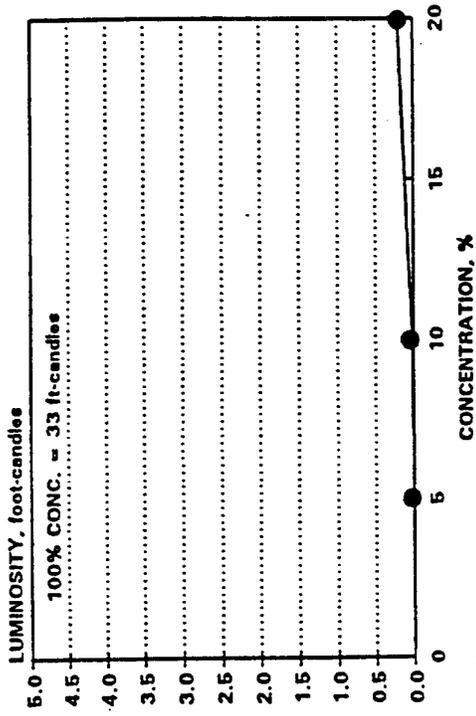


FIGURE A-28. LUMINOSITY CURVES FOR PYRROLE, PYRROLIDINE, PIPERIDINE, PIPERIDINE, AND PYRROLIDINONE

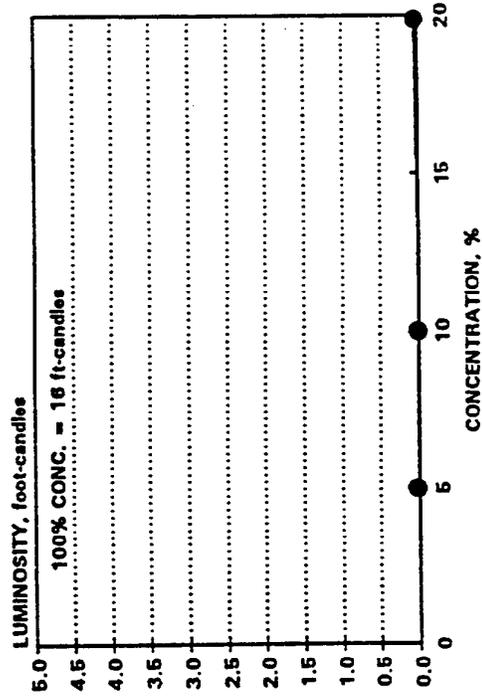
PYRROLE



PYRROLIDINE



PIPERIDINE



PYRROLIDINONE

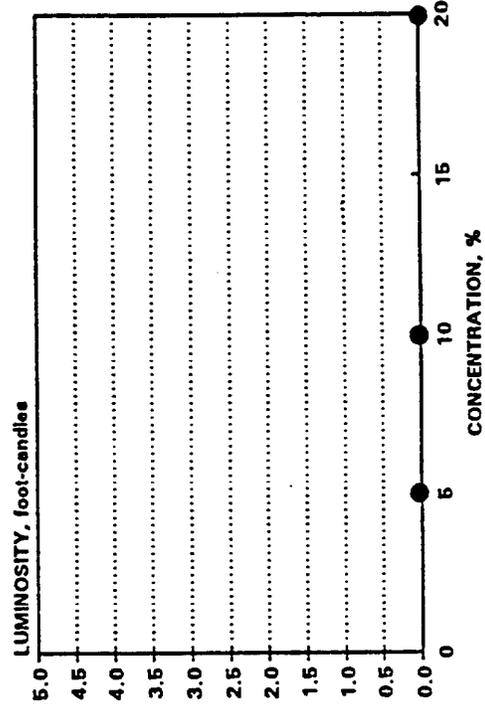
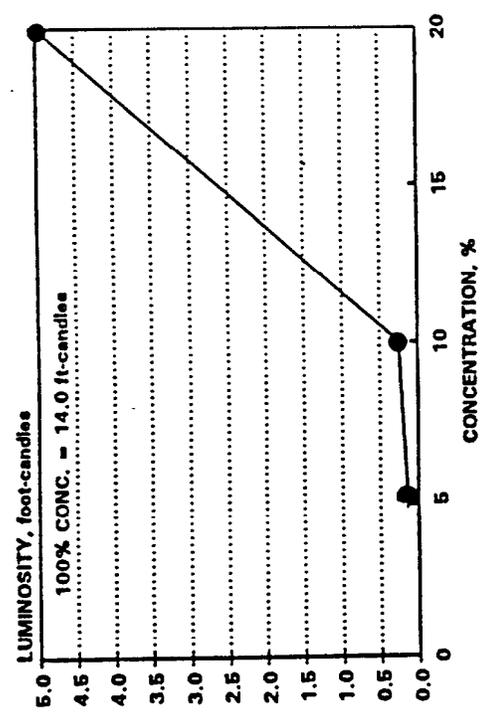
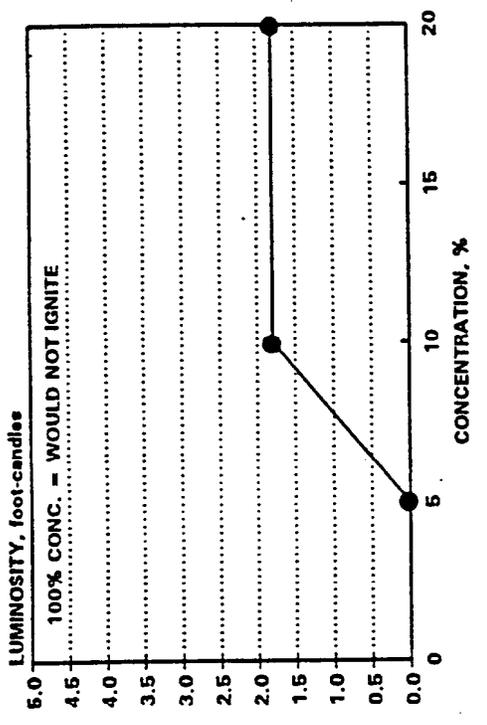


FIGURE A-29. LUMINOSITY CURVES FOR PYRIDINE, 4-T-BUTYL PYRIDINE, BENZOYL PYRIDINE, AND METHYL SULFOXIDE

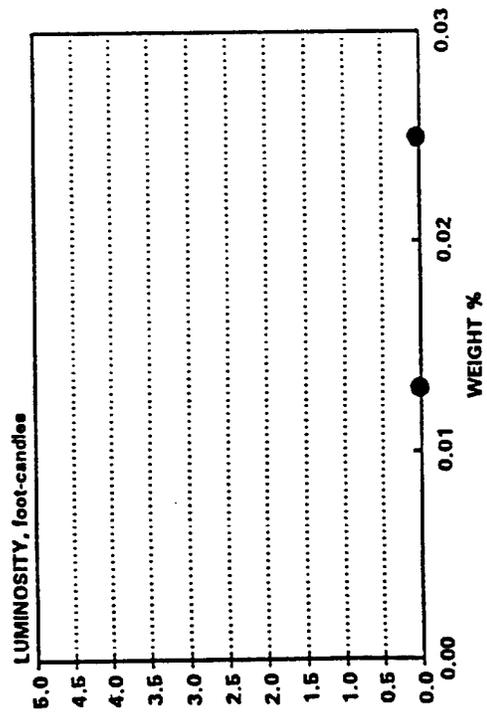
PYRIDINE



4-TERT-BUTYL PYRIDINE



BENZOYL PYRIDINE



METHYL SULFOXIDE

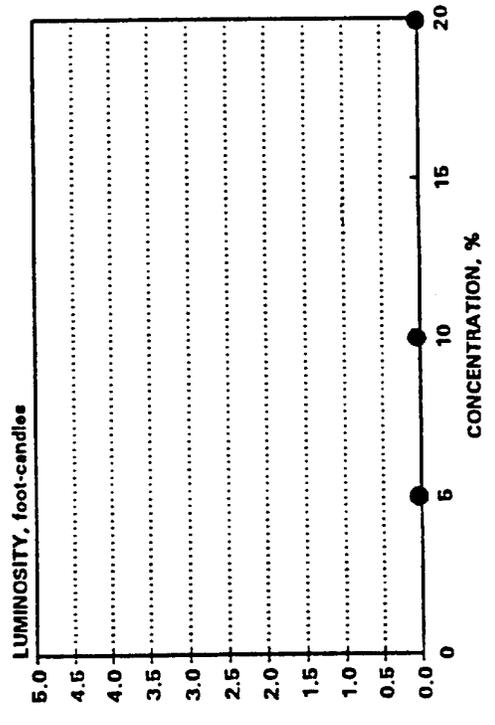
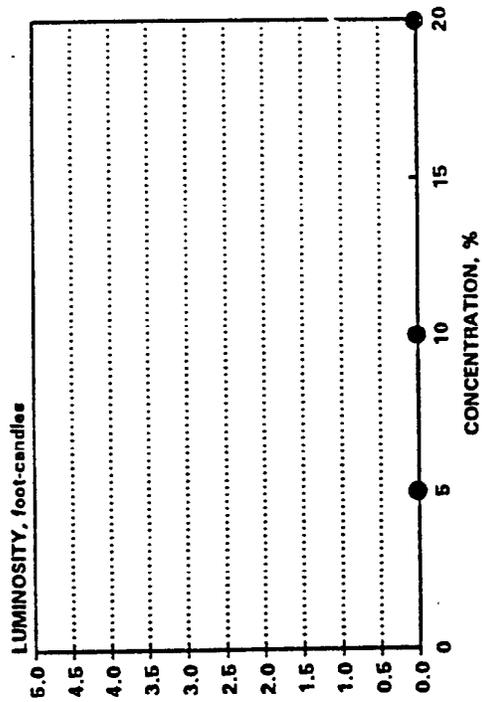
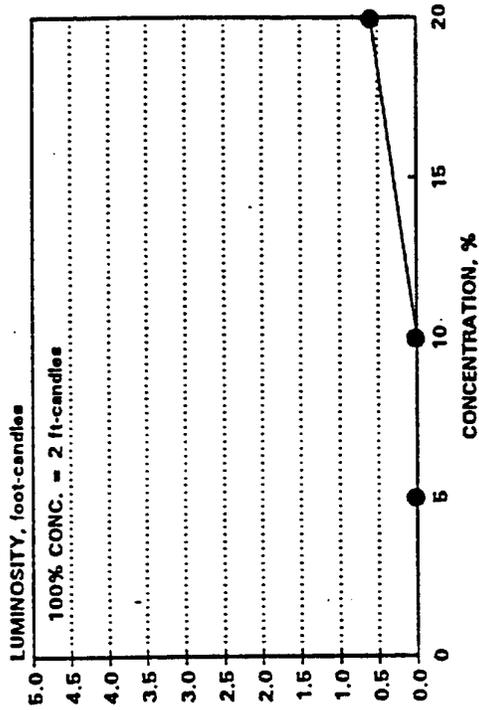


FIGURE A-30. LUMINOSITY CURVES FOR ANILINE, NITROBENZENE, FURFURYLAMINE, AND DICYCLOHEXYLAMINE

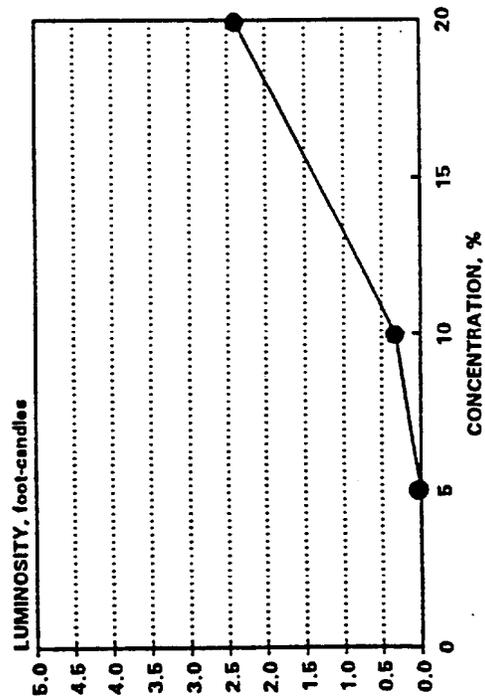
ANILINE



NITROBENZENE



FURFURYLAMINE



DICYCLOHEXYLAMINE

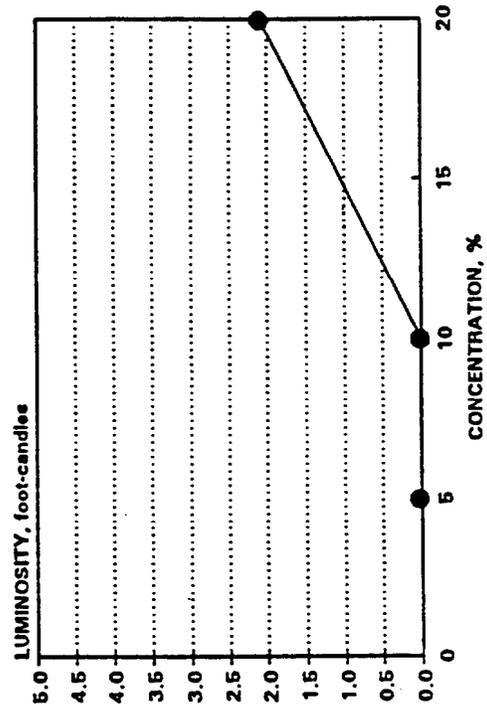
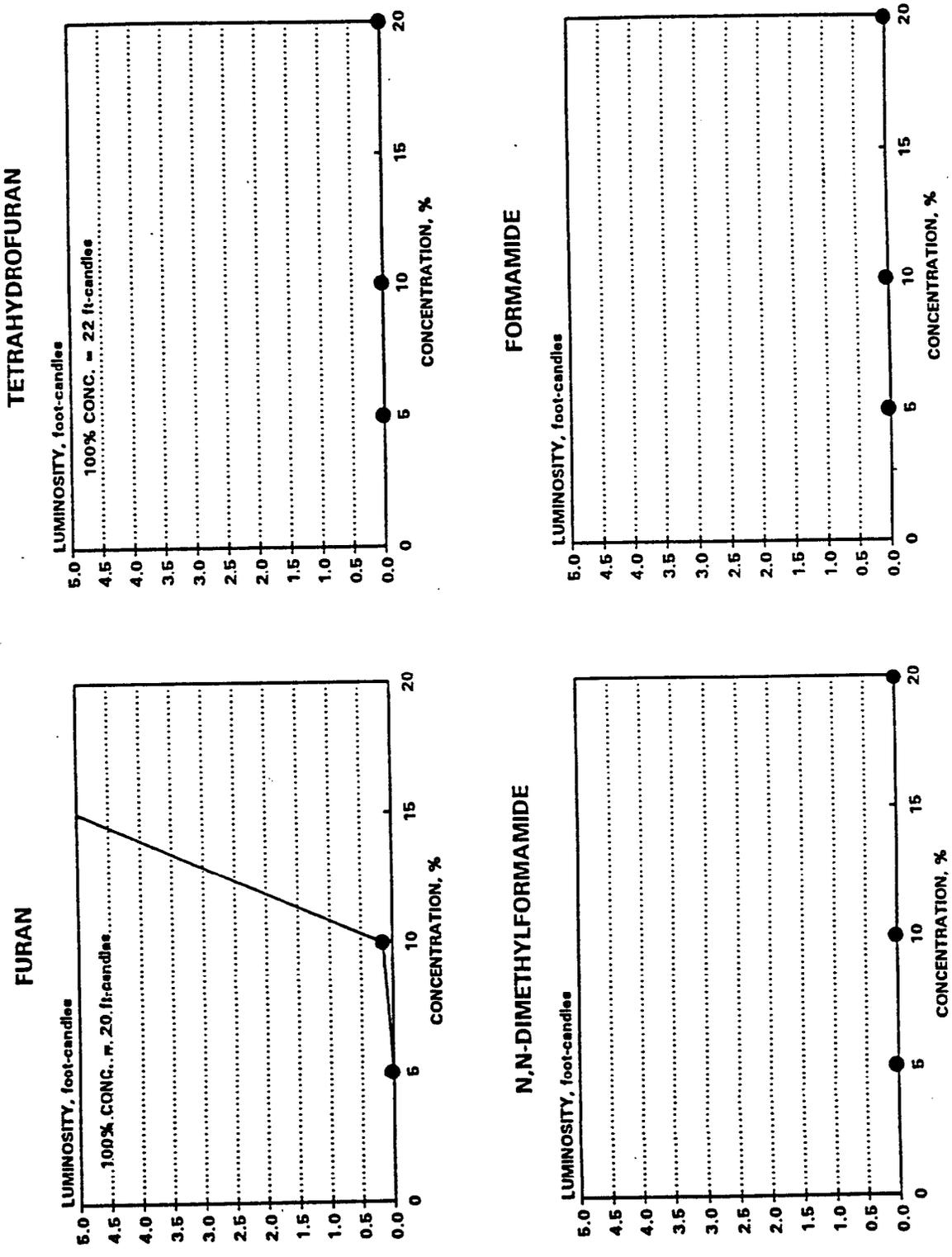
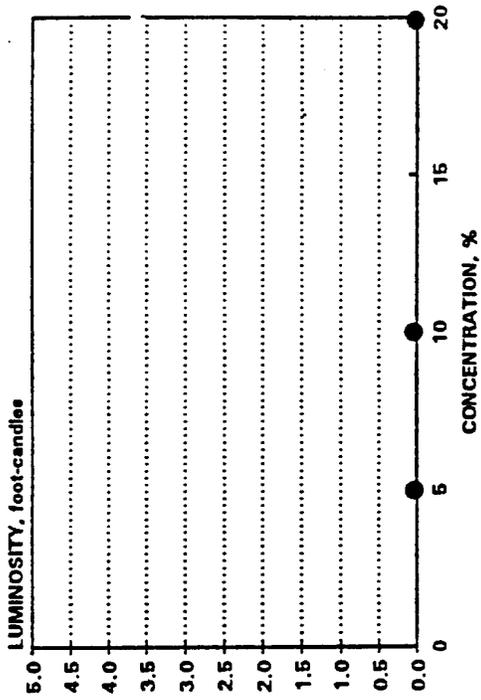


FIGURE A-31. LUMINOSITY CURVES FOR FURAN, TETRAHYDROFURAN, N,N-DIMETHYLFORMAMIDE, AND FORMAMIDE

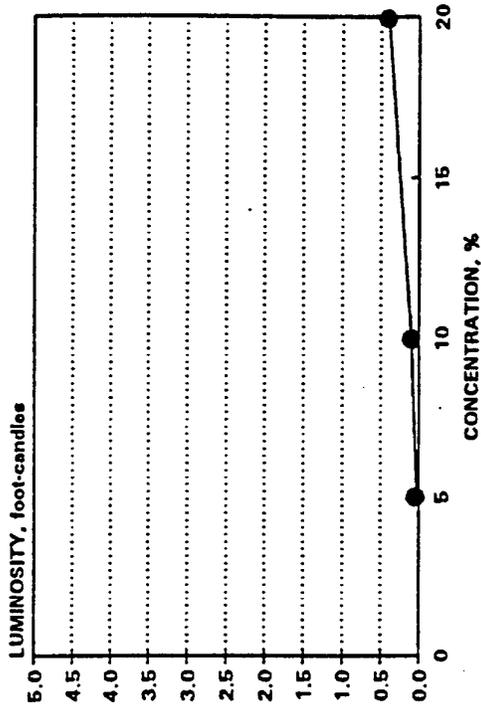


**FIGURE A-32. LUMINOSITY CURVES FOR DIMETHYLNAPHTHALENE,
TETRAHYDRONAPHTHALENE, DECAHYDRONAPHTHALENE, AND
1-METHYLNAPHTHALENE**

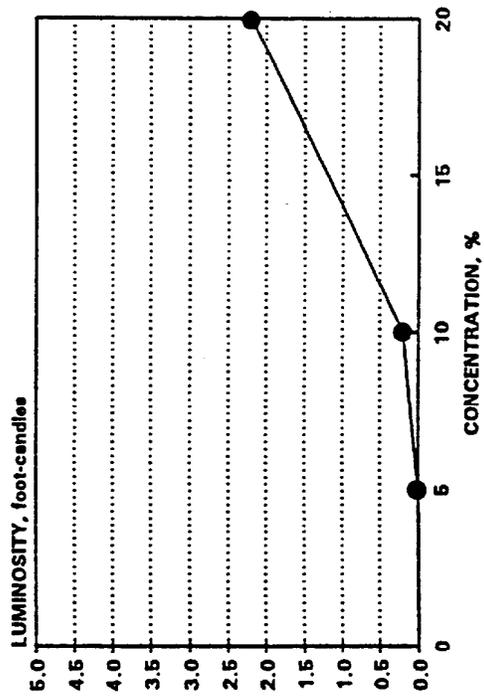
DIMETHYLNAPHTHALENE



TETRAHYDRONAPHTHALENE



DECAHYDRONAPHTHALENE



1-METHYLNAPHTHALENE

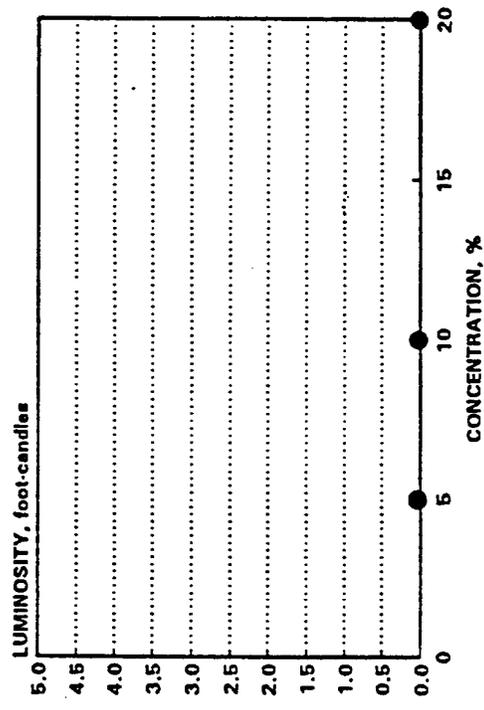
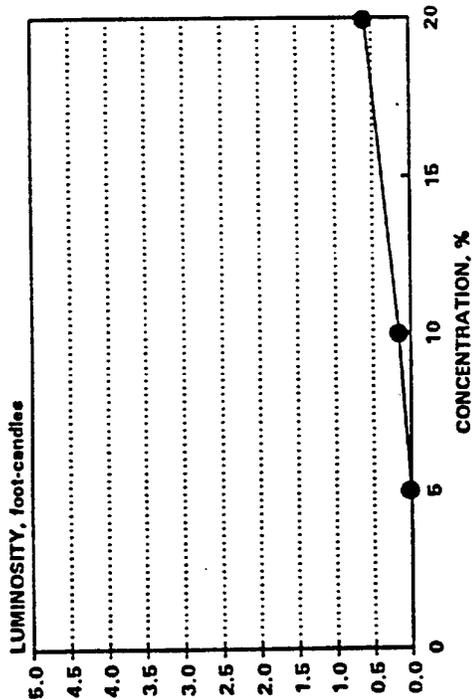
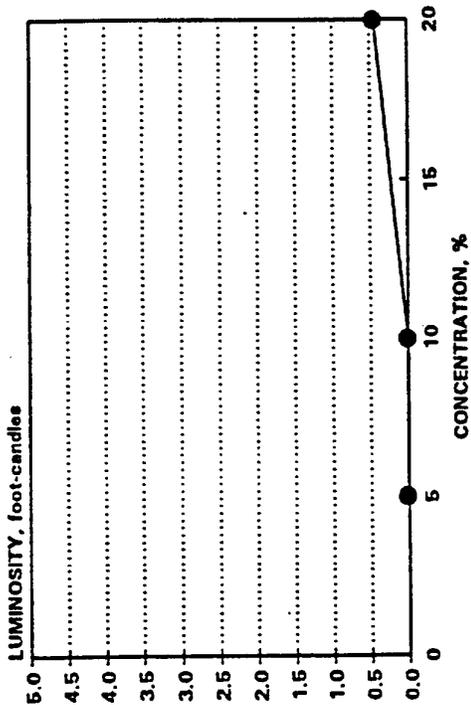


FIGURE A-33. LUMINOSITY CURVES FOR METHACRYLIC ACID, METHACRYLIC ANHYDRIDE, DIMETHOXYMETHANE, AND DIMETHOXYTetraethylene Glycol

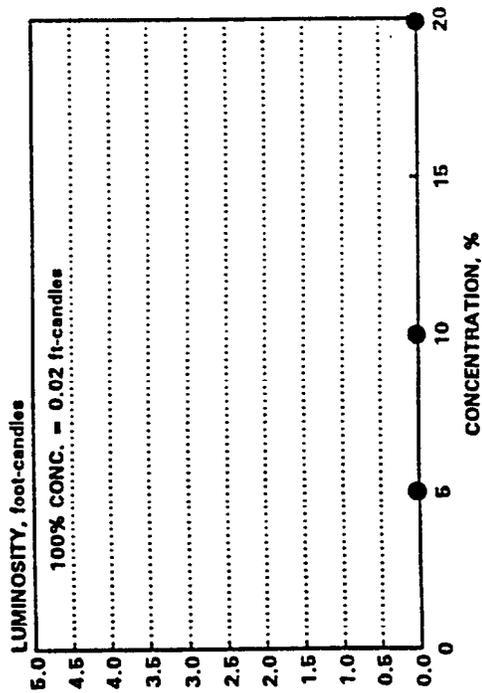
METHACRYLIC ACID



METHACRYLIC ANHYDRIDE



DIMETHOXYMETHANE



DIMETHOXYTetraethylene Glycol

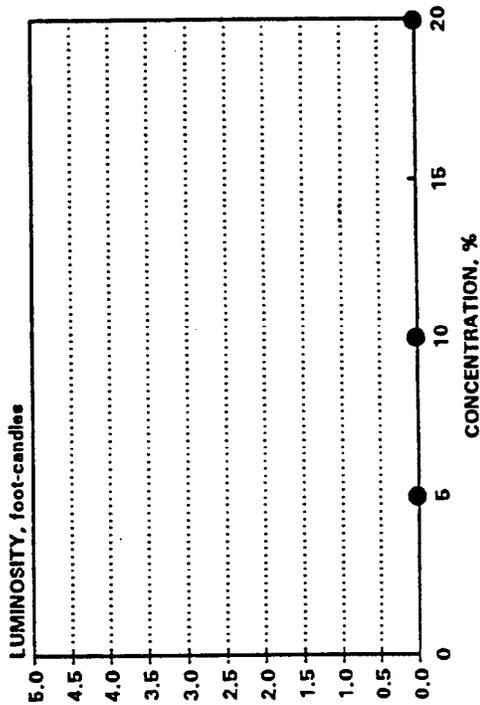
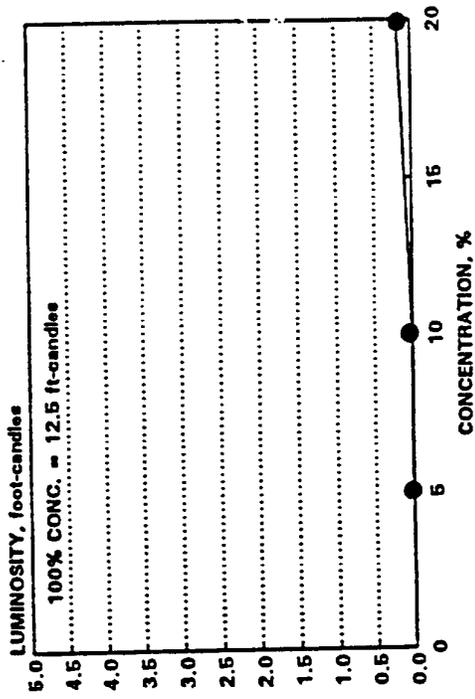
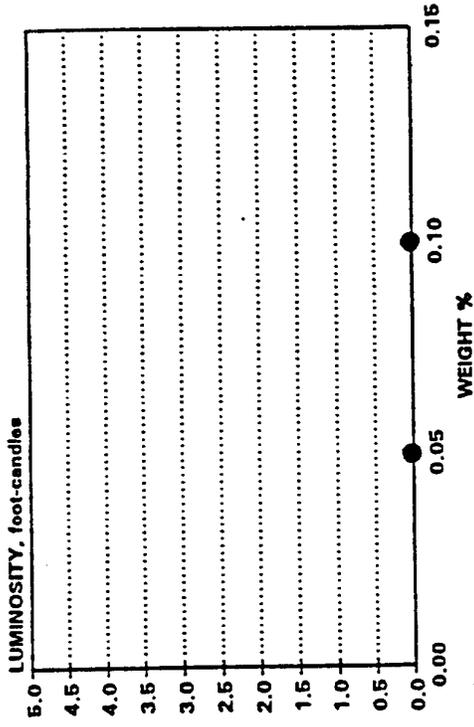


FIGURE A-34. LUMINOSITY CURVES FOR 2,4-PENTANEDIONE, BENZOPHENONE, 4-METHYLOCTANE, AND 1-PHENYL OCTANE

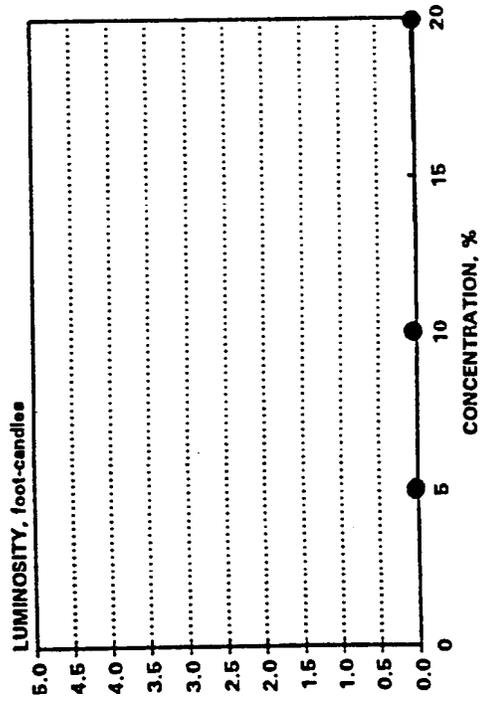
2,4-PENTANEDIONE



BENZOPHENONE



4-METHYLOCTANE



1-PHENYL OCTANE

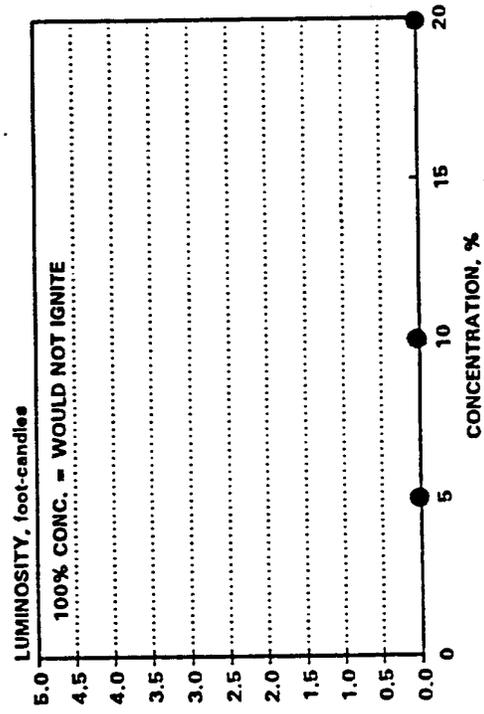
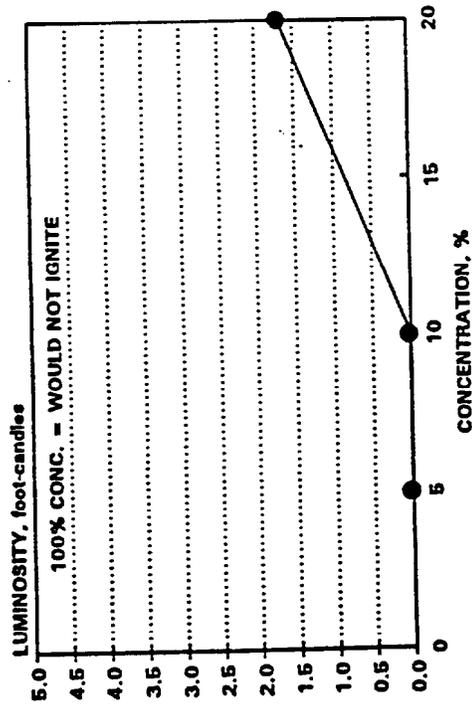
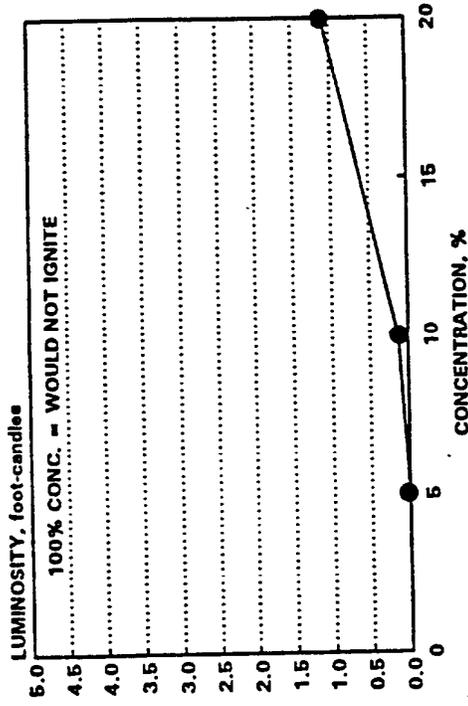


FIGURE A-35. LUMINOSITY CURVES FOR PHENOL, CYCLOHEXANOL, FERROCENE, AND ACETYLFERROCENE

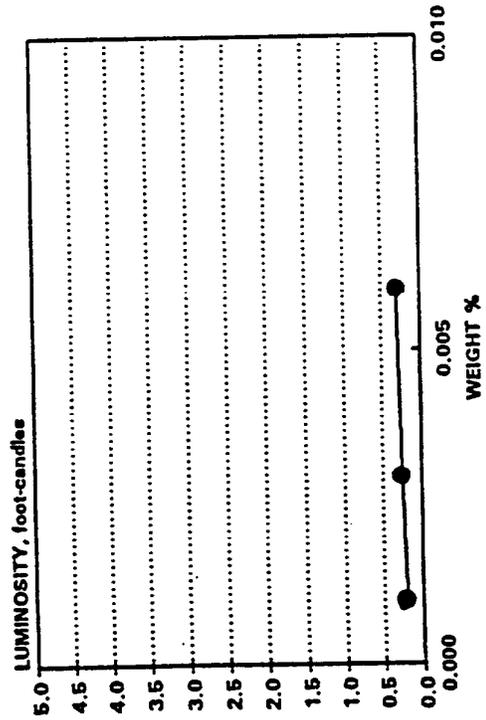
PHENOL



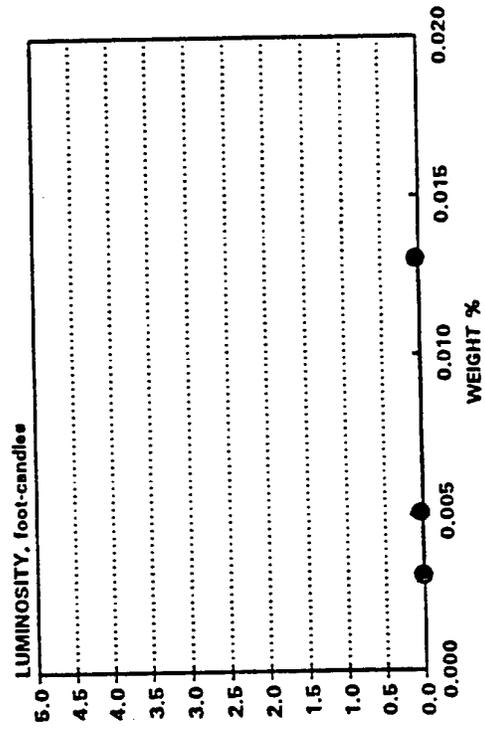
CYCLOHEXANOL



FERROCENE



ACETYLFERROCENE



IV. ADDITIVE COST SURVEY

A. Approach

In this portion of the study, the objective was to determine the cost of the three additives suggested for improving the flame luminosity of fuel methanol from the Task 1 Expansion, namely:

- Toluene
- Cyclopentene
- Indan.

