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ESTIMATING PRODUCTION AND REPAIR EFFORT IN BLAST-DAMAGED PETROLEUM REFINERIES

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D. C. 20310

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STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

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Final Report
Detachable Summary

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By: F. E. WALKER

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DETACHABLE SUMMARY

Method Developed

The study effort was directed toward developing a method for rapidly estimating to what extent petroleum refineries would be affected in the event of a nuclear attack on the United States. The method developed enables the user to estimate the repair requirements, and the corresponding production capabilities, of petroleum refineries after blast damage from overpressures of 0.5, 1, 5, and 10 psi. Thus, it is possible to predict what a given level of repair effort will buy in terms of petroleum products, when it is known which refinery is hit, and with what overpressure.

The estimating method was used during the study to produce the following major conclusions:

- After 0.3-0.5 psi, a refinery can produce the same proportion of products but at about 70 percent of the initial capacity. This reflects the assumption that at this overpressure refinery capacity is directly related to remaining cooling tower capacity.
- After 1.0 psi, a refinery temporarily shuts down, but with minor emergency repair to process controls, it can operate at about 50 percent of initial capacity.
- After 1.5 psi, a refinery is totally shut down, primarily because of process control damage by roof collapse in each of the numerous individual refining process control rooms. Vulnerability at higher overpressures is summarized in Section IV.

The physical items needed for refinery repair after blast damage are:

- Labor in terms of man-days and major skills
- Equipment, by type
- Material, by type

Repair labor requirements were developed by study of the average size refinery of each type at each selected overpressure. The requirements are shown graphically in Figure 2, as best-fit curves of data from average refineries, indicating a range of man-days for a given initial refinery capacity at a specified overpressure level. This report discusses how the repair requirements are developed and describes all the elements that are covered. Analysis of conclusions indicates that repair costs calculated by the method developed are consistent with overall average costs of building new refineries.

Repair Decision

After blast damage to petroleum refineries, certain decisions must be made before repairs to restore production are begun. The decisions will hinge on what products are needed and what repair effort is available.

Reclaiming refinery capability for light fuel products such as gasolines, jet fuels, and diesel fuels (most likely to be in demand during a period of postattack repair) will require decisions in three areas and will be governed by what products are most needed, and what minimum grades will meet users' demands. The three decision areas are:

- The order of repairing refinery processes
- The stage to which the repair is to be made
- The substitution of an alternative crude oil for the refinery's "normal" supply

Reclaiming refinery capability for producing specialty products, such as asphalts and lubes, will require decisions on where to produce these products, for example, whether to:

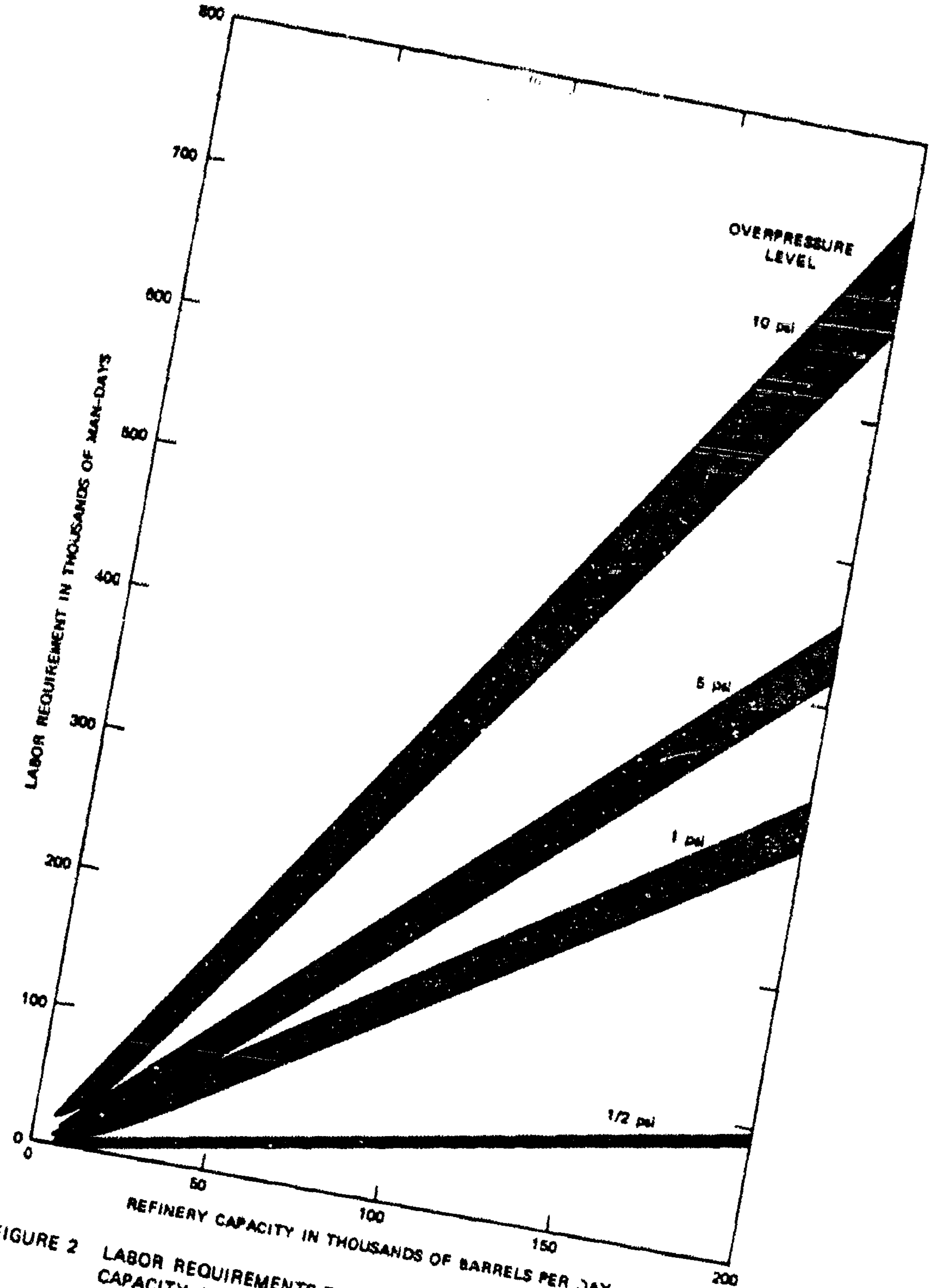


FIGURE 2 LABOR REQUIREMENTS TO RESTORE 100 PERCENT REFINERY CAPACITY AFTER SPECIFIED BLAST OVERPRESSURE LEVELS

- Fully repair the specialty refinery

- Partially repair the specialty refinery, the comparable specialty processing units of fuel, and the complete processing refineries

- Repair the comparable portion of the fuel and the complete processing refineries rather than the specialty refineries

Application of the Method

The following sequence for the repair of petroleum refining processes, emphasizing gasoline production, is used in this report:

Repair Stage	Repair Effort
A	Repair the crude oil topping processing unit
B	Repair processing units that convert heavy petroleum fractions to gasoline-type products
C	Repair processing units which upgrade gasolines
D	Repair all other processing units producing nonfuels

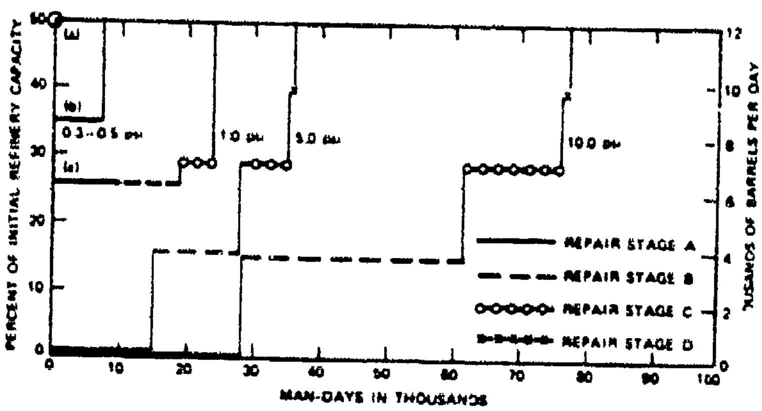
Using this sequence of repair stages, the reader can refer to Figure 2 (based on average refineries) and determine, for any refinery capacity at a specified level of blast overpressure, the level of repair effort in man-days that is required to restore the refinery to 100 percent production. For example:

> A 24,000 B/D refinery is expected to require 60,000 to 90,000 man-days of repair labor to return it to 100 percent of initial capacity after 10 psi overpressure

Also, for any refinery product, by type of refinery, the reader is given tables and charts from which to determine the amount of a product (as a percent of initial refinery capacity) that can be produced after each successive repair stage. These relationships for gasoline are illustrated in Figure 3. For example:

> Before blast damage, gasoline constitutes 50 percent of initial total products from a small fuel refinery. After 10 psi overpressure a 24,000 B/D small fuel refinery has the production capability shown below.

Repair Stage	Cumulative Repair Effort, Man-Days	Gasoline Production: Percent of Initial Total Products	Gasoline Production: Percent of Initial Gasoline Production	Gasoline Production: B/D
A	28,000	15%	30%	3,600
B	61,000	29	58	7,000
C	76,000	40	80	9,600
D	77,000	50	100	12,000



(a) - UNDAMAGED CONDITION
(b) 70 PERCENT OPERATION AFTER 0.3-0.5 psi
(c) - 50 PERCENT OPERATION AFTER 1.0 psi

FIGURE 3 GASOLINE YIELD RESULTING FROM REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: SMALL FUEL REFINERY, 24,000 BARRELS PER DAY CAPACITY

Results of sensitivity analyses on refinery sizes show that for refineries of the same type, but of different sizes, the stages of repair effort (Repair Stages A, B, C, and D) are proportional to the corresponding repair stages of the average size refinery.

This means that, for any refinery type, an estimator can simply calculate the ratio of the individual repair stage to the cumulative repair stage for the average size refinery of a particular type, apply that ratio to the repair requirement estimated for repair to 100 percent capability (total of Repair Stages A, B, C, and D) of that refinery size, and derive repair requirements for the other repair stages. This is illustrated by a simple example, below.

Given: 24,000 B/D small fuel refinery

Repair Stage A = 28,000 man-days

Repair to 100 percent capacity (A+B+C+D)

= 77,000 man-days

Ratio $\frac{A}{A+B+C+D} = 0.36$

Then, to find the repair requirement for Stage A for a small fuel refinery of a different size:

90,000 B/D small fuel refinery

Repair to 100 percent capacity (A+B+C+D)

= 285,000 to 335,000 man-days

Ratio of $\frac{A}{A+B+C+D} = 0.36$ (given above)

Thus: 0.36 x 285,000 and 335,000 = 103,000 to 120,000 man-days for Repair Stage A

Each refinery has its own "normal" input of crude oil. Following an attack, conditions at producing oil fields or in the transportation system may necessitate supplying a refinery with an alternative crude oil. The "normal" crude oil input to fuel and complete processing refineries is considered to be one of the three "major" U.S. crude oil types; "normal" input to specialty refineries is considered to be one of three representative special crude oil types. The effect of supplying a refinery with one of the other two of the three major U.S. crude oil types rather than with what this study judged to be that refinery's "normal" supply of crude oil is illustrated by the following example:

A 24,000 B/D small fuel refinery, after 10 psi overpressure, with its normal crude oil and alternative crude oils has the production capability shown below.

Repair Stage	Total Production as Percent of Initial Capacity: Normal Crude Oil	Total Production as Percent of Initial Capacity: Alternative Crude Oils
A	44	25-28%
B	62	28-33
C	79	31-37
D	100	33-42

Summary of Results

The method for estimating production capabilities and requirements of refineries after a nuclear attack is summarized in Tables 1, 2, and 3. Table 1 gives, for each type of refinery, the product percentages available when the refinery is undamaged (0 psi), and at two levels of low overpressure: the range of 0.3-0.5 psi, with no repair effort, and 1 psi, with only emergency repairs to the crude topping unit. Table 1 can be used for any size refinery of the type specified; it gives the normal product mix and shows the immediate effect of damage in the low overpressure ranges, where refineries are still operable.

Table 1

INITIAL CAPACITY AND PARTIAL PRODUCTION CAPABILITY AFTER 0.3-0.5 PSI AND 1.0 PSI BLAST OVERPRESSURE*

Refinery Type	Blast Condition, psi	Production Capability as a Percent of Initial Refinery Capacity: Gasoline	Kerosene	Diesel	Other	Total
Large fuel	Undamaged	54%	15%	14%	17%	100%
	0.3-0.5	38	10	10	12	70
	1.0	26	8	7	9	50
Small fuel	Undamaged	50	15	15	20	100
	0.3-0.5	35	11	10	14	70
	1.0	26	8	7	9	50
Complete processing	Undamaged	47	15	15	23	100
	0.3-0.5	33	11	10	16	70
	1.0	24	7	7	12	50
Asphalt	Undamaged	11	10	11	68	100
	0.3-0.5	8	7	8	47	70
	1.0	2	1	1	11	15
Asphalt and lube	Undamaged	5	5	15	75	100
	0.3-0.5	4	3	10	53	70
	1.0	1	1	3	17	22
Lube	Undamaged	42	15	15	28	100
	0.3-0.5	30	11	10	19	70
	1.0	21	8	7	14	50

* Using "normal" crude oil.

Table 2

PRODUCTION CAPABILITY BY REPAIR STAGE AFTER 1.5 PSI OR GREATER BLAST OVERPRESSURE*

Refinery Type	Repair Stage	Production Capability as a Percent of Initial Refinery Capacity: Gasoline	Kerosene and Jet Fuel	Diesel	Other	Total
Large fuel	A	13%	6%	5%	13%	37%
	B	22	8	7	13	50
	C	33	10	9	13	65
	D	54	15	14	17	100
Small fuel	A	15	7	7	15	44
	B	29	9	9	15	62
	C	40	12	12	15	79
	D	50	15	15	20	100
Complete processing	A	11	5	5	11	32
	B	14	6	6	11	37
	C	29	10	10	16	65
	D	47	15	15	23	100
Asphalt	A	9	10	10	67	96
	B	9	10	10	67	96
	C	10	10	11	67	98
	D	11	10	11	68	100
Asphalt and lube	A	1	4	12	63	80
	B	1	5	14	74	94
	C	4	5	15	75	99
	D	5	5	15	75	100
Lube	A	11	5	5	11	32
	B	22	9	9	21	61
	C	28	11	11	23	73
	D	42	15	15	28	100

* Using "normal" crude oil.

Table 3

REFINERY REPAIR REQUIREMENT BY REPAIR STAGE AND BLAST OVERPRESSURE LEVELS
(Labor as 000's of Man-Days, Cumulative)

Refinery Type	Initial Capacity, B/D	Repair Stage	Blast Overpressure Level, psi			
			0.3-0.5	1	5	10
Large fuel	78,000	A	15	54	73	97
		B	28	98	136	224
		C	36	126	176	288
		D	36	128	178	292
Small fuel	24,000	A	3	10	15	28
		B	5	19	28	61
		C	7	24	35	76
		D	7	24	36	77
Complete processing	194,000	A	40	140	188	243
		B	62	217	299	468
		C	81	286	397	633
		D	82	289	402	640
Asphalt	12,000	A	1	4	6	9
		B	2	9	12	17
		C	3	9	14	23
		D	3	11	16	28
Asphalt and lube	7,000	A	1	2	3	6
		B	1	5	7	14
		C	1	5	8	18
		D	2	6	10	22
Lube	4,000	A	1	2	2	4
		B	1	3	4	9
		C	1	3	5	14
		D	1	4	6	18

At overpressures of 1.5 psi or greater, repair to refineries becomes necessary for them to operate. Table 2 gives product percentages after each of the four repair stages for an average size refinery of each type, thus showing the incremental production that each repair stage affords.

Table 3 gives the man-days of repair effort required at each repair stage and for each level of overpressure for an average size refinery of each type.

The only data the estimator has to supply are readily available from industry published periodicals, journals, or reference material:[2]

- Refinery type and initial capacity in B/D
- Type of crude oil used, including both the "normal" crude oil supply and an alternative (supplied in the report)

It is recognized that in a postattack environment the relative demand for individual products will not be the same as before an attack. Because refining processes produce a combination of products, a relatively high demand for one product creates a surplus of "other" products. Management and planning must consider uses for, or ways to dispose of, these other surplus products. For example, kerosene and diesel type products normally represent about one-third of total products. In a postattack condition if the demand for gasoline and residual fuel rises so that the demand for kerosene and diesel products drops to one-fourth of the total products, a surplus of kerosene and diesel equivalent to one-twelfth of the total products would occur. Even with reduced total products of 6 million barrels per day (slightly more than 50 percent of current production) this represents a surplus of $1/12 \times 6{,}000{,}000 = 500{,}000$ B/D. The surplus products will eventually create tremendous storage problems. A few potential solutions include: partial blending of surplus products into required products, reprocessing of surplus products to make required products, or re-injecting surplus products into underground storage.

STANFORD RESEARCH INSTITUTE
Menlo Park, California

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1 INTRODUCTION

The U.S. petroleum refining industry is regarded as critical to the continued national viability. In the event of damage by attack, petroleum refining capacity is expected to be of primary interest, with emphasis on restoration of a petroleum refining level required for that viability. To plan the recovery of the petroleum refining industry, it is essential to be able to estimate (1) the extent of damage by blast overpressure levels, (2) the capability of individual refineries to produce products as they stand or with increments of repair effort, and (3) the repair effort needed.