The initial steps included reviewing chemical supplier publications and catalogs and making telephone inquiries for availability and price. Cyclopentene and indan appeared to be available in small, expensive quantities from chemical supply houses. No bulk prices were obtained by calling several chemical supply houses. Neither chemical is a commercial product available in bulk or as an intermediate material for the production of other chemicals.

Toluene is distributed widely in bulk quantities because of its use as an intermediate chemical for the production of solvents, explosives, isocyanates, and other chemicals as well as an octane booster in gasoline. Toluene is also used to make benzene by thermal dealkylation when the benzene price and demand are high. Prices for toluene as a commodity are reported in several publications. The cost for toluene was derived as a projection of the cost for the last year (January through December 1991).

The approach to develop costs for indan and cyclopentene required an estimate for the costs of making them from other starting materials because initial inquiries to major U.S. companies that produce coke and by-product chemicals from coal (possible sources of indan and cyclopentene) produced disappointing results. Those companies sold most of their by-products which contained indan and cyclopentene to other companies for internal use, and the quantities were not sufficient to supply the projected needs as a potential fuel additive.

Since no direct source of indan or cyclopentene was found, then an alternative was needed. Dicyclopentadiene (DCPD) was selected as a source of cyclopentene because DCPD is a dimer of cyclopentadiene (CPD) which could then be converted into cyclopentene. Similarly, indene is an unsaturated homolog which could be converted to indan. Both materials are included in the by-product mixtures from the high temperature carbonization (coking) of coal. The problem was to find a supplier who separates and purifies DCPD and indene. These raw materials would then be processed to saturate one olefinic bond by hydrotreating at relatively mild conditions, thus producing the desired compounds.

A library reference book indicated that large quantities of DCPD were available in the U.S. from steam cracking of hydrocarbons to make ethylene and propylene.⁽⁷⁰⁾ In addition, the quantities of DCPD from these sources were several times the amount available from coal, and a purity of over 95 percent was possible. Other starting materials were considered such as furan or thiophene for cyclopentene and benzothiophene for indan. However, these considerations were dropped because the oxygen or sulfur in the five-member rings would require processing conditions with higher severity to remove the heteroatoms. More severe conditions would result in increased costs and the possibility of more unwanted side reactions.

Indene is present in the same pyrolysis liquids from hydrocarbon cracking as DCPD; however, it is not easily separated from other compounds with similar boiling points in the mixture. One commercial product was found with 16 percent indene and 25 percent methyl and dimethyl indenenes. Review of the literature produced information that indene was used in making resins for adhesives, coatings, printing inks, and paints.⁽⁷¹⁾ Indene has since been replaced as a resin starting material by mixtures of C₈, C₉, and C₁₀ aromatics and diolefins. An indene supplier was finally found who imports 90 percent indene from Germany; the volume may not be sufficient for long-term requirements.

Table 26 lists the weights and volumes of cyclopentene and indan needed for methanol fuel based on the projected demands for methanol fuel. The base methanol volume of 10 million gallons per year is the amount expected in 1993 to provide fuel for bus and truck fleets.⁽⁷²⁾ Tenfold increases to 100 million gallons per year and again to 1 billion gallons per year are expected to occur in the following decade.

TABLE 26. PROJECTED ADDITIVE VOLUMES

Projected Demand for Methanol Fuel, Gal/Yr	Units	Toluene at 4 Vol %	Cyclopentene at 5 Vol %	Indan at 2 Vol %	Indan at 5 Vol %
10 Million	Pounds/year	2.9×10^6	3.2×10^6	1.6×10^6	4.0×10^6
	Gallons/Day	1,100	1,370	548	1,370
	Barrels/Day	25.7	32.6	12.9	32.6
100 Million	Pounds/Year	29×10^6	32×10^6	16×10^6	40×10^6
	Gallons/Day	11,000	13,700	5480	13,700
	Barrels/Day	257	326	129	326
1 Billion	Pounds/Year	290×10^6	324×10^6	161×10^6	403×10^6
	Gallons/Day	109,600	137,000	54,800	137,000
	Barrels/Day	2570	3,260	1,290	3,260

Three units of measurement were used in Table 26 for additive volumes for the following reasons. The petrochemical industry is familiar with millions of pounds per year, and those quantities were defined to facilitate inquiries to suppliers. Gallons per day units are useful for visualizing the number of tank cars (at 30,000 gal) or tank trucks (at 6,000 to 8,000 gal) required to transport feedstocks or products. Barrels per day are used for defining refinery processing capacity.

The highest volume of 3,260 barrels per day for cyclopentene or indan in Table 26 would require a relatively small process unit. Allowing 15 days downtime per year, or 96 percent on-stream efficiency, would increase the capacity to 3,400 barrels of product per stream day (B/SD). This size plant was selected for evaluation because it would provide the most economical product in cost per gallon. Production of the smaller volumes could be done by custom refining (also called toll processing) in existing facilities on a part-time operation as a possible solution to making the initial and possibly the intermediate volumes.

The distribution of products for the discussion below was assumed to be by bulk shipment in tank trucks. The destinations would be terminals where the additives would be blended into methanol or fleet operations with bulk storage to do the same thing. The third possibility would be to put a small, metered volume of additives into a tank truck before it went to a source of M100 for splash blending. The truck loading racks would be automated with card access and controls to permit driver loading.

B. Toluene

Spot prices for unleaded regular gasoline in Los Angeles and for toluene nationwide were tabulated from a weekly newsletter market report for all of 1991.⁽⁷³⁾ Trends of prices with time are shown in Figure 16. The peak prices of both products occurred at about the same time, but there was a slight downward trend for gasoline that was not as apparent for toluene.

A linear regression of the data is shown in Figure 17. The equation for the line is:

$$T = 0.7646UR + 0.4378$$

Where: T = Toluene price in \$/gal, and

UR = Unleaded regular price in \$/gal.

The correlation coefficient, R, of 0.6666 is relatively low as indicated by the scatter shown in the plot. The R-squared value, 0.4444, implies that about 44 percent of the variation in toluene price is accounted for by the unleaded regular price. This result is reasonably good considering:

- Gasoline prices were for Los Angeles
- Toluene prices were national
- Toluene price is affected by other uses in chemical markets.

Figure 18 presents the most direct representation of the 48 data points with a frequency distribution of toluene spot prices. The arithmetic average was \$0.901 per gallon, and the median value of \$0.905 per gallon was exceeded by half of the data points. The middle 50 percent of the sample fell in the range of \$0.870 to \$0.945 per gallon. A price of \$0.90 per gallon will be used in estimating the additive costs for toluene.

C. Cyclopentene Production

DCPD is available from petrochemical plants on the Gulf Coast which can meet the maximum quantities listed above. Three grades of DCPD are available for potential feedstocks to make cyclopentene. Analyses were provided of typical production and were used to estimate purity of the final product, as follows:

<u>Grade</u>	<u>DCPD/CPD In feed, Wt%</u>	<u>Cyclopentene In Product, Wt%</u>
DCPD 97	97.0	98.0
Polyester Resin	82.0	91.3
Hydrocarbon Resin	76.8	88.0

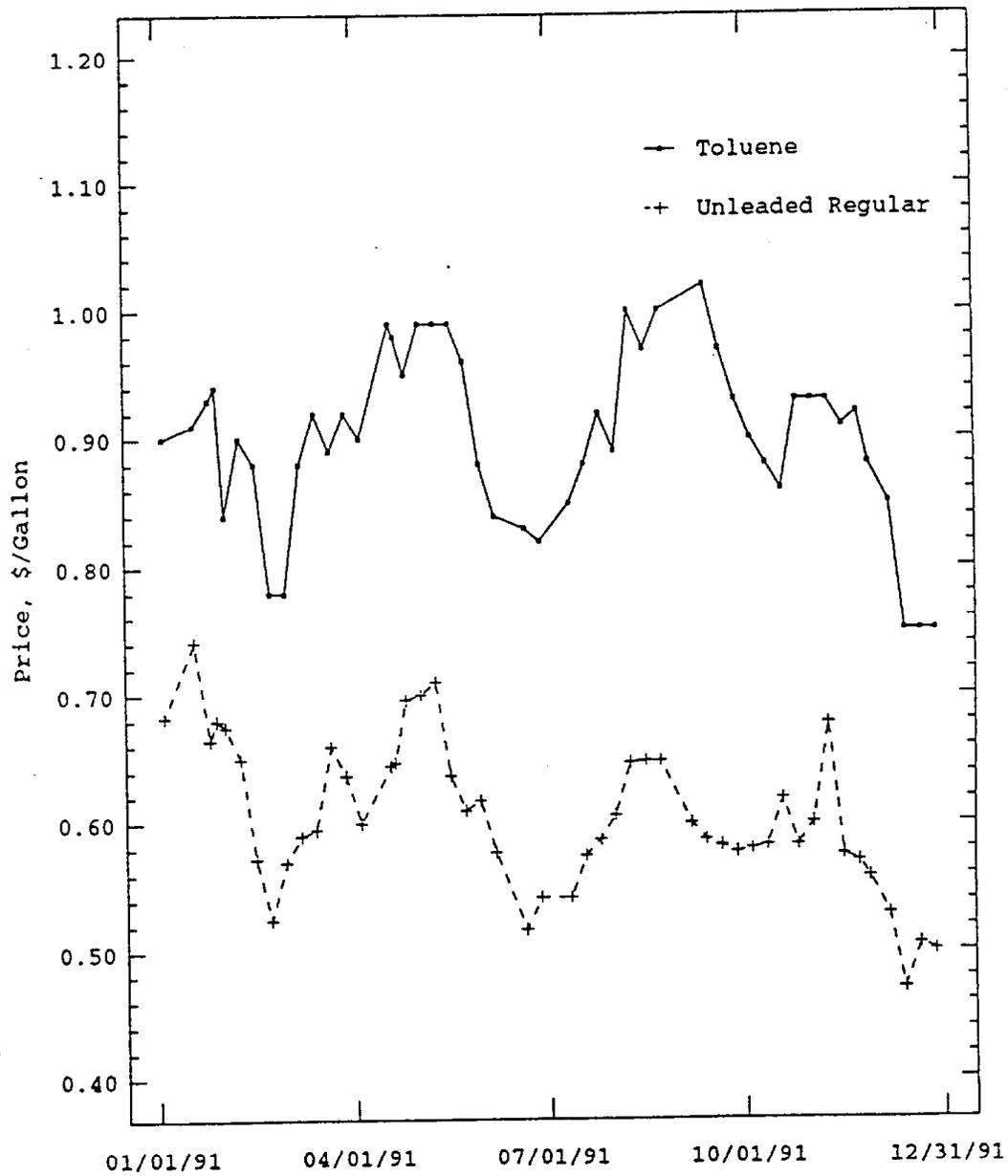


FIGURE 16. TRENDS OF TOLUENE AND UNLEADED REGULAR SPOT PRICES

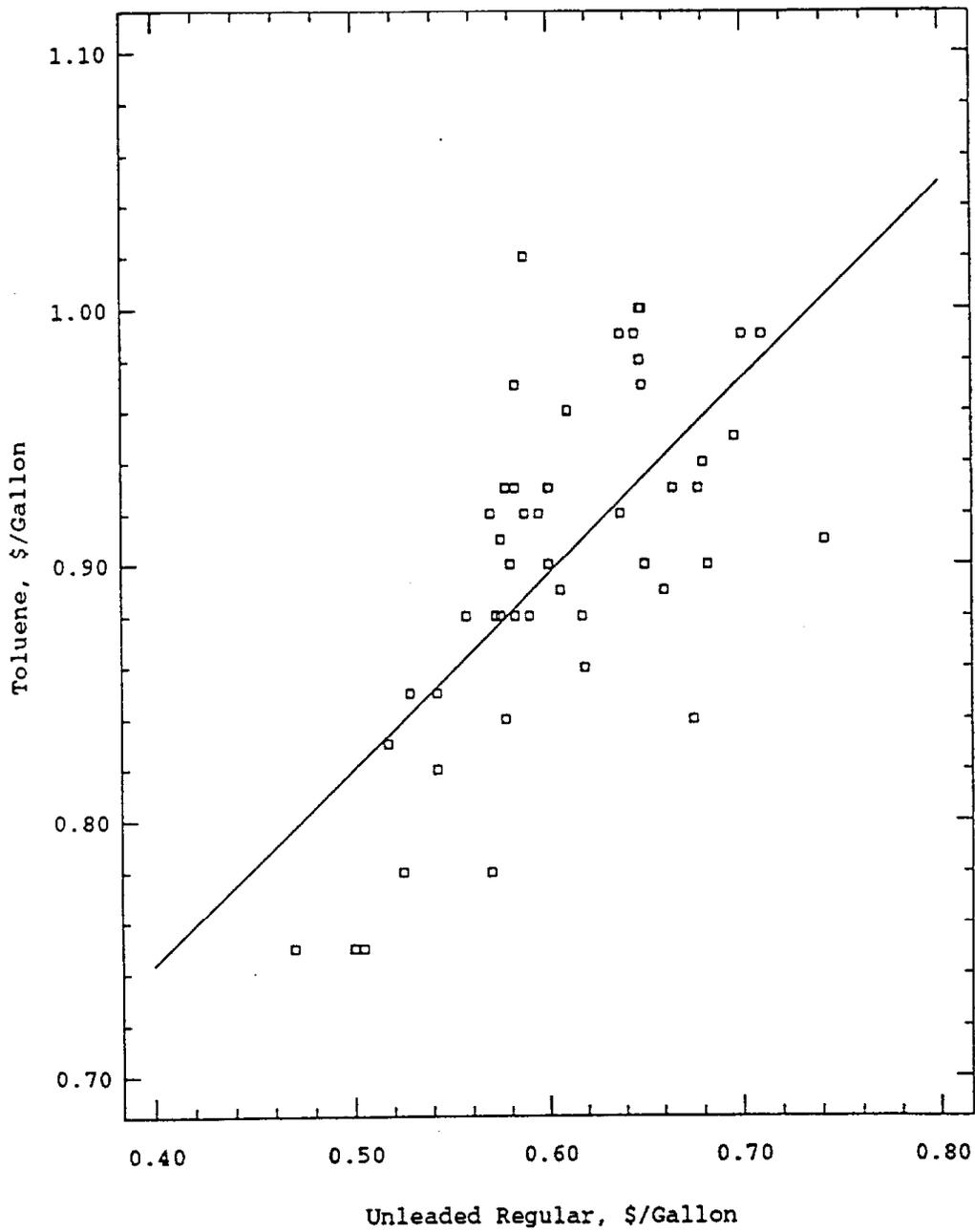


FIGURE 17. COMPARISON OF TOLUENE AND UNLEADED REGULAR SPOT PRICES - 1991

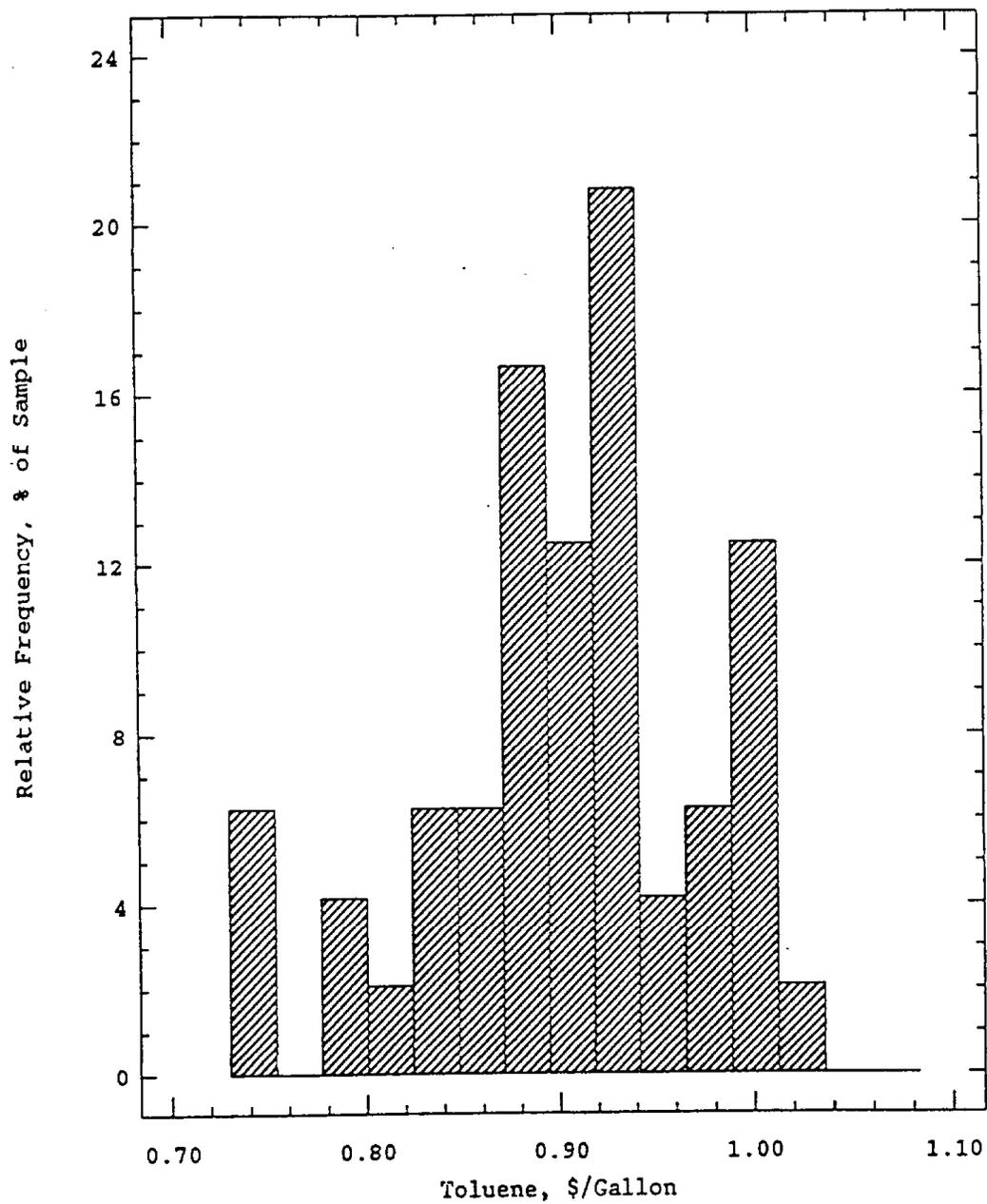


FIGURE 18. TOLUENE SPOT PRICE VARIATION FOR 1991

The product purity increased over the feed because unreactive heavy compounds were discarded to fuel with unconverted DCPD in the DCPD cracking unit. An assumption was made that C₁₀ co-dimers were 50 percent cyclopentadiene which would dissociate and be converted to product. These lower purity grades were included in the economic analysis in Section IV. F. along with the 97 percent purity feedstock. Current prices for the different feedstocks vary with purity and are listed in Table 27.

TABLE 27. CURRENT PRICES FOR DICYCLOPENTADIENE

Purity, wt %	Price Delivered to Southern California		
	Cents/Pound*	Pounds/gal	Dollars/gal
97	35	8.17	2.86
80-85	19-21	8.03	1.53-1.69
70-75	17-18	7.98	1.36-1.44

*includes transportation costs in tank cars from Gulf Coast at 3 cents/lb

The process scheme for converting DCPD to cyclopentene is shown in Figure 19, with a material balance based on actual properties of the 97 percent purity DCPD and a few assumptions of purity of other streams. The DCPD dimer would be received from tank cars and transferred to the DCPD cracking unit where the feed would be converted to essentially pure CPD monomer. A small portion of the DCPD is discarded in fuel oil to avoid high concentration of peroxides. The CPD monomer is then processed in a partial hydrogenation unit to saturate one of its two olefin bonds. A catalyst supplier verified that this hydrogenation step is feasible with a selective palladium catalyst, and provided operating conditions and catalyst cost.⁽⁷⁴⁾

It was assumed that the conversion plant would be located in or immediately adjacent to a refinery to provide access to a source of hydrogen, utilities, and other refinery support systems such as fire protection and administrative functions. The plant would consist of the processing equipment plus facilities for storage and handling of feedstock and product.

Published information on refinery construction plans was reviewed to provide a basis for estimating investment cost for the hydrotreater section. The data for nine hydrotreaters with a wide range of capacities are listed in Table 28.⁽⁷⁵⁾ These process units are located in different areas of the country, and the variation of costs for plants of similar capacity may indicate differences in processing severity or construction standards.

A regression of the data in Table 28 resulted in the following relationship:

$$\text{Ln}(\text{Cost}) = 2.025 + (5.023 \times 10^{-5}) \text{ Capacity}$$

or

$$\text{Cost} = e^{(2.025 + 5.023 \times 10^{-5} \times \text{Capacity})}$$

A plot of the regression line is shown in Figure 20 with dashed lines for the 95 percent confidence limits. The correlation coefficient is 0.9479, and the R-squared value of 0.8986 indicates that almost 90 percent of the variation in Ln(Cost) is explained by the relationship with capacity. Using the equation with the planned capacity of 3,172 barrels of DCPD per stream day gives an investment cost for the hydrotreater section of \$8.9 million.

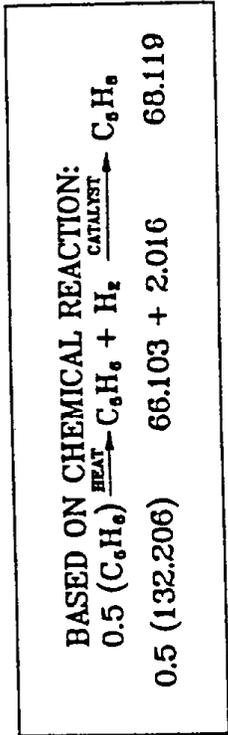
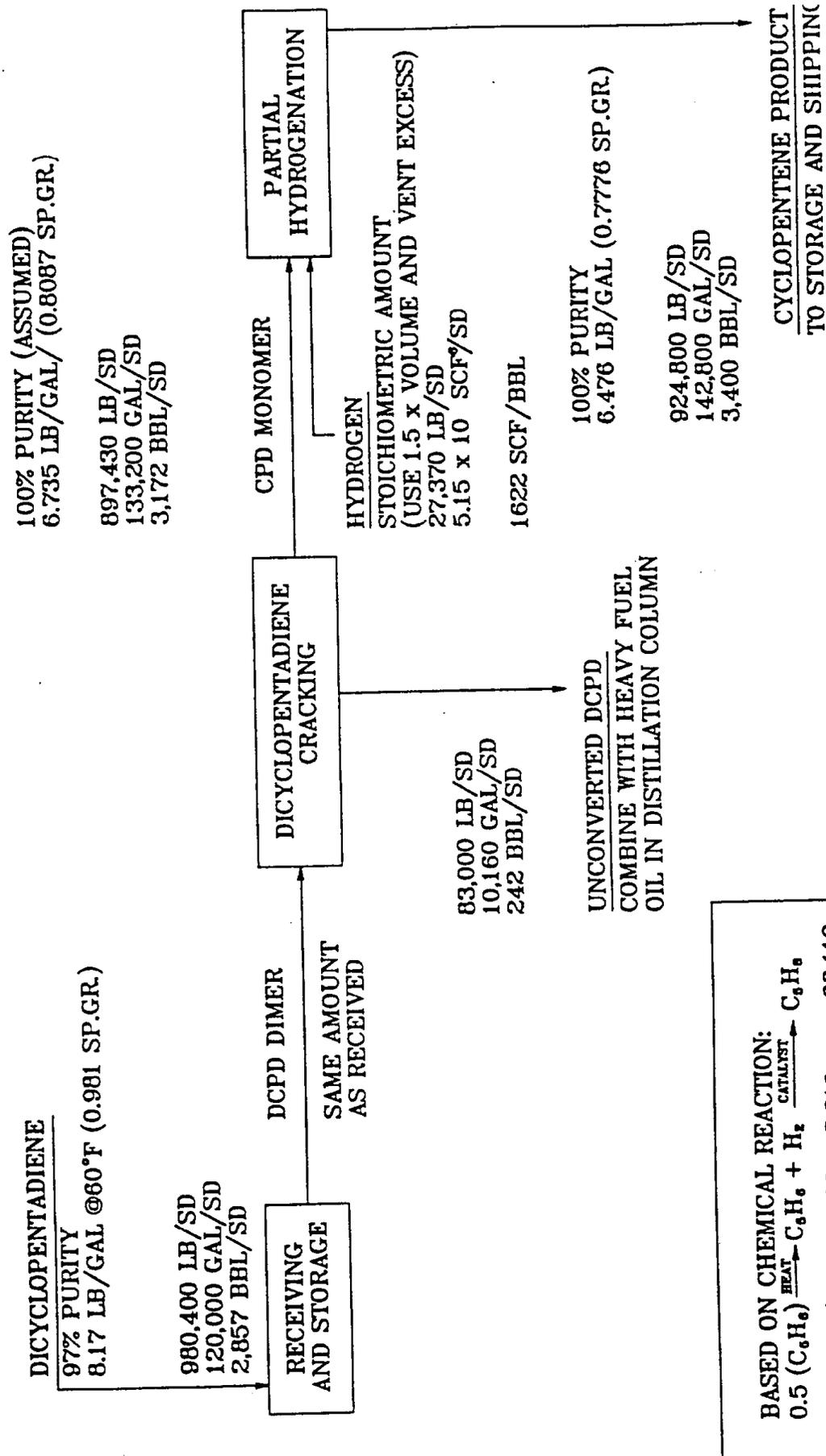


FIGURE 19. PROCESS SCHEME AND MATERIAL BALANCE FOR CONVERSION OF DICYCLOPENTADIENE TO CYCLOPENTENE

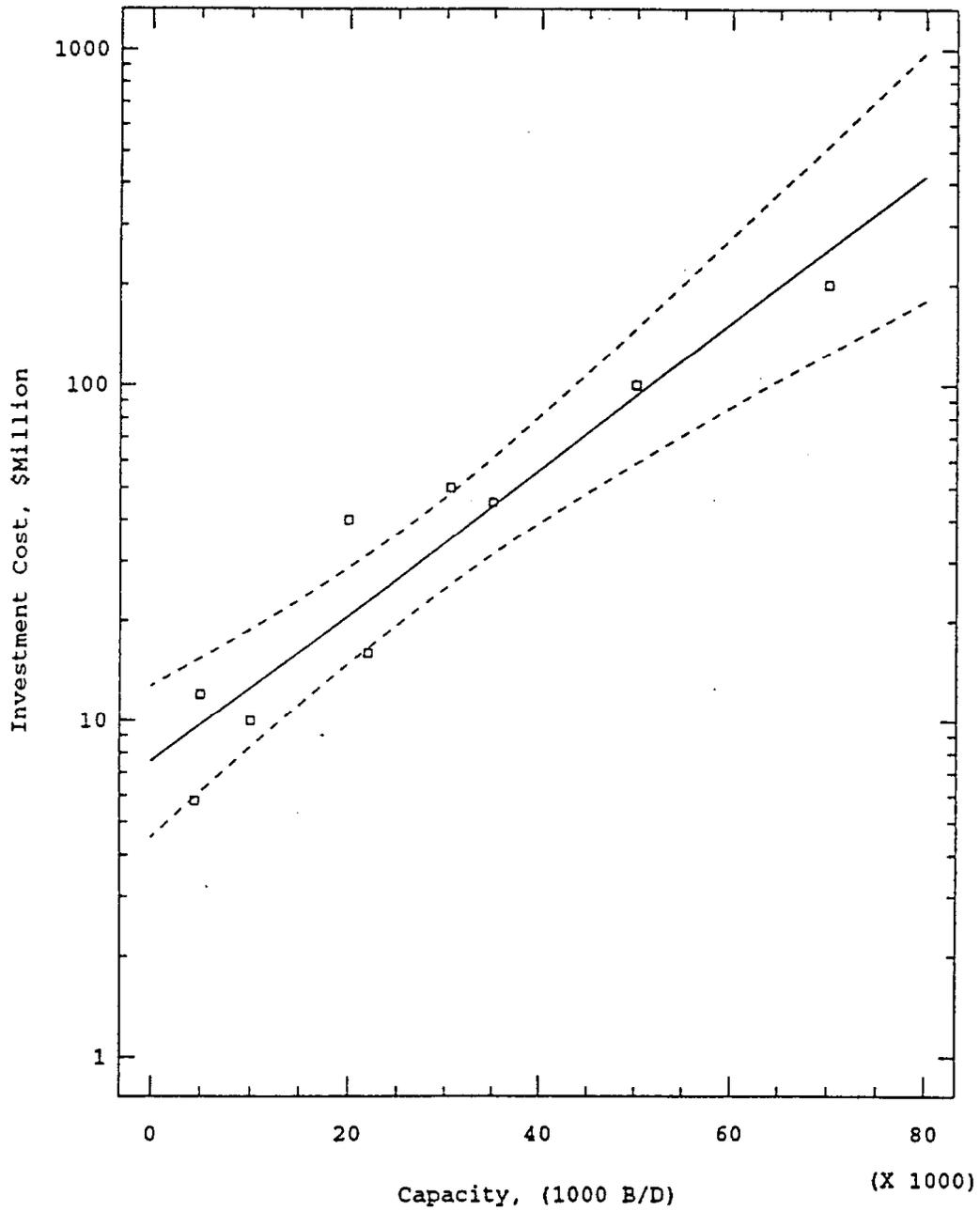


FIGURE 20. HYDROTREATER INVESTMENT COST VS. CAPACITY

TABLE 28. HYDROTREATER INVESTMENT COSTS

Hydrotreater Capacity, barrels per day	Investment Cost, \$ million
4,400	5.8
5,000	12.0
10,000	10.0
20,000	40.0
22,000	16.0
30,500	50.0
35,000	45.0
50,000	100.0
70,000	200.0

Investment costs for the total plant to convert DCPD to cyclopentene are given in Table 29. The DCPD cracking section is a relatively simple fractionation column with an overhead and a bottoms product estimated to cost \$1 million. Off-site facilities were taken as 30 percent of the processing equipment cost. Catalyst cost was added in two increments: the aluminum oxide base which can be depreciated and the palladium metal content which is ultimately recoverable at the end of the project life.

In order to develop operating costs, the material balance was expanded to a heat and material balance. Process design calculations were made in enough detail to estimate utility requirements.⁽⁷⁶⁾ Major equipment items are shown in the process flow diagram (See Figure 21).

Conversion of DCPD dimer to the CPD monomer is done by thermal dissociation or cracking. The operating conditions require high pressure (HP) steam, 565 psig superheated to 650°F, to obtain 480°F at the bottom of the column and to provide the heat of reaction of 1,205 BTU per pound.⁽⁷⁰⁾ The CPD monomer distilled overhead is condensed at 100°F and then chilled to 30°F to reduce the rate of dimerization which occurs spontaneously at ambient temperature.⁽⁷⁷⁾

In the hydrogenation section, the reactor temperature was controlled by generating low pressure (LP) steam, 52 psig saturated at 300°F, to absorb the heat of reaction estimated to be 608 BTU per pound of CPD monomer. The cyclopentene product was separated from the excess hydrogen and sent to a stripper column to remove dissolved hydrogen and any hydrocarbons lighter than cyclopentene. All other heating services were done with medium pressure (MP) steam, 235 psig saturated at 400°F. Cooling water was assumed to be available at 70°F as needed for coolers and condensers. The 3,400 B/SD cyclopentane product was sent to storage at 100°F. Its boiling point of 111-112°F made it advisable to provide low pressure spherical storage tanks to reduce vapor losses and to protect against overpressure on warm days. Utility costs were derived from published data and were shown in Table 30.