Objective

The overall purpose of this study was to describe individual U.S. refineries and their normal modes of operation and derive a means for estimating refinery production capability and the repair effort needed after exposure to selected blast overpressures.

Specifically, this study was aimed at developing a means for estimating the capability of refineries to produce petroleum products after exposure to blast:

- With no repair
- After partial repair
- After full repair
- By product group
- By overpressure level

Scope and Method

The U.S. petroleum refining industry is made up of 267 refineries which process more than 200 different types of crude oils. Over 100 individual refining processes, and at least 50-100 types of equipment are used by these refineries to produce well over 1,000 different products.

Analysis and grouping of the pertinent factors related to these aspects of the U.S. petroleum refining industry represented a major effort in this study. To develop a procedure for estimating production capabilities and repair requirements after a nuclear attack, it was necessary to bring industry descriptors down to a meaningful number. These reductions are described below.

- The 267 refineries are represented by six types:

- Large fuel*	94 percent of U.S. Capacity
- Small fuel*	
- Complete processing	
- Asphalt	6 percent of U.S. capacity
- Asphalt and lube	
- Lube	

- The 200+ crude oils are represented by three major types of crude oil from the largest producing oil fields and three specialty crude oils:

- 30°-40° API Gulf	Largest
- 20°-25° API West Coast	
- 20°-25° API Midcontinent	
- 10°-15° API asphaltic	Specialty
- 10°-15° API asphaltic and lube	
- 30°-45° API lube	

* Large fuel and small fuel refineries are differentiated by included processes.

- The more than 100 individual refining processes are represented by the 16 most used
- The 50-100 types of equipment within processes are represented by 25 items most vital to process operation, most susceptible to blast damage, and requiring largest labor input for repair
- The 1,000+ products are represented by seven groups, according to common characteristics

The reduction process is summarized graphically in Figure 1.

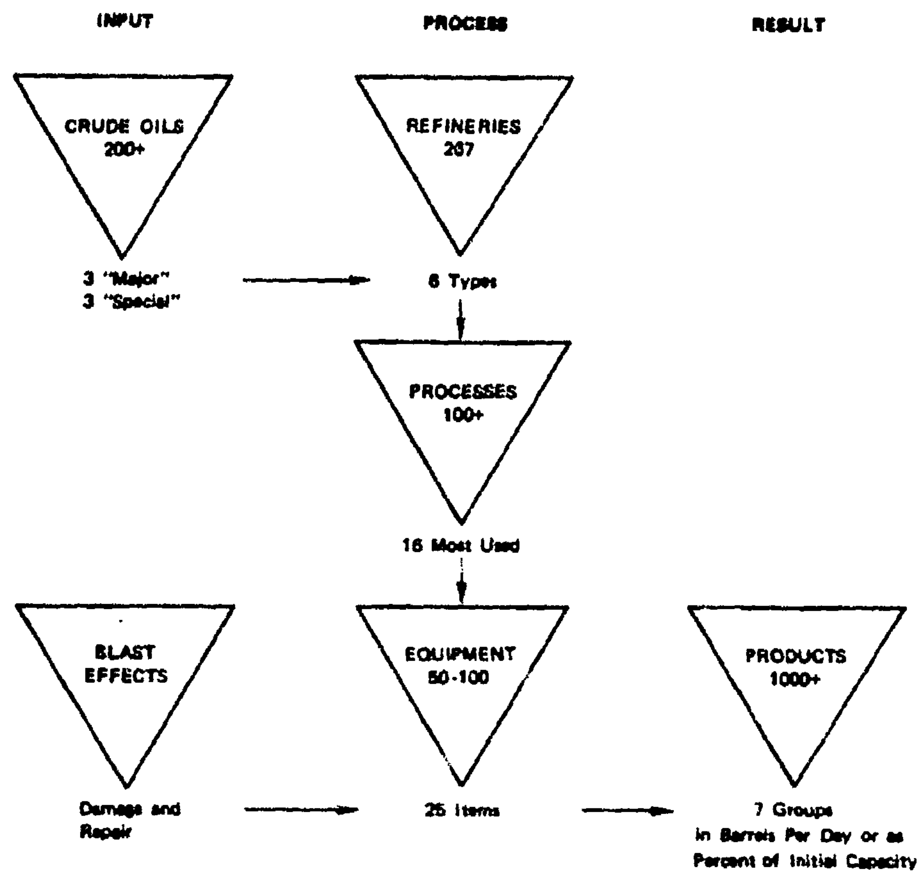

FIGURE 1 PETROLEUM REFINING INDUSTRY MODEL

To abstract the petroleum refining industry to this extent, it was of course necessary to make many simplifying assumptions. These are pointed out throughout the report, where appropriate.

The data used in this study reflect the most recent information available. The topics addressed are described below.

Processing

The petroleum processing characteristics of CONUS crude oil refineries are considered. A representative "normal" crude oil and alternative crude oils for processing are selected on the basis of production records and refining characteristics.

Refineries in Alaska, Hawaii, U.S. protectorates, or areas contiguous to the United States are omitted. These latter areas could prove to be of limited utility to the United States in a time of nuclear conflict.

Blast Effects

Levels of refinery damage are characterized in terms of blast overpressure. This damage mechanism is better understood than other damage mechanisms and, in addition, overpressure provides a direct link with the nuclear environment. Although other damage mechanisms of wind, thermal effects, electromagnetic pulse, or the secondary effects of debris-missile or fire are recognized to be important, their coverage is beyond the scope of this study.

Repair Requirements

The analysis is based on the major requirements for the rebuilding of the essential parts of a petroleum refinery after debris has been cleared and the area determined safe for repair work. Major requirements include labor of reconstruction, principal skills or crafts, and corresponding needs for equipment and supplies. Essential parts of a refinery include only those items necessary to the refining operation.

Capacities and Yields

Accepted abbreviated methods[1]* are used in estimating refining capacities and product yields from selected crude oils after various blast overpressures. The capacities and yields are expressed as B/D (barrels per day) or in terms of initial capacity under conditions of no damage. The capacities and yields and the repair requirements are expressed as functions of blast overpressure.

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Direction and guidance for this study were provided by Michael Pachuta of OCD. Additional information on refinery components was provided by Carl A. Trexel, Jr., Senior Industrial Economist and Viona R. Duncan, Research Assistant, both of the Energy and Resources Economics Department.

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* Superscript numbers denote references listed at the end of the report.

II SUMMARY AND CONCLUSIONS

Method Developed

The study effort was directed toward developing a method for rapidly estimating to what extent petroleum refineries would be affected in the event of a nuclear attack on the United States. The method developed enables the user to estimate the repair requirements, and the corresponding production capabilities, of petroleum refineries after blast damage from overpressures of 0.5, 1, 5, and 10 psi. Thus, it is possible to predict what a given level of repair effort will buy in terms of petroleum products, when it is known which refinery is hit, and with what overpressure.

The estimating method was used during the study to produce the following major conclusions:

- After 0.3-0.5 psi, a refinery can produce the same proportion of products but at about 70 percent of the initial capacity. This reflects the assumption that at this overpressure refinery capacity is directly related to remaining cooling tower capacity.
- After 1.0 psi, a refinery temporarily shuts down, but with minor emergency repair to process controls, it can operate at about 50 percent of initial capacity.
- After 1.5 psi, a refinery is totally shut down, primarily because of process control damage by roof collapse in each of the numerous individual refining process control rooms. Vulnerability at higher overpressures is summarized in Section IV.

The physical items needed for refinery repair after blast damage are:

- Labor in terms of man-days and major skills
- Equipment, by type
- Material, by type

Repair labor requirements were developed by study of the average size refinery of each type at each selected overpressure. The requirements are shown graphically in Figure 2, as best-fit curves of data from average refineries, indicating a range of man-days for a given initial refinery capacity at a specified overpressure level. This report discusses how the repair requirements are developed and describes all the elements that are covered. Analysis of conclusions indicates that repair costs calculated by the method developed are consistent with overall average costs of building new refineries.

Repair Decision

After blast damage to petroleum refineries, certain decisions must be made before repairs to restore production are begun. The decisions will hinge on what products are needed and what repair effort is available.

Reclaiming refinery capability for light fuel products such as gasolines, jet fuels, and diesel fuels (most likely to be in demand during a period of postattack repair) will require decisions in three areas and will be governed by what products are most needed, and what minimum grades will meet users' demands. The three decision areas are:

- The order of repairing refinery processes
- The stage to which the repair is to be made
- The substitution of an alternative crude oil for the refinery's "normal" supply

Reclaiming refinery capability for producing specialty products, such as asphalts and lubes, will require decisions on where to produce these

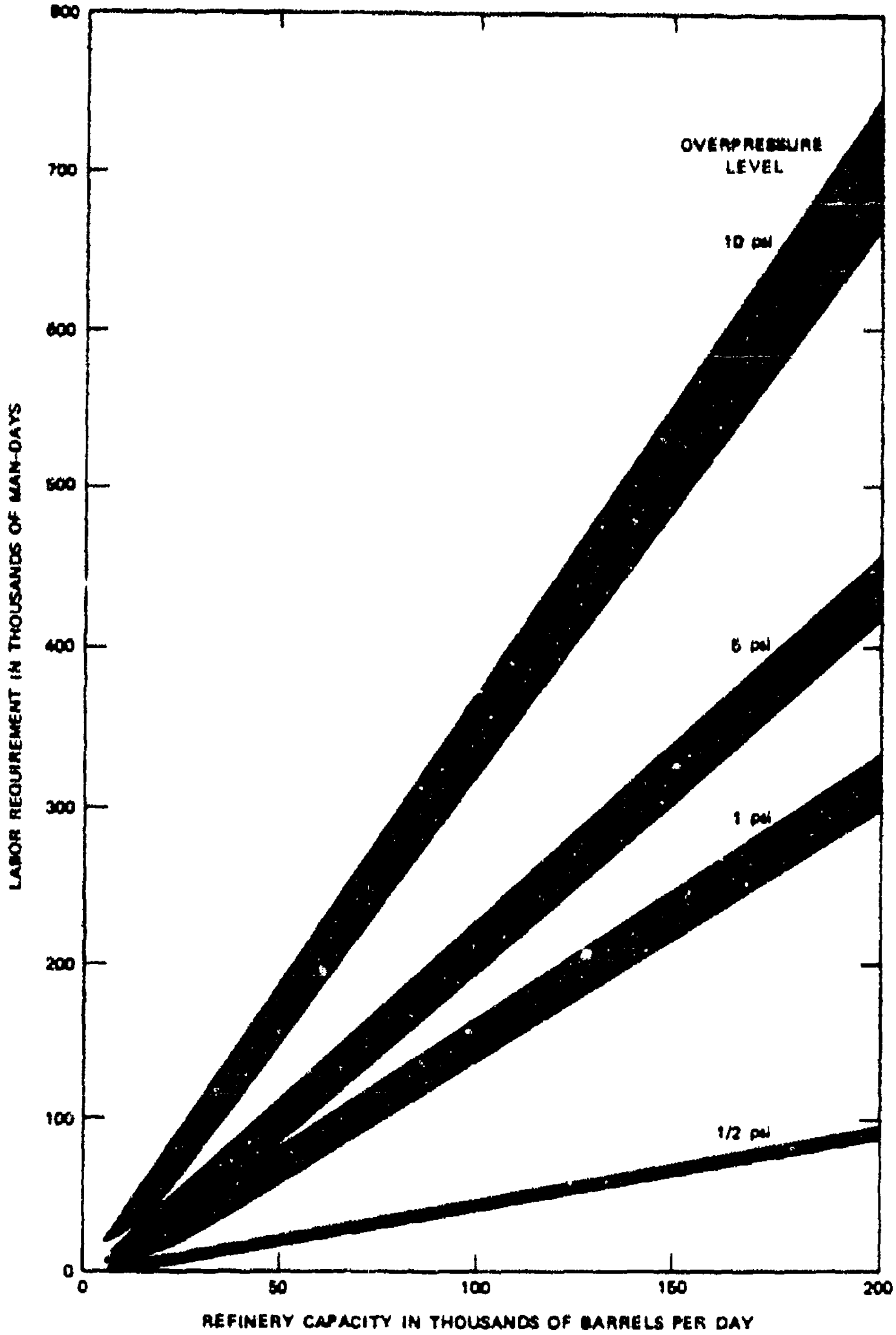


FIGURE 2 LABOR REQUIREMENTS TO RESTORE 100 PERCENT REFINERY CAPACITY AFTER SPECIFIED BLAST OVERPRESSURE LEVELS

products, for example, whether to:

- Fully repair the specialty refinery
- Partially repair the specialty refinery, the comparable specialty processing units of fuel, and the complete processing refineries
- Repair the comparable portion of the fuel and the complete processing refineries rather than the specialty refineries

Application of the Method

The following sequence for the repair of petroleum refining processes, emphasizing gasoline production, is used in this report:

Repair Stage	Repair Effort
A	Repair the crude oil topping processing unit
B	Repair processing units that convert heavy petroleum fractions to gasoline-type products
C	Repair processing units which upgrade gasolines
D	Repair all other processing units producing nonfuels

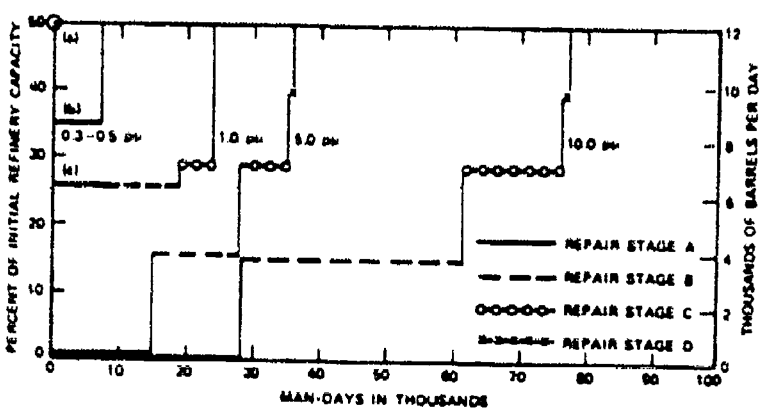
Using this sequence of repair stages, the reader can refer to Figure 2 (based on average refineries) and determine, for any refinery capacity at a specified level of blast overpressure, the level of repair effort in man-days that is required to restore the refinery to 100 percent production. For example:

> A 24,000 B/D refinery is expected to require 60,000 to 90,000 man-days of repair labor to return it to 100 percent of initial capacity after 10 psi overpressure

Also, for any refinery product, by type of refinery, the reader is given tables and charts from which to determine the amount of a product (as a percent of initial refinery capacity) that can be produced after each successive repair stage. These relationships for gasoline are illustrated in Figure 3. For example:

Before blast damage, gasoline constitutes 50 percent of initial total products from a small fuel refinery. After 10 psi overpressure a 24,000 B/D small fuel refinery has the production capability shown below.

Repair Stage	Cumulative Repair Effort, Man-Days	Gasoline Production: Percent of Initial Total Products	Gasoline Production: Percent of Initial Gasoline Production	Gasoline Production: B/D
A	28,000	15%	30%	3,600
B	61,000	29	58	7,000
C	76,000	40	80	9,600
D	77,000	50	100	12,000



(a) = UNDAMAGED CONDITION
(b) = 70 PERCENT OPERATION AFTER 0.3-0.5 psi
(c) = 50 PERCENT OPERATION AFTER 1.0 psi

FIGURE 3 GASOLINE YIELD RESULTING FROM REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: SMALL FUEL REFINERY, 24,000 BARRELS PER DAY CAPACITY

Results of sensitivity analyses on refinery sizes show that for refineries of the same type, but of different sizes, the stages of repair effort (Repair Stages A, B, C, and D) are proportional to the corresponding repair stages of the average size refinery.

This means that, for any refinery type, an estimator can simply calculate the ratio of the individual repair stage to the cumulative repair stage for the average size refinery of a particular type, apply that ratio to the repair requirement estimated for repair to 100 percent capability (total of Repair Stages A, B, C, and D) of that refinery size, and derive repair requirements for the other repair stages. This is illustrated by a simple example, below.

Given: 24,000 B/D small fuel refinery

Repair Stage A = 28,000 man-days

Repair to 100 percent capacity (A+B+C+D)

= 77,000 man-days

$$\text{Ratio } \frac{A}{A+B+C+D} = 0.36$$

Then, to find the repair requirement for Stage A for a small fuel refinery of a different size:

90,000 B/D small fuel refinery

Repair to 100 percent capacity (A+B+C+D)

= 285,000 to 335,000 man-days

$$\text{Ratio of } \frac{A}{A+B+C+D} = 0.36 \text{ (given above)}$$

Thus: 0.36 × 285,000 and 335,000 = 103,000 to 120,000 man-days for Repair Stage A

Each refinery has its own "normal" input of crude oil. Following an attack, conditions at producing oil fields or in the transportation system may necessitate supplying a refinery with an alternative crude oil. The "normal" crude oil input to fuel and complete processing refineries is considered to be one of the three "major" U.S. crude oil types; "normal" input to specialty refineries is considered to be one of three representative special crude oil types. The effect of supplying a refinery with one of the other two of the three major U.S. crude oil types rather than with what this study judged to be that refinery's "normal" supply of crude oil illustrated by the following example:

> A 24,000 B/D small fuel refinery, after 10 psi overpressure, with its normal crude oil and alternative crude oils has the production capability shown below.