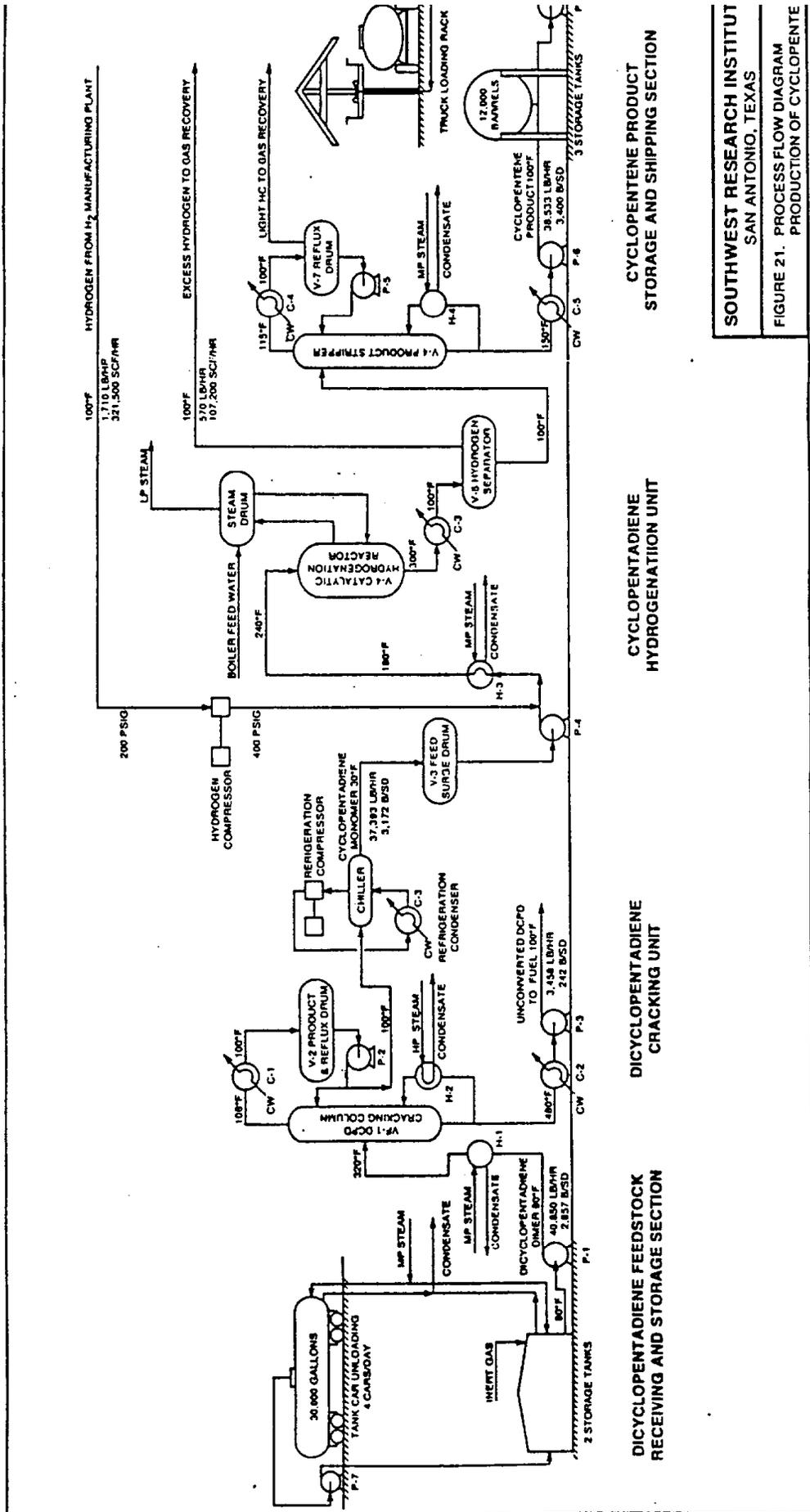
Operating expenses anticipated for cyclopentene production are listed in Table 31. Two operators and a product handler were planned at the hourly rates shown plus percentage allowances for benefits and supervision.⁽⁸²⁾ The 10 percent of facilities cost for maintenance and 3 percent for taxes and insurance are customary factors for this type of estimate.⁽⁷⁹⁾ Utilities and hydrogen costs plus fuel credit for excess

TABLE 29. CYCLOPENTENE UNIT INVESTMENT COST

Dicyclopentadiene Cracking Unit	\$1,000,000
Cyclopentadiene Hydrogenation Unit	<u>8,900,000</u>
Processing Facilities	\$9,900,000
Off-Sites, 30% of Processing Facilities	<u>2,970,000</u>
Total Facilities Cost	\$12,870,000
Catalyst, Depreciable Portion of Cost	<u>104,000</u>
Depreciable Investment	\$12,974,000
Metal Content of Catalyst (Recoverable)	<u>32,300</u>
Total Investment	\$13,006,300

OFF-SITE FACILITIES INCLUDE THE FOLLOWING MAJOR ITEMS:

1. Dicyclopentadiene Receiving and Storage
 - a. Unloading Rack, 8 railroad cars each side
 - b. Two cone roof tanks, 15,000 barrels each (approximately 10 days supply of feedstock)
2. Cyclopentene Product Shipping and Storage
 - a. Loading rack, 4 trucks total
 - b. Three spheres (low pressure), 12,000 barrels each (approximately 10 days production)
3. Connections to Utilities and Other Refinery Support Systems



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FIGURE 21. PROCESS FLOW DIAGRAM
PRODUCTION OF CYCLOPENTE

CYCLOPENTADIENE STORAGE AND SHIPPING SECTION

CYCLOPENTADIENE HYDROGENATION UNIT

DICYCLOPENTADIENE CRACKING UNIT

DICYCLOPENTADIENE FEEDSTOCK RECEIVING AND STORAGE SECTION

TABLE 31. CYCLOPENTENE UNIT OPERATING EXPENSES

<u>Operating Cost</u>	<u>Units</u>	<u>Unit Cost</u>	<u>Cost, \$/SD</u>	<u>Cost, \$/SD</u>
Operating Labor				
No. 1 Operator	24 hr	\$17/hr	408	
Boardman	24 hr	\$15/hr	360	
Shipping & Receiving	16 hr	\$12/hr	<u>192</u>	
Subtotal			960	
Supervision	20%		<u>192</u>	
Subtotal			1,152	
Benefits	30%		<u>346</u>	
Total Operating Labor				1,498
Maintenance	10% of Facilities Cost/Year*			3,677
Taxes & Insurance	3% of Facilities Cost/Year*			1,103
Utilities				
Steam	<u>lb/hr</u>	<u>\$/Mlb</u>		
HP Steam, 565 psig, 650°F	55,980	4.27	5,737	
MP Steam, 235 psig, Sat.	11,270	3.64	985	
LP Steam, 50 psig, Sat.	(24,980)	2.64	(1,583)	
Boiler Feed Water	24,980	0.31	<u>186</u>	
Sub-Total Steam			5,325	
Electric Power	720 Kw	\$0.06/Kwh	1,037	
Cooling Water Usage	13.7 MMBTU/hr	\$0.38/MMBTU	<u>124</u>	
Total Utilities				6,486
Excess DCPD to Fuel	(242 B/SD)	\$16.57/B		(4,010)
Hydrogen	<u>MSCF/hr</u>	<u>\$/MSCF</u>		
Hydrogen Supply	321.5	1.34	10,339	
Excess Hydrogen	(107.2)	0.72	<u>(1,852)</u>	
Net Hydrogen				8,487
Catalyst Consumption	\$104,000, 5-Year Life			<u>60</u>
Total Operating Cost, \$/SD				17,301
Annual Cost, 350 Days/Year				\$6,055,350
Annual Feedstock Cost, 97% Dicyclopentadiene				
\$2.86/gal × 120,000 gal/SD × 350 Days/Year =				\$120,120,000

*Facilities cost does not include cost of hydrogenation catalyst.

TABLE 30. UTILITY COSTS FROM PUBLISHED DATA

<u>UTILITY</u>	<u>COST, \$/UNIT</u>	<u>REFERENCE</u>
1. Steam		
High Pressure	4.27/Mlb	77
Medium Pressure	3.64/Mlb	77
Low Pressure	2.64/Mlb	77
Boiler Feed Water	0.31/Mlb	78
2. Electric Power	0.06/Kwh	79
3. Cooling Water	0.38/MMBTU	79
4. Plant Fuel	2.63/MMBTU	77
Barrel, Fuel Oil Equivalent (6.3 MMBTU)	16.57/BFOE	77
5. Hydrogen (NHV 274 BTU/SCF)		
Supply (1.86 × Fuel Value/BTU)	1.34/MSCF	80
Excess to Fuel (Fuel Value/BTU)	0.72/MSCF	80

DCPD were valued at unit costs from Table 30. Note that hourly rates need to be multiplied by 24 hours per day to obtain costs per stream day. Annual costs assume operating 350 stream days per year. Costs for the remaining days of the year are part of the maintenance budget. Operating costs and feedstock cost were annualized for use in economic calculations in Section IV. F.

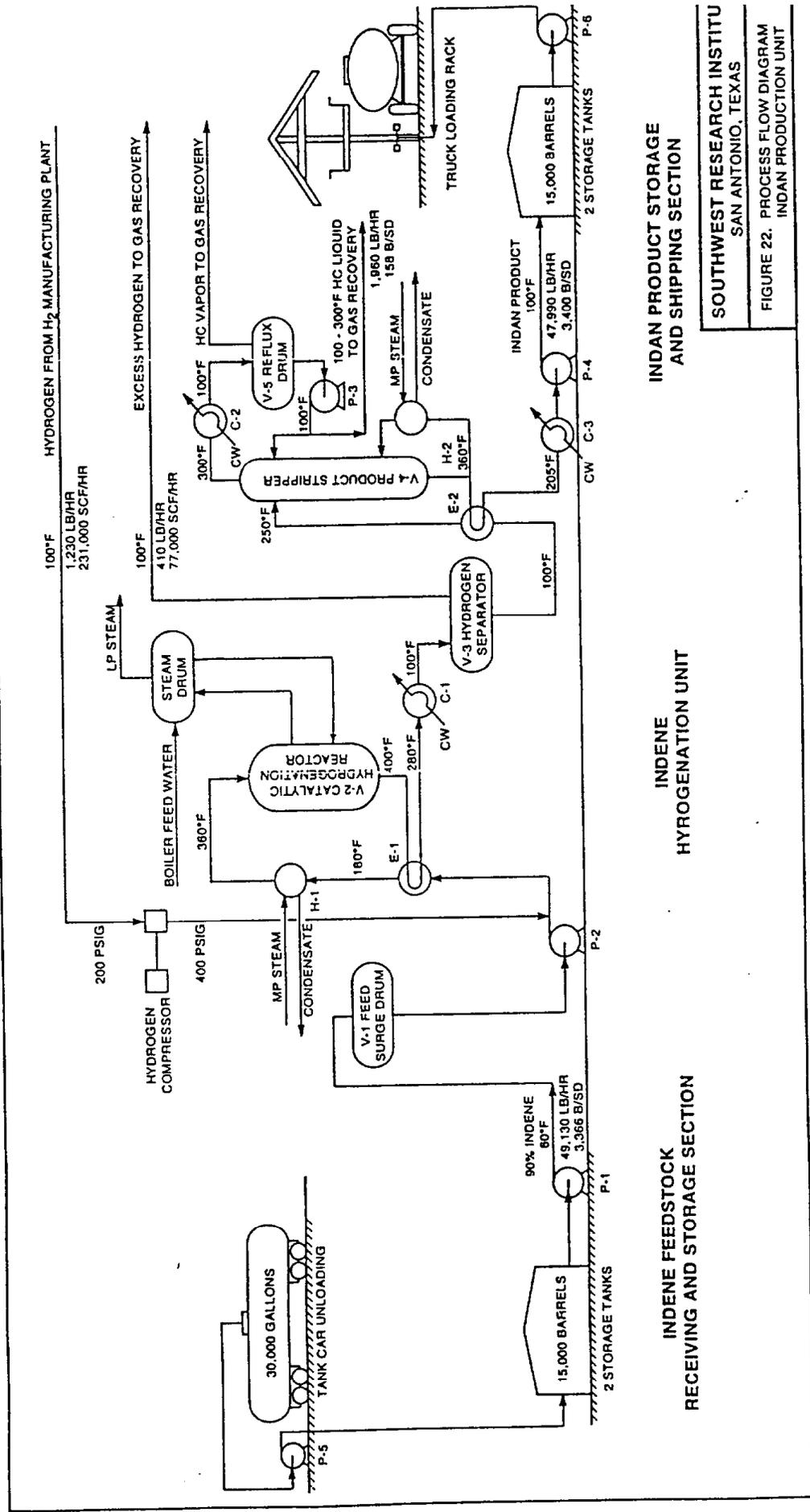
D. Indan Production

The starting material, indene, is available at 90 percent purity on the West Coast at a price of about \$2.00 per kilogram or \$0.9074 per pound. At \$0.9074 per pound and 8.340 pounds/gal,⁽⁸³⁾ indene cost would be \$7.57 per gallon.

The indene is imported from Germany, where it is recovered from liquids produced in coking of coal. The supply should be sufficient for the initial need of 4 million pounds of indene per year, but it is questionable whether the future growth to 10 times and 100 times that amount could be supplied. A domestic supplier or manufacturer has not been located in the course of this study. There is the possibility that a supplier will be found with further effort, or that an assured demand would stimulate increased production.

The process scheme would be similar to that for cyclopentene, to saturate an olefin bond with hydrogen. As with cyclopentene, processing would include hydrogenation, however, a cracking step would not be necessary. Investment costs are listed in Table 32. The 30 percent factor for off-site facilities is directionally correct because indan storage may use cone or floating roof tanks which cost less than low pressure spheres for cyclopentene.

The process flow diagram in Figure 22 shows the major equipment in the feedstock receiving, hydrogenation, and product shipping sections with flow rates and temperatures of all streams. All heating is done with medium pressure (MP) steam. The heat of reaction of 421 BTU per pound of indene for partial hydrogenation produces low pressure (LP) steam. After separating hydrogen from the hydrogenated product, the distillation column removes about 4 volume percent hydrocarbons with boiling points lower than indan. The indan product is estimated to be about 96 percent purity.



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FIGURE 22. INDAN PRODUCTION UNIT

TABLE 32. INDAN UNIT INVESTMENT COST

Indene Hydrogenation Unit	\$8,900,000
Off-Sites, 30% of Processing Facilities	<u>2,670,000</u>
Total Facilities Cost	\$11,570,000
Catalyst, Depreciable Portion of Cost	<u>104,000</u>
Depreciable Investment	\$11,674,000
Metal Content of Catalyst (Recoverable)	<u>32,300</u>
Total Investment	\$11,706,300

OFF-SITE FACILITIES INCLUDE THE FOLLOWING MAJOR ITEMS:

1. Indene receiving and storage
 - a. Unloading rack, 8 railroad cars each side
 - b. Two cone roof tanks, 15,000 barrels each (approximately 10 days supply of feedstock)
2. Indan product shipping and storage
 - a. Loading rack, 4 trucks total
 - b. Two cone roof tanks, 15,000 barrels each (approximately 10 days production)
3. Connections to utilities and other refinery support systems

The heat and material balance calculations provided utility quantities. Operating expenses for the indan unit are summarized in Table 33. These costs are lower than those for cyclopentene production because of:

- Lower investment cost
- No HP steam
- Lower utilities and hydrogen consumption.

E. Combined Plant for Both Cyclopentene and Indan Production

Because the two additives may be used in combination, a combined plant was considered for production of cyclopentene and indan. The feedstocks would not be processed together but would be run separately in blocked operation because of differences in temperatures in the reactor and product stripper. Time blocks of 12 to 15 days would be used for each product. Capacity of the process equipment would be doubled because it would be used half the time for each product. Investment cost would not double,

TABLE 33. INDAN UNIT OPERATING EXPENSES

<u>Operating Cost</u>	<u>Units</u>	<u>Unit Cost</u>	<u>Cost, \$/SD</u>	<u>Cost, \$/SD</u>
Operating Labor				
No. 1 Operator	24 hr	\$17/hr	408	
Boardman	24 hr	\$15/hr	360	
Shipping & Receiving	16 hr	\$12/hr	<u>192</u>	
Subtotal			960	
Supervision	20%		<u>192</u>	
Subtotal			1,152	
Benefits	30%		<u>346</u>	
Total Operating Labor				1,498
Maintenance	10% of Facilities Cost/Year*			3,306
Taxes & Insurance	3% of Facilities Cost/Year*			992
Utilities				
Steam	<u>lb/hr</u>	<u>\$/Mlb</u>		
MP Steam, 235 psig, Sat.	8,920	4.27	914	
LP Steam, 50 psig, Sat.	(22,740)	2.64	(1,441)	
Boiler Feed Water	22,740)	0.31	<u>169</u>	
Sub-Total Steam			(358)	
Electric Power	578 Kw	\$0.06/Kwh	832	
Cooling Water Usage	7.3 MMBTU/hr	\$0.38/MMBTU	<u>67</u>	
Total Utilities				541
Light Hydrocarbons	(158B/D)	\$24.80/B		(3,918)
Hydrogen	<u>MSCF/hr</u>	<u>\$/MSCF</u>		
Hydrogen Supply	237.0	1.34	7,429	
Excess Hydrogen	(77.0)	0.72	(1,331)	
Net Hydrogen				6,098
Catalyst Cost	\$104,000, 5 Year Life			<u>60</u>
Total Operating Cost, \$/Day				8,577
Annual Cost, 350 Days/Year				\$3,001,950
Annual Feedstock Cost, 90% Indene				
\$7.57/gallon × 141,400 gallons/SD × 350 days/year =				\$374,639,300

*Facilities cost does not include catalyst.

but would increase approximately by the ratio of capacities to the 0.6 power.⁽⁸³⁾ For example, doubling the size of the hydrogenation unit would change the investment cost as follows:

$$\begin{aligned}
 \text{Investment} &= \left(\frac{6,800 \text{ B/SD}}{3,400 \text{ B/SD}} \right)^{0.6} \times \$8.9 \text{ million} \\
 &= 1.516 \times \$8.9 \text{ million} \\
 &= \$13.5 \text{ million}
 \end{aligned}$$

The storage capacity for feedstocks and products would be increased to provide at least 15 days volume for all liquids. This was done by increasing off-site allowance from 30 percent to 35 percent of the original investment cost for the separate units. Table 34 shows the elements of investment cost for the combined plant.

TABLE 34. COMBINED PLANT INVESTMENT COST

Hydrogenation Unit	\$13,500,000
DCPD Cracking Unit	1,500,000
Cyclopentene Unit Off-Sites @35% of \$9,900,000	3,465,000
Indan Unit Off-sites @35% of \$8,900,000	<u>3,115,000</u>
Total Facilities Cost	\$21,580,000
Catalyst, Depreciable Portion of Cost	<u>208,000</u>
Depreciable Investment	\$21,788,000
Metal Content of Catalyst (Recoverable)	<u>64,600</u>
Total Investment	\$21,852,600

Operating expenses are listed in Table 35. These values were derived from values for the separate plants given in Tables 31 and 33. Operating labor did not increase. Maintenance and taxes plus insurance were based on the new facilities cost. Other costs for making the two additives were doubled for stream day rates and the sum was multiplied by 175 stream days per year. The investment costs and operating expenses were applied in the economic evaluation to arrive at product prices, as discussed in the following section.

F. Economic Evaluation and Product Prices

To estimate the costs of cyclopentene and indan, the economics of operating the separate and combined plants were evaluated. This method is used in industry to determine if a potential investment will be profitable or to compare investment opportunities. The discounted cash flow (DCF) concept is

TABLE 35. COMBINED PLANT OPERATING EXPENSES

<u>OPERATING COST</u>	<u>\$/SD</u>	<u>\$/Year</u>
Maintenance	10% of Facilities Cost/Year*	2,158,000
Taxes & Insurance	3% of Facilities Cost/Year*	647,400
Cyclopentene Unit, 175 days/year		
Operating Labor	1,498	
Total Utilities	12,972	
Excess DCPD to Fuel	(8020)	
Net Hydrogen	16,974	
Catalyst Cost	120	
Subtotal, Cyclopentene Unit	23,544	4,120,200
Indan Unit, 175 Days/Year		
Operating Labor	1498	
Total Utilities	1082	
Light Hydrocarbons	(7,836)	
Net Hydrogen	12,196	
Catalyst Cost	<u>120</u>	
Subtotal, Indan Unit	7,060	<u>1,235,500</u>
Total Operating Cost		8,161,100
<u>FEEDSTOCK COST</u>		
Dicyclopentadiene, 97%	686,400	120,120,000
Indene, 90%	<u>2,140,796</u>	<u>374,639,300</u>
Total Feedstock Cost	2,827,196	494,759,300

*Facilities cost does not include cost of hydrogenation catalyst.

based on the fact that the present value of future income must be reduced by compound interest factors that decrease with longer time to receipt of the income.

The customary evaluation would use estimates of income, investment cost, and operating expenses to arrive at the expected DCF rate of return. In this evaluation, the DCF rate of return was defined and the estimated costs were used to define earnings and gross income to develop the sales price of the final products.

At least 15 percent rate of return would be needed to justify the investment if there was no risk at all, and 20 to 25 percent return would be more likely to attract the funds to build the unit.⁽⁷⁸⁾ Therefore, all three rates of return were used to determine the effect on price. Typical refinery units are depreciated over 13-year life. However, higher risk petrochemical plants are allowed to use 5-year life for depreciation which will increase cash flow and earnings in the first five years of operation. Both 13-year and 5-year life were used in the calculations. Economic calculations were based on the following factors affected by project life:

<u>Depreciation Life</u>	<u>13 Years</u>	<u>5 Years</u>
Depreciation Policy:		
Double Declining Balance	First 7 Years	First 3 Years
Straight Line	Last 6 Years	Last 2 Years

Common factors for both life periods were:

Income Tax, % of Net Income	
Federal	34.0
California	<u>9.3</u>
Total	43.3

Present Worth Factors: Continuous Income and Annual Compounding

An assumption was made that earnings would be constant over project life, i.e., no change in gross income, feedstock cost, or operating expenses. A spreadsheet program simplified the calculations using pre-calculated depreciation rates. Present worth factors for continuous income and annual compounding were provided in equation form.⁽⁸⁴⁾ The reliability of the computer program was verified by a manual calculation at each life period.

Since depreciation and present worth factors vary in each year, the effects of showing these factors over the project life would be a large tabulation. Table 36 illustrates the format of the calculations for all three plants in the first year of operation for 13-year life and 20 percent DCF return rate. The computer program solved for earnings listed in the upper part of the table which indicates the amount that must be earned after costs, and before taxes and depreciation, to return the investment amount on the top line. In this example, earnings were independent of feedstock and operating costs; those costs could be changed without affecting the DCF return calculations which involved only investment, depreciation, and income tax.

Feedstock and operating costs were used in this example to calculate product sales price. First, they were added to the earnings to obtain gross income from sales. This amount was moved to the sales price calculation in the lower part of Table 36 where it was divided by the product volume to obtain the sales price. The \$2.599 and \$7.623 per gallon prices for cyclopentene and indan, respectively, in the first two columns agreed with the computer results. In the combined plant, the computer produced an average

TABLE 36. EXAMPLE OF ANNUAL CASH FLOW AND PRODUCT PRICE CALCULATION

BASIS: FIRST YEAR OF OPERATION, 13-YEAR LIFE, 20% DCF RETURN

<u>Cash Flow Calculation</u>	<u>Algebraic Symbols</u>	<u>Cyclopentene Plant</u>	<u>Indan Plant</u>	<u>Combined Plant</u>
Depreciable Investment	I	12,974,000	11,674,000	21,788,000
Gross Income from Sales	G	129,881,545	380,976,083	509,144,431
Less Costs				
Feedstock Cost	F	120,120,000	374,639,300	494,759,300
Operating Expense	<u>O</u>	<u>6,055,350</u>	<u>3,001,950</u>	<u>8,161,100</u>
	F+O	126,175,350	377,641,250	502,920,400
Earnings	E	3,706,195	3,334,833	6,224,031
Less Depreciation, D = 0.0769	<u>DI</u>	<u>997,700</u>	<u>897,730</u>	<u>1,675,497</u>
Taxable Income	E-DI	2,708,495	2,437,103	4,548,534
Less Taxes, 43.3%	<u>0.433×(E-DI)</u>	<u>1,172,778</u>	<u>1,055,266</u>	<u>1,969,515</u>
Net Income	0.567×(E-DI)	1,535,717	1,381,837	2,579,019
Add Depreciation	<u>DI</u>	<u>997,700</u>	<u>897,730</u>	<u>1,675,497</u>
Cash Flow	0.567E+0.433DI	2,533,417	2,279,567	4,254,516
<u>Sales Price Calculation</u>				
Gross Income from Sales	G			509,144,431*
Cyclopentene		129,881,545		128,919,051
Indan			380,976,083	380,225,380
Sales Volume, Gallons/Yr	V			
Cyclopentene		49,980,000		49,980,000
Indan			49,980,000	49,980,000
Sales Price, \$/Gallon	G/V			
Cyclopentene		2.599		2.579
Indan			7.623	7.608

*Distributed in proportion to earnings in separate plants.

price of \$5.094 per gallon. Earnings were apportioned to the two products in proportion to the earnings in the individual plants. Adding the feedstock and operating costs, the prices were calculated at \$2.579 per gallon for cyclopentene and \$7.608 per gallon for indan. These prices were about \$0.02 per gallon less than in the separate plants.

Comparing the magnitude of the numbers in Table 36 shows that feedstock costs far overshadow the amounts of earnings and operating expenses that must be recovered in gross income. As a result, feedstock costs are the major factor in determining product price. Table 37 presents the product prices as the rate of return was varied from 15 to 25 percent. In comparison with the feedstock prices listed in Table 36, product prices are the same order of magnitude. The differences between feedstock and prices include not only the economic factors, but also the difference in densities and production of by-products in processing. Lower densities for products resulted in larger volumes than feedstocks. The volumes used in the economic calculations are identical to the material balance by weight used in the process flow diagrams.

Examination of Table 37 shows that for each increment of 5 percent DCF return at 13-year life, product price changed \$0.012 to \$0.016 per gallon. At 5-year life, the increment for 5 percent DCF return varied from \$0.009 to \$0.012 per gallon. These increments would not be altered by a change in feedstock cost; only the magnitude of the product price would change. This effect shows up in the cyclopentene made from lower purity feedstocks. The medium purity feed was \$1.17 per gallon less than high purity, and reduced the product prices about \$0.99 per gallon. A second increment of \$0.25 per gallon to the low purity feed had a similar reduction of about \$0.21 per gallon of product. These lower purity products offer considerable additive cost savings and may work nearly as well in modifying flame luminosity. Product prices did not include distribution costs for transport of the additive to terminals or other point of usage.

Table 38 presents the annual earnings for each product at each rate of return. For the cyclopentene plant, lower price feedstocks did not affect the amount of earnings. The earnings required for the indan plant are slightly lower than the cyclopentene plant because of lower investment and operating costs. Earnings for the 5-year depreciation schedule were higher than the 13-year schedule; this effect caused the slightly higher prices observed in Table 37 for 5-year life.

TABLE 37. PRODUCT PRICES AT VARYING RATES OF RETURN IN DOLLARS/GAL

<u>13-Year Plant Life</u>	<u>Feedstock Price, \$/Gallon</u>	<u>Rate of Return</u>		
		<u>15%</u>	<u>20%</u>	<u>25%</u>
Cyclopentene Plant				
High Purity	2.86	2.584	2.599	2.614
Medium Purity	1.69	1.594	1.610	1.625
Low Purity	1.44	1.381	1.396	1.412
Indan Plant				
Indan	7.57	7.609	7.623	7.637
Combined Plant				
Cyclopentene	2.86	2.566	2.579	2.593
Indan	7.57	7.596	7.608	7.620
<u>5-Year Plant Life</u>				
Cyclopentene Plant				
High Purity	2.86	2.611	2.623	2.635
Medium Purity	1.69	1.622	1.633	1.645
Low Purity	1.44	1.408	1.420	1.432
Indan Plant				
Indan	7.57	7.633	7.644	7.655
Combined Plant				
Cyclopentene	2.86	2.590	2.601	2.611
Indan	7.57	7.617	7.627	7.636

TABLE 38. EFFECT OF RATE OF RETURN ON ANNUAL EARNINGS, \$1,000 (ROUNDED)

<u>13-Year Plant Life</u>	<u>DCF Rate of Return</u>		
	<u>15%</u>	<u>20%</u>	<u>25%</u>
Cyclopentene Plant			
High Purity	2,951	3,706	4,484
Medium Purity	2,951	3,706	4,484
Low Purity	2,951	3,706	4,484
Indan Plant	2,655	3,335	3,776
Combined Plant	4,955	6,224	7,530
<u>5-Year Plant Life</u>			
Cyclopentene Plant			
High Purity	4,303	4,987	5,497
Medium Purity	4,303	4,897	5,497
Low Purity	4,303	4,897	5,497
Indan Plant	3,872	4,406	4,946
Combined Plant	7,226	8,223	9,232

V. DISCUSSION

Potential additive candidates were screened individually and then in combination to determine the concentration of the additive required to reach the desired effect. This experimentation determined the extent of improvement in the properties in relation to the original objectives of the program. One key limitation for the first task was a total additive concentration less than 5 percent by volume. Table 39 lists the nominees and the suggested concentration ranges for each additive based on the criteria in Task 1 - Literature Search and Additive Evaluation. The coded additive MO was included in this list because this compound improved the flame luminosity toward the latter part of the burn; however, MO also left a residue in the bottom of the Petri dish which caused some concern for future applications in a vehicle. The residue may cause plugged injectors or excessive wear in an engine.

TABLE 39. ADDITIVE PACKAGE NOMINEES AND SUGGESTED CONCENTRATION RANGES FOR TASK 1

Property	Additive	Concentration Range
Flammability	Butane	2.2-2.5 Vol%
Flammability	Butene	2.2-2.5 Vol%
Luminosity	Toluene	2.8-5.0 Vol%
Luminosity	MO coded sample ^a	0.75-1.0 Wt%
Luminosity	Ethanol	10-20 Vol%
Lubricity ^b	DCI-4A, OS85798, OS86453, OS86454, OS86455, OS86456, OS86457, OS86458, OS86460, VX3181, VX3182, Metacor 704, Unicor J, IPC 44210	0.12 Wt%
Taste	Bitrex	0.0012 Wt%
Color	Alcohol-soluble Dye	0.00013-0.013 Wt%
Odor	Various	0.007 Wt%
^a This additive formed a residue after burning ^b These corrosion-inhibitor/lubricity improvement additives are considered to be interchangeable as regards their compatibility with other additive package constituents at the nominated low level of concentration.		

In the Task 1 Expansion, the 5 volume percent limitation was lifted and replaced by a limit on the total cost of the additive package not to exceed 125 percent of the gasoline component cost in M85. The leading candidates for luminosity improvement were:

- Toluene
- Cyclopentene

- Indan
- Benzaldehyde

Trimethyl borate improved the flame luminosity at a low concentration with a characteristic green flame, but the residue left behind after the burn caused some concern about possible engine wear. Two compounds at slightly higher concentrations, methylcyclopentane (early in the burn) and mesitylene (late in the burn), improved the luminosity above the minimum threshold visibility. MO and ethanol, recommended in Task 1, were not included in the Task 1 Expansion because ethanol was required at much higher concentrations to enhance flame luminosity and MO left a residue after burning.

A. Lubricity

For lubricity, the mechanism operating with methanol fuel involved the washing away of the lubricant and subsequent corrosion caused by the formation of acids and other oxidizing agents from the fuel. The additives identified for methanol lubricity should handle both lubrication and corrosion. In general, the two most successful classes of compounds included the fatty acids and organic amine salts. Several proprietary lubricity/corrosion additives from this class of compounds were equally effective in improving the lubricity. These compounds compared favorably to M85 for a reduction in wear and showed significant improvement in the lubricity of M100.

B. Flammability

For flammability, the addition of butane or butene lowered the flammability limit to below -18°C at a concentration of about 3 volume percent. The addition of toluene increased the rich flammability limit of the mixture when blended with butane or butene. When the total additive concentration was held to 5 volume percent with combinations of 2 percent butane or butene, 3 percent toluene, and a balance of methanol, the rich flammability limit was about 0°C . With 15 volume percent ethanol and 6 volume percent of the toluene and butane, the rich flammability limit was about -25°C . These rich flammability limits were well below normal ambient temperatures and below the typical daily temperatures in California except in mountainous areas or on extremely cold days. In addition, the RVP was sufficient to provide good fuel volatility. Therefore, the flammability of saturated fuel vapors in underground and vehicle storage tanks can be lowered below typical ambient temperatures with sufficient volatility to provide good cold-starting and warm-up performance to -18°C (0°F). Fuel weathering was not considered in this program.

C. Flame Luminosity

Flame luminosity was improved for fuel methanol through the addition of compounds which burned with visible flames. The luminosity depends on a number of factors:

- Type of fire (pool, spill, or container)
- Path length and size of flame
- Surface where burning takes place (porous or non-porous)
- Background of the flame in relation to the observer
- Lighting conditions (dark, twilight, or bright sunshine)

- Concentration, volatility, and luminosity of additives
- Flame color.

Since the luminosity of neat methanol is poor, the addition of any soot-forming material improves the flame luminosity.

1. Single Component Additives

Ethanol was chosen as the luminosity standard for the experimental procedure, and M85 was the standard of comparison. For M85, the luminosity varied throughout the burn. Through the initial and final portions of the burn, M85 produced 70 to 90 percent of the luminosity of ethanol. During the middle portion of the burn, M85 yielded only a 15 percent increase in luminosity over M100.

Boron compounds produced a green flame when burned. Trimethyl borate achieved the minimum threshold visibility for about 50 percent of the burn at the 5 percent concentration by volume; however, a white residue remained in the Petri dish after burning probably due to boric acid. These compounds showed some promise as luminosity enhancers, but some concern arose about the residue left behind after burning. This residue may cause excessive wear or other problems in the engine or fuel handling system of an actual vehicle. The increase in visibility with respect to luminosity from boron compounds was probably due to the higher sensitivity of the human eye to wavelengths in the green to yellow portion of the spectrum.

Three additives were investigated for their effect on flame luminosity based on their low Carter MIR; pentamethylbenzene, benzaldehyde, and pentamethylbenzaldehyde. Pentamethylbenzene and pentamethylbenzaldehyde resulted in a small increase in the flame luminosity compared to methanol. Benzaldehyde is unique in that it has a negative MIR; however, benzaldehyde is an irritant and considered toxic. If benzaldehyde passes through the combustion process unburned, a lower or negative potential for ozone formation may occur. Benzaldehyde increased the flame luminosity above the minimum threshold visibility toward the latter part of the burn at the 5 percent by volume concentration. This compound was unique among oxygen-containing compounds because it yielded a higher flame luminosity than the homologous compounds without oxygen. In combination with toluene or cyclopentene, benzaldehyde should result in a visible flame throughout the majority of the burn and may contribute to lower ozone formation of the exhaust.

The best combinations for improving flame luminosity were those with unsaturation, cyclization, and aromaticity. Chemicals with unsaturation, cyclization, and aromaticity resulted in molecules with lower hydrogen/carbon number ratios, and lower hydrogen/carbon number ratios tend to improve the flame luminosity more than homologous compounds. Carbon chain branching also increased the luminosity; but in combination with methanol, higher concentrations were required. Unsaturated, branched-chain, and cyclic hydrocarbons typically increased the flame luminosity in the initial part of the burn more than straight chain hydrocarbons; however, many of these compounds required concentrations above 10 volume percent to raise the luminosity to the level of the minimum threshold visibility (0.2 foot-candles). Aromatics and certain substituted cyclic hydrocarbons improved the flame luminosity in the latter part of the burn.

The differences between compounds which enhanced the luminosity at the beginning of the burn and those that improved the luminosity near the end of the burn were related to the volatility of the compounds and the ability to form azeotropes with methanol. Compounds with a carbon number of 5 or 6 yielded the highest luminosity in the early part of the burn. Above and below carbon numbers of 5 and 6, the luminosity during the early part of the burn dropped off dramatically. Compounds with a

hydrogen/carbon number ratio between 1.5 and 2.5 (olefins and paraffins) produced the highest luminosity in the early part of the burn, while compounds with a hydrogen/carbon number ratio less than 1.5 (aromatics) exhibited higher luminosity in the latter part of the burn.

Toluene and cyclopentene provided the highest flame luminosity at the lowest concentration during the initial part of the burn, while indan produced good luminosity at a low concentration in the latter part of the burn. Indan met the minimum threshold visibility at a concentration of approximately 1 percent by volume for a short time near the end of the burn. Alcohols and ethers provided limited improvements in the luminosity except at very high concentrations. One exception was cyclohexanol, but even this compound had a lower luminosity than its homologous cyclic hydrocarbon, cyclohexane.

When toluene was added to methanol at 8 volume percent, the luminosity exceeded ethanol. With 6 volume percent toluene, the luminosity surpassed M85 for the initial part of the burn. At a concentration of 2.8 volume percent, toluene was sufficient to provide luminosity above the estimated minimum threshold visibility of 0.2 foot-candles for the initial portion of the burn. Other compounds such as coded sample MO provided a luminosity improvement during the final portion of the burn, but left a residue in the bottom of the Petri dish. The luminosity of methanol can be improved through the use of additives other than gasoline, but the degree of improvement is dependent on the concentration of the additive, the portion of the burn considered, and the degree of improvement required.

2. Multiple Component Additives

To reach the minimum threshold visibility throughout the burn, multiple component blends were required. Many multiple component mixtures were tried to take advantage of the different volatilities of various compounds which demonstrated good luminosity as single component blends. These combinations included:

- Ethanol + TBA
- Ethanol + MTBE
- Indan + cyclopentene
- Indan + methylcyclopentane
- Toluene + indan
- Toluene + ethyl ether
- Toluene + n-propyl benzene
- Toluene + tetralin
- Ferrocene + cyclopentene + indan
- Feedstocks and commercial products
 - Cycloalkane/olefin blends

- Olefin blends
- Various grades of DCPD
- DP5-160.

Several blends were found to be equivalent to or better than M85 in terms of a visible flame duration above the minimum threshold visibility. A blend of ferrocene, cyclopentene, and indan also produced a flame with a good flame duration, but concern over residue left after the burn precluded additional investigation of this blend. The best blends with the lowest additive concentration by volume were 5 percent indan + 5 percent cyclopentene and 4 percent toluene plus 2 percent indan. Experimentation with these two blends was continued through outdoor luminosity studies and emission testing in a dual fuel vehicle.

D. Outdoor Burns

A set of experiments was designed to compare the laboratory results to real world situations. These experiments were conducted outdoors with larger quantities of fuel on a variety of surfaces to simulate real world conditions. Two of the best multiple component additive combinations from the laboratory investigation were selected for continued investigation. The effect of five different liquids:

- 100% methanol
- 100% ethanol
- M85
- 4% toluene + 2% indan in methanol
- 5% indan + 5% cyclopentene in methanol

on each of five surfaces:

- Concrete
- Asphalt
- Sheet metal
- Grass
- Soil

was determined to make these comparisons. A panel of eight to nine observers watched the burns, rated the visibility, and answered questions about the lighting conditions, flame color, flame luminosity, flame height, background, and other distinguishing features. All burns were performed during bright sunlight or partly cloudy conditions. In general, the additive blends performed as well as or better than ethanol and M85 on most surfaces, and the additive blends were significantly better than M100 in all cases. These results, while limited to a small number of observers, indicated that the flame visibility of methanol can be improved through the use of selected additives.

E. Emission Measurements

Emission testing was performed on two different vehicles with different additive blends. The measured emissions included a complete hydrocarbon speciation (C₁ - C₃ hydrocarbons plus benzene and toluene, C₄ hydrocarbons including 1,3-butadiene, and C₅ - C₁₀ hydrocarbons), aldehydes, and methanol. All exhaust emissions were measured on a bag by bag basis and compared for their ozone formation potential based on the most current Carter MIRs.

A 1986 Toyota Camry (dedicated M85 vehicle) was tested with an SwRI methanol blend and with an actual commercial blend of M85 fuel obtained from California. The SwRI methanol blend was made from M100 blended to contain the following additives:

- 6 volume percent toluene
- 2.5 volume percent butane
- 0.12 weight percent DCI-4A (Dupont)
- 0.0001 weight percent Bitrex (denatonium benzoate)
- 0.007 weight percent odorant.

In a separate set of tests, a 1989 dual-fuel Volkswagen Jetta was tested with five fuels:

- M100
- 4% toluene + 2% indan blended with M100
- 5% indan + 5% cyclopentene blended with M100
- Auto/Oil industry average gasoline (RF-A)
- M85 blended from RF-A

Both vehicles were tested with different additive blends, but the results from these tests were similar in many ways even though the engines and emission control systems were different on each vehicle. In general, the hydrocarbons in the exhaust were analogous to the hydrocarbons in the fuel. For example, when toluene was added to the fuel, higher concentrations of toluene were detected in the exhaust. Some other comparisons for both vehicles were:

- Cold-start emissions contributed to the majority of the exhaust emissions from both vehicles.
- Methanol was the major organic constituent in the exhaust when present in the fuel.
- Speciated hydrocarbons in the exhaust reflected the additives in the fuel.
- Regulated emissions from the Jetta with the two fuel additives had minimal emissions impact when compared to M100.

- Ozone formation potential from both vehicles was lower for the additive blends when compared to M85, but the criterion for no more than 50 percent of the exhaust reactive hydrocarbon emissions for the blend compared to M85 was not met.
- Toxic emissions from the Jetta were variable compared to M100; the additive with T&I had more toxic emissions, and the additive with I&C had less toxic emissions.
- Toxic emissions from the Camry with the methanol additive package were lower when compared to M85, but higher than M85 with the Jetta; the total additive package concentration was also greater with the Jetta.
- When the additive blends were compared to gasoline, the total and NMOG hydrocarbons were greater, but the toxics were less.

In general, the additive blends performed well when compared to M85 and M100. Minimal emissions impact was observed for the regulated emissions, but the criterion for no more than 50 percent of the exhaust reactive hydrocarbons as compared to M85 without the additive was not met. It should be noted that even M100 did not meet this criterion. The toxic emissions found to be more dependent on the additive package.

F. Cost

One consideration in the selection of potential additives was the cost to achieve the desired effect. The additional costs depended on the specific additives and concentration of each additive in the package. In Task 1 - Literature Search and Additive Evaluation, an additive package was proposed to meet the safety and performance criteria for the initial part of the program. Table 40 lists the costs for the individual additive package nominees based on their suggested concentrations from Table 39. As an example, the fuel cost increase for an additive package which would address each of the fuel properties may include the following:

- 2.2 volume percent butane (1 cent/gal)
- 2.8 volume percent toluene (3 cents/gal)
- 0.12 weight percent of a lubricity additive (1 cent/gal)
- 0.0012 weight percent Bitrex (2 cents/gal)
- 0.007 weight percent odorant (0.04 cent/gal)
- Dye for coloration (0.2 cent/gal).

With the cost of methanol at 37 cents/gal based on an average of the spot market prices from January to May 1992⁽⁸⁶⁾, the total cost of the fuel with the example additive package listed above would be about 42 cents/gal. If ethanol were included in the blend at a concentration of 20 percent with the same additive package listed above, the fuel cost was about 58 cents/gal. It should be noted that these costs do not include blending and other related costs such as transportation and handling since some of these costs would be similar for any fuel. The costs for the additive package in methanol are within an acceptable range to improve the properties of the fuel without pricing the fuel out of the market.

TABLE 40. ADDITIVE COSTS FOR TASK 1 ADDITIVE COMBINATIONS(86,87)

Additive	Bulk Price	Cost Increase, \$/Gal Fuel*
Methanol	\$0.37/gal	--
Butane	\$17.50/bbl	\$0.01
Toluene	\$0.90/gal	\$0.02 - \$0.045
Butene	\$2.50/gal	\$0.055 - \$0.063
Ethanol	\$1.17/gal	\$0.12 - \$0.23
MO	\$4.00/lb	\$0.20-\$0.26
DCI-4A	\$0.84/lb	\$0.01
Bitrex	\$14.00/oz	\$0.02
Odorant	\$1.00/lb	\$0.0004
Colorant (dye)	\$19.00/lb	\$0.002 - \$0.02

*Cost increase based on suggested concentration ranges in Table 38 and price per gallon of the additive without transportation costs.

In the Task 1 Expansion, efforts continued to find alternative luminosity additives with the additive cost not to exceed 125 percent of the gasoline cost in M85. The additive package above was successful in improving all of the fuel properties except flame luminosity. To achieve a luminous flame throughout the majority of the burn, higher concentrations of the luminosity additives must be used. Two combinations were found which provided adequate luminosity throughout the burn. These combination were plus 5 percent indan + 5% cyclopentene and 4 percent toluene plus 2 percent indan. Table 41 lists the individual estimated additive costs for these two combinations, and the associated costs increases for each additive concentration.

TABLE 41. ADDITIVE COST FOR TOLUENE, CYCLOPENTENE, AND INDAN ADDITIVE COMBINATIONS (TASK 1 EXPANSION)

Additive	Bulk Price, \$/gal	Cost Increase, \$/gal Fuel*
4% Toluene	0.90	0.036
2% Indan	7.62	0.152
5% Cyclopentene	1.61	0.081
5% Indan	7.62	0.381

*Cost increase based on percentage of suggested concentration range and price per gallon of the additive without transportation costs.

To compute the additive costs, the spot price for toluene was reviewed for calendar year 1991 and compared with gasoline in Section IV. B. Toluene prices tend to follow the gasoline price, but it is also affected by demand as a chemical intermediate. The average price was \$0.901 per gallon, and the median value was \$0.905 per gallon. A price of \$0.90 per gallon was used in the estimation of additive cost.

Cyclopentene and indan were not available as bulk chemicals, so the approach to developing costs was to estimate the cost of production from other available materials. DCPD was available in the desired quantities as a starting material to make cyclopentene by partial hydrogenation of CPD monomer. Estimates of investment cost, operating expenses, and economic evaluation in Section IV. C. indicate that cyclopentene can be made in California for \$1.38 to \$2.58 per gallon depending on the purity. Slightly higher prices of \$1.41 to \$2.61 per gallon may be needed to encourage construction of a plant. A cost of \$1.61 for medium purity based on a 20 percent rate of return and a 13 year plant life was used in estimating the additive cost for cyclopentene.

Indene was selected as the starting material to produce indan, but no bulk producer of indene was found in the United States. Indene was available in bulk quantities in Europe, but at a high price which may not meet the long term needs as a fuel additive. A plant to make indan would be similar to the cyclopentene plant in size and design. Economic evaluation in Section IV. D. indicates that indan could be produced in California for \$7.62 per gallon. This value was used to calculate the cost of adding indan to methanol.

To estimate the additive package price in comparison to the gasoline in M85, the current cost of gasoline added to M85 was determined. The average cost of the premium unleaded wholesale rack prices from January to May 1992 was 74.9 cents/gal.⁽⁸⁶⁾ With M85, the gasoline contribution to the total cost equated to 11.2 cent/gal based on 15 percent of the average premium unleaded cost per gallon. At the pump in California, the average retail price for M85 is currently about 80 cents/gal, and ranges from 71.9 to 93.9 cents/gal depending on the transportation costs and mark up involved with the particular station.⁽⁸⁸⁾ If 85 percent of the spot market price for methanol (31.5 cents/gal) was subtracted from the average retail price for M85, then the costs yielded an increase for the gasoline, transportation, and station margin costs of between 40 and 62 cents/gal with an average of 48.5 cents/gal. By subtracting the gasoline contribution cost (11.2 cents/gal) from the remainder, the transportation costs plus station margin were 37.3 cents/gal of the average price for M85 in California. (Note: Since the transportation costs and the station margin should be similar for any fuel, no attempt was made to separate these two figures.)

To meet the criterion for the flame luminosity additive costs of less than 125 percent of the gasoline portion of M85 (11.2 cents/gal), the cost increase for the additive packages should be less than about 14 cents/gal. Neither of the two additives were capable of meeting this criterion because the raw material costs for indan were too high (See Table 40). If a substitute for indan or a lower priced feedstock could be found, then the additive package might meet the cost requirement proposed for this program. The additive package with 4 percent toluene plus 2 percent indan was the closest to meeting the cost criterion. This blend yielded a cost increase of 18.8 cents/gal, which equated to a 168 percent increase over the gasoline contribution to M85. With the 4 percent toluene plus 2 percent indan flame luminosity additive package, the average cost of the fuel at the pump would be about 91 cents/gal, including the transportation costs and the station margin calculated above. This fuel cost equates to a total cost increase of about 14 percent more than the average pump price for M85.

If the additives for flammability limit, fuel lubricity, taste, odor, and color were also added to the fuel cost for the luminosity additive, then the price at the pump would be about 94 cents/gal for an increase of about 18 percent more than the pump price of M85. On this basis, the total cost increase of

a complete additive package in the fuel was less than 125 percent of the total cost at the pump, but not less than 125 percent of the gasoline portion in M85.

A similar exercise could be performed with the 5 percent indan plus 5 percent cyclopentene flame luminosity additive. With the flame luminosity additive alone, the average cost of the fuel at the pump, including transportation costs and station margin, would be about \$1.17/gal. This cost was 46 percent more the average pump price of M85. If the additives for flammability limit, fuel lubricity, taste, odor, and color were added to the fuel cost for the luminosity additive, then the price at the pump would be about \$1.20/gal for an increase of about 50 percent more than the M85 pump price.

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GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS

AO - Coded alcohol-soluble dye

B/SD - Barrels per stream day

bbl - Barrel, 42 U.S. gal

BFOE - Barrel, fuel oil equivalent (6.3 MM BTU)

BOCLE - Ball-on-Cylinder Lubricity Evaluator

CARB - California Air Resources Board

Carter Maximum Incremental Reactivity (MIR) - Used to predict relative levels of ozone formation based on the individual hydrocarbon components in the exhaust

CEC - California Energy Commission

CO - Carbon monoxide

CPD - Cyclopentadiene monomer

DCF - Discounted cash flow

DCPD - Dicyclopentadiene dimer

DER - Department of Emissions Research at Southwest Research Institute

DME - Dimethyl ether

F - Coded alcohol-soluble dye

Foot-candle - Unit of illuminance on a surface that is everywhere one foot from a uniform point source of light of one candle

FTP - Federal Test Procedure

Gray-body radiation - Carbonaceous particles heated by a flame and emit light in the visible region of the spectrum

HP - High pressure (steam)

I&C - 5 percent indan plus 5 percent cyclopentene

Kw - Kilowatt or kilowatt hours per hour

Kwh - Kilowatt hour

GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS (CONT'D)

Lean flammability limit - Temperature where the gases in the vapor space of a closed container are too lean (insufficient fuel) to ignite; occurs at lower temperatures

LP - Low pressure (steam)

M - Thousand

M100 - neat methanol; 100 percent methanol fuel with no additives or blending components

Minimum threshold visibility - Based on a subjective consensus as the lowest level that a luminous flame would be detected under lighted conditions as measured with the instrumentation described above (about 0.2 foot-candles)

M85 - Mixture of 85 percent methanol with 15 percent gasoline

MIR - Maximum incremental reactivity

MM - Million

MMBTU/hr - Million BTU per hour

MO - Coded alcohol-soluble dye

MP - Medium pressure (steam)

MSCF/hr - Thousand standard cubic feet per hour

MTBE - Methyl t-butyl ether

NMOG - Non-methane organic gases

NO_x - Oxides of nitrogen

Ozone formation potential - Relative estimation of the contribution of the exhaust constituents to produce ozone; obtained by dividing the mass of ozone formed from hydrocarbon components in the exhaust based on the Carter MIR by the mass of NMOG

PFI - Port Fuel Injector Deposit test

RF-A - Auto/Oil industry average gasoline

Rich flammability limit - Temperature where the gases in the vapor space of a closed container are too rich (insufficient oxygen) to ignite; occurs at higher temperatures

RVP - Reid Vapor Pressure

SCAQMD - South Coast Air Quality Management District

GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS (CONT'D)

SD - Stream day or operating day

SwRI - Southwest Research Institute

T&I - 4 percent toluene plus 2 percent indan

TBA - t-butyl alcohol

Toxic emissions - Summation of benzene, 1,3-butadiene, the three isomers of xylene, formaldehyde, acrolein, and acetaldehyde based on CARB list of known and suspected toxic air contaminants

UDDS - Urban Dynamometer Driving Schedule

WSD - Wear Scar Diameter

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APPENDIX A

LUMINOSITY MEASUREMENT DATA AND LUMINOSITY CURVES

APPENDIX A

LUMINOSITY MEASUREMENT DATA AND LUMINOSITY CURVES

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TABLE A-1. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE METHANOL FORMULATIONS (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles.^a</u>	<u>Burn Time, Sec.</u>
Ethanol (reference)	1.0	60
Regular unleaded gasoline	2.5-3.0	60
M85	0.90/0.15/0.70 ^a	60
M88	0.50/0.02/0.35	56
M90	0.35/0.01/0.20	56
M92	0.15/0.005/0.10	56
M95	0.03/0.001/0.10	58
M100	0.001	60
<u>Hydrocarbon Mixtures</u>		
5% 90 RON Reformate	0.005	54
5% H229 ^b	0.08	54
5% H400 ^c	0.10	56
5% Light hydrocrackate	0.15/0.001	56
5% Jet A	0.001	60
5% Refined peanut oil	0.001	60
<u>Aromatics</u>		
1% Toluene	0.001	60
2% Toluene	0.008	58
4% Toluene	0.20	60
5% Toluene	0.25	54
6% Toluene	0.65	60
10% Toluene	1.3	58
5% Ethyl benzene	0.001/0.1	60
5% n-Propyl benzene	0.001/0.3	58
5% n-Butyl benzene	0.001/0.25	56
5% n-Pentyl benzene	0.001/0.1	60
5% n-Hexyl benzene	0.001	60
5% Pyridine	0.001	60
5% Naphthalene	0.001	58
5% Methyl naphthalene	0.001	60
5% Decalin	0.005	60
5% Tetralin	0.005	60
<u>Aliphatics and Olefins</u>		
5% Butane	0.005	56
5% 1-Butene	0.005	54
5% 1,3-Butadiene	0.5/0.005	54
5% Pentane	0.001	56
5% Isooctane	0.01 (first 1/3 burn)	60
5% Dicyclopentadiene	0.001/0.25	54
5% 7-trans-7-Tetradecene	0.001	60

TABLE A-1 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE METHANOL FORMULATIONS (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles.^a</u>	<u>Burn Time, Sec.</u>
<u>Ethers</u>		
5% Ethyl ether	0.001	54
5% Dimethyl ether	0.003	56
5% Ethylene glycol monomethyl ether	0.003	60
5% MTBE	0.001	60
5% ETBE	0.001	60
5% Polyphenyl ether	0.005	60
5% m-Butyl acetate	0.001	60
<u>Metal Organic Salts</u>		
5% Sodium acetate	0.001	60
5% Isoamyl acetate	0.001	60
2% Lithium acetate	0.001	60
2% Calcium acetate	0.001	60
2% Aluminum acetate	0.001	60
2% Iron stearate	0.001	60
2% Sodium stearate	0.001	60
2% Zinc stearate	0.001	60
5 Vol% VX 3174 ^d	0.001	58
5 Vol% VX 3181 ^d	0.001	56
5 Vol% VX 3182 ^d	0.001	60
5 Vol% VX 3194 ^d	0.001	58
5 Vol% VX 3195 ^d	0.001	60
5 Vol% OS 85800 ^d	0.001	56
5 Vol% OS 85801 ^d	0.001	58
5 Vol% OS 85802 ^d	0.001	56
5 Vol% OS 85803 ^d	0.001	60
<u>Alcohol Soluble Dyes</u>		
5% Methyl orange dye	0.001	60
5% Acid yellow dye No. 38	0.001	60
5% Mordant Brown No. 4	0.001	60
5% Rhodamine B dye	0.001	60
5% Pylam blue dye	0.001	60
5% Pylam bright red dye	0.001	60
5% Pylam orange dye	0.001	60
5% Pylam lemon yellow dye	0.001	60
5% Nigrosine	0.001	50
<u>Proprietary Formulations</u>		
0.1% MO ^d	0.05	60
0.5% MO ^d	0.25 (last 1/4 burn)	58

TABLE A-1 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE METHANOL FORMULATIONS (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles^a</u>	<u>Burn Time, Sec.</u>
1.0% MO ^d	0.3 (last 1/4 burn)	60
0.1% AB ^d	0.05	60
0.5% AB ^d	0.05	60
1.0% AB ^d	0.05	58
0.1% AO ^d	0.05	60
0.5% AO ^d	0.10 (last 1/4 burn)	60
1.0% AO ^d	0.25 (last 1/4 burn)	60
0.1% BBR ^d	0.05	60
0.5% BBR ^d	0.05	56
1.0% BBR ^d	0.05	58
0.1% DB7 ^d	0.05	60
0.5% DB7 ^d	0.05	60
1.0% DB7 ^d	0.05	56
0.1% Fd	0.05	60
0.5% Fd	0.07	58
1.0% Fd	0.10	60
0.1% PBVF ^d	0.05	58
0.5% PBVF ^d	0.05	58
1.0% PBVF ^d	0.05	60
5% G1280X ^e	0.001	60
5% D1280X ^e	0.001	60
<u>Alcohols</u>		
5% Ethyl alcohol	0.001	60
10% Ethyl alcohol	0.001	60
20% Ethyl alcohol	0.05	60
5% n-Butanol	0.001	58
10% n-Butanol	0.001	58
15% n-Butanol	0.08 (last 1/3 burn)	56
5% Tertiary butyl alcohol	0.001	60
10% Tertiary butyl alcohol	0.001	58
15% Tertiary butyl alcohol	0.18 (last 1/3 burn)	58
5% Isopropyl alcohol	0.001	60
5% Cyclohexanol	0.001	60
5% Tridecylalcohol	0.001	60
5% Decyl alcohol	0.001	60

^aNOTE: Multiple numbers listed under average luminosity indicates changes from beginning, middle and end of burn.

^bH229: C₇ - C₉ hydrocarbon mix (Naphtha solvent) boiling range 240 - 360°F.

^cH400: Middle distillate solvent C₁₀-C₁₃ aromatics boiling range 340 - 490°F.

^dCoded sample.

^eAdditive provided by Omstar.

TABLE A-2. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR ADDITIVE COMBINATION IN METHANOL (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles,^a</u>	<u>Burn Time, Sec.</u>
1% Toluene + 4% Tetralin	0.001/0.01	58
3% Toluene + 2% Tetralin	0.02	60
4% Toluene + 1% Tetralin	0.08	54
4% Toluene + 1% 1-Pentene	0.20	58
3% Toluene + 2% n-Propyl benzene	0.10	60
4% Toluene + 1% n-Propyl benzene	0.30	56
3% Toluene + 2% n-Butyl benzene	0.05	60
4% Toluene + 1% n-Butyl benzene	0.20	58
3% Toluene + 2% Butene	0.10	56
4% Toluene + 1% Butene	0.30	58
3% Toluene + 2% Butane	0.05	58
3% Toluene + 3% Butane	0.04 (1/2 burn)	60
3.5% Toluene + 2.5% Butane	0.08 (1/2 burn)	60
4% Toluene + 1% Butane	0.20	56
4% Toluene + 2% Butane	0.10 (2/3 burn)	60
5% Toluene + 1% Butane	0.30 (2/3 burn)	58
2% Toluene + 1% Butane + 2% H400	0.03	58
2% Toluene + 2% Butane + 1% H400	0.001	56
2% Toluene + 1% Butane + 1% H229	0.05	60
2% Toluene + 2% Butane + 1% H229	0.001	58
2.5% Toluene + 2.5% H229	0.15	56
2.4% Toluene + 2.5% H400	0.04	56
4% Toluene + 4% H400	0.4	54
3% Toluene + 3% H400	0.09	58
1.67% Toluene + 1.67% H229 + 1.67% H400	0.04	56
2% Toluene + 2% H229 + 2% H400	0.15	58
3% Toluene + 1% H229 + 1% H400	0.08	54
6% Toluene + 2% H229 + 2% H400	1.2	54
2.5% H229 + 2.5% H400	0.001/0.20	56
4% H229 + 4% H400	0.5	56
2.5% Toluene + 2.5% Dicyclopentadiene	0.05	54
3% Toluene + 3% Dicyclopentadiene	0.2	54

TABLE A-2 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR ADDITIVE COMBINATION IN METHANOL (TASK 1)

<u>Additive Concentration by Volume</u>	<u>Avg. Luminosity, Foot Candles,^a</u>	<u>Burn Time, Sec.</u>
1% Toluene + 4% Ethyl Ether	0.002	56
2% Toluene + 3% Ethyl Ether	0.005	56
2% Toluene + 8% Ethyl Ether	0.06	56
3% Toluene + 2% Ethyl Ether	0.01	56
4% Toluene + 1% Ethyl Ether	0.1	56
4% Toluene + 6% Ethyl Ether	0.24	54
6% Toluene + 4% Ethyl Ether	0.90	54
8% Toluene + 2% Ethyl Ether	1.2	56
0.8 Toluene + 2.5% Ethyl Ether + 1.7% HSR Naphtha	0.001	54
1.3% Toluene + 4% Ethyl Ether + 2.7% HSR Naphtha	0.04/0.001	54
2% Toluene + 6% Ethyl Ether + 4% HSR Naphtha	0.35/0.08	54
1% Toluene + 1% Ethyl Ether + 3% 90 RON Reformate	0.01	54
2% Toluene + 2% Ethyl Ether + 6% 90 RON Reformate	0.4	54
4% Toluene + 6% 90 RON Reformate	1.1	58
5% EtOH + 5% TBA	0.001	60
10% EtOH + 5% TBA	0.001	60
2% Toluene + 10% EtOH + 10% TBA	0.05 (7/10 burn)	60
4% Toluene + 10% EtOH + 10% TBA	0.40 (7/10 burn)	60
6% Toluene + 15% EtOH	0.80 (9/10 burn)	60
5% Toluene + 15% EtOH	0.60 (9/10 burn)	58
4% Toluene + 15% EtOH + 2% Butane	0.30 (9/10 burn)	60
3% Toluene + 15% EtOH + 2.5% Butane	0.30 (9/10 burn)	60
3% Toluene + 15% EtOH + 3% Butane	0.10 (3/4 burn)	60
2% Toluene + 1% Butene + 2% H400	0.005	58
2% Toluene + 2% Butene + 1% H400	0.001	58
3% Toluene + 1% Butene + 1% H400	0.04	56
2% Toluene + 1% Butene + 1% H229	0.001	60
2% Toluene + 1% Butene + 2% H229	0.06	58
3% Toluene + 1% Butene + 1% H229	0.10	58

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Ethanol(reference)	1.0	53	NA	NA
5% Ethanol	0.004	57	--	--
10% Ethanol	0.005	48	--	--
20% Ethanol	0.006	48	--	--
30% Ethanol	0.004	51	--	--
50% Ethanol	0.004/0.008	54	--	--
75% Ethanol	0.08	51	--	--
90% Ethanol	0.12/0.38	54	32	59
100% Isopropanol	13.5	57	NA	NA
5% Isopropanol	0.005	48	--	--
10% Isopropanol	0.006	48	--	--
20% Isopropanol	0.007	52	--	--
100% t-Butyl alcohol	14.3	61	NA	NA
5% t-Butyl alcohol	0.004	48	--	--
10% t-Butyl alcohol	0.004/0.02	49	--	--
20% t-Butyl alcohol	0.005/0.2/0.09	58	10	17
30% t-Butyl alcohol	0.35	71	27	38
50% t-Butyl alcohol	4/1.0/0.1	108	75	69
75% t-Butyl alcohol	11.8/1.0	89	83	93
100% t-Amyl alcohol	13.8	68	NA	NA
5% t-Amyl alcohol	0.004/0.009	51	--	--
10% t-Amyl alcohol	0.003/0.008	72	--	--
20% t-Amyl alcohol	0.005/0.03/0.1	125	--	--
100% Cyclohexanol	would not ignite	--	NA	NA
5% Cyclohexanol	0.002	52	--	--
10% Cyclohexanol	0.005/0.13	92	25	27
15% Cyclohexanol	0.005/0.35	86	25	29
20% Cyclohexanol	0.005/1.1	98	40	41
100% Phenol	would not ignite	--	NA	NA
5% Phenol	0.004	45	--	--
10% Phenol	0.005	46	--	--
20% Phenol	0.005/1.7/1.1	98	55	56
100% Diethanolamine	would not ignite	--	NA	NA
5% Diethanolamine	0.005	45	--	--
10% Diethanolamine	0.006	43	--	--
20% Diethanolamine	0.005	39	--	--
100% 1-Propanol	6	73	NA	NA
5% 1-Propanol	0.004	50	--	--
10% 1-Propanol	0.004	53	--	--
20% 1-Propanol	0.004	87	--	--
100% n-Butanol	6.6	104	NA	NA
5% n-Butanol	0.004	72	--	--
10% n-Butanol	0.004/0.001	93	--	--
20% n-Butanol	0.002/0.012	124	--	--

TABLE. A-4. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ALDEHYDES, KETONES, ACIDS,
AND ESTERS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Acetone	13	38	NA	NA
5% Acetone	0.006	50	--	--
10% Acetone	0.005*	78	--	--
20% Acetone	0.008	45	--	--
5% Ethyl acetoacetate	0.002	50	--	--
10% Ethyl acetoacetate	0.004/0.03	74	--	--
20% Ethyl acetoacetate	0.003/0.4	104	25	24
100% Ethyl acetate	5.5	54	NA	NA
5% Ethyl acetate	0.004	49	--	--
10% Ethyl acetate	0.004	47	--	--
20% Ethyl acetate	0.004	47	--	--
5% Pyrrolidinone	0.004	47	--	--
10% Pyrrolidinone	0.004	46	--	--
20% Pyrrolidinone	0.004	43	--	--
5% 1-Indanone	0.004	49	--	--
10% 1-Indanone	0.004	47	--	--
20% 1-Indanone	0.004	50	--	--
5% Methacrylic acid	0.005/0.001	62	--	--
10% Methacrylic acid	0.004/0.16	99	--	--
20% Methacrylic acid	0.004/0.001/0.6	101	30	30
5% Methacrylic anhydride	0.004	48	--	--
10% Methacrylic anhydride	0.004	48	--	--
20% Methacrylic anhydride	0.004/0.45	114	48	42
100% Ethyl formate	1/1.6	46	NA	NA
5% Ethyl formate	0.005	50	--	--
10% Ethyl formate	0.005	47	--	--
20% Ethyl formate	0.005	46	--	--
0.006 wt % trans-Cinnamic acid	0.004	48	--	--
0.013 wt % trans-Cinnamic acid	0.004	47	--	--
100% 2,4-Pentanedione	12.5	65	NA	NA
5% 2,4-Pentanedione	0.004	48	--	--
10% 2,4-Pentanedione	0.005	54	--	--
20% 2,4-Pentanedione	0.004/0.18	74	5	7