	Total Production as Percent of Initial Capacity	
Repair Stage	Normal Crude Oil	Alternative Crude Oils
A	44	25-28%
B	62	28-33
C	79	31-37
D	100	33-42

Summary of Results

The method for estimating production capabilities and requirements of refineries after a nuclear attack is summarized in Tables 1, 2, and 3. Table 1 gives, for each type of refinery, the product percentages available when the refinery is undamaged (0 psi), and at two levels of low overpressure: the range of 0.3-0.5 psi, with no repair effort, and 1 psi, with only emergency repairs to the crude topping unit. Table 1 can be used for any size refinery of the type specified; it gives the normal product mix and shows the immediate effect of damage in the low overpressure ranges, where refineries are still operable.

Table 1

INITIAL CAPACITY AND PARTIAL PRODUCTION CAPABILITY
AFTER 0.3-0.5 PSI AND 1.0 PSI BLAST OVERPRESSURE*

Refinery Type	Blast Condition, psi	Production Capability as a Percent of Initial Refinery Capacity				
		Gasoline	Kerosene	Diesel	Other	Total
Large fuel	Undamaged	54%	15%	14%	17%	[illegible]
	0.3-0.5	38	10	10	12	[illegible]
	1.0	26	8	7	9	50
Small fuel	Undamaged	50	15	15	20	100
	0.3-0.5	35	11	10	14	70
	1.0	26	8	7	9	50
Complete processing	Undamaged	47	15	15	23	100
	0.3-0.5	33	11	10	16	70
	1.0	24	7	7	12	50
Asphalt	Undamaged	11	10	11	68	100
	0.3-0.5	8	7	8	47	70
	1.0	2	1	1	11	15
Asphalt and lube	Undamaged	5	5	15	75	100
	0.3-0.5	4	3	10	53	70
	1.0	1	1	3	17	22
Lube	Undamaged	42	15	15	28	100
	0.3-0.5	30	11	10	19	70
	1.0	21	8	7	14	50

* Using "normal" crude oil.

Table 2

PRODUCTION CAPABILITY BY REPAIR STAGE
AFTER 1.5 PSI OR GREATER BLAST OVERPRESSURE*

Refinery Type	Repair Stage	Production Capability as a Percent of Initial Refinery Capacity				
		Gasoline	Kerosene and Jet Fuel	Diesel	Other	Total
Large fuel	A	13%	6%	5%	13%	37%
	B	22	8	7	13	50
	C	33	10	9	13	65
	D	54	15	14	17	100
Small fuel	A	15	7	7	15	44
	B	29	9	9	15	62
	C	40	12	13	15	79
	D	50	15	15	20	100
Complete processing	A	11	5	5	11	32
	B	14	6	6	11	37
	C	29	10	10	16	65
	D	47	15	15	23	100
Asphalt	A	9	10	10	67	96
	B	9	10	10	67	96
	C	10	10	11	67	98
	D	11	10	11	68	100
Asphalt and lube	A	1	4	12	63	80
	B	1	5	14	74	94
	C	4	5	15	75	99
	D	5	5	15	75	100
Lube	A	11	5	5	11	32
	B	22	9	9	21	61
	C	28	11	11	23	73
	D	42	15	15	28	100

* Using "normal" crude oil.

Table 3

REFINERY REPAIR REQUIREMENT BY REPAIR STAGE AND BLAST OVERPRESSURE LEVELS
(Labor as 000's of Man-Days, Cumulative)

Refinery Type	Initial Capacity, B/D	Repair Stage	Blast Overpressure Level, psi 0.3-0.5	1	5	10
Large fuel	78,000	A	15	54	73	97
		B	28	98	136	224
		C	36	126	176	288
		D	36	128	178	292
Small fuel	24,000	A	3	10	15	28
		B	5	19	28	61
		C	7	24	35	76
		D	7	24	36	77
Complete processing	194,000	A	40	140	188	243
		B	62	217	299	468
		C	81	286	397	633
		D	82	289	402	640
Asphalt	12,000	A	1	4	6	9
		B	2	9	12	17
		C	3	9	14	23
		D	3	11	16	28
Asphalt and lube	7,000	A	1	2	3	6
		B	1	5	7	14
		C	1	5	8	18
		D	2	6	10	22
Lube	4,000	A	1	2	2	4
		B	1	3	4	9
		C	1	3	5	14
		D	1	4	6	18

At overpressures of 1.5 psi or greater, repair to refineries becomes necessary for them to operate. Table 2 gives product percentages after each of the four repair stages for an average size refinery of each type, thus showing the incremental production that each repair stage affords.

Table 3 gives the man-days of repair effort required at each repair stage and for each level of overpressure for an average size refinery of each type.

The only data the estimator has to supply are readily available from industry published periodicals, journals, or reference material:[9]

- Refinery type and initial capacity in B/D
- Type of crude oil used, including both the "normal" crude oil supply and an alternative (supplied in the report)

It is recognized that in a postattack environment the relative demand for individual products will not be the same as before an attack. Because refining processes produce a combination of products, a relatively high demand for one product creates a surplus of "other" products. Management and planning must consider uses for, or ways to dispose of, these other surplus products. For example, kerosene and diesel type products normally represent about one-third of total products. In a postattack condition if the demand for gasoline and residual fuel rises so that the demand for kerosene and diesel products drops to one-fourth of the total products, a surplus of kerosene and diesel equivalent to one-twelfth of the total products would occur. Even with reduced total products of 6 million barrels per day (slightly more than 50 percent of current production) this represents a surplus of $1/12 \times 6{,}000{,}000 = 500{,}000$ B/D. The surplus products will eventually create tremendous storage problems. A few potential solutions include: partial blending of surplus products into required products, reprocessing of surplus products to make required products, or re-injecting surplus products into underground storage.

III INDUSTRY DESCRIPTORS

In the United States today there are 267 crude oil refineries[2,3] which use many different processes and modifications of these processes. They refine crude oil, or mixtures of crude oils, from at least 200 different oil fields.[2] The product markets they serve are as varied as the U.S. economy is diversified.

As a result of these factors, no two refineries are exactly alike. There are, however, some overall similarities. The contribution of this study is in analyzing the components of the U.S. petroleum refining industry, abstracting the similarities, assembling representative types to make it possible to apply estimating factors and carrying out the calculations in making the estimates. This section details the bases and assumptions used to arrive at the initial production capabilities in the industry.

This study approaches the analysis from the standpoint that the effect of nuclear blast on refineries is similar for similar types of refineries and that these effects can be related to refinery type and capacity. Simplifying assumptions are made and relationships are developed in the following areas:

- Crude oils
- Refinery types
- Processing
- Equipment included in refineries
- Products

A petroleum refinery is a group of manufacturing processes organized and coordinated to achieve both physical and chemical transformation of a particular type of crude oil into salable products that meet the qualities and quantities required by the product market supplied. In general, petroleum refining consists of separation of a crude oil into its parts, changing the structure of these parts under various conditions of temperature and pressure (using catalysts where necessary), and recombining and treating those parts with chemicals and additives to meet a product mix demand.

Many of the processes used to separate the crude oil into its parts are fairly standard throughout the industry. Normally, the separation is by fractional distillation (fractionation). All of the materials that boil above a given temperature, at a particular pressure, are separated from those that boil below that temperature at that pressure. Sequential selection of temperatures and pressures permits the separation of a crude oil into many fractions. This separation process is used in all the initial processing steps and in the preparation of products intermediate to structural change.

Refinery processes and equipment are chosen, sized, arranged, and interrelated according to the crude oil that is available and the product market that the refinery serves. For each refinery type, the author has postulated an average refinery. This consists of typical processing equipment sized to operate at capacity and produce the product mix representative of that refinery type when using a "normal" crude oil represented by the predominant U.S. crude oil.

It is recognized that, within a particular refinery type, the crude oils input to individual refineries will differ. Some refineries process a heavier crude, while others process a lighter crude. However, it is assumed that there are compensating differences in the included processing equipment to permit refineries of one type to produce similar product mixes. It is also assumed that the equipment differences do not materially change the postattack refinery repair requirements or production capabilities from those shown for the average refineries.

Substitution of alternative crude oils in each of the postulated refineries will influence the product mix, depending on the characteristics of the alternative crude oils and the refinery processing equipment. The result is potentially an unbalanced product mix (the product mix volumes do not coincide with product market demand) and a resultant refinery throughput decrease because of individual process limitations. For example, a refinery specializing in the heavier products, such as asphalts, also produces gasoline; a refinery that is producing light products (gasoline, kerosene, and diesel) also simultaneously produces higher-boiling fuel oil materials. If the amounts of fuel oil produced by the latter exceed the demand in that refinery's market area, the overall operation of that refinery is unbalanced: fuel oil will accumulate, and eventually storage problems will force the refinery to shut down. Similar problems would occur with light products, if refineries use alternative crude oils lighter than they are designed to process. For example, the use of a light crude in a refinery specializing in heavy products, such as asphalt, would create a light products storage problem. To balance its operations, a refinery would have to include a degree of cracking and related processing to convert enough of the heavier fuel oils into the lighter products to meet market demands. Such factors have been taken into consideration in the development and equipping of refineries.

Crude Oils

At the well-heads or in the producing oil fields, small amounts of gas and light gasolines are removed from crude oils. The remaining major portion of the crude oil then goes on to become input to a petroleum refinery. The crude oil that reaches the refinery is still a complex mixture, ranging from light hydrocarbons that can be used in gasoline to the heaviest hydrocarbons, which can only be used in asphalts.

The composition of crude oil from some producing fields is distinct, and a few particular crude oils are segregated for specific purposes--some for use in specialty-type refineries, others because of undesirable refining characteristics that require specialized refining processes. However, most of the crude oils from the producing fields are blended with similar crude oils from the same locality during the delivery to a refinery. The characteristics of the blended crude oil stream may in many respects be similar to characteristics of the crude oil that constitutes the largest field volume in the blend.

In this study, the normal crude oil supply to the major portion of petroleum refining compares to the largest volume of U.S. crude oil produced; alternative supply available compares to the next largest volumes produced.

In the Gulf Coast area, crude oils from the largest producing fields are relatively light (30°-40° API gravity range). On the West Coast there are fewer large fields, but all the crudes are somewhat heavier than those from the Gulf (in the range of 10°-40° API, clustering around 20°-30° API). In the Midcontinent area there are a few large, widely separated fields with some moderately heavy (20°-30° API) and some light (30°-40° API) crude oils.[3,4,5,6]

Published production volumes[6,7] from the 88 largest producing oil fields include about 42 percent of the total U.S. production of crude oil. The percentages from these largest volume oil fields grouped by gravity range are shown below.

Producing Fields	Gravity Range, API* 10°-20°	20°-30°	30°-40°	40+°
Gulf Coast area		4%	22%	5%
West Coast area	1%†	4‡	1	
Midcontinent area	—	2‡	3§	—
Total	1%	10%	26%	5%

The largest volume of crude oil used by refineries is in the 30°-40° API gravity range; over half of the 42 percent is in this range. The crude oil production most representative is that from the Gulf Coast area. This crude oil was selected as being comparable to the "normal" crude supplied to the largest part of U.S. petroleum refining industry, the fuel and complete processing refineries. Crude oils selected as being comparable to alternative crudes available to these refineries were:

- 20°-25° API West Coast area
- 20°-25 API Midcontinent area

The 20°-25° API Midcontinent crude (2 percent of U.S. production) was selected over the 30°-40° API Midcontinent crude (3 percent of U.S. production), because, under postattack conditions, the widespread geographical locations of fields in the latter gravity range group could limit the availability of that crude oil to the refineries.

These considerations apply principally to the larger refineries, which produce a complete range of products or mainly fuels. Smaller

* High gravity numbers in degrees API reflect light crude oils.
† In the 10°-15° API range.
‡ In the 20°-25° API range.
§ Widely separated oil fields.

specialty refineries normally use only crude oils segregated specifically for their use. A process similar to that described above resulted in a selection of three representative specialty crude oils, again with the consideration that a crude oil comparable to only one of these would represent that specialty refinery's "normal" supply. The specialty crude oils selected were as follows:

Type of Refinery	Comparable Crude Oil
Asphalt	10°-15° API asphaltic
Asphalt and lube	10°-15° API asphaltic and lube
Lube	30°-45° API lube

Usable alternative crude oils for specialty refineries are the three largest production crudes selected for fuel and complete processing refineries. This is shown in summary form as follows:

Crude Oil	Fuel and Complete Processing	Asphalt	Asphalt and Lube	Lube
30°-40° API Gulf	N	A	A	A
20°-25° API West Coast	A	A	A	A
20°-25° API Midcontinent	A	A	A	A
10°-15° API asphaltic		N		
10°-15° API asphaltic and lube			N	
30°-45° API lube				N

Note: N = comparable to "normal" crude oil supply.
A = comparable to alternative crude oil supply.

Underlying the selection of representative types of crude oils was the assumption that in the event that "normal" crude oils were unavailable after an attack, crude oils comparable to the other categories would be available. Because an attack might disrupt a refinery's "normal" supply, and because differences in crude oil input affect a refinery's production capability. Each refinery would be able to operate, but at differing levels of production, by use of one of the alternative crudes for input.

Refinery Types

Refineries may be grouped by similarities in size and in types of products produced. Similar types of products imply similar types of processing units, and this in turn reflects similar refining equipment in those processing units. Refineries primarily producing fuels comprise about 94 percent of the nation's crude oil refining capacity. The primary purpose of the remaining 6 percent is the production of specialty products, asphalt or lube, or a combination of these. Within each of these two groups, fuels and specialties, there are similarities in size and degree of completeness in the line of products.

In general, the small refineries include only the simple processes, such as skimming or topping, and produce a limited number of types of fuel and asphalt products. Conversely, the large refineries are complex and produce many products. Both characteristics, refinery size and types of products, are important.

The details necessary for categorizing refineries are available in published trade journals.[8] The categorization selected for this study was that developed by W. L. Nelson.[9] In using Nelson's categorization system, each refinery's processing characteristics were investigated separately, rather than with refineries grouped by large company ownership. Peacetime operations by large multirefinery companies frequently include shipments of intermediate or partially finished oil products between owned refineries. In the event of attack, these shipments may cease, changing somewhat the processing characteristics of some refineries. For this reason, the categorization used in this study, reflecting conditions after blast damage, may differ slightly from the usual peacetime categorization. Petroleum refineries have been grouped into six categories that give recognition to both the types of products and the refinery size:

- Large fuel
- Small fuel
- Complete processing
- Asphalt
- Asphalt and lube
- Lube

This grouping reflects the use of particular refining processes in the manufacture of particular products. In developing the six categories, each refinery, with its production capacities, is identified according to five types of processes in combinations:

- Alkylation (manufacture of aviation gasolines)
- Polymerization (manufacture of gasolines from light gases)
- Lube products
- Coke
- Asphalt

Table 4 summarizes the six refinery types by combinations of process types, and details the capacities, number of refineries, and average capacity for each type.

All large fuel refineries include alkylation processing, while combinations of the other four selected processes are fairly well distributed. The large fuel refineries account for the largest part of U.S. refining--about one-half of the total U.S. capacity--but this category includes less than one-fourth of the total number of refineries. Capacity of the large fuel refineries averages 78,000 B/D, with the largest capacity at 241,000 B/D and the smallest at 36,000 B/D.

Table 1

REFINERY CATEGORIZATION

Refinery Type	Processing Combinations: Alkylation	Polymerization	Lube	Coke	Asphalt	Total U.S. Crude Oil Capacity: 000's of B/D	Percent	Refineries: No.	Average (000's of B/D)	Range of Production: Low (000's of B/D)	High (000's of B/D)
Large fuel	X	X				740.0	6.7%	10	74.0		
	X		X			333.2	3.2	2	176.5		
	X			X		658.9	5.9	11	59.9		
	X	X		X		562.0	5.1	10	56.2		
	X	X			X	742.0	6.7	14	53.0		
	X		X	X		199.0	1.8	2	99.5		
	X		X		X	935.2	8.4	8	116.9		
	X			X	X	399.6	3.6	4	99.9		
	X	X		X	X	630.0	5.7	6	10.5		
All large fuel						5,219.9	47.1%	67	77.9*	38.0	341.0
Small fuel	X					1,137.5	10.3%	25	45.5		
	X				X	1,048.0	9.6	24	44.3		
		X				150.0	1.3	6	25.0		
		X		X	X	30.0	0.2	1	30.0		
		X		X		43.6	0.4	1	43.6		
			X	X	X	112.0	1.0	2	56.0		
	- - - - - - -	None indicated	- - -	- - -	- - -	324.0	2.9	60	5.4		
All small fuel						2,855.1	25.7%	119	24.0*	0.7	183.0
Complete processing	X	X	X	X		680.4	6.2%	3	226.8		
	X	X	X		X	335.0	5.0	3	185.0		
	X		X	X	X	805.1	5.5	3	201.7		
	X	X	X	X	X	481.5	4.3	3	160.5		
All complete processing						2,322.0	21.0%	12	183.5	34.0	419.0
Asphalt					X	297.6	2.7%	32	9.3		
		X			X	234.0	2.1	13	18.0		
				X	X	38.4	0.4	2	19.2		
All asphalt						570.0	5.2%	47	12.1*	1.1	35.0
Asphalt and lube		X	X		X	14.0	0.1%	1	14.0		
			X		X	52.0	0.5	8	6.5		
All asphalt and l						66.0	0.6%	9	7.3*	1.4	30.0
Lube		X	X			10.0	0.1%	1	10.0		
			X			37.2	0.3	12	3.1		
All lube						47.2	0.4%	13	3.6*	0.8	10.0
Total						11,080.2	100.0%	267	41.5*	0.7	419.0 (Highest)

* Rounded to nearest to 100 B/D.