TABLE A-4 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALDEHYDES, KETONES, ACIDS, AND ESTERS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
0.001 wt% Pentamethylbenzaldehyde	0.004	52	--b	--
0.003 wt% Pentamethylbenzaldehyde	0.005	51	--	--
0.006 wt% Pentamethylbenzaldehyde	0.005	53	--	--
100% Benzaldehyde	5	83	83	NA
5% Benzaldehyde	0.004/0.5	61	17	28
10% Benzaldehyde	0.5	88	71	81
20% Benzaldehyde	1	95	86	91
0.001 wt% Benzoic acid	0.001	57	--	--
0.003 wt% Benzoic acid	0.001	53	--	--
0.006 wt% Benzoic acid	0.001	49	--	--

TABLE A-5. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALICYCLIC COMPOUNDS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Cyclohexene	10	113	NA	NA
5% Cyclohexene	0.006	48	--	--
10% Cyclohexene	0.005	47	--	--
20% Cyclohexene	0.005/0.88	74	35	47
100% Cyclohexane	17.8	63	NA	NA
5% Cyclohexane	0.002	46	--	--
10% Cyclohexane	1.2/0.002	47	10	21
20% Cyclohexane	4/0.1/0.002	46	12	26
100% Cyclohexanol	would not ignite	--	NA	NA
5% Cyclohexanol	0.002	52	--	--
10% Cyclohexanol	0.005/0.13	92	25	27
15% Cyclohexanol	0.005/0.35	86	25	29
20% Cyclohexanol	0.005/1.1	98	40	41
100% Cyclopentane	21.3	42	NA	NA
5% Cyclopentane	0.2/0.004	48	3	6
10% Cyclopentane	1.0/0.03/0.003	44	10	23
20% Cyclopentane	20/0.13/0.004	42	15	36
100% Methylcyclopentane	19.3	44	NA	NA
5% Methylcyclopentane	1.0/0.2/0.004	44	5	11
10% Methylcyclopentane	2.2/1.1/0.004	45	15	33
20% Methylcyclopentane	14.5/0.25/0.004	45	20	44
100% Phenylcyclohexane	would not ignite	--	NA	NA
5% Phenylcyclohexane	0.005	46	--	--
10% Phenylcyclohexane	0.045	45	--	--
20% Phenylcyclohexane	0.005/0.22	43	3	7
100% Cyclopentene	10/19.5	30	NA	NA
5% Cyclopentene	1/0.005	47	12	26
10% Cyclopentene	2/0.005	44	10	23
20% Cyclopentene	2.5/0.005	39	10	26
5% Decahydronaphthalene	0.005	48	--	--
10% Decahydronaphthalene	0.009/0.2	75	10	13
20% Decahydronaphthalene	0.005/2.2	87	47	54
100% Cyclooctane	16.5	87	NA	NA
5% Cyclooctane	0.005	48	--	--
10% Cyclooctane	0.008	47	--	--
20% Cyclooctane	0.025/2.3	83	40	48

TABLE A-5 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ALICYCLIC COMPOUNDS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
5% Dicyclohexylamine	0.004	41	--	--
10% Dicyclohexylamine	0.004	48	--	--
20% Dicyclohexylamine	0.004/0.87/2.1	148	88	59
5% Tetrahydronaphthalene	0.005/0.03	50	--	--
10% Tetrahydronaphthalene	0.005/0.1	50	--	--
20% Tetrahydronaphthalene	0.005/0.03/0.4	40	5	13
100% Dicyclopentadiene	2	59	52	88
5% Dicyclopentadiene	0.003/0.2	48	8	17
10% Dicyclopentadiene	1/0.3	84	29	35
20% Dicyclopentadiene	1.5/0.4	100	82	82

TABLE A-6. LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ALKENES AND ALKYNES IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Cyclohexene	10	113	NA	NA
5% Cyclohexene	0.006	48	--	--
10% Cyclohexene	0.005	47	--	--
20% Cyclohexene	0.005/0.88	74	35	47
5% 2-methyl-2-pentene	0.006	52	--	--
10% 2-methyl-2-pentene	0.004/0.008	85	--	--
20% 2-methyl-2-pentene	0.005/0.17	100	20	20
5% 2-methyl-1-butene	0.004	47	--	--
10% 2-methyl-1-butene	0.05/0.006	48	--	--
20% 2-methyl-1-butene	11.2/0.006	42	10	24
100% 2,4,4-Trimethyl-1-pentene	15/3/0.5	124	NA	NA
5% 2,4,4-Trimethyl-1-pentene	0.005	52	--	--
10% 2,4,4-Trimethyl-1-pentene	0.01/0.005	53	--	--
20% 2,4,4-Trimethyl-1-pentene	1.2/0.005/0.02	80	15	19
100% 4-Methyl-2-pentene	18	33	NA	NA
5% 4-Methyl-2-pentene	0.006	48	--	--
10% 4-Methyl-2-pentene	1.2/0.005	44	6	14
20% 4-Methyl-2-pentene	18/0.005	40	10	25
100% 1-Pentene	35	24	NA	NA
5% 1-Pentene	0.005	45	--	--
10% 1-Pentene	0.005	46	--	--
20% 1-Pentene	0.25/0.005	42	3	7
100% Cyclopentene	10/19.5	30	NA	NA
5% Cyclopentene	1/0.005	47	12	26
10% Cyclopentene	2/0.005	44	10	23
20% Cyclopentene	2.5/0.005	39	10	26
5% Methacrylic acid	0.005/0.001	62	--	--
10% Methacrylic acid	0.004/0.16	99	--	--
20% Methacrylic acid	0.004/0.001/0.6	101	30	30
5% Methacrylic anhydride	0.004	48	--	--
10% Methacrylic anhydride	0.004	48	--	--
20% Methacrylic anhydride	0.004/0.45	114	48	42
100% 2-Methyl-1-pentene	27/25/0.01	81	--	NA
5% 2-Methyl-1-pentene	0.004	52	--	--
10% 2-Methyl-1-pentene	0.22/0.008	50	10	20
20% 2-Methyl-1-pentene	6.8/0.008	50	18	36
100% 2-Methyl-2-butene	27	31	NA	NA
5% 2-Methyl-2-butene	0.2/0.005	48	2	4
10% 2-Methyl-2-butene	0.75/0.005	49	3	6
20% 2-Methyl-2-butene	10/0.006	46	14	30
100% cis-2-Pentene	27.5	36	NA	NA
5% cis-2-Pentene	0.004	56	--	--
10% cis-2-Pentene	0.35/0.004	54	5	9
20% cis-2-Pentene	0.8/0.004	52	13	25
trans-Cinnamic acid	0.004	48	--	--
trans-Cinnamic acid	0.004	47	--	--

FOR SINGLE-ADDITIVE AROMATICS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Indan	would not ignite	—	NA	NA
1% Indan	0.005/0.18	47	3	6
2% Indan	0.008/1.1	48	8	17
3% Indan	0.005/1.2	49	15	31
4% Indan	0.005/1.6	51	18	35
5% Indan	0.02/1.6	48	23	48
6% Indan	0.02/2.1	47	25	53
7% Indan	0.02/2.0	48	25	52
10% Indan	1.6	60	42	70
20% Indan	1.8	73	65	89
100% Phenol	would not ignite	—	NA	NA
5% Phenol	0.004	45	—	—
10% Phenol	0.005	46	—	—
20% Phenol	0.005/1.7/1.1	98	55	56
0.003 wt.% Ferrocene	0.02/0.2	50	8	16
0.005 wt.% Ferrocene	0.02/0.25	49	10	20
0.013 wt.% Ferrocene	0.21/0.3	51	23	45
Saturated ferrocene	0.3	48	20	42
100% Pyridine	14	55	NA	NA
5% Pyridine	0.002/0.14	53	—	—
10% Pyridine	0.006/0.25	60	8	13
20% Pyridine	0.005/5.5/0.25	70	35	50
5% Naphthalene	0.015	58	—	—
5% <i>s</i> -Butylbenzene	0.005/0.25	49	5	10
10% <i>s</i> -Butylbenzene	0.005/4.0	54	18	33
20% <i>s</i> -Butylbenzene	0.005/0.25/4.5/1.6	61	37	61
100% 1-Phenyl octane	would not ignite	—	NA	NA
5% 1-Phenyl octane	0.005	48	—	—
10% 1-Phenyl octane	0.005	48	—	—
20% 1-Phenyl octane	0.005	43	—	—
100% Phenylcyclohexane	would not ignite	—	NA	NA
5% Phenylcyclohexane	0.005	46	—	—
10% Phenylcyclohexane	0.045	45	—	—
20% Phenylcyclohexane	0.005/0.22	43	3	7
100% Dimethylnaphthalene	would not ignite	—	NA	NA
5% Dimethylnaphthalene	0.005	47	—	—
10% Dimethylnaphthalene	0.005	45	—	—
20% Dimethylnaphthalene	0.005	43	—	—
100% 4- <i>t</i> -Butylpyridine	would not ignite	—	NA	NA
5% 4- <i>t</i> -Butylpyridine	0.005	48	—	—
10% 4- <i>t</i> -Butylpyridine	0.005/1.8	74	25	33
20% 4- <i>t</i> -Butylpyridine	0.005/1.8	118	70	59
0.003 wt.% Acetylferrocene	0.015	48	NA	NA
0.005 wt.% Acetylferrocene	0.012	48	—	—
0.013 wt.% Acetylferrocene	0.015	48	—	—

TABLE A-7 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE AROMATICS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
0.013 wt.% Benzoylpyridine	0.005	47	--	--
0.025 wt.% Benzoylpyridine	0.005	48	--	--
0.013 wt.% Benzophenone	0.003	50	--	--
0.025 wt.% Benzophenone	0.004	48	--	--
Saturated carbazole	0.012/0.04/0.008	56	--	--
0.013 wt.% 1,2,4,5-Benzenetetracarboxylic acid	0.004/0.006	48	--	--
0.025 wt.% 1,2,4,5-Benzenetetracarboxylic acid	0.005/0.02/0.006	50	--	--
100% Toluene	6.1/8.8	40	NA	NA
5% Toluene	0.35/0.004	46	25	54
10% Toluene	5.5/0.004	45	37	82
20% Toluene	14	46	40 (Yellow)	87
5% Pyrrole	0.006/0.02	50	2	4
10% Pyrrole	0.01/1.7	60	8	13
20% Pyrrole	0.012/9	73	25	34
5% Aniline	0.005	48	--	--
10% Aniline	0.005	46	--	--
20% Aniline	0.006	44	--	--
1-Indanone	0.004	49	--	--
1-Indanone	0.004	47	--	--
1-Indanone	0.004	50	--	--
1% Mesitylene	0.004	52	--	--
2% Mesitylene	0.004/0.02	50	--	--
3% Mesitylene	0.004/0.2	49	5	10
4% Mesitylene	0.004/0.45	52	12	23
5% Mesitylene	0.004/0.95	48	20	42
10% Mesitylene	0.05/2	52	38	73
20% Mesitylene	2.2	81	73	90
5% 1-Methylnaphthalene	0.004/0.008	46	--	--
10% 1-Methylnaphthalene	0.006	45	--	--
20% 1-Methylnaphthalene	0.005/0.015	40	--	--
trans-Cinnamic acid	0.004	48	--	--
trans-Cinnamic acid	0.004	47	--	--
5% Tetrahydronaphthalene	0.005/0.03	50	--	--
10% Tetrahydronaphthalene	0.005/0.1	50	--	--
20% Tetrahydronaphthalene	0.005/0.03/0.4	40	5	13
5% Indene	0.001/1.2	51	22	43
10% Indene	2	65	48	74
20% Indene	4	66	56	85
0.001 wt% Pentamethylbenzaldehyde	0.004	52	_b	--
0.003 wt% Pentamethylbenzaldehyde	0.005	51	--	--
0.006 wt% Pentamethylbenzaldehyde	0.005	53	--	--
0.001 wt% Pentamethylbenzene	0.001	52	--	--
0.003 wt% Pentamethylbenzene	0.001	52	--	--
0.006 wt% Pentamethylbenzene	0.003	58	--	--

FOR SINGLE-ADDITIVE AROMATICS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
0.001 wt% Benzoic acid	0.001	57	--	--
0.003 wt% Benzoic acid	0.001	53	--	--
0.006 wt% Benzoic acid	0.001	49	--	--
100% Borane-pyridine complex	3	55	49	89
5% Borane-pyridine complex	0.05/0.002	82	--	--
10% Borane-pyridine complex	0.2/0.02/0.5	63	13/8	33
20% Borane-pyridine complex	0.3/2	47	42	89
100% Nitrobenzene	0.8/2	59	59	NA
5% Nitrobenzene	0.003	43	--	--
10% Nitrobenzene	0.003	45	--	--
20% Nitrobenzene	0.003/0.6	77	28	36
100% Benzaldehyde	5	83	83	NA
5% Benzaldehyde	0.004/0.5	61	17	28
10% Benzaldehyde	0.5	88	71	81
20% Benzaldehyde	1	95	86	91

**TABLE A-8 LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR SINGLE-ADDITIVE ETHERS IN METHANOL**

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
5% Methyl-t-butyl ether	0.005	47	--	NA
10% Methyl-t-butyl ether	0.008	46	--	--
15% Methyl-t-butyl ether	0.11/0.005	48	--	--
20% Methyl-t-butyl ether	0.33/0.006	44	15	34
5% t-Amyl methyl ether	0.005	47	--	--
10% t-Amyl methyl ether	0.005	47	--	--
20% t-Amyl methyl ether	0.05/0.02	44	--	--
5% Diethyl ether	0.005	49	--	--
10% Diethyl ether	0.006	47	--	--
20% Diethyl ether	0.025/0.006	46	--	--
100% Dimethoxytetraethylene glycol	would not ignite	--	NA	NA
5% Dimethoxytetraethylene glycol	0.005	47	--	--
10% Dimethoxytetraethylene glycol	0.005	47	--	--
20% Dimethoxytetraethylene glycol	0.004	52	--	--
100% Tetrahydrofuran	22	47	NA	NA
5% Tetrahydrofuran	0.008	48	--	--
10% Tetrahydrofuran	0.005	48	--	--
20% Tetrahydrofuran	0.008	46	--	--
100% Butylethyl ether	18	51	NA	NA
5% Butylethyl ether	0.005	50	--	--
10% Butylethyl ether	0.005	49	--	--
20% Butylethyl ether	0.008	48	--	--
5% t-Butylethyl ether	0.005	50	--	--
10% t-Butylethyl ether	0.006	49	--	--
20% t-Butylethyl ether	0.35/0.012	48	18	38
100% Butyl ether	15	74	NA	NA
5% Butyl ether	0.004	48	--	--
10% Butyl ether	0.004/0.001	69	--	--
20% Butyl ether	0.004/0.001/0.005	88	--	--
100% Dimethoxymethane	0.02	43	NA	NA
5% Dimethoxymethane	0.004	49	--	--
10% Dimethoxymethane	0.004	49	--	--
20% Dimethoxymethane	0.005	45	--	--
100% Furan	20	29	NA	NA
5% Furan	0.005	51	--	--
10% Furan	0.15/0.005	47	1	2
20% Furan	10.5/0.5/0.005	44	22	50

TABLE A-9. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE HETEROCYCLIC COMPOUNDS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Pyridine	14	55	NA	NA
5% Pyridine	0.002/0.14	53	--	--
10% Pyridine	0.006/0.25	60	8	13
20% Pyridine	0.005/5.5/0.25	70	35	50
100% 4-t-Butylpyridine	would not ignite	--	NA	NA
5% 4-t-Butylpyridine	0.005	48	--	--
10% 4-t-Butylpyridine	0.005/1.8	74	25	34
20% 4-t-Butylpyridine	0.005/1.8	118	70	59
0.013 wt.% Benzoylpyridine	0.005	47	--	--
0.025 wt.% Benzoylpyridine	0.005	48	--	--
Saturated carbazole	0.012/0.04/0.008	56	--	--
100% Tetrahydrofuran	22	47	NA	NA
5% Tetrahydrofuran	0.008	48	--	--
10% Tetrahydrofuran	0.005	48	--	--
20% Tetrahydrofuran	0.008	46	--	--
5% Pyrrole	0.006/0.02	50	2	4
10% Pyrrole	0.01/1.7	60	8	13
20% Pyrrole	0.012/9	73	25	34
5% Furfurylamine	0.005	47	--	--
10% Furfurylamine	0.005/0.32	88	8	9
20% Furfurylamine	0.006/2.4	101	35	35
100% Pyrrolidine	33	69	NA	NA
5% Pyrrolidine	0.005	51	--	--
10% Pyrrolidine	0.006/0.02/0.002	76	--	--
20% Pyrrolidine	0.009/0.2/0.003	79	5	6
100% Piperidine	16	70	NA	NA
5% Piperidine	0.005	53	--	--
10% Piperidine	0.005/0.001	88	--	--
20% Piperidine	0.006/0.045	85	--	--
5% Pyrrolidinone	0.004	47	--	--
10% Pyrrolidinone	0.004	46	--	--
20% Pyrrolidinone	0.004	43	--	--
100% Furan	20	29	NA	NA
5% Furan	0.005	51	--	--
10% Furan	0.15/0.005	47	1	2
20% Furan	10.5/0.5/0.005	44	22	50
100% Borane-pyridine complex	3	55	49	89
5% Borane-pyridine complex	0.05/0.002	82	--	--
10% Borane-pyridine complex	0.02/0.02/0.5	63	13/8	33
20% Borane-pyridine complex	0.3/2	47	42	89

TABLE A-10. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALKANES IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
5% 2,2-Dimethylbutane	0.008	47	--	--
10% 2,2-Dimethylbutane	0.2/0.006	44	3	7
20% 2,2-Dimethylbutane	7.5/0.1/0.006	43	5	12
100% Heptane	25	52	NA	NA
5% Heptane	0.004	48	--	--
10% Heptane	0.02/0.004	46	--	--
20% Heptane	0.7/0.005	42	15	36
100% Octane	19	79	NA	NA
5% Octane	0.006	49	--	--
10% Octane	0.006	46	--	--
20% Octane	0.16/0.006	46	3	7
100% 1-Phenyl octane	would not ignite	--	NA	NA
5% 1-Phenyl octane	0.005	48	--	--
10% 1-Phenyl octane	0.005	48	--	--
20% 1-Phenyl octane	0.005	43	--	--
100% Isooctane	20	55	NA	NA
5% Isooctane	0.005	50	--	--
10% Isooctane	0.7/0.005	45	8	18
20% Isooctane	4/0.005	42	20	48
100% Cyclohexane	17.8	63	NA	NA
5% Cyclohexane	0.002	46	--	--
10% Cyclohexane	1.2/0.002	47	10	21
20% Cyclohexane	4/0.1/0.002	46	12	29
100% Phenylcyclohexane	would not ignite	--	NA	NA
5% Phenylcyclohexane	0.005	46	--	--
10% Phenylcyclohexane	0.045	45	--	--
20% Phenylcyclohexane	0.005/0.22	43	3	7
100% Pentane	28	43	NA	NA
5% Pentane	0.005	45	--	--
10% Pentane	0.005	46	--	--
20% Pentane	0.8/0.005	43	4	9
100% 3-Methylpentane	38	46	NA	NA
5% 3-Methylpentane	0.005	45	--	--
10% 3-Methylpentane	0.06/0.005	45	1	2
20% 3-Methylpentane	7.5/0.005	42	8	19
100% Isopentane	30	38	NA	NA
5% Isopentane	0.005	47	--	--
10% Isopentane	0.005	46	--	--
20% Isopentane	0.4/0.005	41	8	20
5% 4-Methyloctane	0.005	57	--	--
10% 4-Methyloctane	0.01	58	--	--
20% 4-Methyloctane	0.04	57	--	--
100% Hexane	22.5	67	NA	NA
5% Hexane	0.004	49	--	--
10% Hexane	0.012/0.004	46	--	--
20% Hexane	2.7/0.004	45	18	40

TABLE A-11. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR SINGLE-ADDITIVE ALKENES AND ALKYNES IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% 1-Pentyne	16.5	25	NA	NA
5% 1-Pentyne	0.012/0.005	47	--	--
10% 1-Pentyne	3.4/0.005	47	7	15
20% 1-Pentyne	16.5/0.005	44	12	27
100% 1-Hexyne	14.2	30	NA	NA
5% 1-Hexyne	0.005	49	--	--
10% 1-Hexyne	2.2/0.005	48	15	31
20% 1-Hexyne	13/0.005	41	22	54
5% Indene	0.001/1.2	51	22	43
10% Indene	2	65	48	74
20% Indene	4	66	56	85

TABLE A-12. LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR ADDITIVE COMBINATIONS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
15% Gasoline (California M-85)	0.8/0.15/0.25	46	34	74
5% Ethanol + 5% TBA	0.005	53	--a	--
5% Ethanol + 10% TBA	0.005/0.02	52	--	--
10% Ethanol + 5% TBA	0.006	53	--	--
10% Ethanol + 10% TBA	0.004/0.025	51	--	--
10% Ethanol + 20% TBA	0.005/0.20	60	8	13
20% Ethanol + 10% TBA	0.005/0.13	50	--	--
20% Ethanol + 20% TBA	0.005/0.6	61	15	25
5% Ethanol + 5% MTBE	0.005	49	--	--
10% Ethanol + 10% MTBE	0.006	47	--	--
20% Ethanol + 20% MTBE	0.65/0.008	49	17	35
5% Cyclopentene + 1% Indan	0.6/0.01/0.5	46	10	22
5% Cyclopentene + 2% Indan	1.4/0.02/1.3	47	20	43
5% Cyclopentene + 3% Indan	1.3/0.05/1.6	48	25	52
5% Cyclopentene + 5% Indan	2.2/0.15/2	46	36	78
6% Cyclopentene + 3% Indan	2.1/0.05/1.6	49	25	51
6% Cyclopentene + 4% Indan	2/0.12/1.6	46	30	65
6% Cyclopentene + 5% Indan	2.1/0.15/1.6	48	40	83
5% Methylcyclopentane + 1% Indan	0.08/0.025/0.12	48	--	--
5% Methylcyclopentane + 2% Indan	0.12/0.006/0.9	47	10	21
5% Methylcyclopentane + 3% Indan	0.18/0.006/1.3	47	20	43
5% Methylcyclopentane + 4% Indan	0.2/0.04/1.9	45	25	56
5% Methylcyclopentane + 5% Indan	0.15/2.1	46	25	54
6% Methylcyclopentane + 2% Indan	0.2/0.006/1.2	47	10	21
6% Methylcyclopentane + 3% Indan	0.2/0.05/1.3	47	18	38
6% Methylcyclopentane + 4% Indan	0.5/0.1/1.4	47	30	64
7% Methylcyclopentane + 3% Indan	0.21/0.08/1.5	49	25	51

TABLE A-12 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS
FOR ADDITIVE COMBINATIONS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
1% Toluene + 1% Indan	0.005/0.15	48	--	--
2% Toluene + 2% Indan	0.25/0.04/1.2	49	11	22
3% Toluene + 3% Indan	0.5/1.7	50	35	70
4% Toluene + 2% Indan	0.15/0.5/1.3	48	39	81
4% Toluene + 4% Indan	0.7/2.8	48	42	88
100% Cycloalkane/olefin mix ^b	13.8	93	--	--
5% Cycloalkane/olefin mix	0.004	51	--	--
10% Cycloalkane/olefin mix	0.2/0.004	51	--	--
20% Cycloalkane/olefin mix	0.88/0.35	49	33	67
100% Olefin mix ^c	15.5/11/5.5	99	--	--
5% Olefin mix	0.004	53	--	--
10% Olefin mix	0.015/0.005	50	--	--
20% Olefin mix	1/0.2/0.005	48	15	31
5% Chevron α -olefins (C ₉ -C ₁₁)	0.005	50	--	--
10% Chevron α -olefins (C ₉ -C ₁₁)	0.005/0.01	51	--	--
20% Chevron α -olefins (C ₉ -C ₁₁)	0.005/0.62	76	25	33
5% C ₅ -C ₆ mix ^d	0.005	53	--	--
10% C ₅ -C ₆ mix	0.11/0.005	50	--	--
20% C ₅ -C ₆ mix	1.8/0.005	80	12	15
0.006 wt% Ferrocene + 5% Cyclopentene + 5% Indan	0.75/0.17/1.2	49	38	78
2% Cyclopentene + 2% Toluene + 2% Indan	0.1/0.04/1	49	12	24
100% Hydrocarbon grade DCPD ^e	8	58	57	98
5% Hydrocarbon grade DCPD	0.002/0.1	50	4	8
10% Hydrocarbon grade DCPD	0.2/1	59	30	51
20% Hydrocarbon grade DCPD	0.3/2	66	44	67
100% Polyester grade DCPD ^f	3	63	62	98
5% Polyester grade DCPD	0.002/0.1	103	5	5
10% Polyester grade DCPD	0.003/1	67	31	46
20% Polyester grade DCPD	2/0.7/0.3	131	102	78

TABLE A-12 (CONT'D). LUMINOSITY MEASUREMENTS AND BURN DURATIONS FOR ADDITIVE COMBINATIONS IN METHANOL

Additive	Avg. Luminosity, Foot-Candles	Burn Time, Sec.	Visibility Duration, Sec.	Percent Luminous Flame
100% Dicyclopentadiene 97 ^g	3	57	50	88
5% Dicyclopentadiene 97	0.003/0.1	84	1	1
10% Dicyclopentadiene 97	0.003/1	73	26	36
20% Dicyclopentadiene 97	0.05/1.5/0.3	101	80	79
100% DP5-160 ^h	2	81	78	96
5% DP5-160	0.003/0.03	44	--	--
10% DP5-160	0.005/0.6	79	36	46
20% DP5-160	0.05/1	77	42	55
100% DP6-46 ⁱ	6	72	71	99
5% DP6-46	0.02/0.1	47	--	--
10% DP6-46	0.1/1.5	52	24	46
20% DP6-46	0.5/5	66	61	92

^aIndicate luminosity did not reach minimum threshold visibility (0.2 foot-candles)

^b40% hexane, 11% cycloheptane, 10% cyclopentene, 10% cis-1,2-dimethylcyclopentane, 10% 1,1,3-trimethylcyclohexane, 10% n-propylcyclohexane, 4% cis-1,2-dimethylcyclohexane, 4% cyclooctane, and 1% 4-methylcyclohexene

^c15% hexane, 10% 1-pentene, 10% cis-2-pentene, 10% 4-methylpentene, 10% cyclohexene, 5% 1-hexene, 5% 1-octene, 2.5% 2-heptene, 1.5% cycloheptene, 1% 2-methyl-2-butene, 1% 3,3-dimethyl-1-butene, 1% (cis & trans) 4-methyl-2-pentene, 1% 2-methyl-1-pentene, 1% 2-methyl-2-pentene, 1% (cis & trans) 4-methylcyclohexene, and 25% combination of 1-nonene, 1-decene, and 1-undecene

^d30% 2-methyl-2-butene, 15% (cis & trans) 4-methyl-2-pentene, 10% pentane, 10% hexane, 10% 2-methyl-1-butene, 10% cis-2-pentene, 10% 2-methyl-2-pentene, and 5% 2-methyl-1-pentene

^e76.0% DCPD, 15.8% C₁₀ codimers, 4.8% C₁₁ codimers, 2.1% C₉ codimers, 0.8% cyclopentadiene, and 0.4% C₅ and C₆ hydrocarbons

^f81.6% DCPD, 12.5% C₁₀ codimers, 3.9% C₁₁ codimers, 1.6% C₉ codimers, and 0.3% cyclopentene

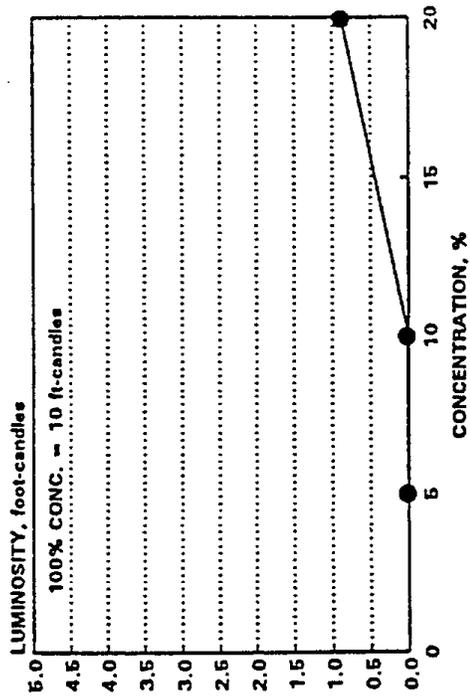
^g95% DCPD, 2% cyclopentadiene, 1.5% C₅ acyclic dienes, and 1.5% cyclic diene and trimers

^h40% C₁₀ hydrocarbons, 25% methyl and dimethyl indenenes, 17% C₉ aromatics, 16% indene, and 2% C₈ aromatics

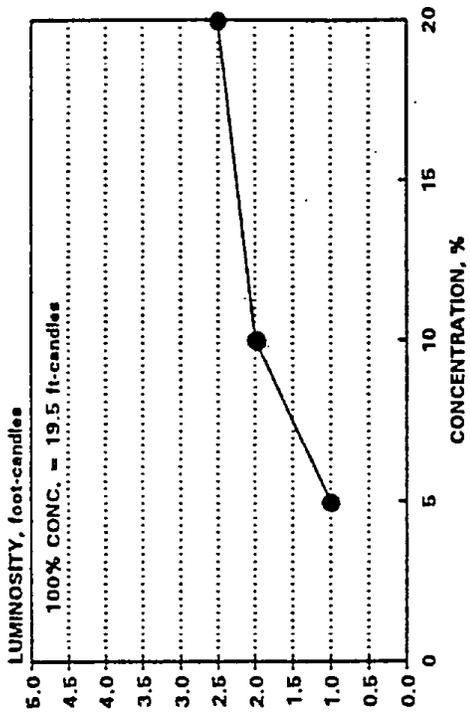
ⁱ61.8% DCPD, 8.1% cyclopentane plus 2-methylcyclopentane, 1.9% cyclopentene, and 1.1% cis-piperylene; the balance had less than 1% each of trans-piperylene, n-pentane, isoprene, 1-pentene, 2-methyl-1-butene, 2-methyl-2-butene, benzene, other C₆ hydrocarbons, and about 25% other undetermined compounds

FIGURE A-13. LUMINOSITY CURVES FOR CYCLOHEXENE, CYCLOPENTENE, DICYCLOPENTADIENE, AND PHENYL CYCLOHEXANE

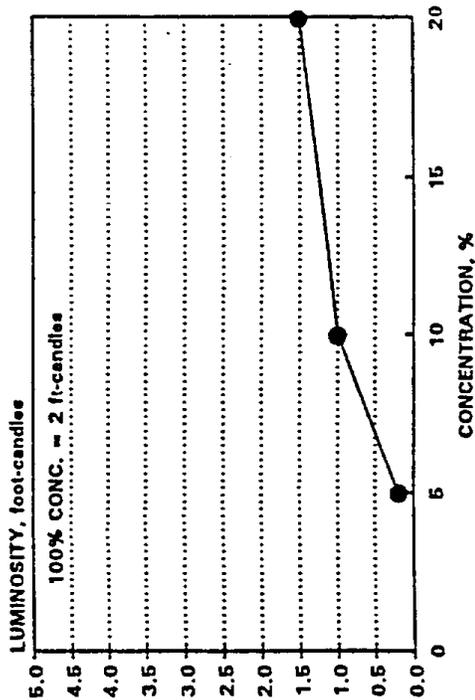
CYCLOHEXENE



CYCLOPENTENE



DICYCLOPENTADIENE



PHENYL-CYCLOHEXANE

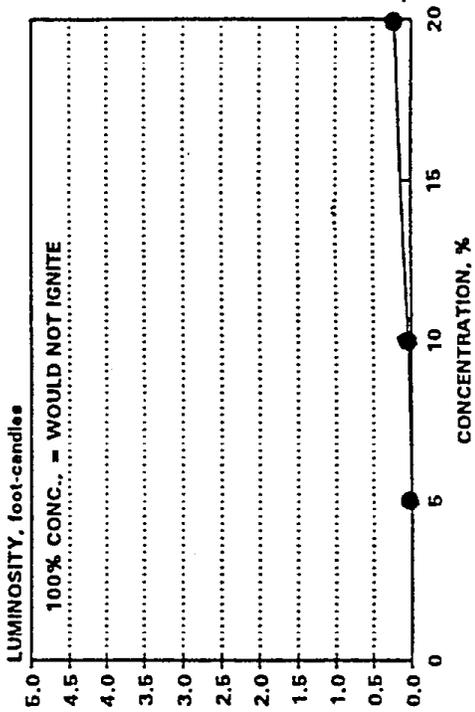
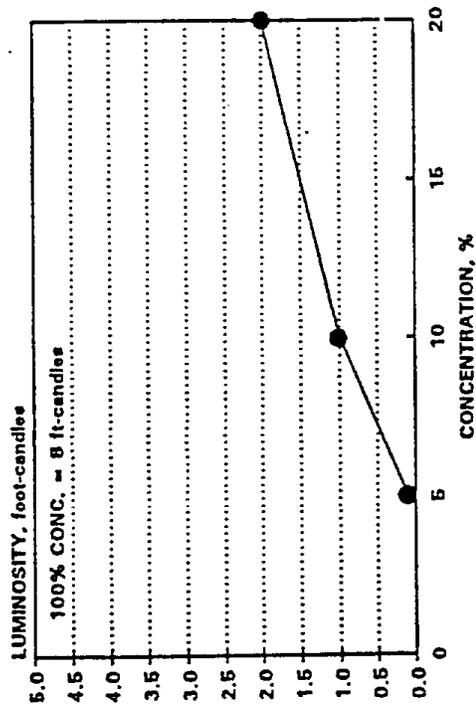
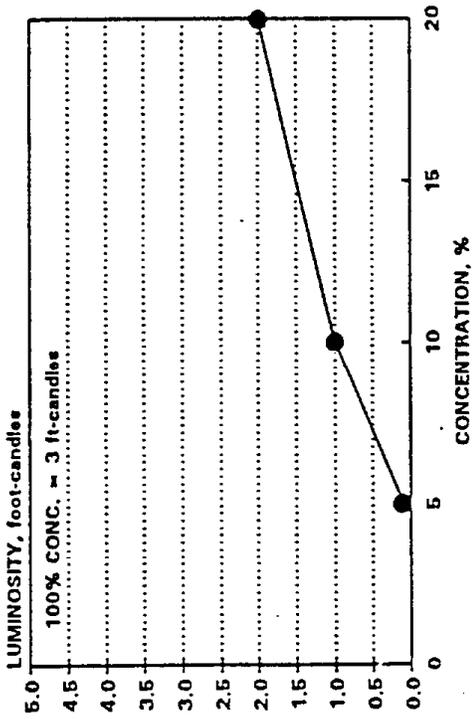