About one-half of the number of small fuel refineries average only about 5,400 B/D capacity and do not include any of the five major refining processes listed above. Most of the other half of the small fuel refineries have alkylation and asphalt processes. The total number of small fuel refineries is about one-half of the total number of refineries, but the total small fuel capacity is only one-fourth of the total U.S. capacity. The average capacity of the small fuel refineries approximates 24,000 B/D, with a capacity range from 185,000 B/D to 700 B/D.

In the complete processing refinery category, processing is fairly evenly distributed among the combinations of the five selected processes. Capacity approximates one-fifth of total U.S. capacity and is contained in only 12 refineries--less than 5 percent of the total number of U.S. refineries. The average capacity of this type of refinery is about 194,000 B/D, with a range from 419,000 to 34,000 B/D.

The remaining three types of refineries include the small specialty refineries: asphalt, asphalt and lube, and lube. None of them have alkylation processing, but each has either asphalt or lube processing, or both, depending on their primary product line. Capacities of the three types together comprise only 6 percent of the U.S. total refining capacity. Capacities range from a high of 35,000 B/D to a low of less than 1,000 B/D.

Processing

Within the refinery, the crude oil is fractionated into parts, the parts processed to change their structures, and the resulting products fractionated further, recombined, and treated as necessary to meet market demand. Technology in the structure-change processes has progressed rapidly, so that there are more than 100 identifiable processes[8] and their modifications, with no one process being dominant.

W. L. Nelson[2] has developed a grouping of processes adaptable to this study; he reduces the more than 100 processes to 16. Table 5 details the 16 process types.

This study considers that the processing unit in major use in each type of structure-change is representative of that process. For example, Orthoflow Fluid catalytic cracking is selected as representative of all catalytic cracking. Table 5 shows both the choice of the individual process within each process type and the index of capacity of each of these 16 processes, in terms of crude topping capacity for each of the six refinery categories. Because sequential processing, recycling, and reprocessing of the various intermediate products is necessary in normal refining operations, the total of the processing unit capacity indices exceeds 100 for all refineries.

The sequences and relative capacities (capacity indices) of processes are illustrated in Figure 4, a simplified flow diagram of a complete processing type of refinery. This shows the respective locations and capacities of the principal types of processes in the overall refining process flow.

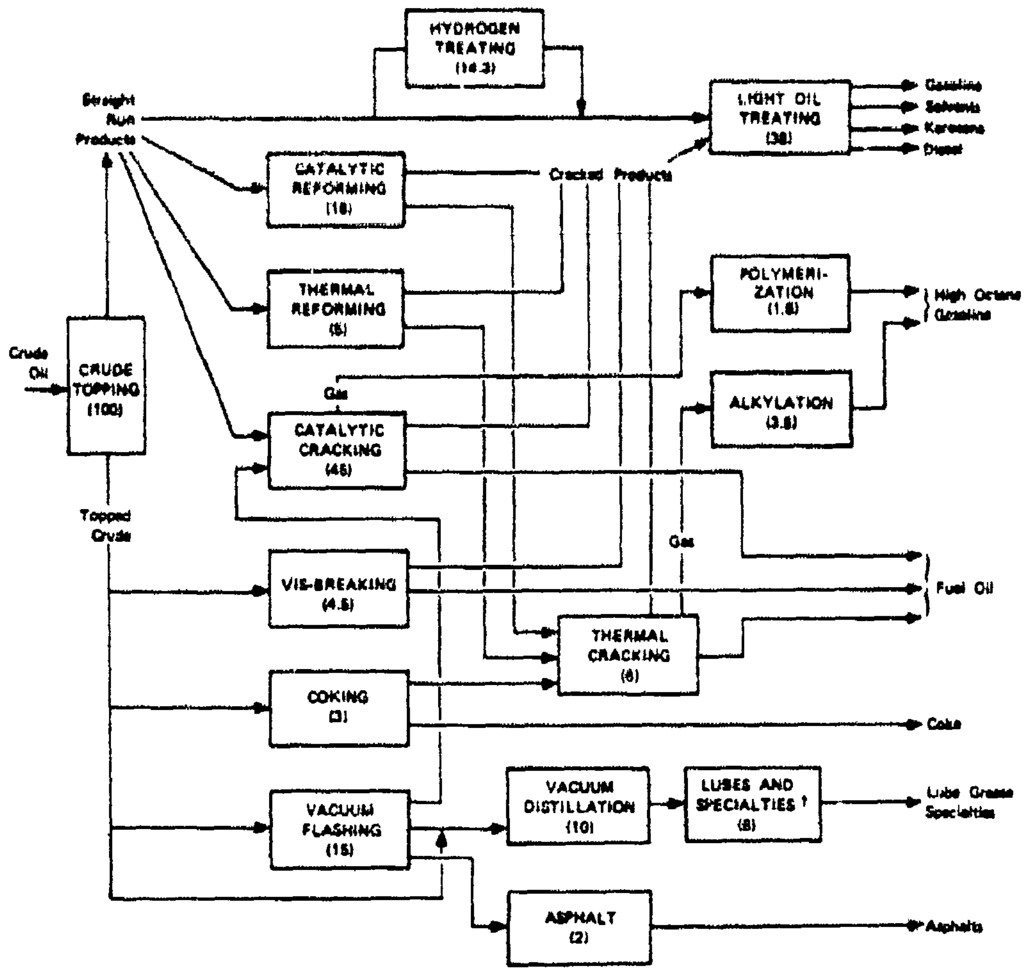
Equipment

The study took into consideration that, ideally, all equipment in a petroleum refinery is needed during the normal day-to-day operations. However, emergency refining operations, such as could exist in a postattack period, may be performed with some pieces of equipment out of service. To estimate accurately both a refinery's postattack production capability and repair requirement, it is essential to know three factors: the operational criticality, the blast vulnerability, and the repair requirements for each piece of equipment in each refining process.

Table 5

REFINERY PROCESSING UNIT CAPACITY INDICES
(Process capacity index with crude topping = 100)

Processing Unit	Process Selected	Refinery Type: Large Fuel	Small Fuel	Complete Processing	Asphalt	Asphalt and Lube	Lube
Crude topping	(Standard)	100.	100.	100.	100.	100.	100.
Thermal cracking	Mixed phase thermal cracking	19.	12.	6.	17.	17.	9.
Thermal reforming	(Standard)	2.4		5.	2.	2.	7.
Viscosity breaking	(Standard)	6.	6.	4.5			
Coking	Delayed coking	5.4	1.2	3.			
Catalytic cracking	Orthoflow Fluid catalytic cracking	52.	54.	45.	4.	7.	27.
Catalytic reforming	Platforming	23.	24.	18.	3.	3.	15.
Polymerization	Phosphoric acid polymerization	1.4	1.6	1.8	1.7	1.3	1.
Alkylation	Sulfuric acid alkylation	4.3	3.6	3.2			3.2
Hydrogen treating	Hydro desulfurization	18.6	6.	14.3			
Vacuum flashing	(Standard)	28.	28.	15.	72.		
Vacuum distillation	(Standard)			10.		72.	35.
Lubes and specialties	(Standard)			6.			23.
Asphalt	(Standard)		3.6	2.	30.	30.	
Light oil treating	(Standard)	49.	48.	38.	41.	38.	34.
Naphthenic lubes and specialties	(Standard)					12.	



* Process capacity indices (with crude topping = 100) applicable to all complete processing refineries.
† Including naphthenic lubes and specialties processes.

FIGURE 4 PROCESSES, CAPACITIES,* AND PRODUCTS: COMPLETE PROCESSING REFINERY

Operational Criticality

It is necessary to know how reducing or eliminating the operability of each piece of equipment affects the production capability of the corresponding process unit and of the refinery. The equipment whose reduced or eliminated operation causes the greatest degradation of refinery production capability is of most concern.

Blast Vulnerability

For the equipment that is critical to refining operations, it is also necessary to know its vulnerability to overpressure. Information on both the overpressure level that causes damage and the extent of the damage is needed. The equipment that is extensively damaged at low overpressures is of most concern.

Repair Requirements

For the equipment that is both critical to refining operations, and vulnerable to blast overpressure, it is necessary to know what is required to repair and restore it to operation. Emphasis is placed on the critical vulnerable equipment that requires a large amount of labor and multiple skills to repair.

Selection of Items of Equipment

The refinery control rooms are examples of equipment of concern in all three categories. Equipment that may be critical to operation but is relatively invulnerable to low overpressure, or that requires a relatively small amount of repair effort, is of less concern. Examples of these are heat exchangers and pumps.

Sources of information about equipment vulnerability are published reports[9,10] on both petroleum refineries and the chemical industry.

(Much of the equipment used in petroleum refining processes is comparable to that used in the chemical processes.)

Twenty-five representative items of equipment applicable to the various refinery processing units were selected on the following bases:

- Criticality of equipment to process unit operation
- Vulnerability of equipment to blast damage
- Necessity for a large amount of labor and multiple skills to repair the equipment

Table 6 details the selected items of equipment and indicates their inclusion in the 16 types of processing units.

Although a particular piece of equipment performs a specific function regardless of its location in a process unit or its inclusion in a particular refinery category, its size and therefore its reclamation requirement is a direct function of both the processing requirement and refinery capacity. Each of the included pieces of equipment are individually sized for each processing unit in each refinery category. Calculation methods and bases of equipment sizing are detailed in Appendix A.

Products

Equipment developed in today's industry needs specialized fuel and lubricant products. Those specialized needs designate characteristics, requirements, or specifications for petroleum products, so the equipment can meet performance standards considered to be normal or acceptable. As a result, the total number of petroleum products, separately identified by specification, is well over 1,000. However, many large groups of products are made in the same kinds of processing units and serve similar markets with only slight differences in specifications.

Table 6

REFINING EQUIPMENT INCLUDED IN PROCESSING UNITS

Processing Unit	Control House: Steel Roof	Control House: Concrete Roof	Cooling Tower	Tank: Cone Roof	Instrument Cubicle	Fired Heater	Reactor: Chemical	Filter	Regenerator	Tank: Floating Roof	Reactor: Cracking	Pipe Supports	Utilities: Gas Meter	Utilities: Elec. Transformer	Electric Motor	Blower	Fractionation Column	Pressure Vessel: Horizontal	Utilities: Gas Regulator	Extraction Column	Steam Turbine	Heat Exchanger	Tank: Spherical	Pressure vessel: Vertical	Pump
Crude topping	X		X	X		X						X	One item common to entire refinery	One item common to entire refinery	X		X	X	One item common to entire refinery		X	X		X	X
Thermal cracking		X	X	X	X	X				X		X			X		X				X	X		X	X
Thermal reforming		X	X	X	X	X				X		X			X		X				X	X		X	X
Vis breaking		X	X	X	X	X				X		X			X		X				X	X		X	X
Coking		X	X	X	X	X				X		X			X		X	X			X	X		X	X
Catalytic cracking		X	X	X	X	X			X	X	X	X			X	X	X	X			X	X	X	X	X
Catalytic reforming		X	X	X	X	X				X	X	X			X	X	X				X	X	X	X	X
Polymerization*		X	X		X		X			X		X			X		X	X			X	X	X	X	X
Alkylation		X	X	X	X	X	X					X			X		X	X			X	X	X	X	X
Hydrogen treating		X	X	X	X	X				X	X	X			X		X	X			X	X	X		X
Vacuum flashing	X		X	X		X						X			X		X				X	X		X	X
Vacuum distillation		X	X	X	X	X						X			X		X				X	X		X	X
Lube and specialties		X	X	X	X	X		X		X		X			X		X	X		X	X	X	X	X	X
Asphalt	X		X	X		X						X			X		X				X	X			X
Light oil treating	X		X	X		X				X		X			X		X	X		X	X	X		X	X
Naphthenic lubes and specialties		X	X	X	X	X		X		X		X			X		X	X		X	X	X	X	X	X

* Catalytic polymerization.

This study assumed that all products can be grouped into seven categories, combining physical characteristics and general market end-use:

- Gasoline
- Kerosene
- Diesel
- Lube
- Fuel oil
- Asphalt
- Coke

Gasoline includes all types of motor and aviation gasolines. Kerosene includes napthas, solvents, and jet fuels. Diesel includes all types of fuel for diesel use. Lube includes all waxes, greases, and lubricating oils. Fuel oil includes all types of residual fuels for both stationary boiler and seagoing vessel boiler use. Asphalt includes roofing asphalt and all types of paving and road oils. Coke is used primarily for fuel for stationary boilers, for electrodes in the aluminum industry, and for barbecue briquettes.

Product specifications cannot be met in postattack production quantities required using simple "batch-still" or simple "pipe-still" distillation equipment. Modern refining equipment and methods must be available.

Validity of Industry Descriptors

Before attempting to estimate production after damage and repair effort, the descriptors chosen for the petroleum refining industry were tested for their ability to picture the industry as it now stands. In total, the selected descriptors give results that are representative of U.S. petroleum refining. The designated types of refineries, their respective processing units and pieces of equipment--weighted by the relative capacities of these types in the United States, and using the "normal" crude oils selected for each refinery type--were analyzed by the accepted abbreviated methods of estimating production, by product. This yielded a calculated product mix that closely approximates reported U.S. production, as shown by the following comparison with Bureau of Mines production data:[4]

Product	Calculated Yield (%)	Bureau of Mines Data[*] (%)
Gasoline	48%	49%
Kerosene and diesel	29	30
Lube	2	2
Fuel oil	12	7
Asphalt	6	4
Coke	3	2
Other*	—	6
Total	100%	100%

Inclusion of still gas with fuel oil in the abbreviated calculation method accounts for the only large discrepancy. Bureau of Mines data show this separately, under "Other."

In some instances, it may be desirable to estimate postattack production capabilities of individual refineries whose crude oil and processing equipment differ appreciably from the averages selected. On the basis that all refineries of one type produce similar product mixes, product changes resulting from change of crude oil characteristics (i.e., degrees API gravity) may be roughly approximated by applying ratios derived from the average refinery of that type. This is illustrated by gasoline production capabilities of a large fuel type refinery with change of crude oil:

	Crude Oil, API Gravity	Gasoline Production, Undamaged (%)
"Normal"	30°-40°	54%
Alternative	20°-25°	8-10
Approximate decrease	12°	44†

* Includes still gas, petrochemical feedstocks, and other finished products.

† Large decrease reflects limited capacity of fuel oil equipment and processing equipment used for converting heavy oils to lighter products.

The approximate ratio is 44/54 parts of gasoline per 12° API crude oil change, or about 0.07 parts per 1° API.

Then, for a particular large fuel refinery that usually is supplied with a crude oil of "X" degrees API and must be supplied with alternative crude oil of "X" - 10° API, the gasoline will decrease by

$$-10 \times 0.07 = 0.7 \text{ parts}$$

With initial gasoline production capability at 54 percent, the reduced production using the alternative crude oil of "X" - 10° API will roughly approximate

$$54 \times (1 - 0.7) = 16\%$$

Similar approximations may be made for other products.

In this illustration the large decrease of gasoline with use of a heavier crude oil is based on the refinery initially having all processing units sized to operate at full capacity with the "normal" crude. With heavier crudes, the heavy oil processing units limit the total refinery capacity. Gasoline production from individual refineries with excess heavy oil processing capacity of course would not drop as far as the 16 percent. The determination of the decrease would require further study.

IV REFINERY VULNERABILITY

The vulnerability of petroleum refinery equipment to blast damage, drawn from published sources,[9,10] indicates that cooling towers, control rooms, fired heaters, and tanks--essential items in nearly all types of petroleum processing--are susceptible to blast damage at low overpressures.

Cooling Tower

A cooling tower is the essential part of a water cooling system. Cooled water from a large basin or reservoir at the foot of a cooling tower is pumped to the individual refinery processing units, where it cools various hydrocarbon streams in heat exchangers. As the warmed water returns to the top of the cooling tower, it is distributed or sprayed over baffles. Atmospheric evaporation, either with natural convection air currents or with forced draft fans, cool the water as it drains back to the basin or reservoir.

Characteristically, these water cooling towers are lightweight. To function, they must have numerous water and air flow baffles with sufficient open space for large quantities of air to enter, flow through, and exhaust. The only strength required by such a tower, other than that needed to withstand normal wind pressure, is that needed to support its own weight. This weight consists of structural members and appropriate baffles to properly channel air flows and water flows, piping to return the warmed water to the top, distribute it, and possibly forced-draft fans.[8,1,11,12]

Construction materials here must withstand a constant warm and moist atmospheric condition. Refiners have found the most satisfactory materials for this service to be redwood and asbestos.

Published sources[9,10] indicate that these cooling towers are susceptible to blast damage at about 0.3-0.5 psi overpressure. A large cooling tower 90 ft wide, 76 ft high, and 325 ft long is damaged at about 0.3 psi.[9] At this overpressure, the corrugated asbestos louvers on the windward side will shatter and their fragments will be blown into the interstices of the tower, with little or no damage to the internal parts of the structure. A small cooling tower of three cells, each 20 ft wide, 20 ft long, and 15 ft high, is damaged at about 0.5 psi to 1.0 psi,[10] when corrugated asbestos louvers on the blast-loaded side shatter and are blown into the interstices of the tower; probability of failure is 1 percent at 0.5 psi, 50 percent at 0.75 psi, and 99 percent at 1.0 psi.