FIGURE A-14. LUMINOSITY CURVES FOR HYDROCARBON GRADE DCPD, POLYESTER GRADE DCPD, POLYESTER GRADE DCPD, DICYCLOPENTADIENE 97, AND DP6-46

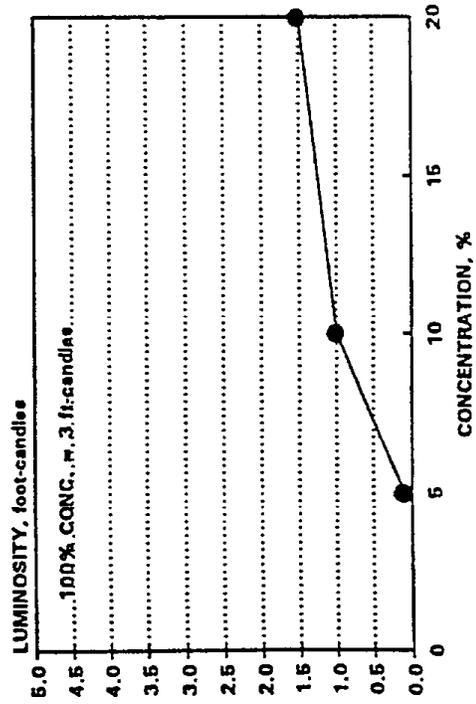
HYDROCARBON GRADE DCPD



POLYESTER GRADE DCPD



DICYCLOPENTADIENE 97



DP6-46

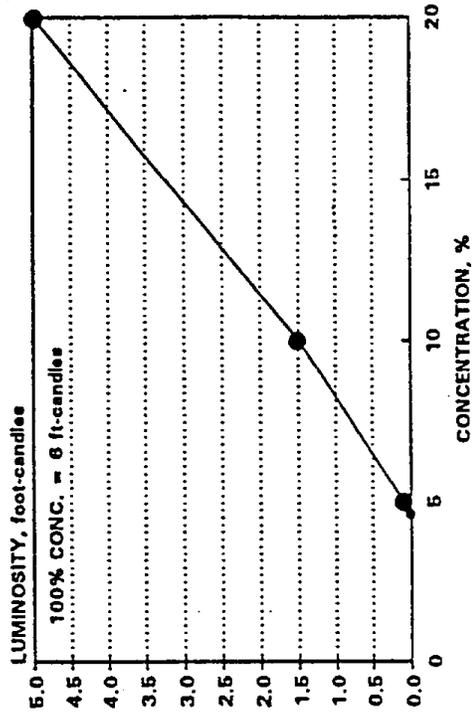
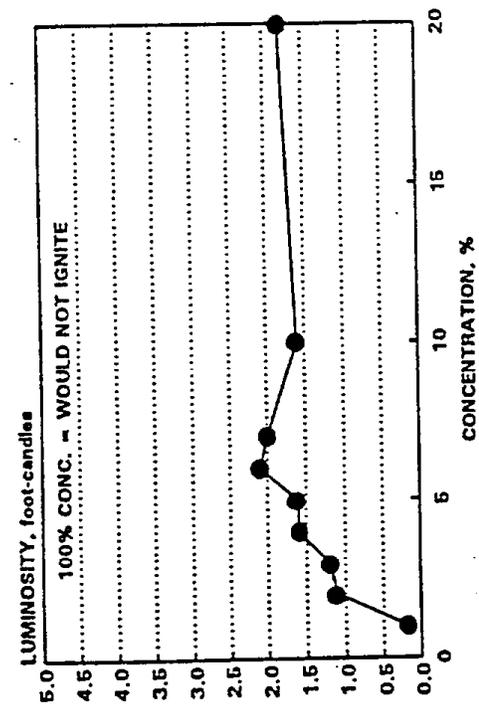
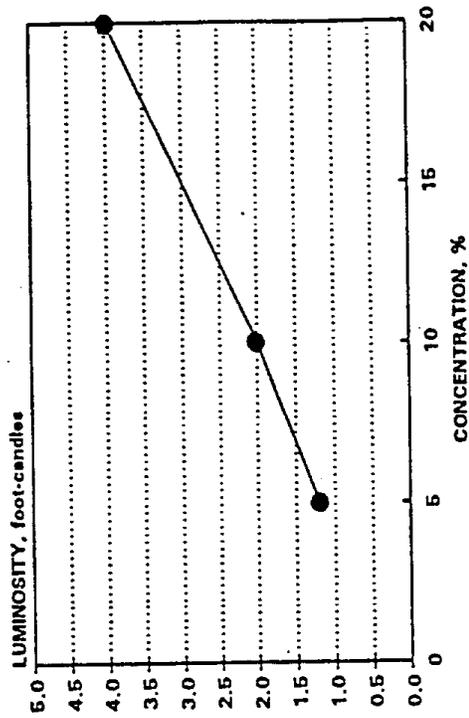


FIGURE A-15. LUMINOSITY CURVES FOR INDAN, INDENE, 1-INDANONE, AND DP5-160

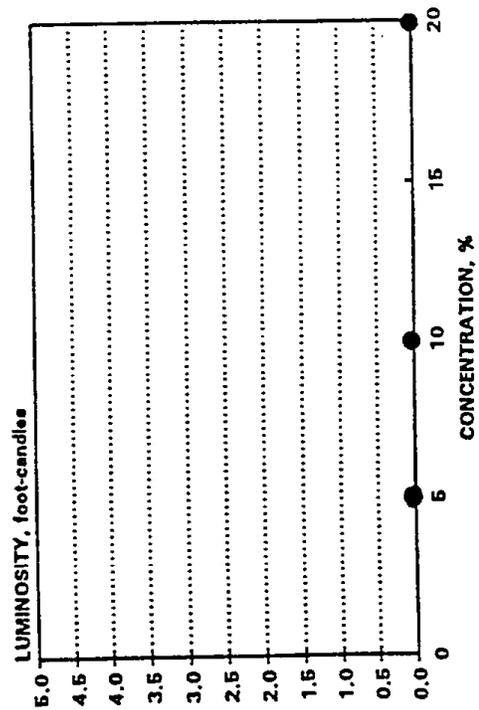
INDAN



INDENE



1-INDANONE



DP5-160

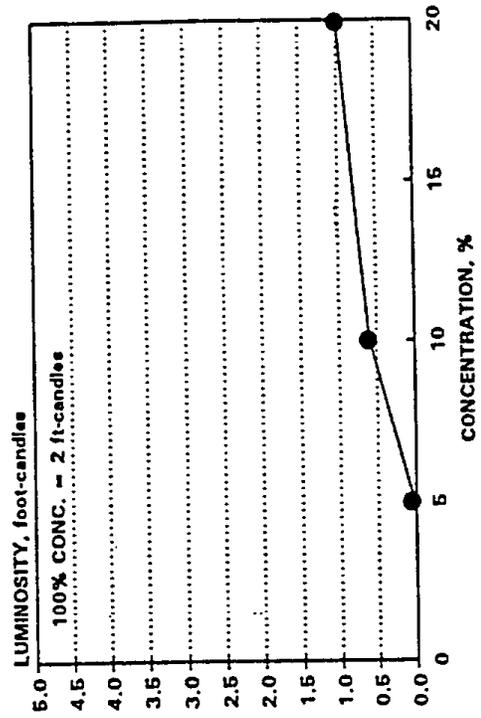


FIGURE A-16. LUMINOSITY CURVES FOR TOLUENE, MESITYLENE, *s*-BUTYLBENZENE, AND PENTAMETHYLBENZENE

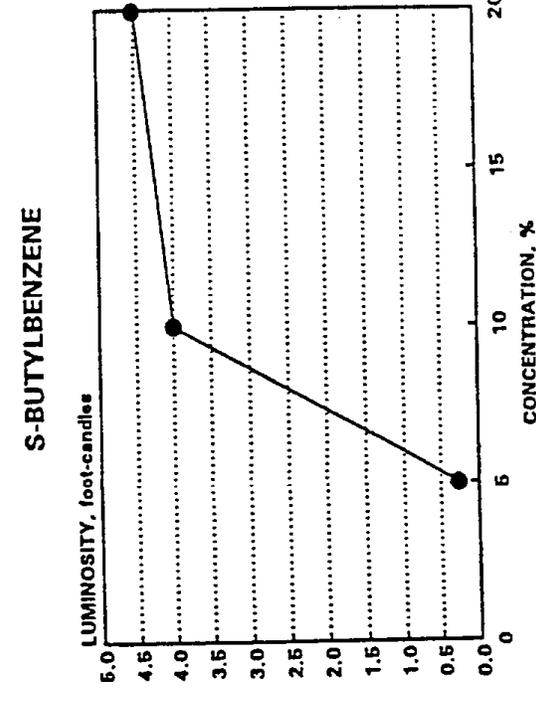
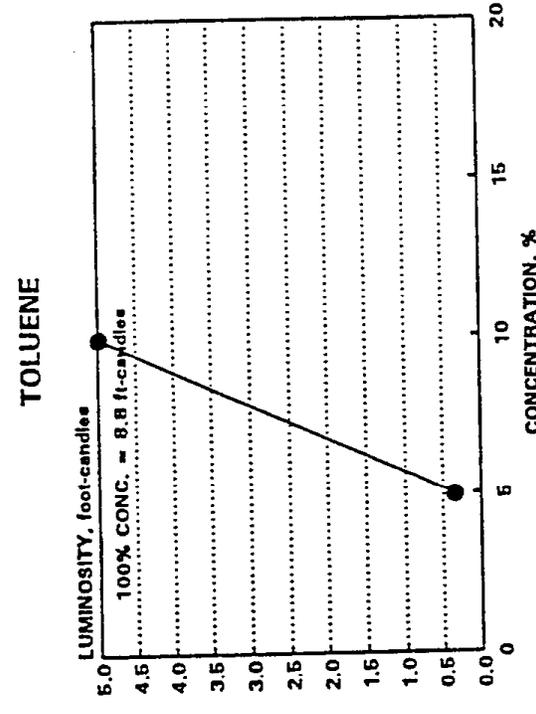
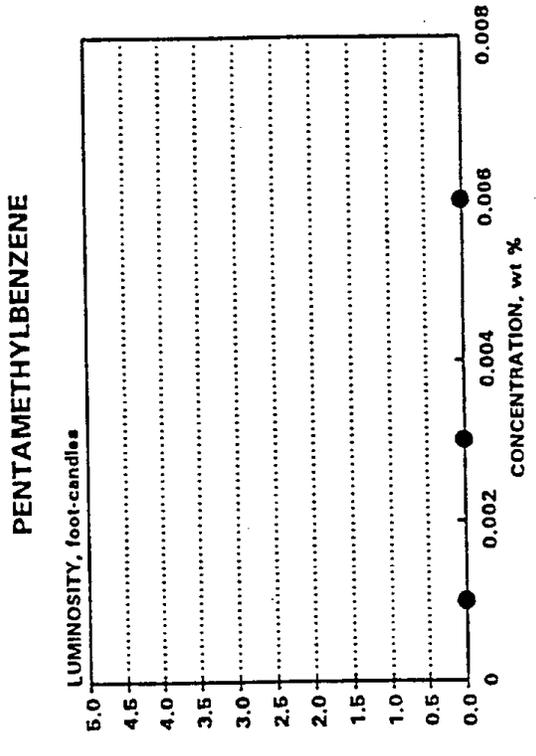
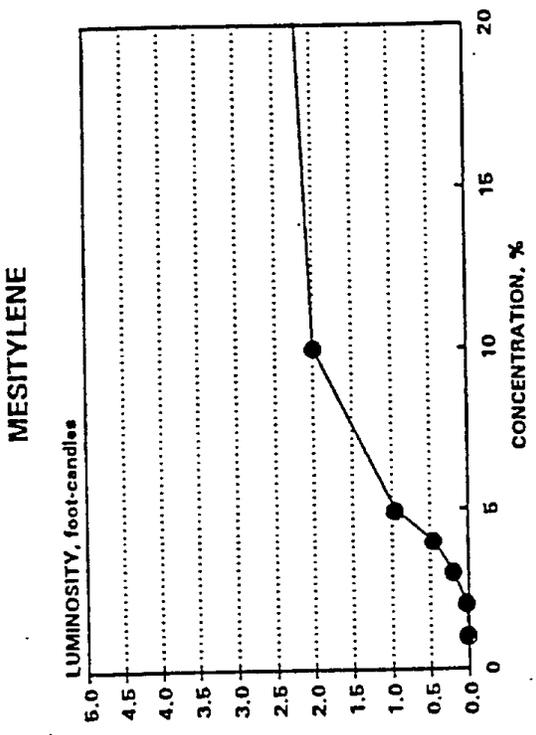
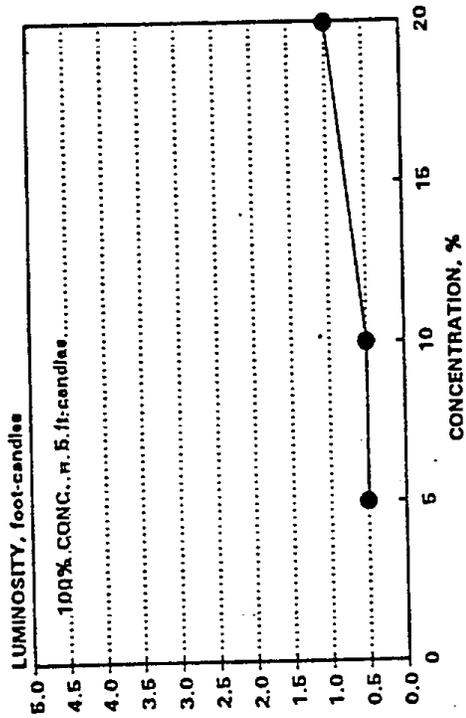
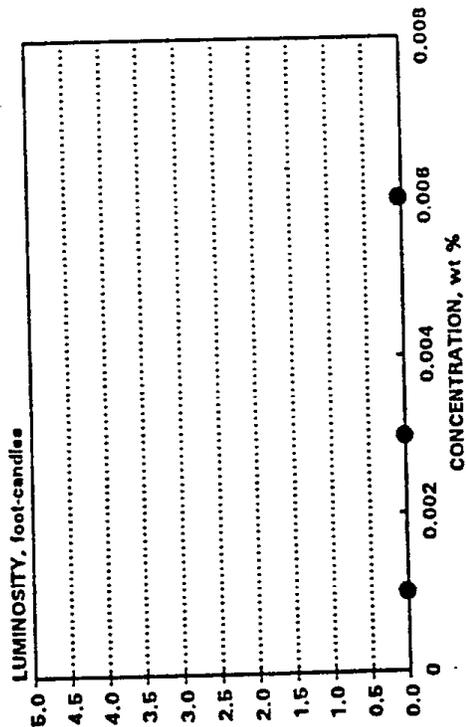


FIGURE A-17. LUMINOSITY CURVES FOR PENTAMETHYLBENZALDEHYDE,
 BENALDEHYDE, BENZOIC ACID, 1,2,4,5-BENZENETETRA CARBOXYLIC ACID

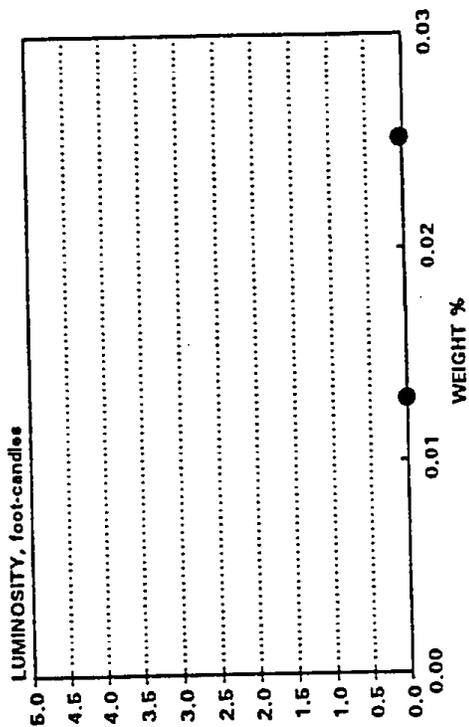
BENZALDEHYDE



PENTAMETHYLBENZALDEHYDE



1,2,4,5-BENZENETETRA CARBOXYLIC ACID



BENZOIC ACID

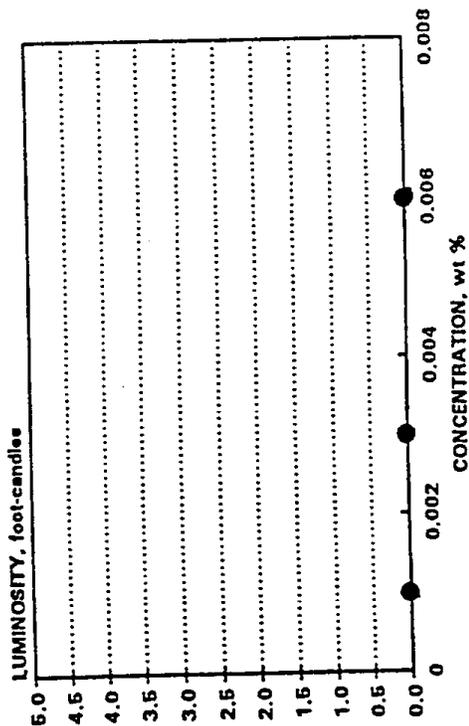
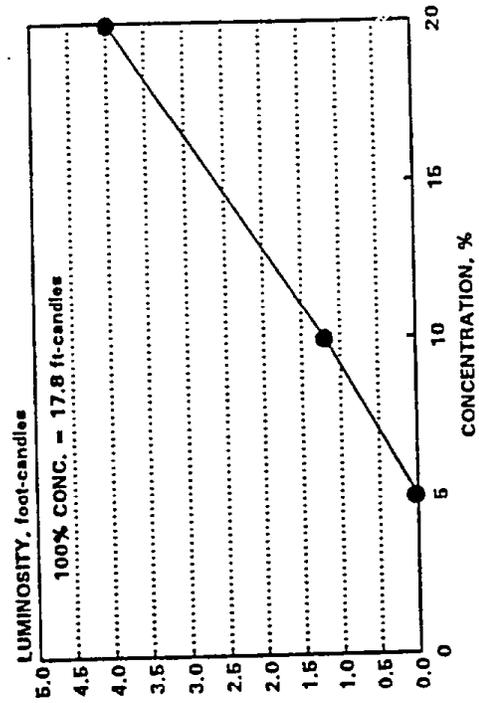
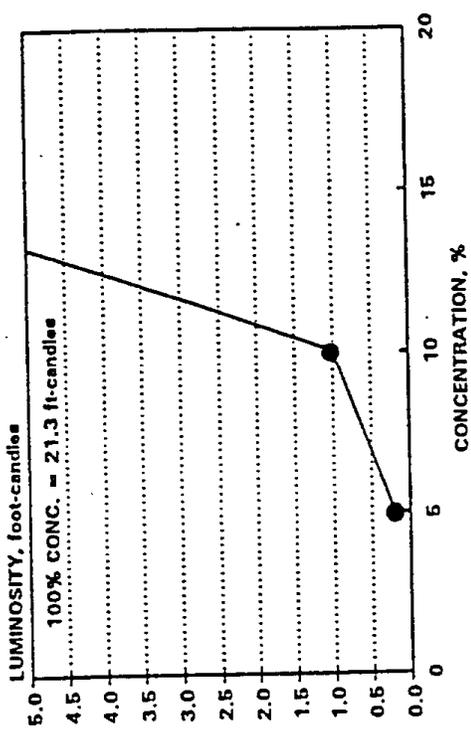


FIGURE A-18. LUMINOSITY CURVES FOR CYCLOHEXANE, CYCLOPENTANE, METHYLCYCLOPENTANE, AND CYCLOOCTANE

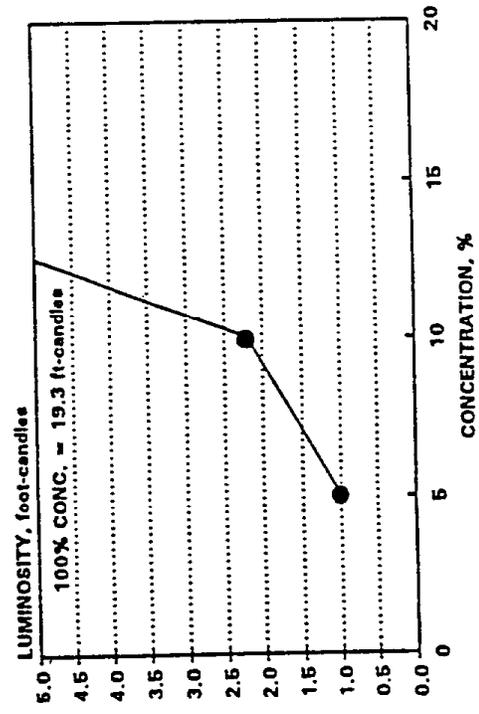
CYCLOHEXANE



CYCLOPENTANE



METHYLCYCLOPENTANE



CYCLOOCTANE

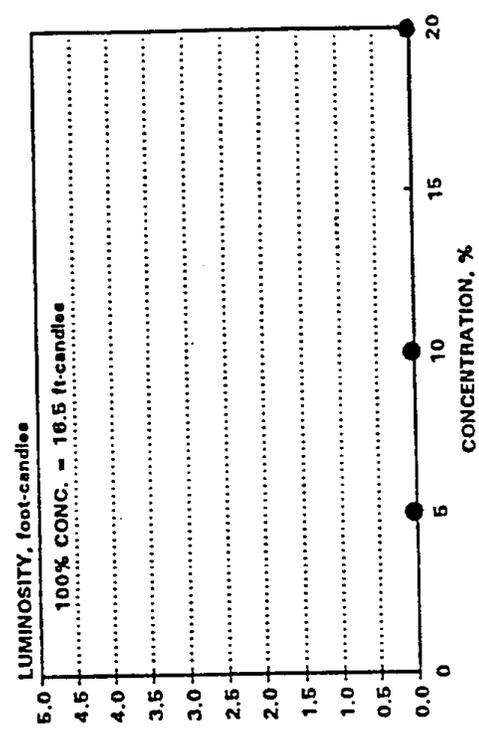
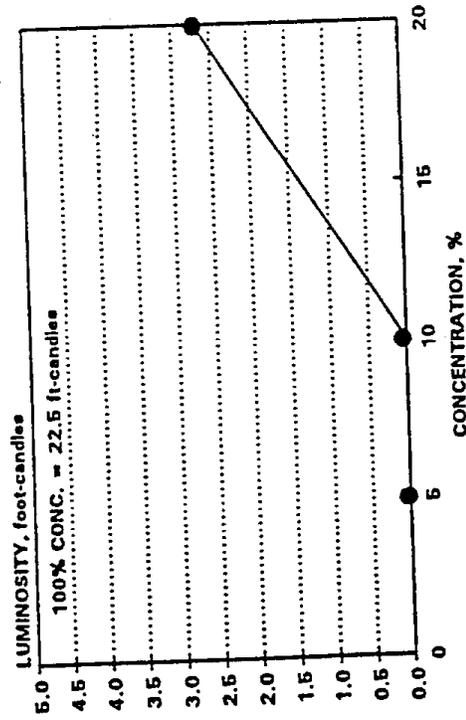
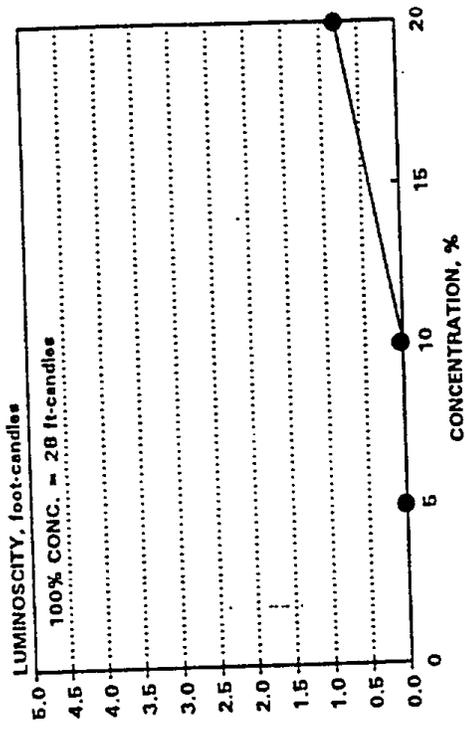


FIGURE A-19. LUMINOSITY CURVES FOR HEXANE, PENTANE, HEPTANE, AND OCTANE

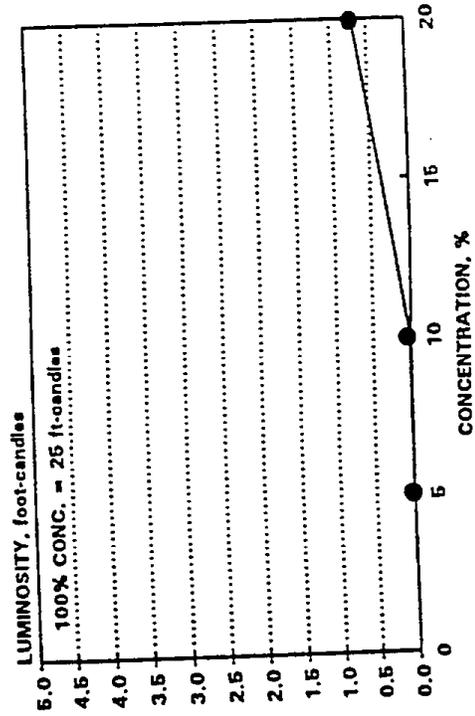
HEXANE



PENTANE



HEPTANE



OCTANE

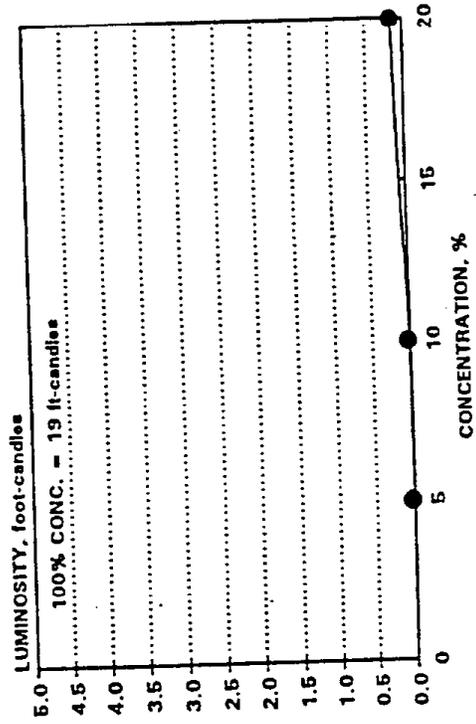
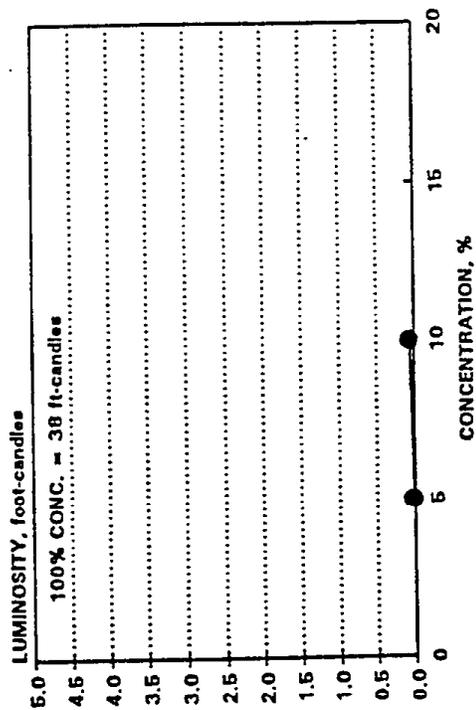
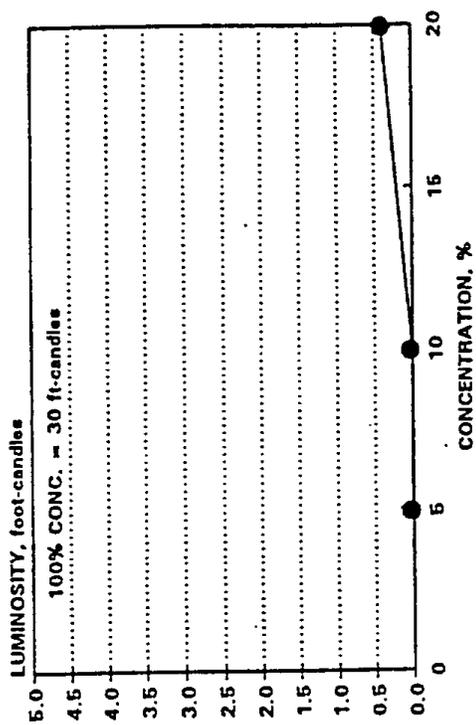


FIGURE A-20. LUMINOSITY CURVES FOR 3-METHYLPENTANE, ISOPENTANE, 2,2-DIMETHYLBUTANE, AND ISOCTANE

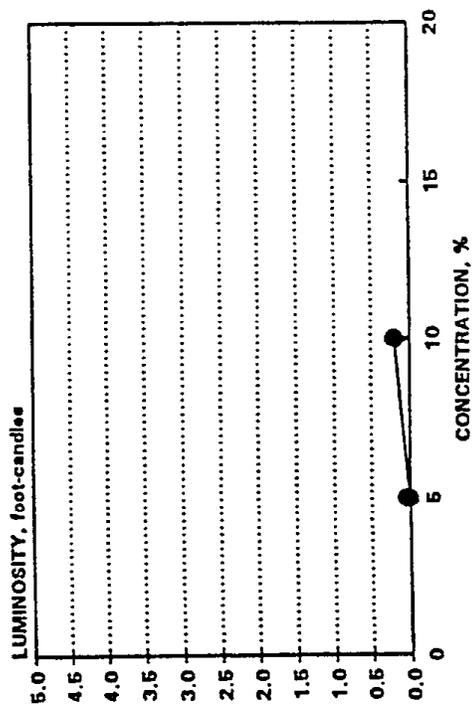
3-METHYLPENTANE



ISOPENTANE



2,2-DIMETHYLBUTANE



ISOCTANE

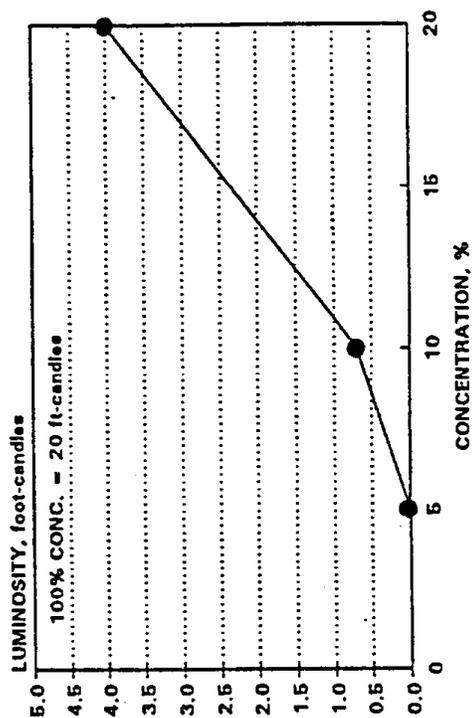
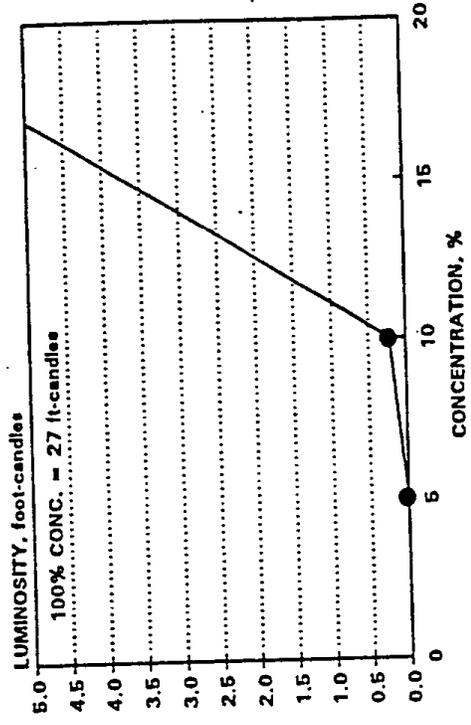
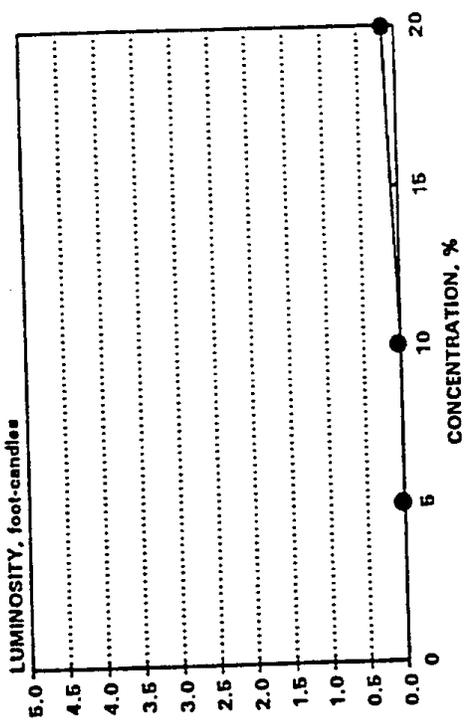