For this study, the outer louvers were assumed to break at about 0.3 to 0.5 psi overpressure, because petroleum refineries normally use large cooling towers. The loss of the louvers decreases the efficiency of the tower to about 70 percent but does not completely shut down the refinery.

Higher overpressures result in greater damage. At about 1.5 psi overpressure, approximately 25 percent of the interior baffles are destroyed,[10] reducing cooling tower efficiency to about 50 percent. At about 3.5 psi, the tower structure collapses[9] and must be rebuilt. Before rebuilding, water could temporarily be cooled on an emergency basis, if other refinery equipment still operable required cool water, by spraying the circulating warmed water over the surface of the collecting basin or on the mass of debris that may remain. This would accomplish some cooling, similar to a simple cooling spray pond.

Controls

The electrical controls of a processing unit (manual switches and remote-operated electrical switches for motor operated equipment) are a part of its control system. These controls, or switchgear, are characteristically housed in rooms with structural steel roofs. Published data[9] indicate that the steel type roofs of switchgear rooms collapse at 1.0 psi, causing damage to the switchgear.

In the central instrument control room are the various instruments required for adequate indication and control of process conditions. Characteristically, these instruments are glass-fronted and some may contain jewel-bearing wheatstone bridge galvanometers. A low overpressure level of about 0.5 psi will break the glass fronts and possibly damage the jewel-bearing parts, rendering the instruments unusable.

The instrument control equipment of a process unit is normally housed in rooms with either a structural steel roof or a precast concrete roof. This study assumed that the steel roof is used on the older, less expensive, and less complex process units, i.e., the crude topping, vacuum flashing, light oil treating, and asphalt process units.

Published data[9] indicate that structural steel roofs on instrument control rooms survive a 1.0 psi overpressure because outer windows have broken, relieving the roof pressure. However, it was assumed that instruments are damaged from flying shattered glass particles at 1.0 psi.

The concrete roof is found in instrument control rooms in complex process units or in process units requiring "double-deck" structures. Published data[9] indicate that control rooms with concrete roofs suffer frame deformation at 1.0 psi and that the roofs of all control rooms collapse at 1.5 psi overpressure.

Control systems, from the instrument to the equipment that is controlled, normally consist of pressure-controlled pneumatic systems or low energy electrical systems. The pneumatic systems are susceptible to dust and pinched tubing difficulties; the electrical systems are susceptible to wiring breakage or short-circuiting. These conditions of instrument damage can be expected after collapse of the control room roof.

Thus, it is considered that at 1.0 psi the crude topping, vacuum flashing, light oil treating, and asphalt processing units would be shut down because of damage to their control rooms. It is recognized that emphasis would be placed on repair of the crude topping unit sufficiently to permit production of at least some products. Because the crude topping process is moderately simple in operation, it can operate to some degree with partial manual control. The author has assumed that sufficient emergency repair could be made to the crude topping unit to permit it to operate at 50 percent of initial capacity.

The vacuum flashing, light oil treating, and asphalt processes would remain shut down until scheduled postattack repair could be made. Until these units are repaired, the fuels, complete processing, and lube refineries could not operate at more than 50 percent of initial capacity; some products do not meet normal specifications. However, the asphalt and asphalt and lube refineries suffer greater capacity reduction because the process units of their principal product, asphalt, are shut down.

At 1.5 psi overpressure, all refinery processing is shut down because of damage to control systems.

Fired Heater

The application of heat in petroleum processing is primarily by means of a fired heater. Characteristically, this is an insulated brickwork fire box with oil-flow tubes along its inner surfaces.[1 8 10] At about 2.0 psi overpressure, the insulated brickwork breaks and pieces fall to the bottom of the box, damaging the burners and redirecting the flow of heat in the fire box.[9] This allows excessive channeling of hot flue gases to one part of the firebox, with resultant overheating and equipment failure. It is assumed that the fired heater is unusable after 2.0 psi.

Tanks

The fourth item of refinery equipment that suffers damage at low blast overpressure is tankage, for storage of crude oil, intermediate products, and finished products. Adequate storage capacity is essential to maintaining proper relative throughputs among processing units within a refinery. Blast damage to tanks occurs over a wide range of overpressure. However, the damage effects that could stop refining operations occur at overpressures above 1.5 psi, where operations are already stopped because of control house roof collapse.

The roofs of cone roof tanks collapse and sink to the bottom of the tank after about 1 psi overpressure,[9] although the tank may still be used in this condition on an emergency basis. For either a cone roof or a floating roof type of tank, the overpressure level that will cause damage that stops storage operation will vary with the relative amount of liquid in the tank.[9,10] About 3 psi overpressure will rupture and uplift a half-filled tank, while about 6.5 psi overpressure will rupture and uplift a tank 0.9 filled. Under normal operating conditions, refinery tankage averages about one-half filled. Thus, tankage is considered to be unusable after about 3 psi overpressure.

Based on the above, the pattern of continued production capability after low overpressure is as follows:

		Production Capability as Percent of Initial Capacity	
Overpressure	Damage To	Fuel, Complete Processing and Lube Refineries	Asphalt, and Asphalt and Lube Refineries
< 0.3		100%	100%
0.3-0.5	Cooling tower, glass-fronted instruments	70	70
1.0	Control instruments and switchgear	50	15-22
≥ 1.5	All processes, because of damage to control rooms	0	0

Figure 5 summarizes the complete range of blast damage effects from 0.3 to 20 psi, drawn from published literature[9,10] for each of the selected 25 types of equipment critical to petroleum refineries.

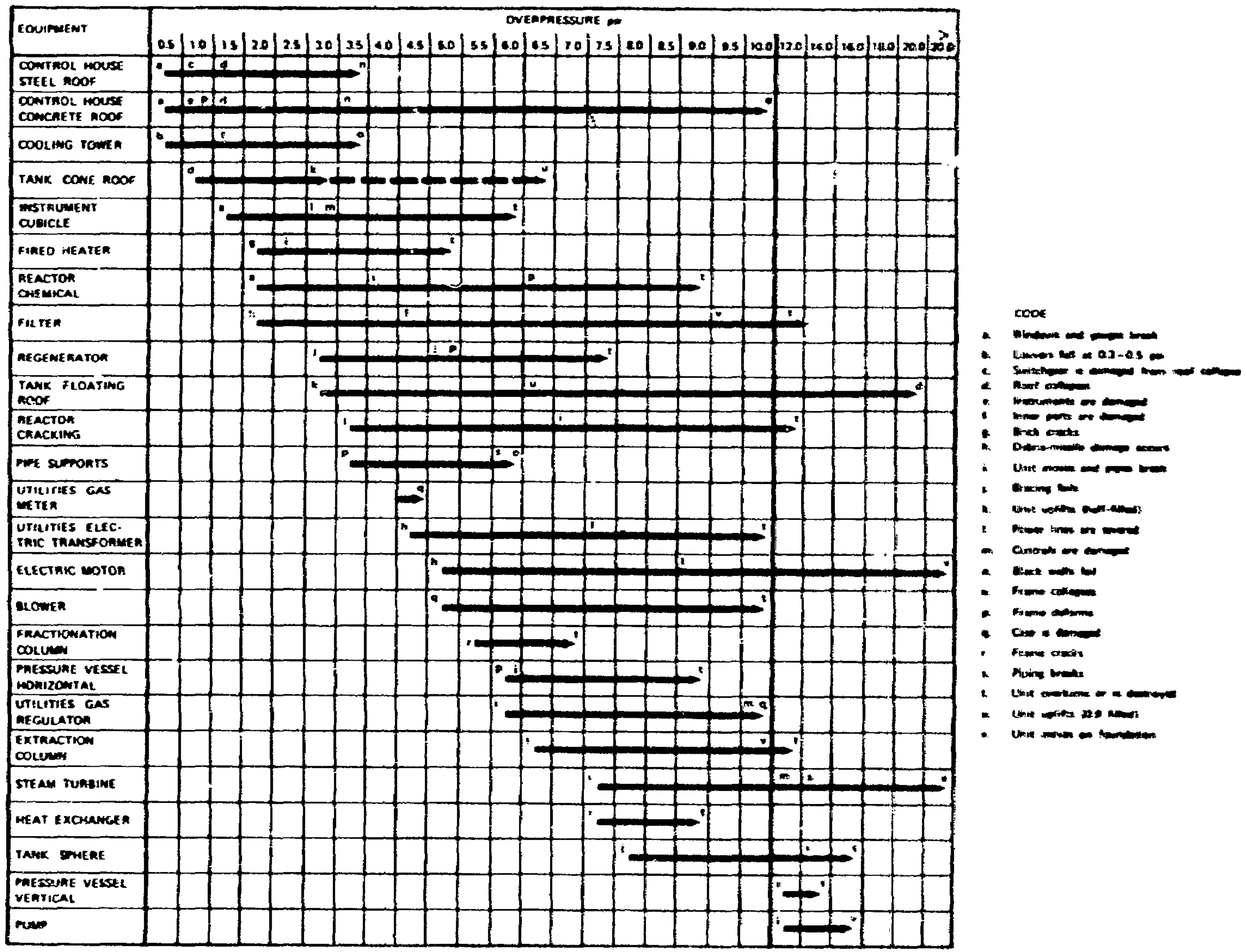


FIGURE 5 BLAST OVERPRESSURE EFFECTS ON VULNERABLE REFINERY PARTS

V REFINERY REPAIR

After a refinery is subjected to blast overpressures of 1.5 psi or greater, there will be equipment to be repaired in many process units; even under normal conditions, the magnitude of repair effort would be such that only a few process units could be repaired simultaneously. Thus, it can be assumed that the repair of process units will take place in sequential stages. Selection of the sequence of refining unit repair will be determined by which products to produce and in what volume, or conversely, the selection of the sequence will determine products, volumes, and quality of product.

This study selected the repair sequence according to the logic that:

- It is most important to restore enough operating capability to produce some engine fuels--gasoline, kerosene (including jet fuels), and diesel--regardless of individual product quality.
- Next in importance is to increase the volume of those fuels.
- Next in importance is to improve fuel quality.
- Last in importance is the production of nonfuels.

Repair Stages

On this basis, the repair sequence selected consists essentially of four major stages:

Repair Stage A - Repair the crude topping unit

Repair Stage B - Repair the processing units used in cracking processes

Repair Stage C - Repair the processing units used in upgrading products

Repair Stage D - Repair all other processing units

This sequence applies principally to fuels and complete processing refineries. In the postattack period there will be some need for lube and asphalt products, even though their volumes are expected to be small with respect to the demand for fuels. To permit production of these, the repair of specialty refineries differs from the sequence above enough for specialty products to be produced in conjunction with whatever fuels these refineries can produce.

The sequence of processing unit repair for each refinery type is summarized in Table 7.

One underlying principle used in establishing estimating factors for repair is that the repair effort will be completed only to the degree necessary to permit refining unit operation, but that for the particular equipment repaired, the repair must be complete. The repaired equipment or system would be virtually identical to the preattack system condition, and all equipment that forms a part of the process unit's operation must be repaired before that process unit can operate. (When a completely repaired process unit goes back on stream, production increases by the increment of product processed in this unit.)

While following this principle means complete reclamation of most parts of the repaired refining process unit (fired heaters, control houses, fractionation columns, and so forth), it excludes repair not necessary to refining unit operation at that time (spare equipment, unneeded steel structural work, painting, and the like).

Repair requirements data were drawn from published sources.[9 10] In instances of conflict of data, or of incomplete data, appropriate estimates were made.

Table 7

PROCESS UNITS ASSUMED REPAIRED AT EACH REPAIR STAGE, BY REFINERY TYPE

Repair Stage	Process Unit	Large Fuel	Small Fuel	Complete Processing	Asphalt	Asphalt and Lube	Lube
A	Crude topping	X	X	X	X	X	X
B	Vacuum flashing	X	X	X	X		
	Vis breaking	X	X	X			
	Thermal cracking	X	X	X			
	Thermal reforming	X		X			
	Catalytic cracking	X	X	X			
	Catalytic reforming	X	X	X			
	Coking		X				
	Asphalt				X	X	
	Vacuum distillation					X	X
	Lube and specialties					X	X
C	Vacuum distillation			X			
	Thermal cracking				X	X	X
	Thermal reforming				X	X	X
	Catalytic cracking				X	X	X
	Catalytic reforming				X	X	X
	Polymerization	X	X	X			
	Alkylation	X	X	X			
	Hydrogen treating	X	X	X			
	Lube and specialties			X			
	Light oil treating	X	X	X			
D	Polymerization				X	X	X
	Alkylation						X
	Light oil treating				X	X	X
	Asphalt		X	X			
	Coking	X		X			

Quantity of Production in Repaired Refineries

Under normal conditions a refinery operates at or near its capacity, at a nearly balanced condition with regard to operating equipment; the crude topping unit operates at maximum crude oil throughput to produce raw stocks of gasoline, kerosene, diesel, and residual products at the percentages appropriate to the crude oil supply. All processing units are sized to process these raw stock quantities. With a major change in crude oil supply, one of the subsequent processing units may become the limiting factor of total refinery production, because the components of the alternative crude oil may not necessarily be in the proportions required by the existing processes to make the desired product mix. Refinery production capability can be limited by the capacity of one particular processing unit. Further, if the capacity of that processing unit has been reduced by blast damage effects, total refinery capability is reduced correspondingly. This can be illustrated by a simple example:

> A 165,000 B/D refinery may be designed to operate on a crude oil that normally has a maximum of 15 percent of raw product, P. The processing units for product P are sized accordingly at 0.15 × 165,000 = 24,750 B/D. If the crude oil is changed to one with 45 percent of P, the processing of P is still limited to 24,750 B/D. This limits crude oil throughput to 24,750/0.45 = 55,000 B/D, even though the refinery was designed for 165,000 B/D.
>
> If the capacity of the process units for product P have been reduced to one-half of normal (from blast damage), the crude oil throughput is limited to 1/2 × 55,000 B/D = 27,500 B/D.

Table 8 compares, at each repair stage, the product yields from the six selected types of refineries, using the selected "normal" crude oils and the product yields that could be expected from crude oils comparable to the selected alternative crude oils.

Table 8

REFINERY PRODUCTION CAPABILITY BY REPAIR STAGE
WITH "NORMAL" AND ALTERNATIVE CRUDE OILS

Repair Stage	Selected Crude Oil*	Percent of Initial Refinery Capacity					
		Large Fuel	Small Fuel	Complete Processing	Asphalt	Asphalt and Lube	Lube
A	Specialty crude oil				96	80	32
	30°-40° API Gulf	37	44	32	31	14	32
	20°-25° API West Coast	24	28	21	61	28	20
	20°-25° API Midcontinent	22	25	18	69	31	19
B	Specialty crude oil				96	94	61
	30°-40° API Gulf	50	62	37	31	14	59
	20°-25° API West Coast	28	33	22	61	28	31
	20°-25° API Midcontinent	23	28	19	69	31	26
C	Specialty crude oil				98	99	73
	30°-40° API Gulf	65	79	65	26	14	68
	20°-25° API West Coast	32	37	31	44	24	33
	20°-25° API Midcontinent	26	31	23	48	28	26
D	Specialty crude oil				100	100	100
	30°-40° API Gulf	100	100	100	24	13	92
	20°-25° API West Coast	38	42	35	41	23	34
	20°-25° API Midcontinent	31	33	27	44	26	26

* See Section III for selection of "normal" and alternative crude oils.

The limits placed on production capability by the use of alternative crude oils are pronounced in the asphalt and the asphalt and lube refineries. This limited capability reflects the emphasis on only light fuel products coupled with the volume limitations of repaired and operable processes, as well as the difference in crude oil supply. The refinery normally uses heavy crude oils to produce mainly asphalt-type products and has limited process capacity to produce gasoline.

In Repair Stage A, the crude topping process unit is repaired and some light fuel products can be produced. If the refinery must use an alternative crude oil that contains a large percentage of a gasoline-type raw product, the refinery throughput is limited by the gasoline processing capacity. As successive repair stages B, C, and D are completed, more of the crude oil is converted into a gasoline-type product. However, the gasoline processing units remain the limiting capacity factor, so that the resultant total throughput never achieves production levels equalling initial refinery capacity.

If gasoline could be blended into kerosene and diesel, the throughput would be expected to increase with increased repair completed. The degree of this increase could be determined only after further study.

Quality of Products After Repair

Products that can be produced after the early stages (A and B) of refinery repair will not necessarily be "on-grade" (meet today's specifications). Under postattack conditions after low overpressure (0.3-0.5 psi), it is assumed that refineries can operate with balanced operating conditions: capacities of process units within a refinery remain proportional to preattack capacities, and products receive adequate processing to meet specifications.

After 1.0 psi, all process units except vacuum flashing, light oil treating, and asphalt are capable of operating at 50 percent of initial capacity. Some products could meet specifications.

After 1.5 psi or higher overpressures, however, all refinery processing units are shut down. Making repairs in sequential stages temporarily leaves some process units inoperable. It is assumed that in the early repair stages, raw gasoline stock (and other fuel stocks) can be produced, but other process units to upgrade the gasoline and keep it "on-grade" are temporarily inoperable. As a result, gasoline (and other fuels) are expected to be of lower quality than that normally produced.

This study took into consideration that in the postattack period the short term operability of engines is of much importance. While the light oil treating process units are shut down, fuel specifications cannot be met, so that short term operation of engines must take precedence over possible degradation of engine life over the long term.