FIGURE A-21. LUMINOSITY CURVES FOR 2-METHYL-2-PENTENE,
2-METHYL-1-PENTENE, 4-METHYL-2-PENTENE, AND cis-2-PENTENE

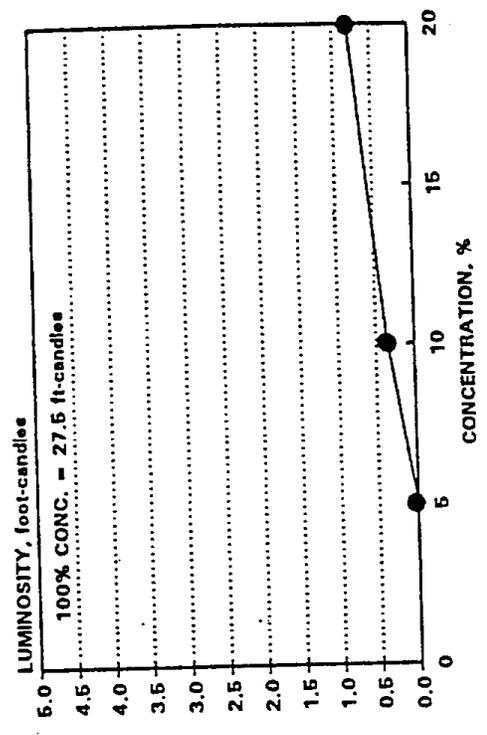
2-METHYL-1-PENTENE



2-METHYL-2-PENTENE



CIS-2-PENTENE



4-METHYL-2-PENTENE

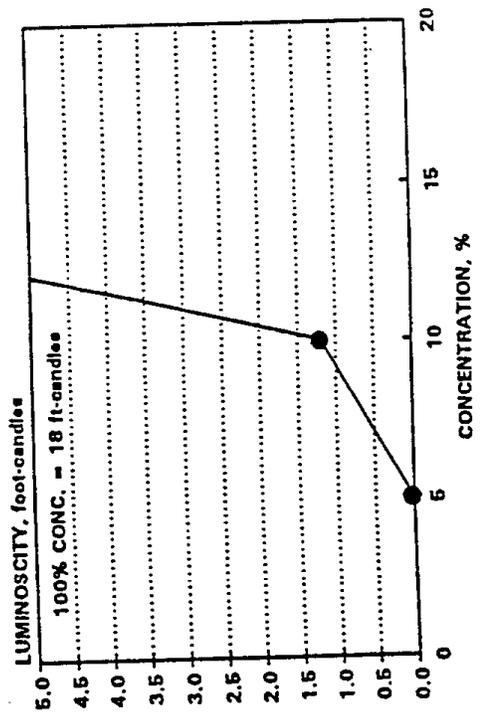
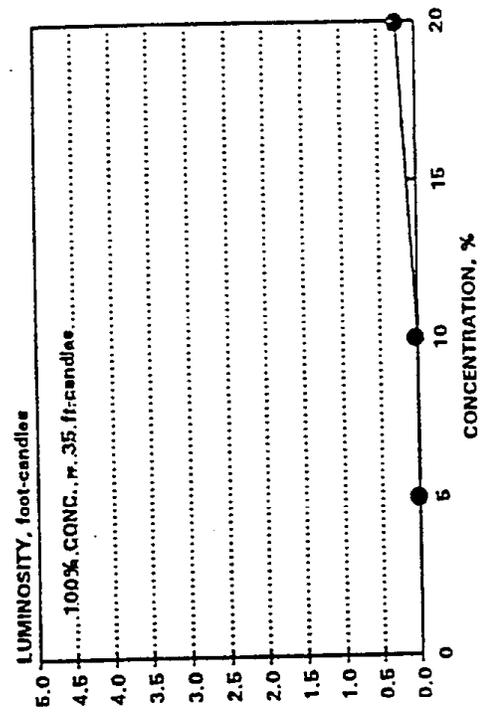
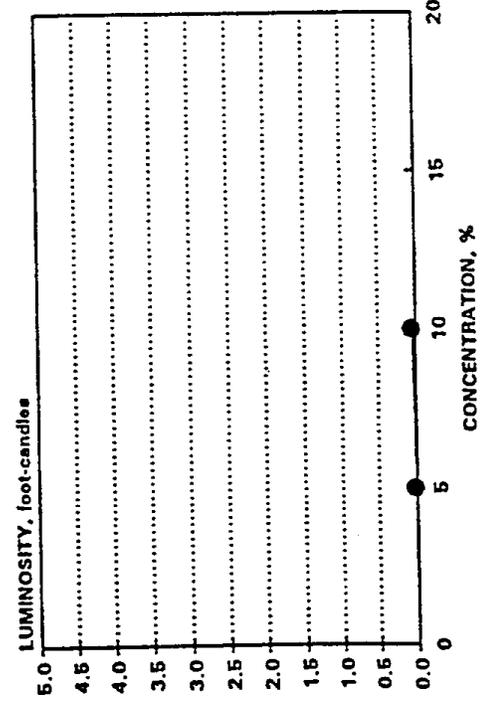


FIGURE A-22. LUMINOSITY CURVES FOR 1-PENTENE, 2,4,4-TRIMETHYL-1-PENTANE,
2-METHYL-1-BUTENE, AND 2-METHYL-2-BUTENE

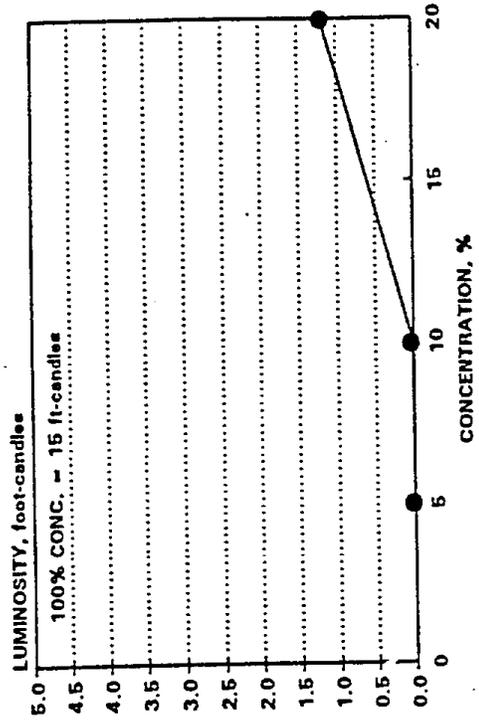
1-PENTENE



2-METHYL-1-BUTENE



2,4,4-TRIMETHYL-1-PENTANE



2-METHYL-2-BUTENE

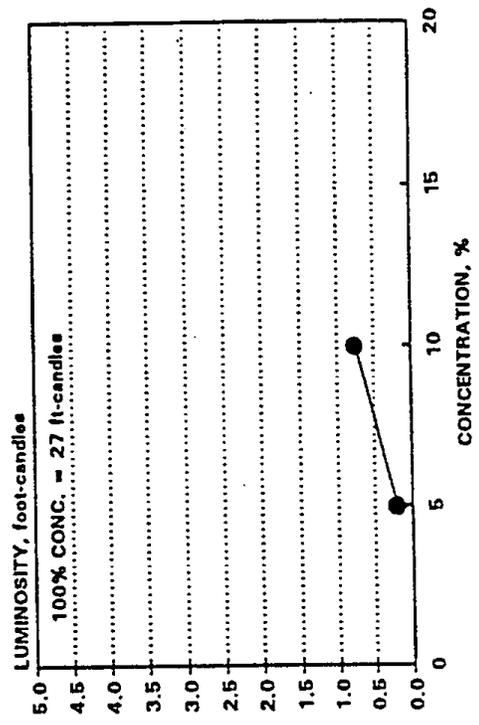
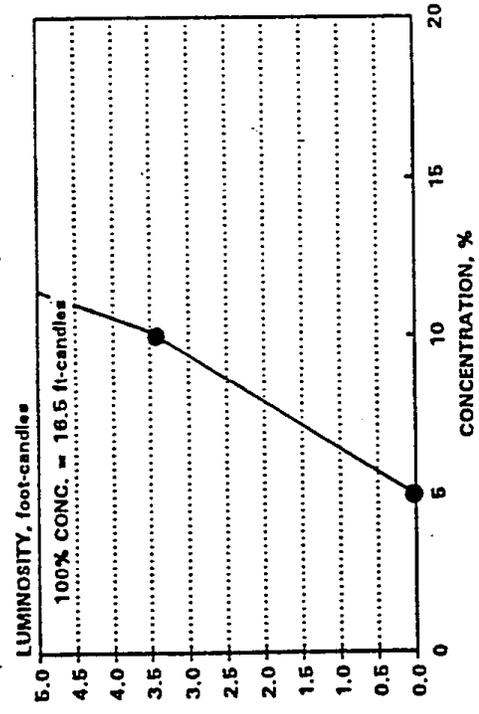
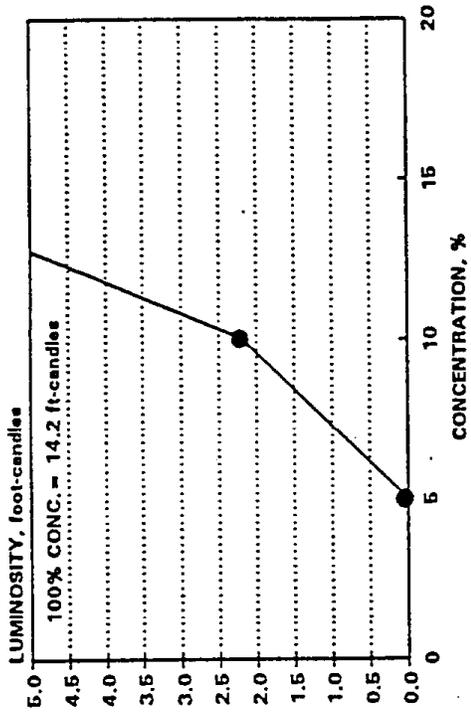


FIGURE A-23. LUMINOSITY CURVES FOR 1-PENTYNE, 1-HEXYNE, ACETONITRILE,
AND DIETHANOLAMINE

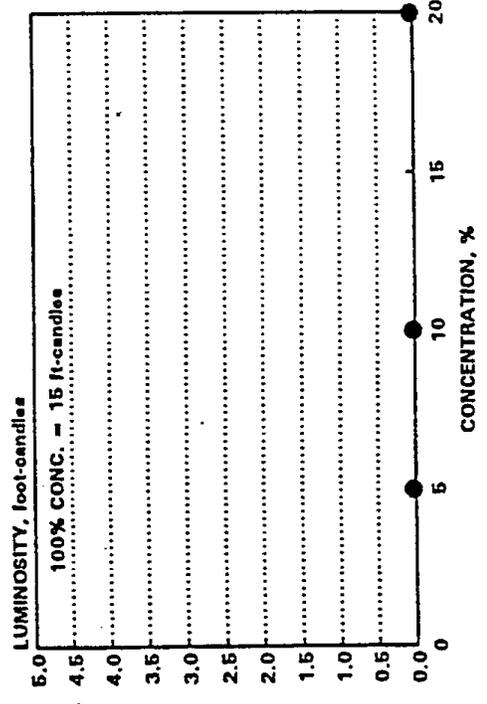
1-PENTYNE



1-HEXYNE



ACETONITRILE



DIETHANOLAMINE

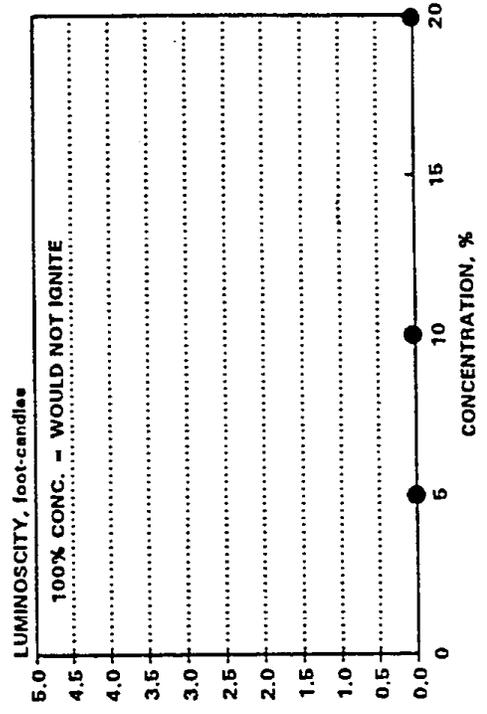
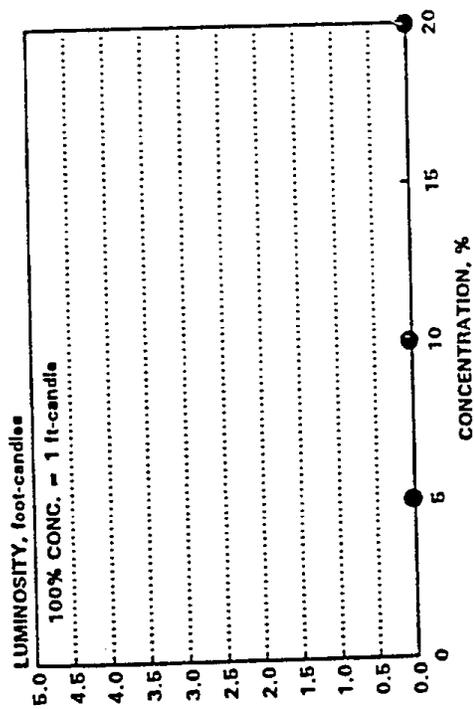
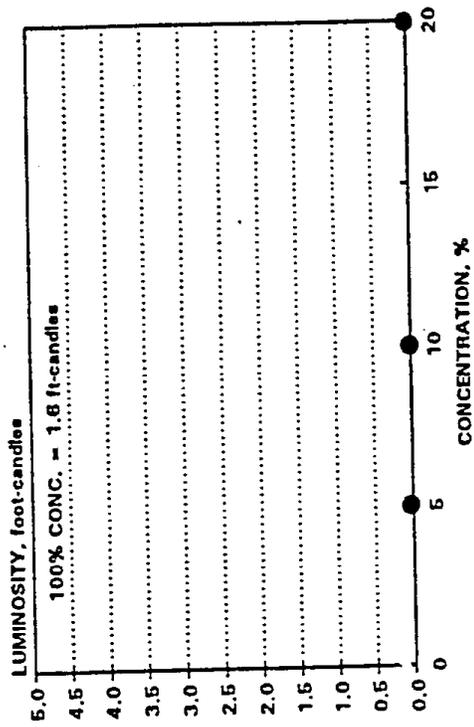


FIGURE A-24. LUMINOSITY CURVES FOR ETHANOL, ETHYL FORMATE, ETHYL ACETOACETATE, AND ETHYL ACETATE

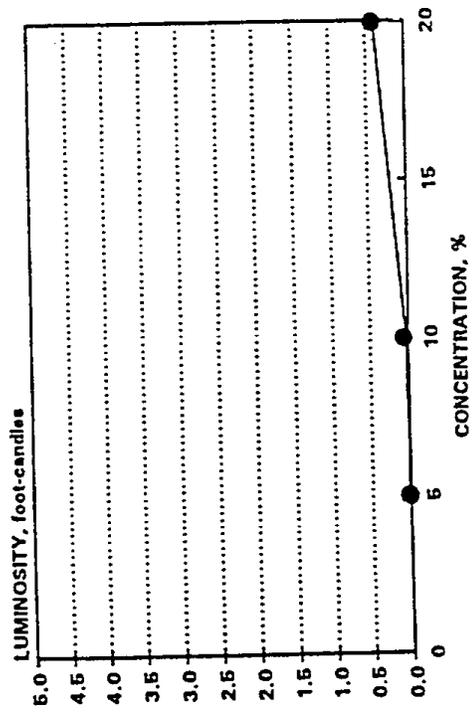
ETHANOL



ETHYL FORMATE



ETHYL ACETOACETATE



ETHYL ACETATE

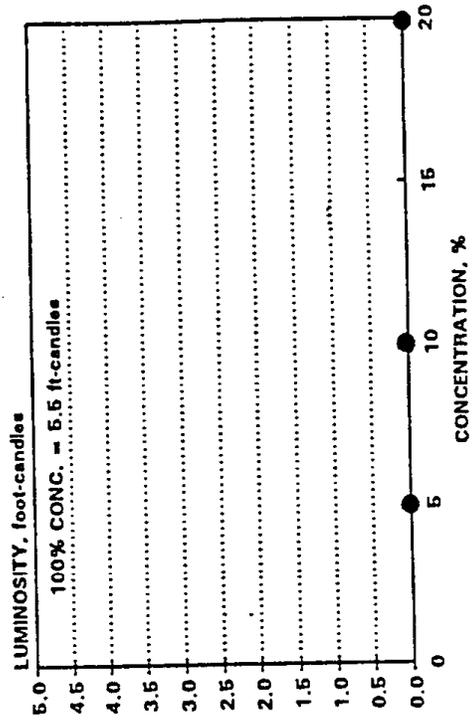
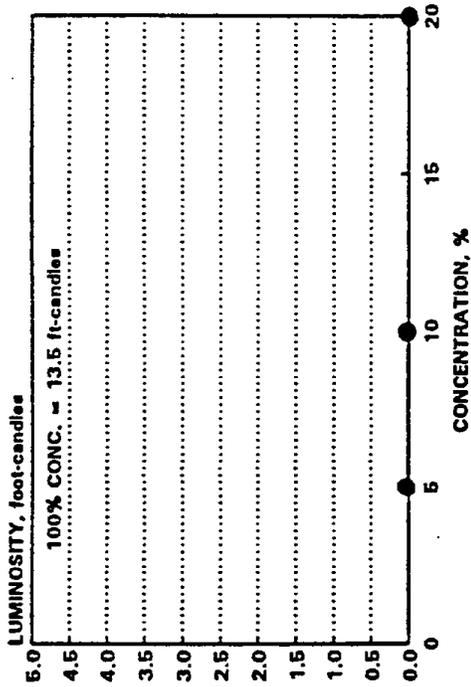
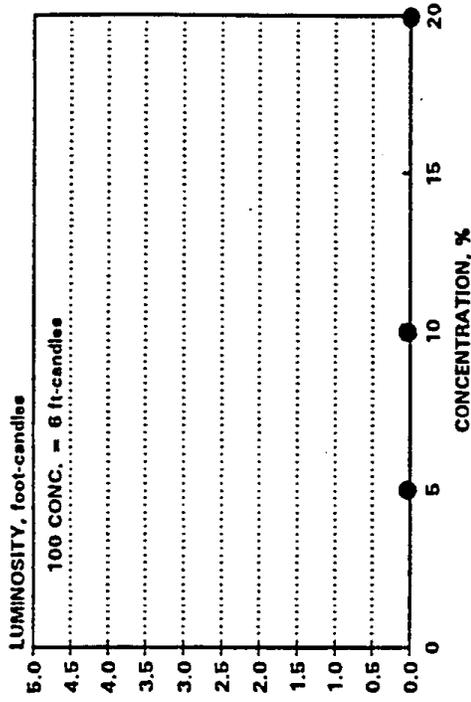


FIGURE A-25. LUMINOSITY CURVES FOR ISOPROPANOL, 1-PROPANOL, t-BUTYL ALCOHOL, AND n-BUTANOL

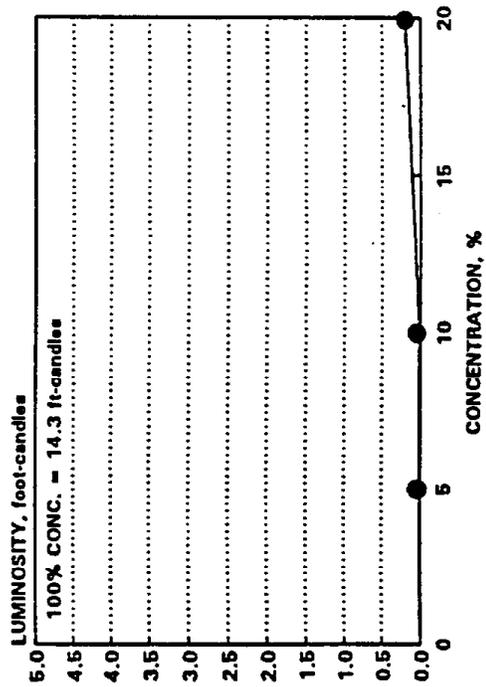
ISOPROPANOL



1-PROPANOL



T-BUTYL ALCOHOL



n-BUTANOL

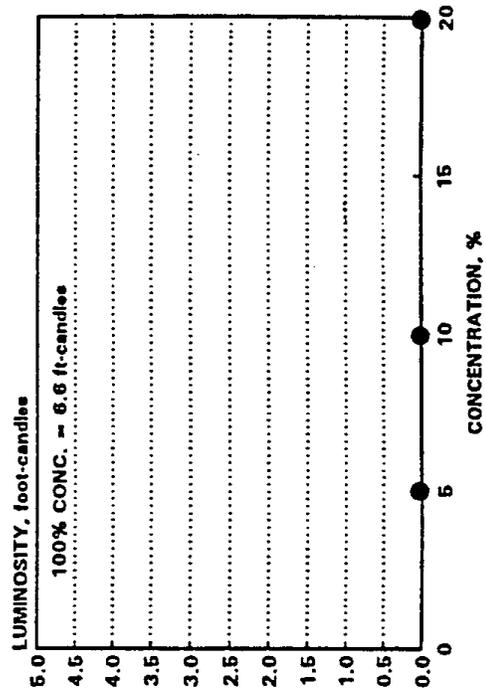
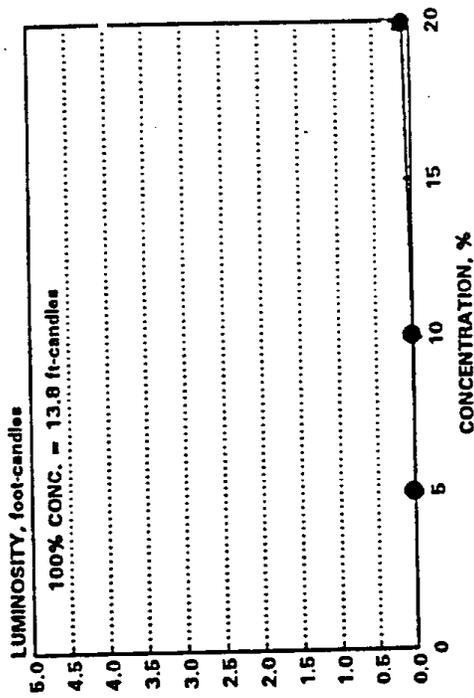
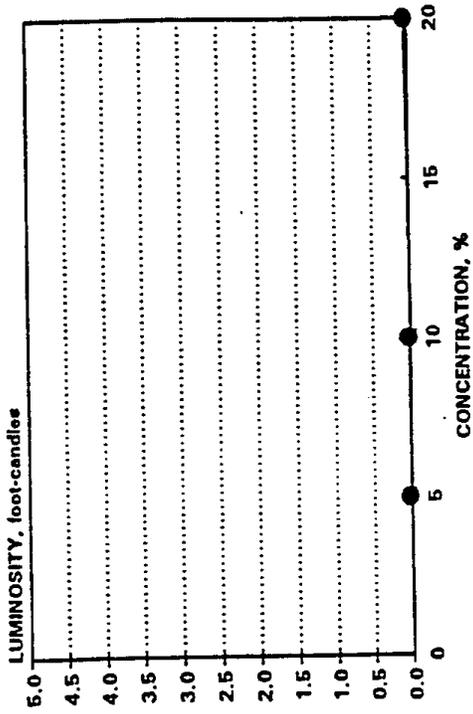


FIGURE A-26. LUMINOSITY CURVES FOR t-AMYL ALCOHOL, t-AMYL METHYL ETHER, DIETHYL ETHER, AND ACETONE

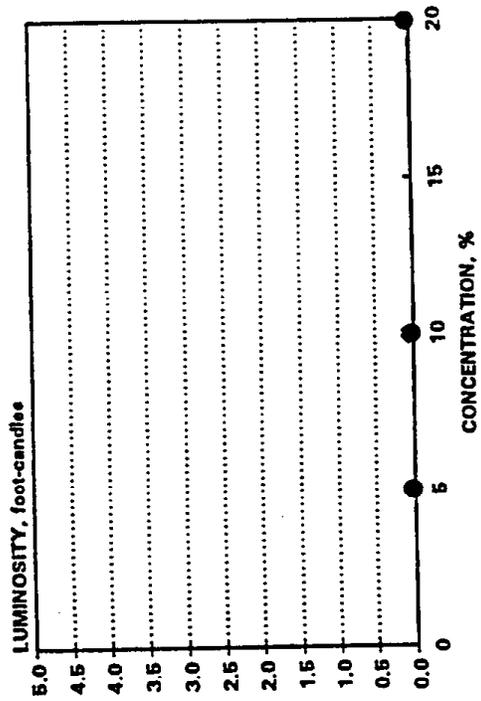
T-AMYL ALCOHOL



T-AMYL METHYL ETHER



DIETHYL ETHER



ACETONE

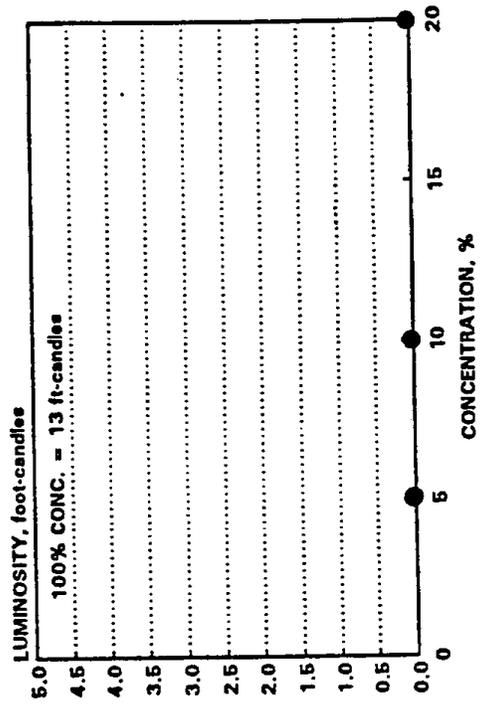
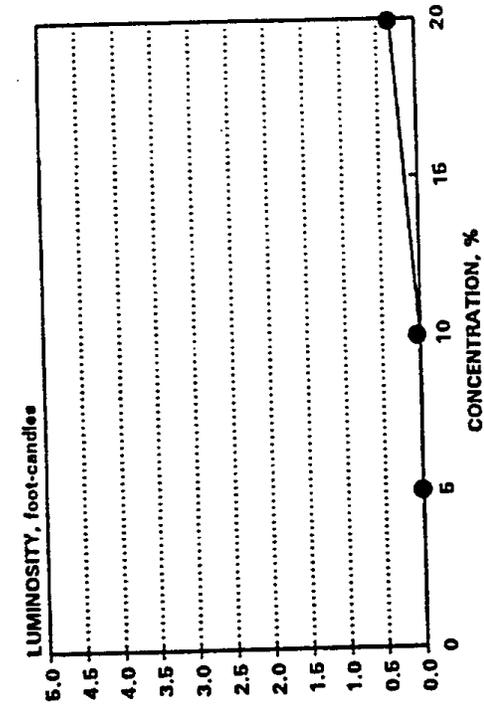
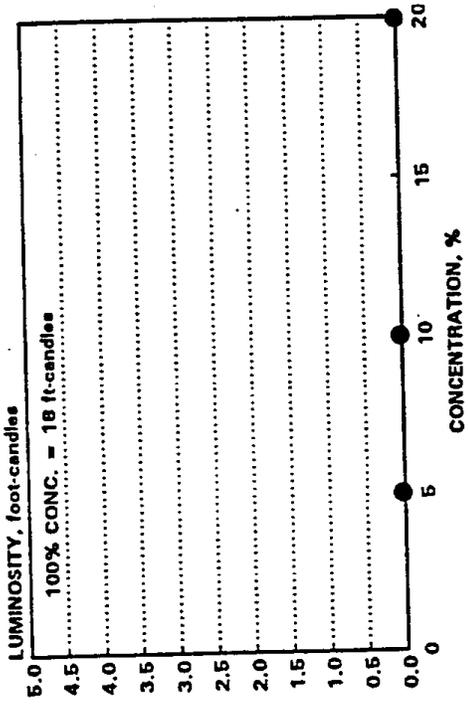


FIGURE A-27. LUMINOSITY CURVES FOR METHYL-t-BUTYL ETHER, BUTYLETHYL ETHER, t-BUTYLETHYL ETHER, AND BUTYL ETHER

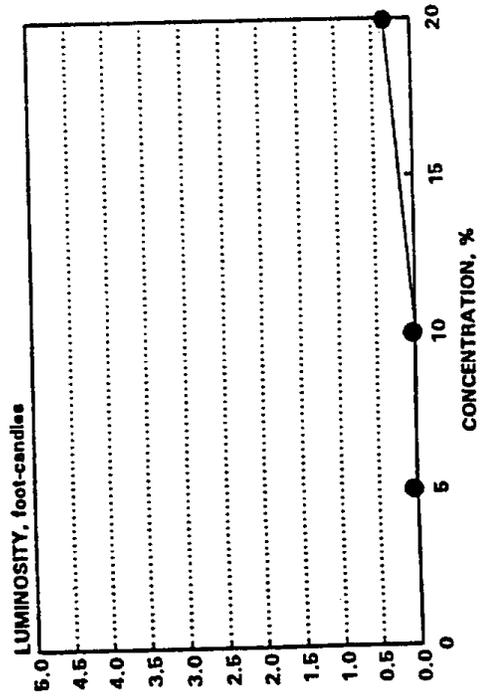
METHYL-T-BUTYL-ETHER



BUTYLETHYL ETHER



t-BUTYLETHYL ETHER



BUTYL ETHER

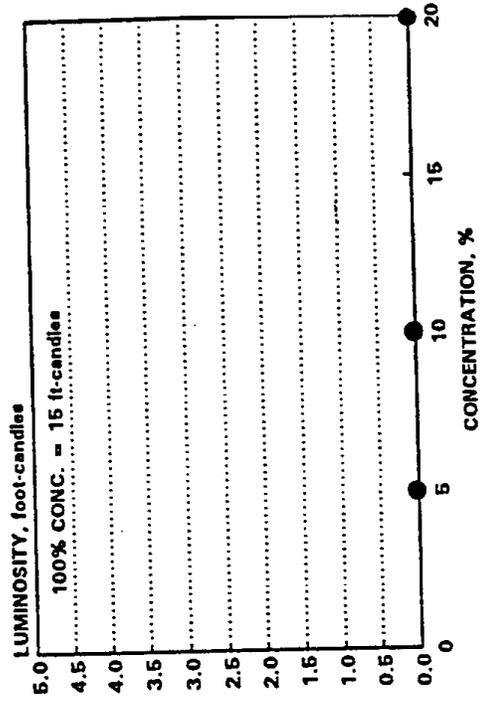
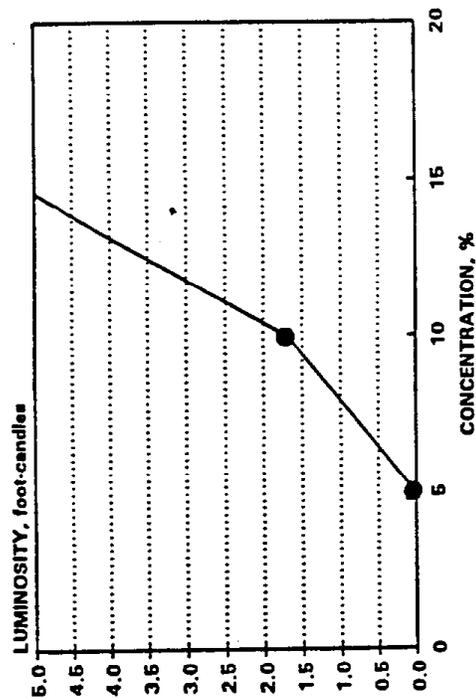
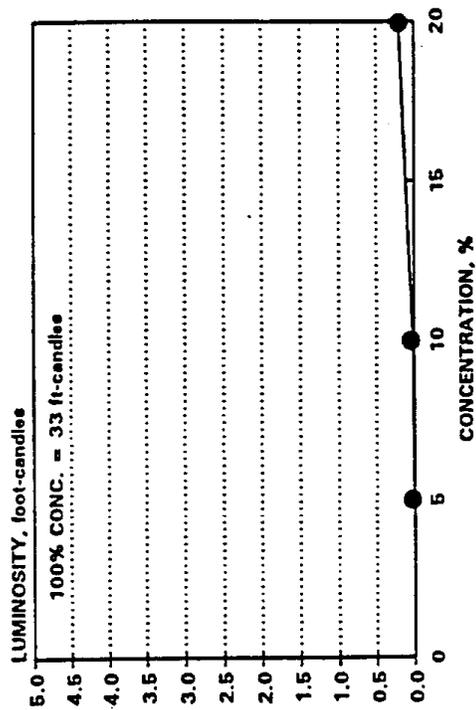