The study also recognized that engines can operate on fuels other than those for which they were designed. Tests have been made of this, and in many instances results have been satisfactory with the acceptance of a decreased efficiency and a potential increase of maintenance. The degree of decreased efficiency and the degree of increased maintenance that could be tolerated would reflect the urgency of the need for the work of the engines and for the refineries' production. Investigation of these trade-offs is beyond the scope of this study, so a refinery product is considered usable as long as it is within its normal boiling range.

Labor

Model Formulation

The labor effort required to repair a particular piece of equipment after blast damage is, in general, a function of both the complexity of that equipment and its vulnerability to damage, as well as a function of its size and type. To adequately relate the required repair labor to the equipment condition after blast overpressure, the labor is expressed as a function of:

- Overpressure level
- Lowest overpressure level to cause equipment damage
- Maximum labor to completely repair the equipment
- Equipment size

For the purpose of estimating labor requirements, a mathematical model developed by URS Systems Corporation was selected.[10] This model combines a basic model or mathematical function describing the repair labor required for a particular size of equipment with a scaling model describing the effects of equipment size. The basic model is:

$$R = L\left[1 - e^{-k(p-x)^{y}}\right],$$

where R = repair effort (man-days)

L = maximum repair effort (man-days)

p = overpressure (psi)

x = lowest overpressure (50 percent probability estimate) at which damage is observed, psi

k = a constant for given equipment

y = a constant for given equipment

The constants k and y give an expression that best fits existing data for repair requirements of each type of equipment. The base of the natural or naperian logarithms is represented by the letter e.

This basic model, however, describes the repair effort for only one equipment size. Because a petroleum refinery may have many different-sized pieces of equipment of the same type, it is necessary to scale the labor requirements to the particular equipment size. This is done with the scaling factor:

$$m\left(\frac{C}{C_o}\right) + b ,$$

where m = a constant for a given equipment component

C = capacity or size of equipment component being investigated

C_o = capacity or size of equipment component standard

b = a constant for a given equipment component.

The constants m and b are selected for each type of equipment to yield appropriate scaling for types of repair that could change with equipment size (welding a seam on a large or on a small tank), or remain the same without regard to size (replace instrument gauges). At the overpressure levels at which damage effects change, these constants will change value.

The combined model used in this study is:

$$R_s = L\left[1 - e^{-k(p-x)}\right]\left[m\left(\frac{C}{C_o}\right) + b\right],$$

where R_s = repair effort in man-days for each specified size piece of equipment.

Table 9 lists the seven parameters (L, k, x, y, m, b, C_o) for the labor requirement model for each of the selected 25 types of equipment. These are applied to the size characteristics of each piece of equipment to estimate the labor required for repair after blast overpressures of 0.5, 1, 5, and 10 psi.

Table 8

PARAMETER VALUES FOR LABOR REQUIREMENT MODEL

$$N_s = L\left[1 - e^{-k(p-x)^y}\right]\left[m\left(\frac{C}{C_o}\right) + b\right]$$

	L	k	x	y	m	b	C_o Number	C_o Units
Control house, BR*	480.	0.7	1.0	1.3	1	0.	32,000	cu ft
Control house, CR*	610.	0.7	1.5	1.3	1	0.	32,000	cu ft
Fired heater	370.	1.5	0.9	1.	1	0.	45,000	cu ft
Fractionation column	380.	0.003	5.	4.	1.1 $p \le 8$; 0.84 $p > 8$	−0.08 $p \le 8$; +0.13 $p > 8$	1,100	cu ft
Extraction column	340.	0.004	6.	4.	1.1 $p \le 8$; 0.84 $p > 8$	−0.08 $p \le 8$; +0.13 $p > 8$	1,100	cu ft
Cooling tower	88.	0.1	0.	2.	Number	0.	18,000	cu ft
Reactor, cracking	24.	0.3	2.1	1.	1.4 $p \le 4$; 1.2 $p > 4$	0.3 $p \le 4$; 0.2 $p > 4$	850	cu ft
Reactor, chemical	36.	0.015	1.9	2.	1	0.	336	cu ft
Regenerator*	24.	0.3	2.1	1.	1.4 $p \le 4$; 1.2 $p > 4$	0.3 $p \le 4$; 0.2 $p > 4$	850	cu ft
Pressure vessel, horizontal	31.	0.37	12.	3.	0	1.		
Pressure vessel, vertical	30.	1.1	12.	1.	0	1.		
Pipe supports	82.	0.8	4.5	1.7	0.83	0.16	20	Length
Storage tank, CR*	175.	2.5	0.4	1.	1.	0.	38,400	cu ft
Storage tank, FR*	175.	2.5	0.4	1.	1.	0.	38,400	cu ft
Storage tank, S	200.	0.005	7.	3.	0.9	0.18	65,400	cu ft
Centrifugal pump	9.	0.7	12.5	1.	1.	0.	60,000	GPM x TDH
Electric motor	54.	0.16	3.5	1.	0.88 $p \le 5$; 0.74 $p > 5$	0.10 $p \le 5$; 0.25 $p > 5$	1,000	HP
Steam turbine	18.	0.007	8.	2.5	0.64 $p < 14$; 0.80 $p \ge 14$	0.47 $p < 14$; 0.25 $p \ge 14$	25	HP
Blower, centrifugal	17.	0.45	4.	1.	1.	0.	150	HP
Heat exchanger (stacked)	30.	0.8	7.	2.	0.	1.		
Filter, rotary (vacuum)	27.	0.22	0.1	1.	0.91 $p < 4$; 0.70 $p \ge 4$	0.10 $p < 4$; 0.30 $p \ge 4$	6	Diam in ft
Instrument cubicles	20.	1.	1.	1.	Number	0.	120	cu ft
Utilities, gas meter	2.1	0.9	1.5	1.	Number	0.	1	Industrial size
Utilities, gas regulator	2.1	0.7	5.	1.	Number	0.	1	Industrial size
Utilities, elec. transformer	130.	0.0007	1.	4.	Number	0.	10	MVA

* Calculated values.

Source: URS Systems Corporation, Report No. 687-4, June 1968.

The results of this application show the amount of repair required in terms of blast overpressure level, for the average or representative size of each type of refinery. To determine the effect of refinery size, on repair requirement, the capacities of the refinery types--large fuel, asphalt, and lube--were varied and the resultant repair requirements determined.

The results for the six types of refineries at average capacities and for the three capacity variations are summarized in Table 10. The results indicate that the initial capacity or size of a refinery is the predominant influence in determining the repair requirement. Refinery repair needed after blast damage is within a given range, regardless of the type of refinery. This is illustrated in Figure 6.

An example of the application of the seven parameters (Table 9) to selected refinery equipment is as follows:

Refinery type	Small fuel
Refinery capacity	24,000 B/D
Processing unit	Crude topping
Equipment	Fired heaters
Number	2
Volume, each	15,000 cu ft
Overpressure	10 psi

$$R_s = L \left[1 - e^{-k(p-x)^y} \right] \left[m \left(\frac{C}{C_o} \right) + b \right]$$

$$R_s = 370 \left[1 - e^{-1.5(10-0.9)^{1.0}} \right] \left[1.0 \left(\frac{15,000}{45,000} \right) + 0 \right] \times 2$$

= 247 man-days to repair these two fired heaters.

Table 10

REPAIR REQUIREMENTS, BY REFINERY TYPE

Refinery Type	Capacity, B/D	Labor in Man-Days			
		0.5 psi	1 psi	5 psi	10 psi
Large fuel	78,000	36,000	128,000	178,000	292,000
	150,000*	70,000	245,000	341,000	556,000
Small fuel	24,000	7,000	24,000	36,000	77,000
Complete processing	194,000	82,000	289,000	402,000	640,000
Asphalt	12,000	3,000	11,000	16,000	28,000
	14,000*	4,000	13,000	18,000	31,000
Asphalt and lube	7,000	2,000	6,000	10,000	22,000
Lube	4,000	1,000	4,000	6,000	18,000
	27,000*	7,000	25,000	37,000	72,000

* Included to determine the effect of refinery size variation on repair requirement.

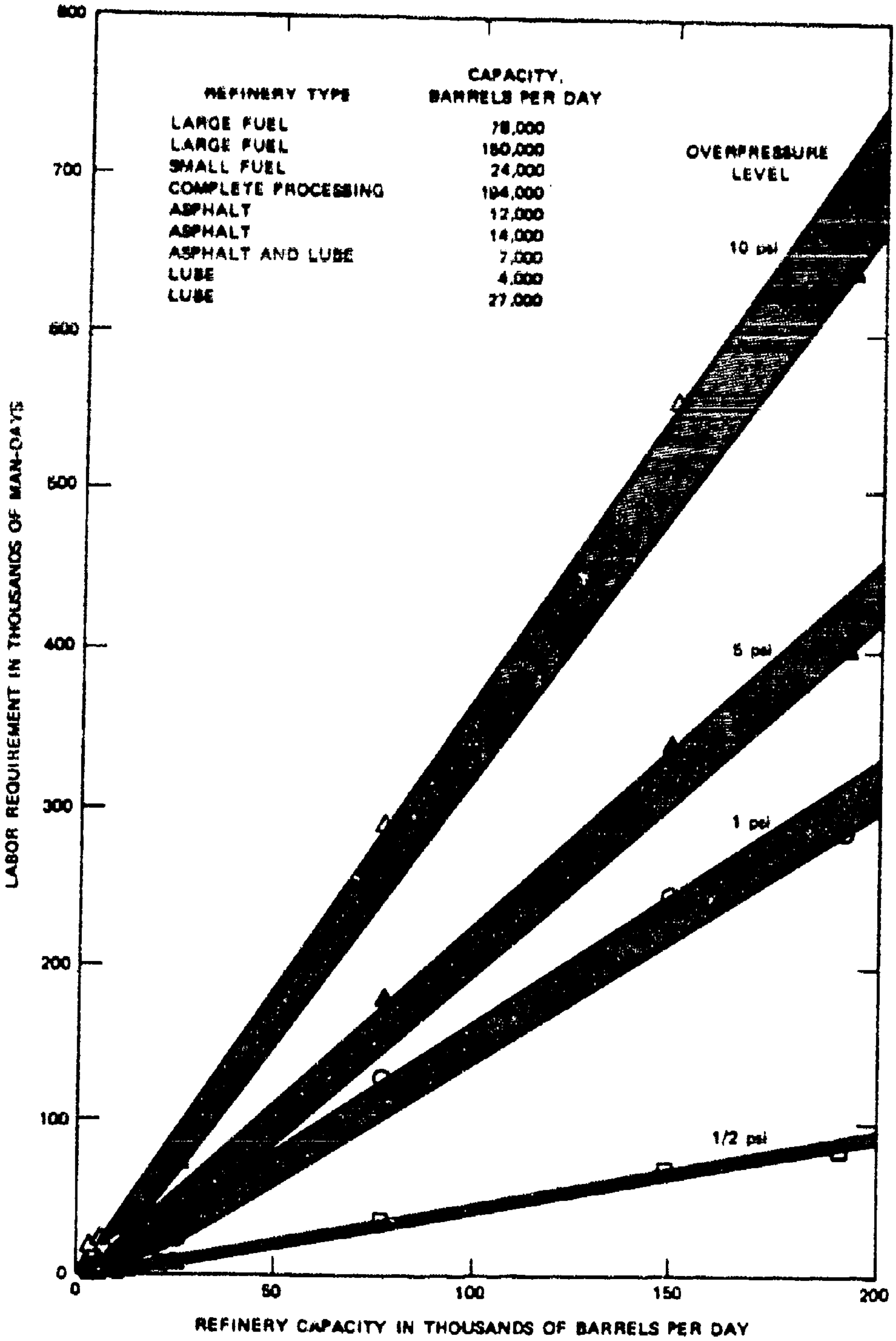


FIGURE 6 INDIVIDUAL REFINERY LABOR REQUIREMENTS TO RESTORE 100 PERCENT CAPACITY AFTER SELECTED BLAST OVERPRESSURE LEVELS

Similar calculations were made for the other equipment and process units included in that same refinery. To repair the crude topping process unit after 10 psi requires about 24,800 man-days out of a total of 77,000 man-days to repair the entire refinery. These calculations highlight the fact that in that type of refinery, the crude topping unit requires one-third of the total repair effort after 10 psi.

Because of the differing vulnerabilities of different pieces of equipment and the variations in the amount of labor needed to repair that equipment, the total repair labor required to restore 100 percent capacity of a refinery is not a linear function of blast overpressure level. However, the amount of labor after a specific overpressure level is roughly proportional to the amount of equipment in a refinery. The repair labor requirement can be expressed as a range of labor required for a given initial refinery capacity and blast overpressure level. Figure 6 illustrates this graphically. For example:

> Any 24,000 B/D refinery is expected to require between about 60,000 and 90,000 man-days of repair labor after 10 psi overpressure.

The range increases with increasing overpressure. At very low overpressure levels, only a moderate amount of equipment is damaged (cooling towers and storage tanks) and the range of repair effort is small. Since specialized equipment in different process units is damaged at higher overpressures, there is a wider range of repair effort at any given refinery capacity, depending on the type of refinery and the equipment included.

The consistency of the calculated labor requirements may be visualized by comparing them with new refinery construction costs. For a rough approximation, the current labor rate is about $6.10 per hour,[13] and labor cost constitutes about 60 percent of total refinery costs.[2]

On these bases, the approximate cost of refinery repair after a 10 psi blast is calculated as shown in Table 11. These data are compared with the overall average costs of new refineries in Figure 7. The results indicate that the calculated labor repair requirements bear a similar relation to refinery size and type. The difference between the repair cost after 10 psi and full refinery costs includes design engineering, equipment damaged but considered not absolutely essential to immediate operation (i.e., spare equipment), and the cost of the equipment pieces not yet damaged at 10 psi overpressure.

Crafts

For each piece of refinery equipment that has been considered to be damaged by blast overpressure, published sources[9,10] have detailed the individual crafts or skills that would be entailed, the equipment that those crafts would require, and the types of materials necessary to do the repair work.

While there is a strict differentiation maintained among the crafts, there are instances of basic similarities. In a time of emergency, it is conceivable that one craft could quickly learn the techniques of a similar craft to circumvent skill or craft shortages. A published article, Oil and Gas Journal, December 5, 1966,[9] indicates current thought along this line. Crafts can be grouped by similarities of repair requirements. One possible grouping is:

Group	Included Current Craft or Skill
General construction	Mason, rigger, carpenter
Metal fabrication	Welder, boilermaker, pipefitter
Machining	Machinist, millwright
Electrician/instrument	Crafts for control instruments

Table 11

REPAIR COST AFTER 10 PSI OVERPRESSURE

Refinery Type	Capacity, B/D	Labor Required After 10 psi* (man-days)	Labor Cost† ($000's)	Calculated Total Cost‡ ($000's)
Large fuel	78,000	292,000	$14,200	$23,700
	150,000	556,000	27,100	45,200
Small fuel	24,000	77,000	3,800	6,300
Complete processing	194,000	640,000	31,200	52,000
Asphalt	12,000	28,000	1,400	2,300
	14,000	31,000	1,500	2,500
Asphalt and lube	7,000	22,000	1,100	1,800
Lube	4,000	18,000	900	1,500
	27,000	72,000	3,500	5,800

* Man-days rounded to nearest 1,000.
† Rate = $6.10/hr × 8 hr/day = $48.8/day.
‡ Labor cost ÷ 0.6.

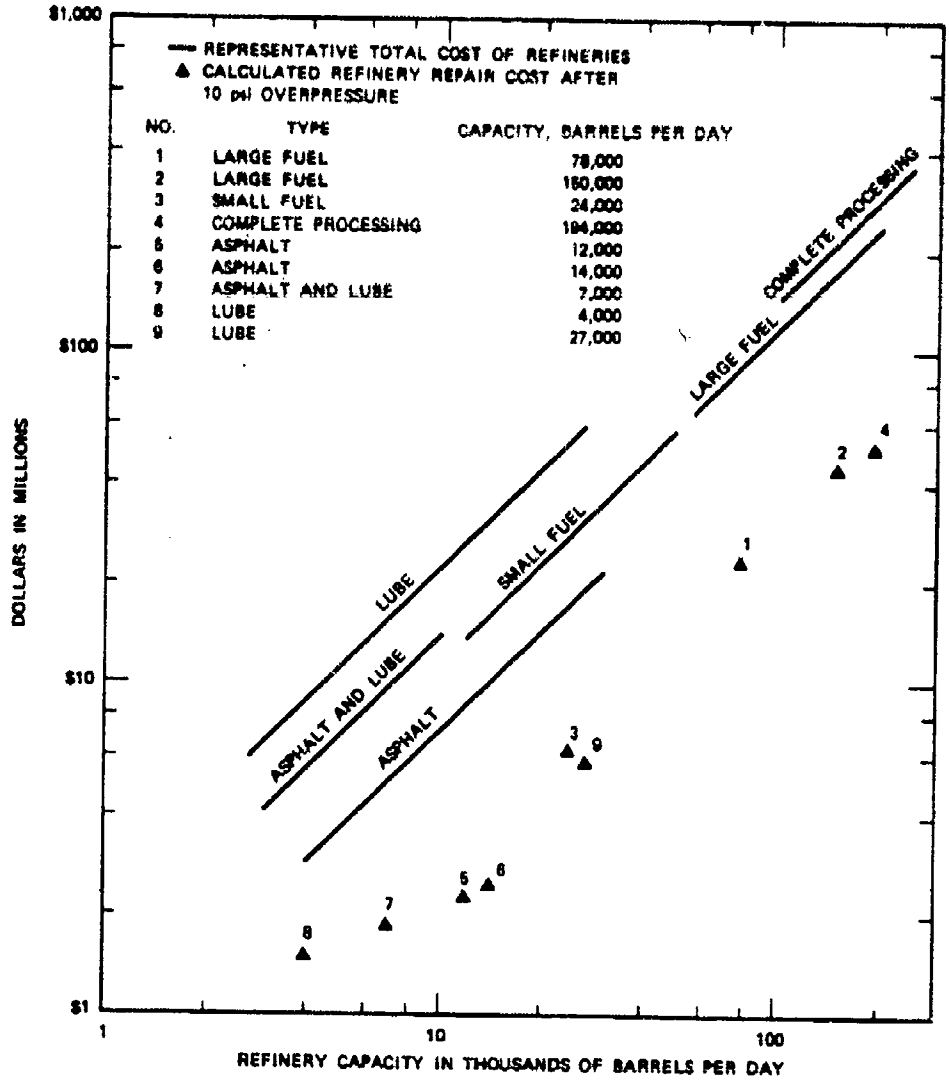


FIGURE 7 COST TO RESTORE REFINERIES TO 100 PERCENT CAPACITY AFTER 10 PSI BLAST OVERPRESSURE, COMPARED WITH NEW REFINERY CONSTRUCTION COST

Based on such groupings, the general craft requirements for refinery repair after the various overpressure levels can be summarized as follows:

psi	Equipment Repair	Craft	Comments
0.3-0.5	Cooling tower	Carpenter	Outer louvers broken
0.5	Instruments	Glazier	Glass fronts broken
1.0-5.0	Structure and and tank	General construction Metal fabrication Electrician/instrument	Structures deformed and "soft" equipment damaged
5-10	Equipment relocation	General construction Metal fabrication Machining Electrician/instrument	Equipment displaced from foundation
10 and higher	Nearly total rebuilding	General construction Metal fabrication Machining Electrician/instrument	"Hard" equipment suffers damage

Repair Materials

The materials required for repair of refineries are readily classified by type. However, the quantities of materials will vary with the blast overpressure level, the type of equipment being repaired, and the size of that equipment. The characteristics of equipment (see Appendix A) are given in dimensions such that the required quantities of materials for repair may be calculated when necessary. For example, the amount of brick required for a fired heater may be estimated as follows:

- Simplest configuration - cube of "W" ft on each side
- Brick wall thickness - 1 ft
- One internal fire-bridgewall, 2 ft thick, 3/4 of wall height

- Roof, equal to wall dimensions
- Floor, equal to wall dimensions

Outer brick shell volume = $6\ W^2 \times 1 = 6.0\ W^2$

Bridgewall brick volume = $3/4\ W^2 \times 2 = \underline{1.5\ W^2}$

Total brick volume $7.5\ W^2$

Heater volume = W^3

Brick volume = $7.5 \times (\text{heater volume})^{2/3}$

One brick = $2'' \times 4'' \times 8'' = 0.037$ cu ft

$$\text{Number of brick} = \frac{7.5 \times (\text{heater volume in cu ft})^{2/3}}{0.037 \text{ cu ft}}$$

$$= 202.5 \times (\text{heater volume in cu ft})^{2/3}$$

If a heater size is 45,000 cu ft

No. of brick = $202.5 \times (45{,}000)^{2/3}$

= 260,000

Similar approximations may be made for:

- Steel plate in terms of tankage volume
- Piping in terms of footage of pipe supports
- Wood in terms of cooling tower volume

In each instance, the supply points and suppliers of materials may be found in published supplier listings.[14]

In the event that equipment is beyond repair, the refinery has the alternatives of:

- Cannibalization - the situation of taking repairable equipment from a processing unit that is shut down
- Replacement - buying new equipment and completely rebuilding the processing units needed

Cannibalization

The equipment characteristics data (see Appendix A) have been presented in such a way as to make them usable for making cannibalization decisions. For example, if it is found necessary to obtain a pump, it is possible to refer to the list of representative equipment of processes that are shut down, verify approximate pump size and operational characteristics, and, with proper authorization, cannibalize one that is appropriate.

Replacement

The suppliers of each of the many types of equipment may be found by reference to published supplier lists.[14] In addition to the listed suppliers of equipment, there are possible instances in which equipment could be manufactured by companies that are not in that particular line of business, but who have the inherent manufacturing capability. For example, pressure vessels could be manufactured by shipbuilding companies.

In the postattack period, the time lapse between equipment order placement and delivery will be related to both the extent of damage to the supply industry and the use of an appropriate priority procedure. It is conceivable that in spite of some damage to supplier industries, the use of priorities could result in delivery times less than those under normal preattack conditions.

Operational Materials

The types of materials required for the operation of petroleum refining processes have been identified with the classification of the product with which each is used. This information, together with an approximation of the number of supply sources, is summarized in Table 12.

Sulfur and sulfur dioxide constitute a part of the supplies to nearly all refineries. The characteristics of the remaining supply material will vary according to the refining processes and crude oils

Table 12

OPERATIONAL SUPPLIES

Supply	Number of Suppliers 1-10	11-20	21-50	> 50	Representative Process	Representative Product
Sulfur			X		Light oil treating	Automotive gasoline
Sulfur dioxide		X			Light oil treating	Solvents
Sulfuric acid	X				Light oil treating Alkylation Lube manufacture	Aviation gasoline Automotive gasoline Solvents Kerosene Lubes
Inhibitors	X				Light oil treating	Gasolines Diesel
Caustic				X	Light oil treating	Gasolines Solvents
Refrigerants		X			Alkylation Polymerization	Gasolines
Catalyst			X		Cracking Polymerization	Gasolines
Additives				X	Light oil treating Asphalt	Lubes and greases Gasolines Diesel Asphalt

used. Various strengths or concentrations of sulfuric acid are used, depending on the refining processes requiring it. The inhibitors used will be determined by the products produced, the processes used, and the crude oils supplied. Catalysts will depend on the processes used and possibly on royalty or patent agreements.

In general, most of the operational supplies can be obtained from any of several manufacturers. Exceptions are sulfuric acid and inhibitors. Sulfuric acid is primarily used in the manufacture of aviation type gasolines (alkylation process) and in the treatment of the light oils to maintain quality specifications. Shortage of sulfuric acid could curtail the production of aviation and high octane gasolines and reduce the quality of light oil products.

Inhibitors are added to the light oil products to retard or limit possible degradation of the products before use. Shortage of inhibitors could create product quality problems.

Although additives as a group have many suppliers, the gasoline additives TEL (tetra ethyl lead) and TML (tetra methyl lead), which are used to increase gasoline octane rating, have a limited number of suppliers. Shortage of TEL or TML would reduce the octane rating of gasolines produced.

A detailed listing of all possible suppliers' materials required in petroleum processing is readily available from published sources.[14]

VI USING THE METHOD

This section describes how to use the tables and figures presented to estimate production capability and repair effort in blast-damaged refineries. An example is carried through the procedure for illustration.

Example: At Watson, California, the Atlantic Richfield refinery receives 1.0 psi blast overpressure.

Knowing which refinery is hit, with what overpressure, the method of estimating production capability and repair effort is:

• Determine refinery size and type	(Table 13)
• Determine crude oil supply	(Table 14)
• Estimate initial production capability and remaining capability with no repair	(Table 15)
• Estimate repair requirements by repair stages	(Figure 8)
• Estimate production capability by repair stages	(Figures 10-15)

With the estimation of postattack refinery repair efforts and production capabilities, the necessity for making several decisions before making actual repair efforts becomes evident. These decisions are discussed, and bases on which to make the decisions are indicated at appropriate points in the discussion.

<u>Determine Refinery Size and Type</u>

From published sources,[2] determine the initial capacity and the type of refinery, based on the listed combination of production capabilities from the following five processes (see "Refinery Types" in Section III):

- Alkylation
- Polymerization
- Lube
- Coking
- Asphalt

The Oil and Gas Journal[2] shows the example refinery to be a 165,000 B/D refinery with production capacities for:

- Alkylation
- Polymerization
- Coking
- Asphalt

Location of this combination of processes among those included in the columns of Table 13 (taken from Table 4 but rotated 90°) determines that this refinery is a large fuel type, according to this study's categorization.

Determine Crude Oil Supply

Crude oils available to refineries have been grouped as discussed in Section III. The "normal" crude oil and alternative crude oils are summarized by refinery type in Table 14. As discussed in Section III, a fuel refinery is considered to use a crude oil comparable to 30°-40° API Gulf Coast crude oil as its "normal" supply. Table 14 shows which alternative crude oils are considered usable for each refinery type, in the event that crude oil supplies or delivery systems have been disrupted by the nuclear attack. From this table, the "normal" crude oil supply to the example refinery is seen to be comparable to 30°-40° API Gulf crude oil; alternatives are comparable to 20°-25° API West Coast and 20°-25° API Midcontinent crude oils.

Table 13

DETERMINING REFINERY TYPE FROM PROCESSING COMBINATIONS

Processing	Refinery Type: Large Fuel	Small Fuel	Complete Processing	Asphalt	Asphalt and Lube	Lube
Alkylation	XXXXXXXXX	X X	XXXX			
Polymerization	X XX X	XX X	XXX	X	X	X
Lube	XX X	X	XXXX		XX	XX
Coke	XX XX X	XXX	XX X	X		
Asphalt	X XX X	XX X	XXX	XXX	XX	
No processing combination indicated		X				

Table 14

NORMAL AND ALTERNATIVE CRUDE OILS, BY REFINERY TYPE

Crude Oil	Fuel and Complete Processing	Asphalt	Asphalt and Lube	Lube
30°-40° API Gulf	N	A	A	A
20°-25° API West Coast	A	A	A	A
20°-25° API Midcontinent	A	A	A	A
10°-15° API asphaltic		N		
10°-15° API asphaltic and lube			N	
30°-45° API lube				N

N = comparable to "normal" crude oil supply; A = comparable to alternative crude oil supply.

Estimate Production Capability

The effect of limited process capability, as discussed in Section III, has been taken into account in Appendix B in calculating refinery partial production capability, both with alternative crude oils and after overpressures of 0.3-0.5 and 1.0 psi with only minor emergency repair.

Table 15 summarizes, for the six refinery types, refinery capacities for normal operations at initial capacity and partial production capabilities after damage from 0.3-0.5 psi and 1.0 psi overpressure, with "normal" and alternative crude oils. Whether the refinery has its "normal" supply of crude oil or has to operate on either of the alternative crude oils will be determined by conditions after a nuclear attack.

From Table 15, production from the example refinery after 1.0 psi overpressure would approximate 50 percent of initial capacity with "normal" crude oil and 15-19 percent of initial capacity with alternative crude oils. By using the product percentages shown in Appendix B, the individual product volumes would approximate:

	Initial Capacity of "Normal" Crude		Production Capability after 1.0 psi			
			"Normal" Crude		Alternative Crude	
Product	Percent	B/D	Percent	B/D	Percent	B/D
Gasoline	54%	89,100	26%	42,900	4- 6%	6,600-9,900
Kerosene	15	24,700	8	13,200	2	3,300
Diesel	14	23,100	7	11,600	2- 3	3,300-5,000
Lube	--	--	--	--	--	--
Fuel oil	13	21,500	7	11,600	7	11,600
Asphalt	--	--	--	--	--	--
Coke	4	6,600	2	3,300	0- 1	0-1,700
Total	100%	165,000	50%	82,600	15-19%	24,800-31,400

Table 15

REFINERY PRODUCTION CAPABILITY WITH SELECTED CRUDE OILS
AFTER 0-1 PSI BLAST OVERPRESSURE

Blast Overpressure, psi	Crude Oil Type	Percentage of Initial Refinery Capacity: Large Fuel	Small Fuel	Complete Processing	Asphalt	Asphalt and Lube	Lube
Undamaged	Specialty crude oil				100%	100%	100%
	30°-40° API Gulf	100%	100%	100%	24	13	92
	20°-25° API West Coast	38	42	35	41	23	34
	20°-25° API Midcontinent	31	33	27	44	26	26
0.3-0.5	Specialty crude oil				70	70	70
	30°-40° API Gulf	70	70	70	17	10	62
	20°-25° API West Coast	26	31	24	29	12	22
	20°-25° API Midcontinent	22	24	19	33	21	17
1.0	Specialty crude oil				15	22	50
	20°-25° API Gulf	50	50	50	5	1	49
	20°-25° API West Coast	19	23	20	3	5	19
	20°-25° API Midcontinent	15	16	15	5	6	15

Source: Appendix B.

It is possible that a nuclear attack will influence the crude oil supply. If it is necessary to supply this example refinery with a heavier than normal alternative crude oil, the gasoline production will decrease. With a crude oil comparable to the selected alternatives, gasoline production will drop to about 6,600-9,900 B/D, instead of being about 42,900 B/D with "normal" crude oil.

Planning decisions regarding the use of crude oils will hinge on the relative need for products. In this case, an increment of 33,000 to 36,300 B/D of gasoline would be gained by use of the light crude oil over the heavy.

Estimate Repair Requirements

Figure 8 (a repeat of Figure 2) indicates that the overall cost to restore the example refinery to initial capacity is in the range from 240,000 to 280,000 man-days.

For greater detail of repair effort by repair stage, refer to Appendix D. Table D-1 details effort by repair stage for an average 78,000 B/D large fuel refinery. This is scaled up to the example refinery size of 165,000 B/D as:

Repair Requirement in Man-Days

	Average Refinery, 78,000 B/D		Example Refinery, 165,000 B/D
Repair Stage	Cumulative Repair Requirement	Ratio to Full Repair	Corresponding Cumulative Repair Requirement
A	54,062	0.42	101,000*-118,000†
B	97,955	0.77	185,000 -216,000
C	126,238	0.99	238,000 -277,000
D	127,699	1.00	240,000 -280,000

* 0.42 × 240,000 = 101,000.
† 0.42 × 280,000 = 118,000.

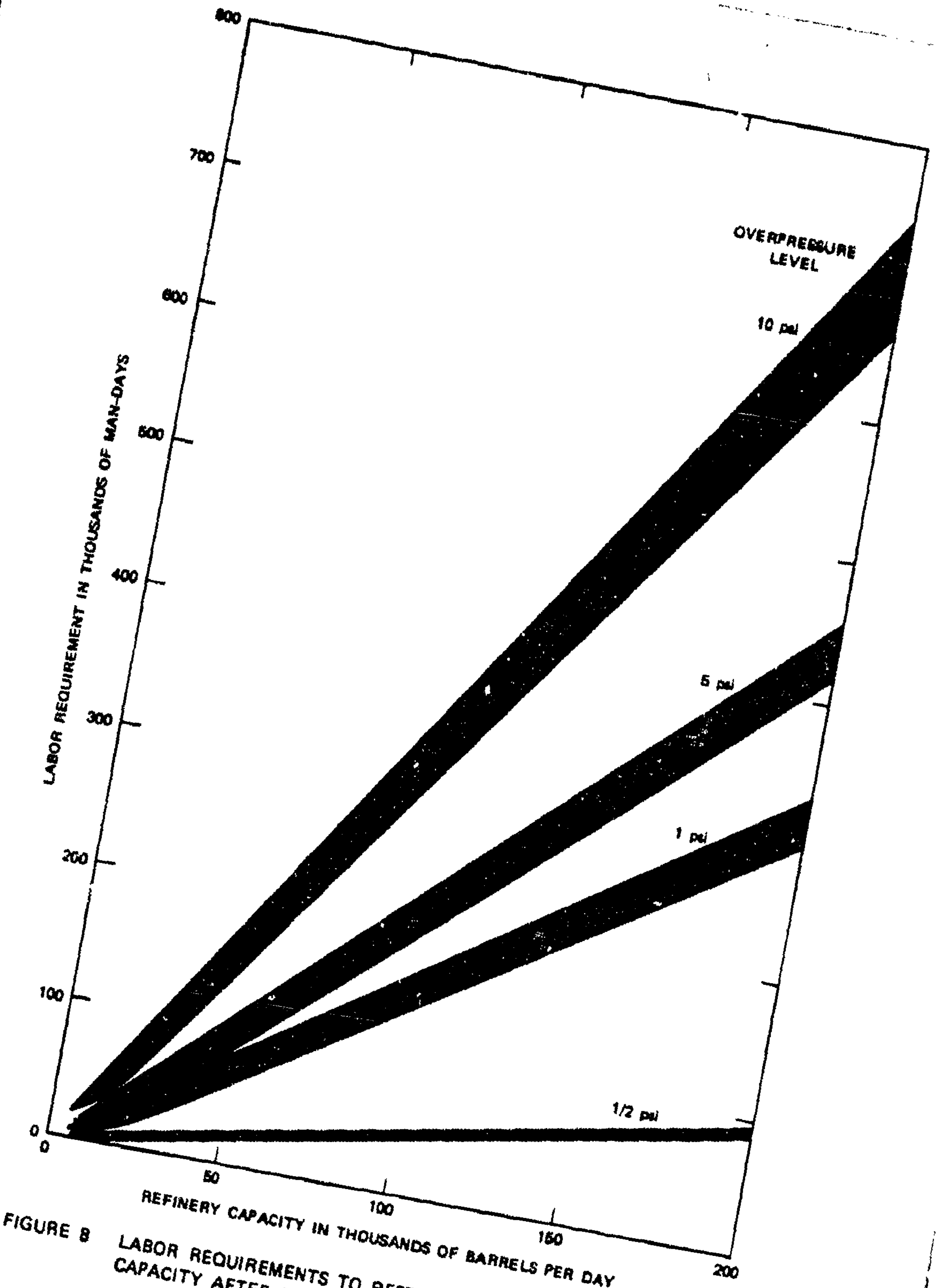


FIGURE 8 LABOR REQUIREMENTS TO RESTORE 100 PERCENT REFINERY CAPACITY AFTER SPECIFIED BLAST OVERPRESSURE LEVELS

Estimate Production Capability by Repair Stage

How much production each increment of repair effort will buy can be determined by estimating the production capability for each repair stage. This is done by combining the data of Appendix B and Appendix C.