FIGURE A-28. LUMINOSITY CURVES FOR PYRROLE, PYRROLIDINE, PIPERIDINE, AND PYRROLIDINONE

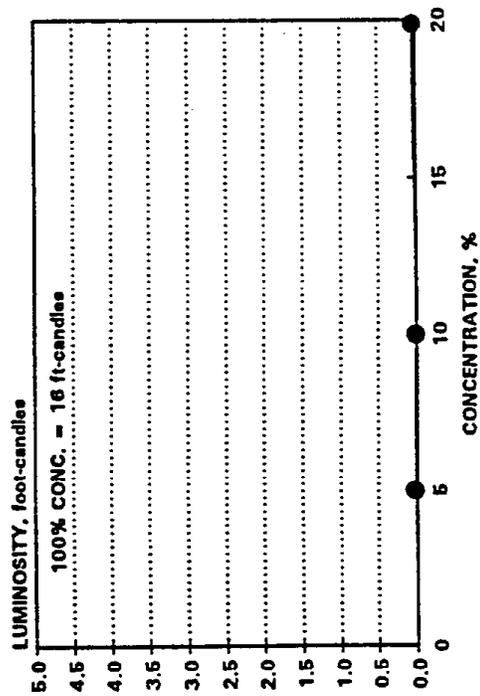
PYRROLE



PYRROLIDINE



PIPERIDINE



PYRROLIDINONE

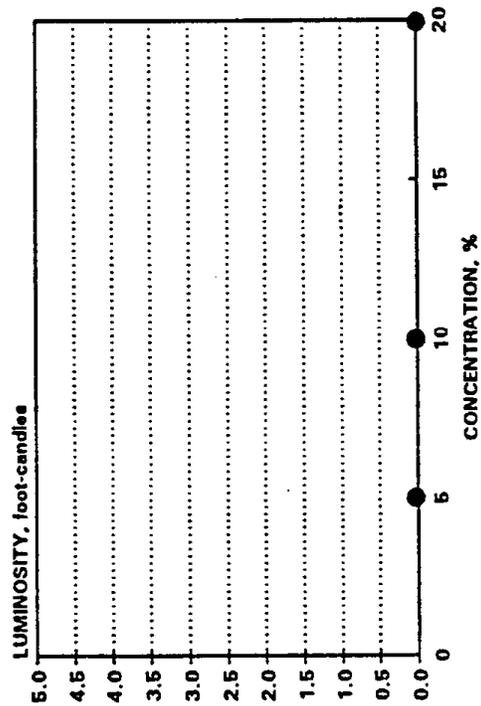
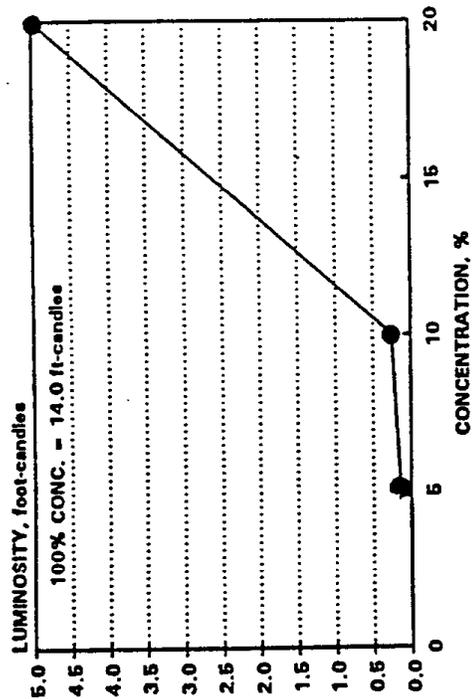
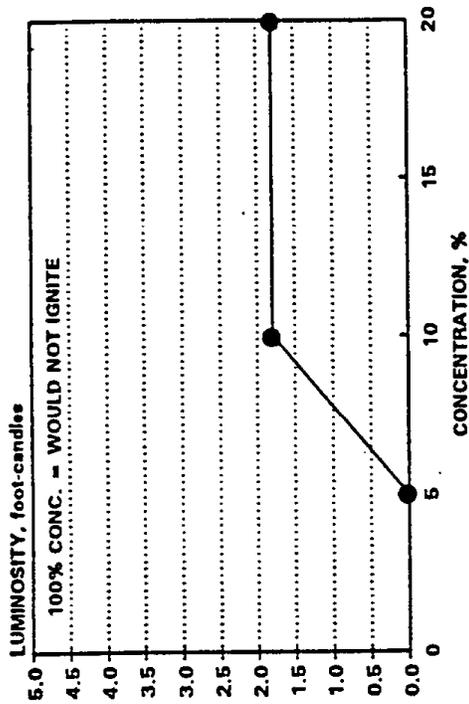


FIGURE A-29. LUMINOSITY CURVES FOR PYRIDINE, 4-4-BUTYLPYRIDINE, BENZOYL PYRIDINE, AND METHYL SULFOXIDE

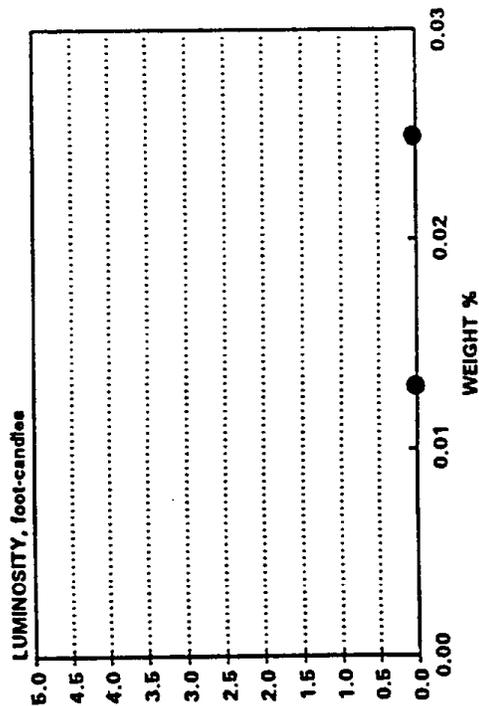
PYRIDINE



4-TERT-BUTYLPYRIDINE



BENZOYL PYRIDINE



METHYL SULFOXIDE

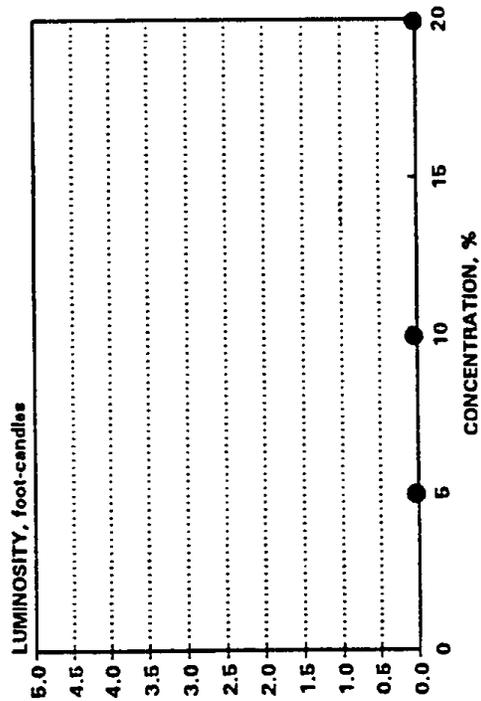
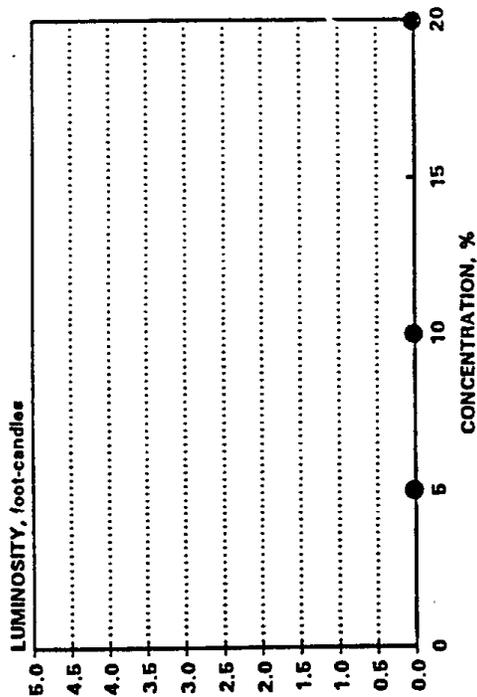
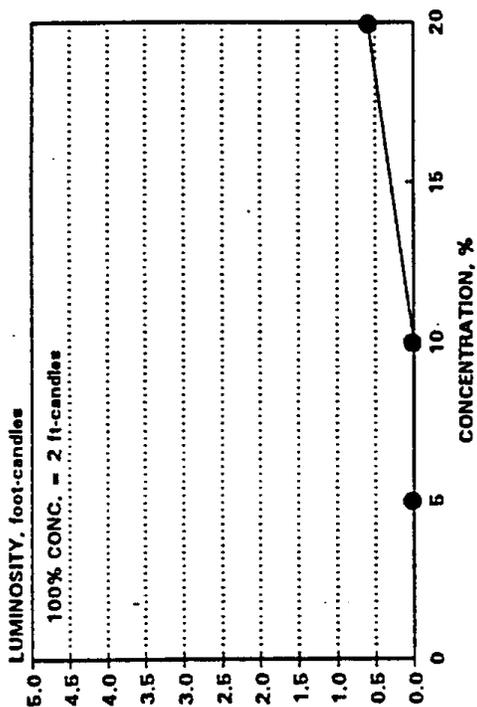


FIGURE A-30. LUMINOSITY CURVES FOR ANILINE, NITROBENZENE, FURFURYLAMINE, AND DICYCLOHEXYLAMINE

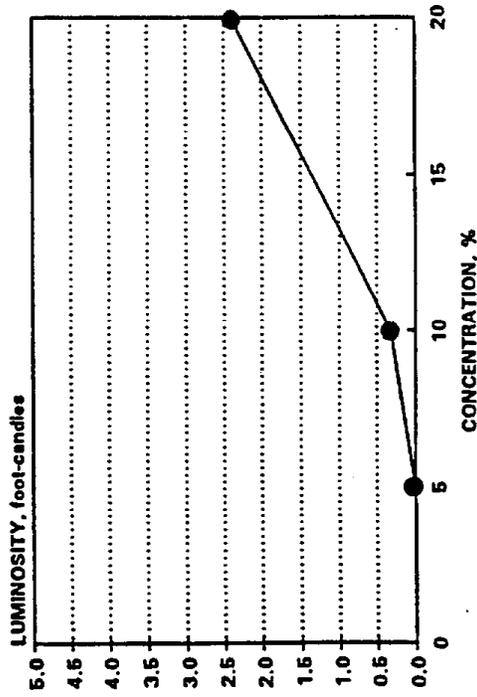
ANILINE



NITROBENZENE



FURFURYLAMINE



DICYCLOHEXYLAMINE

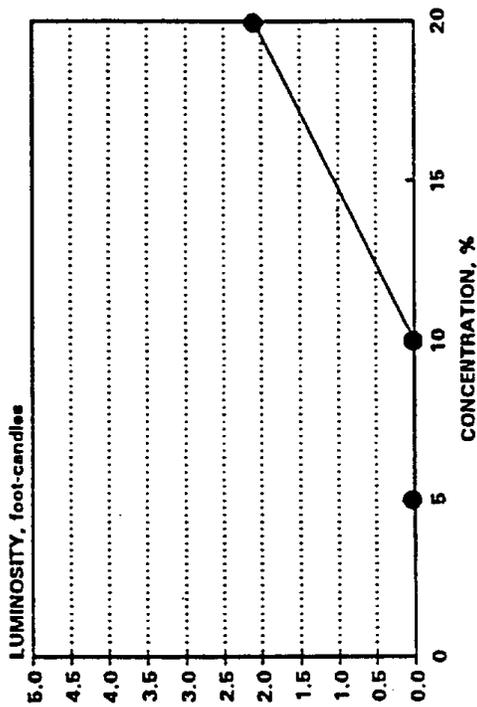


FIGURE A-31. LUMINOSITY CURVES FOR FURAN, TETRAHYDROFURAN,
N,N-DIMETHYLFORMAMIDE, AND FORMAMIDE

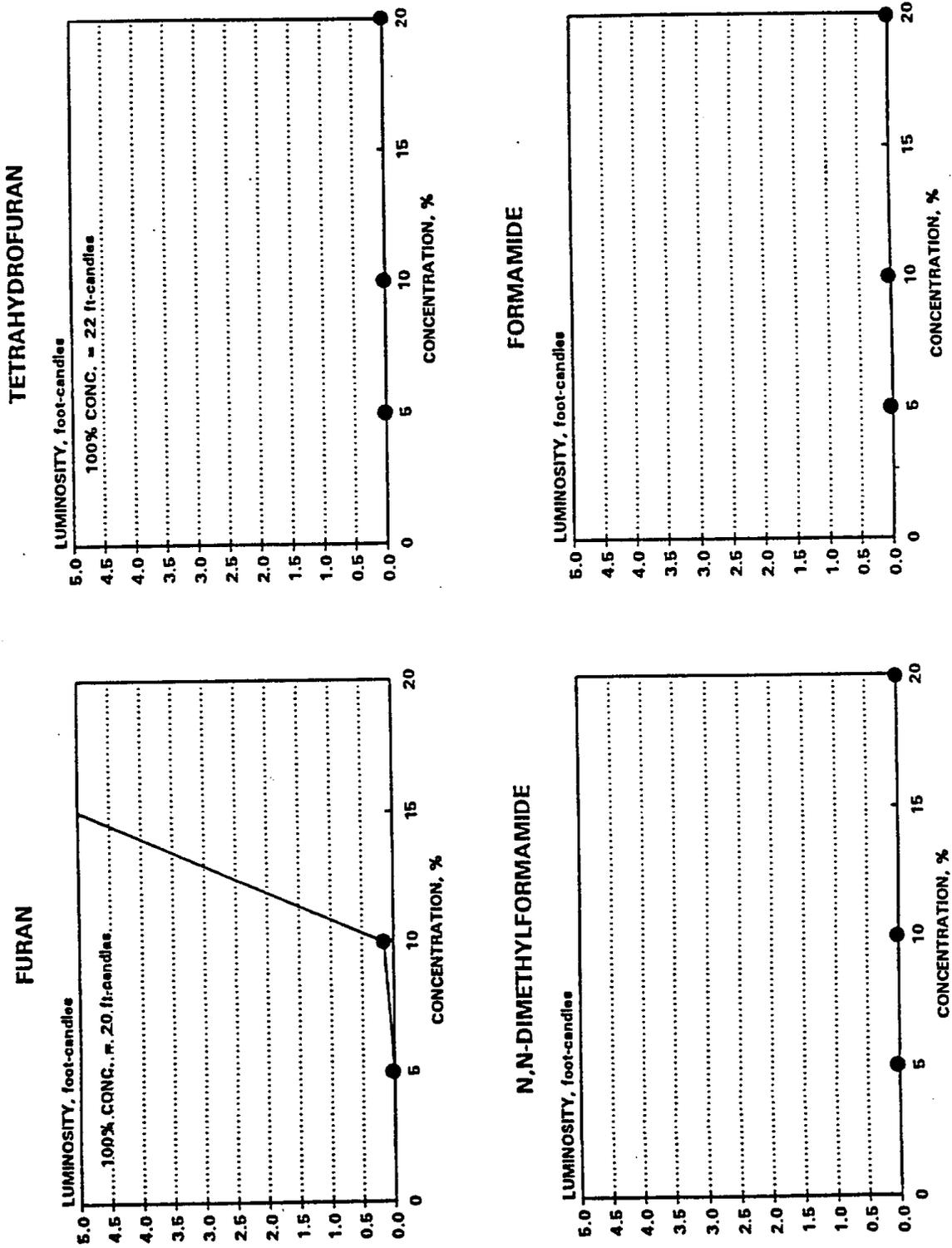
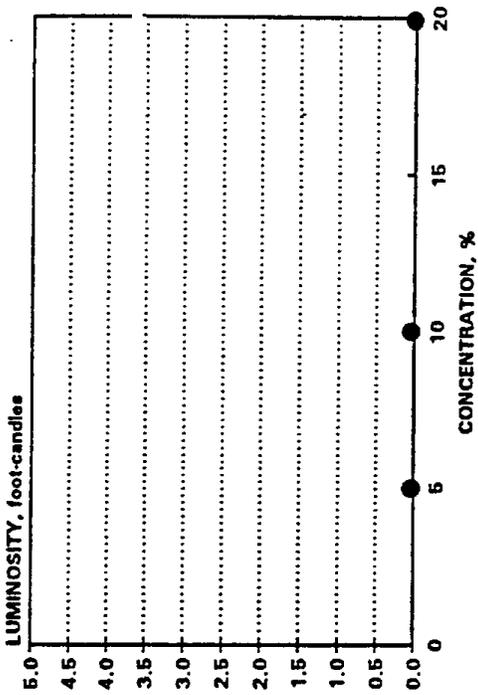
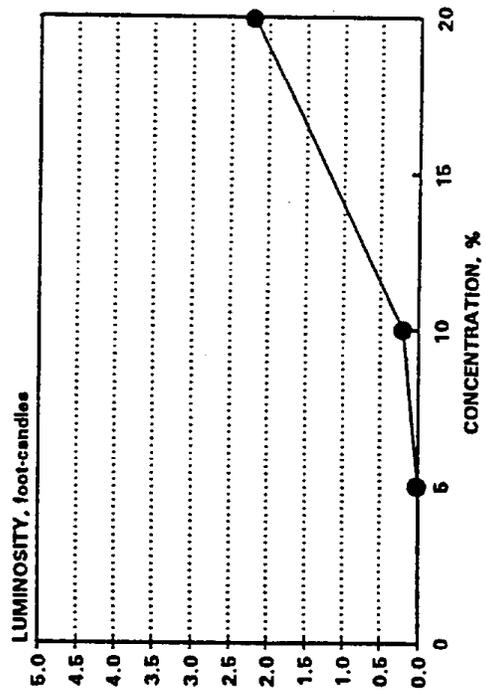


FIGURE A-32. LUMINOSITY CURVES FOR DIMETHYLNAPHTHALENE,
 TETRAHYDRONAPHTHALENE, DECAHYDRONAPHTHALENE, AND
 1-METHYLNAPHTHALENE

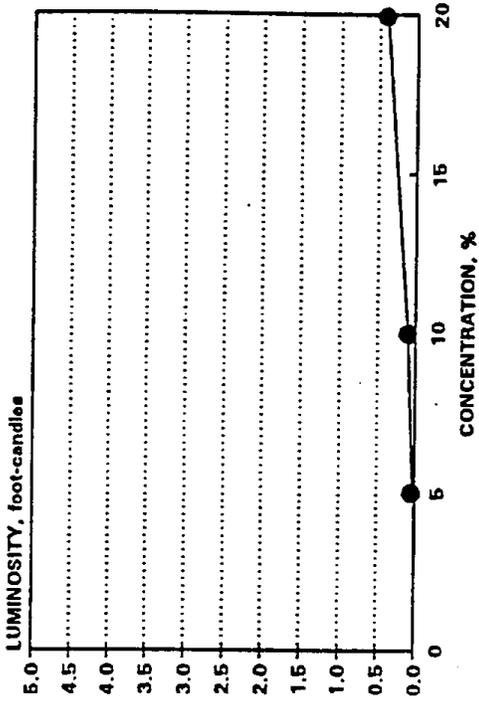
DIMETHYLNAPHTHALENE



DECAHYDRONAPHTHALENE



TETRAHYDRONAPHTHALENE



1-METHYLNAPHTHALENE

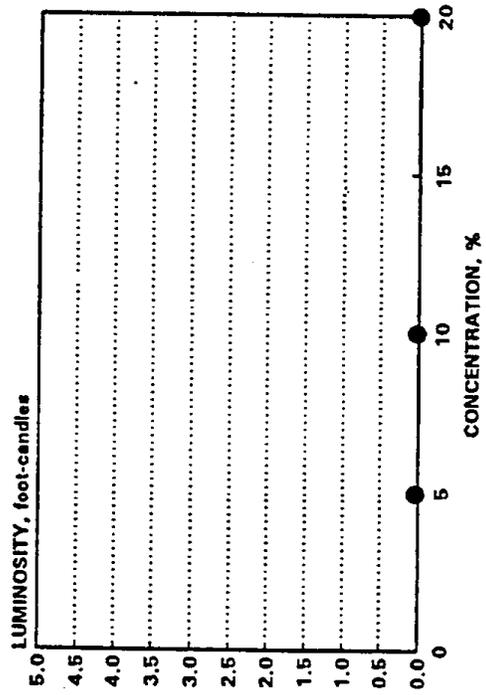
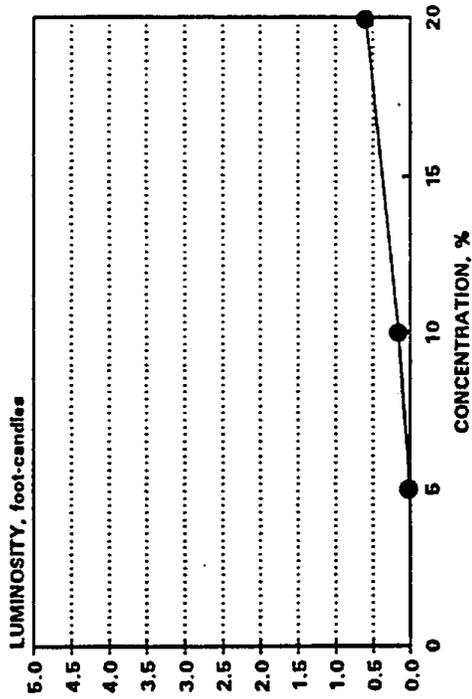
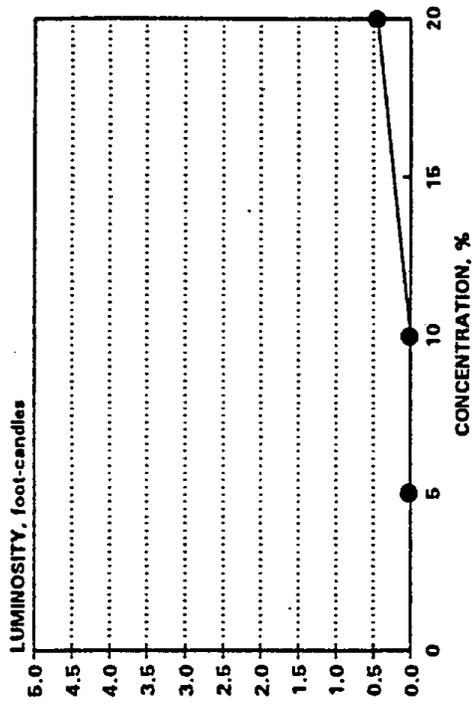
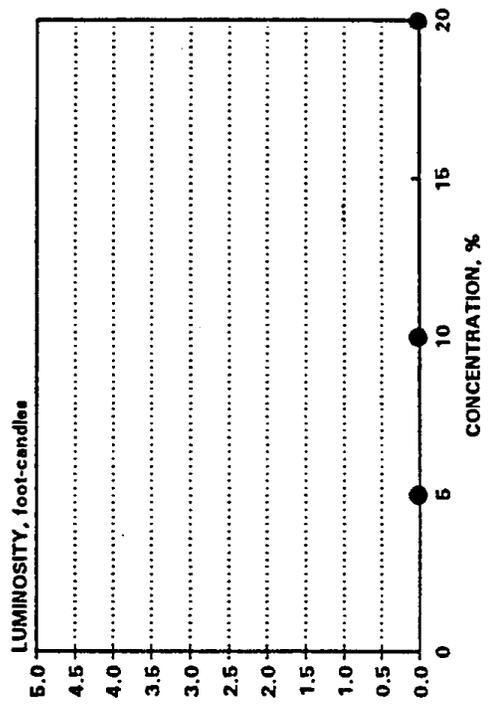


FIGURE A-33. LUMINOSITY CURVES FOR METHACRYLIC ACID, METHACRYLIC ANHYDRIDE, DIMETHOXYMETHANE, AND DIMETHOXYTetraethylene glycol



DIMETHOXYTetraethylene glycol



DIMETHOXYMETHANE

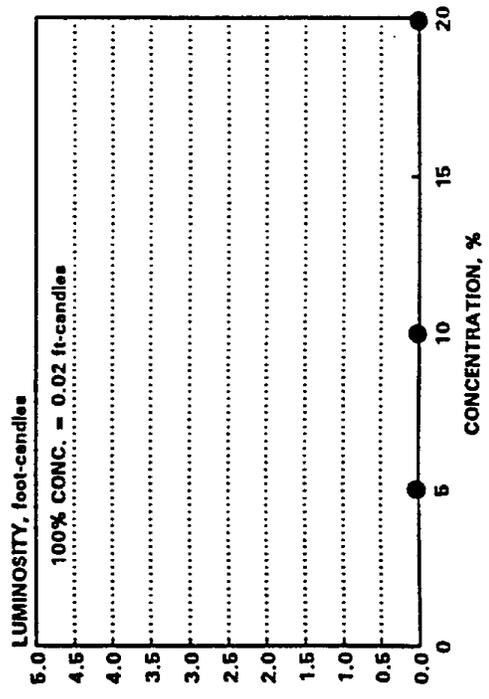
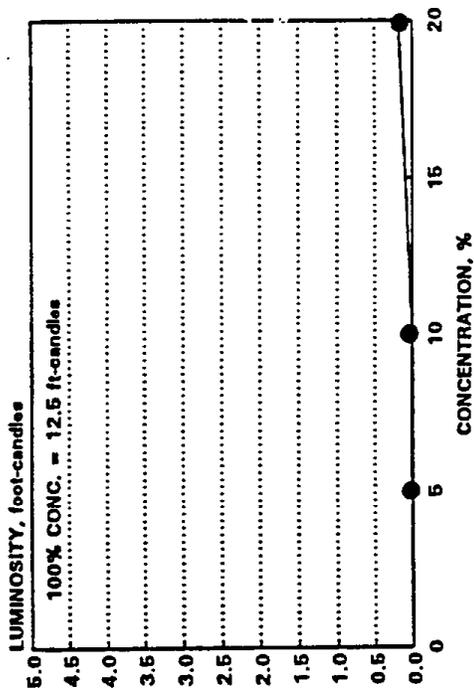
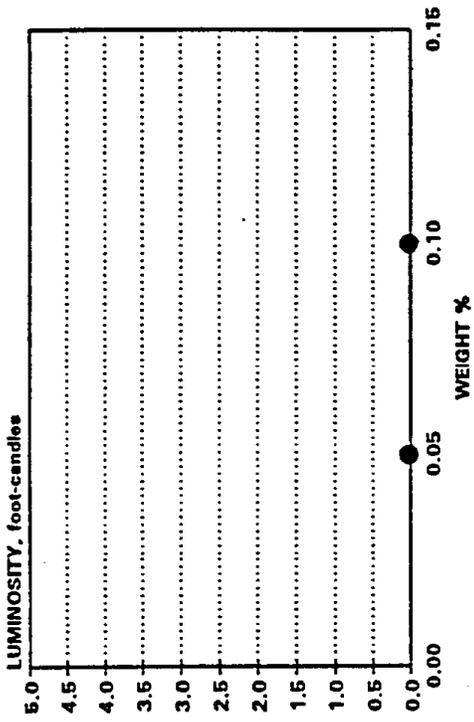


FIGURE A-34. LUMINOSITY CURVES FOR 2,4-PENTANEDIONE, BENZOPHENONE, 4-METHYLOCTANE, AND 1-PHENYL OCTANE

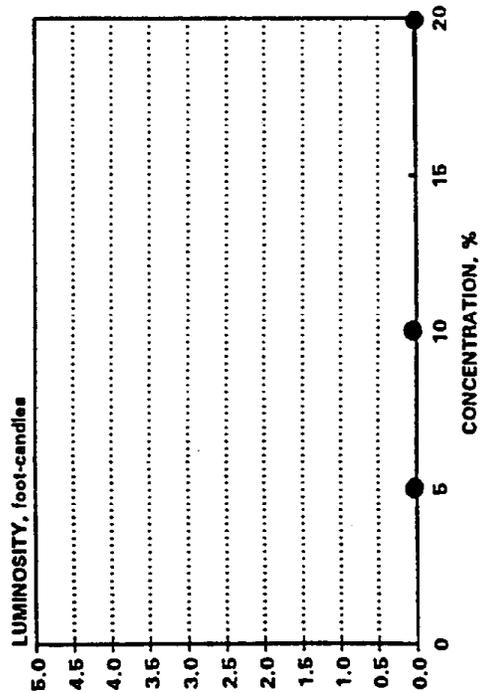
2,4-PENTANEDIONE



BENZOPHENONE



4-METHYLOCTANE



1-PHENYL OCTANE

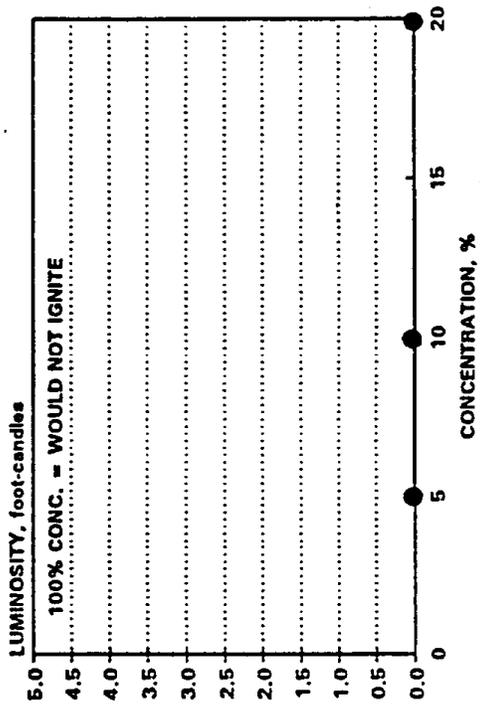
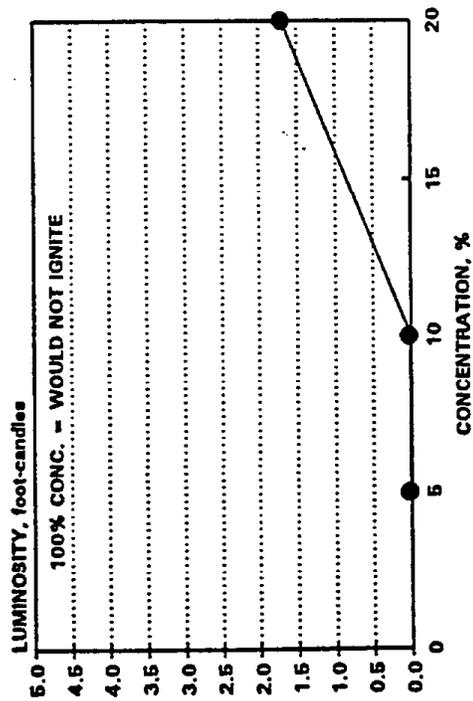
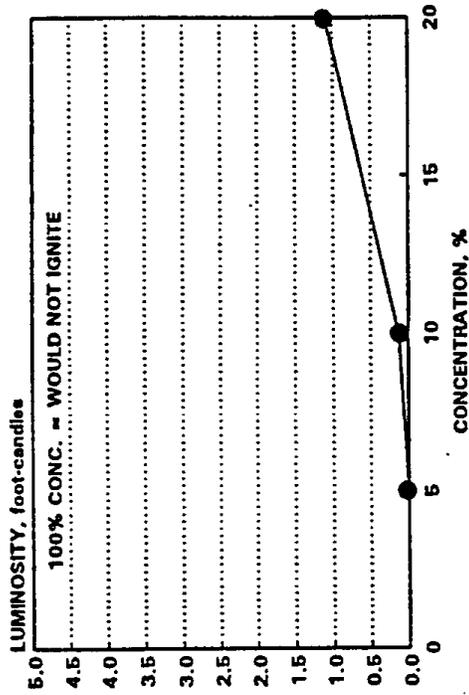


FIGURE A-35. LUMINOSITY CURVES FOR PHENOL, CYCLOHEXANOL, FERROCENE, AND ACETYLFERROCENE

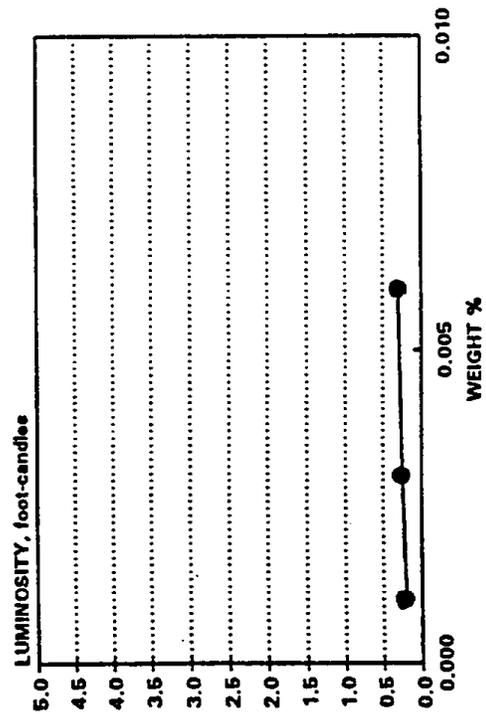
PHENOL



CYCLOHEXANOL



FERROCENE



ACETYLFERROCENE