This study assumed that refinery production capability will continue at the levels achieved with only emergency repair (to units damaged at low overpressures) until scheduled repair effort is made. Each repair stage completed will then permit a production increase corresponding to restored production in those process units damaged at higher overpressures.

Table B-1, in Appendix B, indicates that after 1.0 psi overpressure, sufficient emergency repairs can be made to permit production of gasoline equal to 26 percent of the initial refinery capacity. Table C-1 shows that this production capability is not surpassed until Repair Stages A, B, and C have been completed. Combining these data for "normal" crude oil yields the result:

	Gasoline Yield as a Percent of Initial Capacity	
Repair Stage	Production After Overpressure = 1.5 psi*	Production After 1.0 psi
A	13%	26%†
B	22	26†
C	33	33
D	54	54

* Percentage production with repair by stages.
† Production permitted by emergency repair after 1.0 psi.

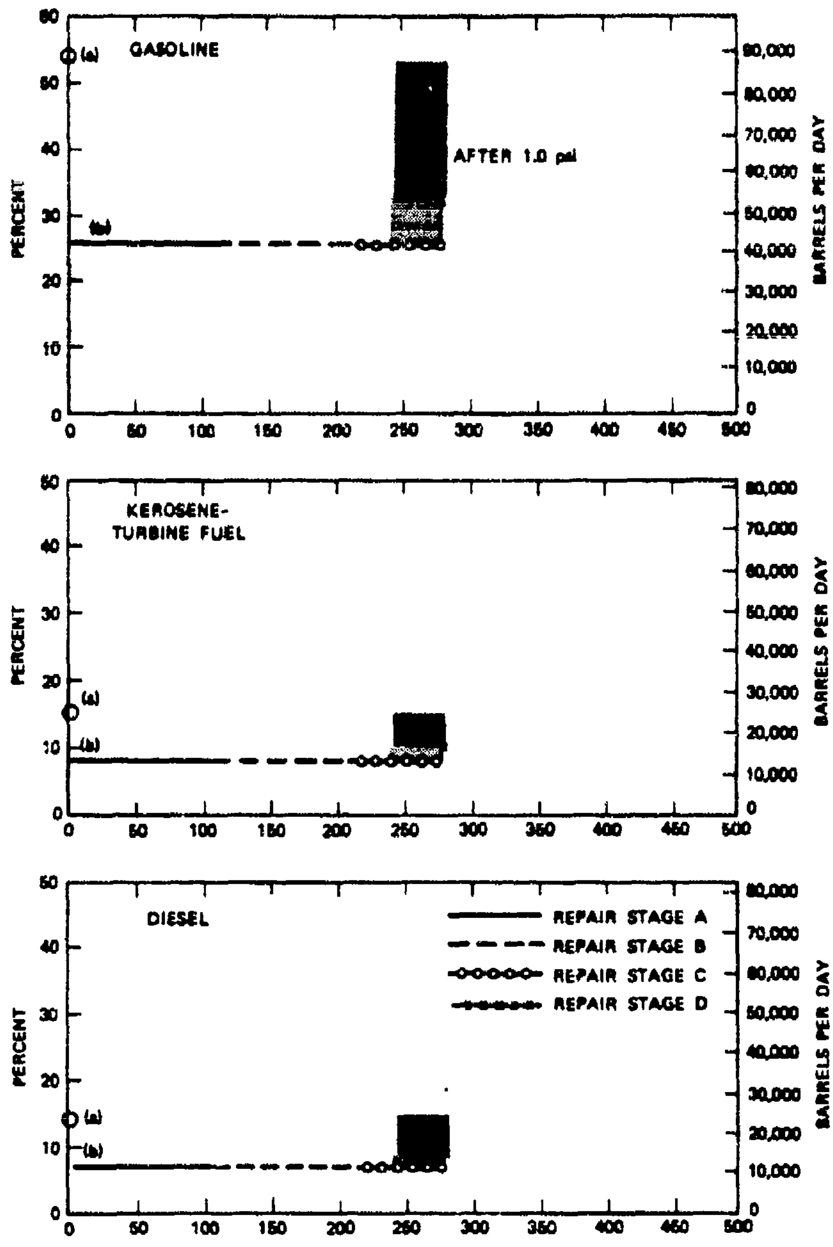
On this basis, the gasoline production from the example refinery after 1.0 psi would be:

Repair Stage	Cumulative Repair Effort in Man-Days	Gasoline Production Percent	Gasoline Production B/D
A	101,000-118,000	26%	42,900
B	185,000-216,000	26	42,900
C	238,000-277,000	33	54,500
D	240,000-280,000	54	89,100

In other words, 238,000-277,000 man-days of repair effort will buy an increment of 11,600 B/D of gasoline (42,900-54,500 B/D); a further small increment of 2,000-3,000 man-days of repair effort will buy an additional large increment of 34,600 B/D (54,500 B/D-89,000 B/D). Similar relationships are developed for kerosene and diesel products and are shown in Figure 9. These form a part of the base of decisions on planning of repair effort. By comparing the product yields resulting from effort expended on several refineries requiring repair, the estimator may develop a basis for deciding where the least repair effort will gain the maximum quantities of the products needed.

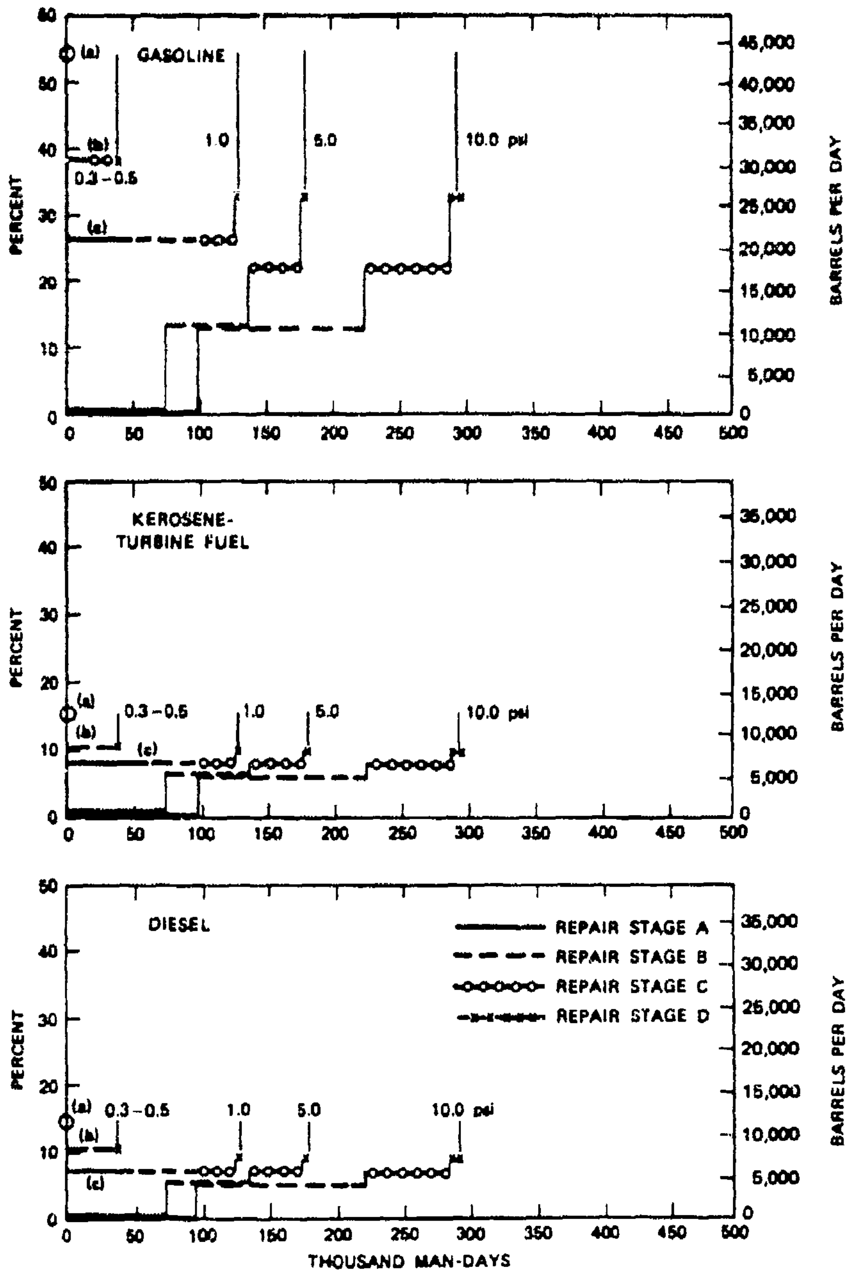
This is illustrated by the Figures 10-15 that demonstrate the product yields from "normal" crudes for average-sized refineries of each type after selected overpressures. From these, basic decisions may be made after it is known which products are needed most and how much labor is available. Examples are:

- If gasoline is in great demand and sufficient labor is available, completion of repairs through Repair Stage D gives the best results (see Figures 10-12).
- If kerosene and diesel are in great demand, it is not advantageous to repair an asphalt, or an asphalt and lube refinery beyond Repair Stage C (see Figures 13 and 14).
- If repair labor is limited, and specialty refineries are hit, in addition to fuel and complete processing refineries, it may



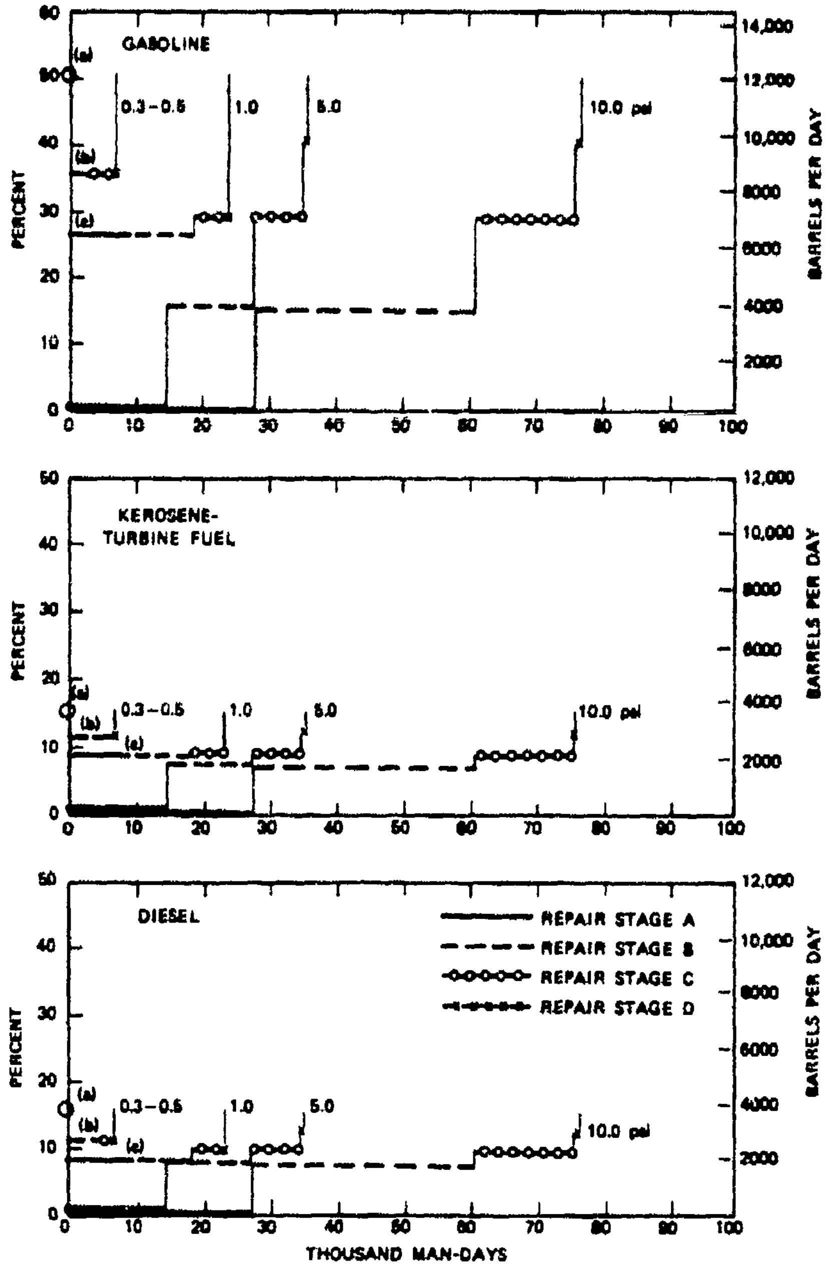
(a) UNDAMAGED CONDITION
(b) 50 PERCENT OPERATION AFTER 1.0 psi UNTIL STAGE C REPAIR

FIGURE 9 PRODUCT YIELD VERSUS REPAIR EFFORT, UNDAMAGED AND AFTER 1.0 PSI OVERPRESSURE: LARGE FUEL REFINERY; 165,000 BARRELS PER DAY CAPACITY



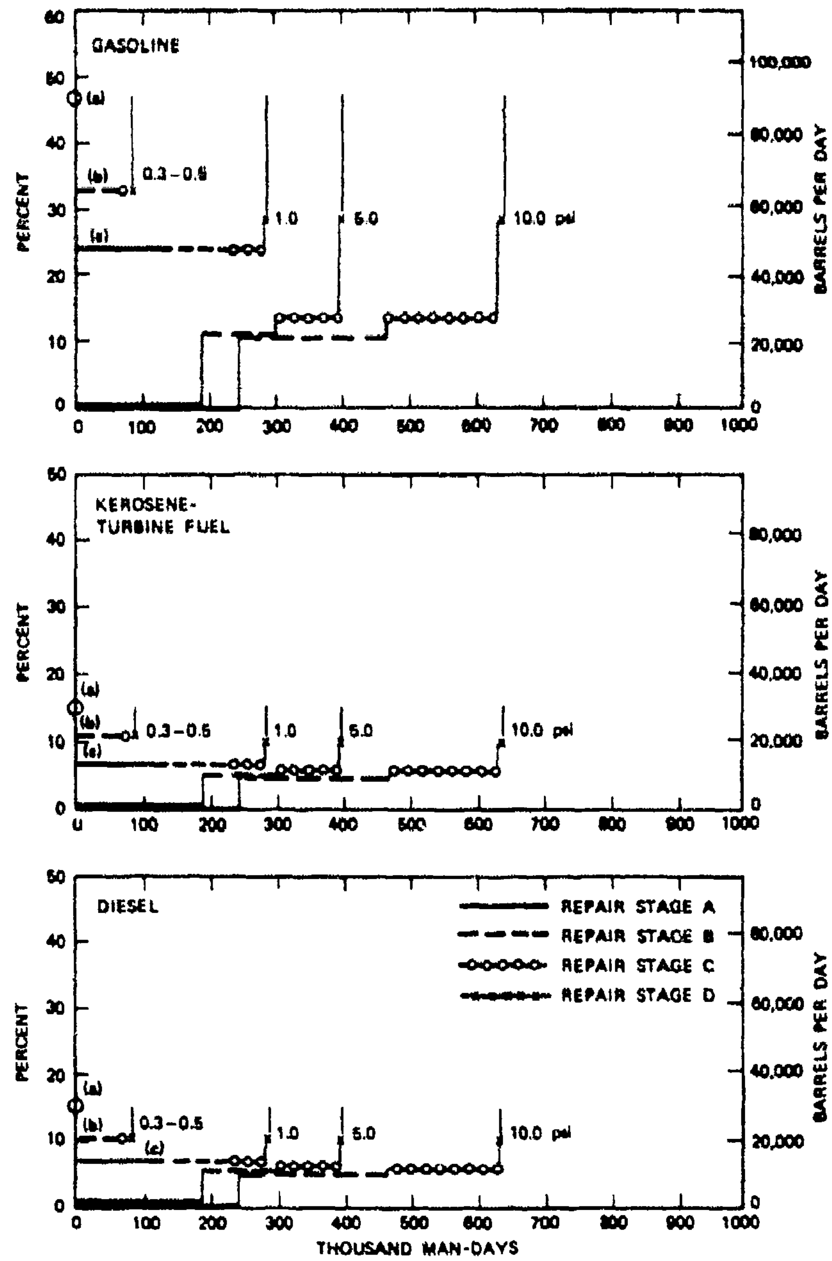
(a) UNDAMAGED CONDITION
(b) 70 PERCENT OPERATION AFTER 0.3–0.5 psi
(c) 50 PERCENT OPERATION AFTER 1.0 psi UNTIL STAGE C REPAIR

FIGURE 10 PRODUCT YIELD VERSUS REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: LARGE FUEL REFINERY; 78,000 BARRELS PER DAY CAPACITY



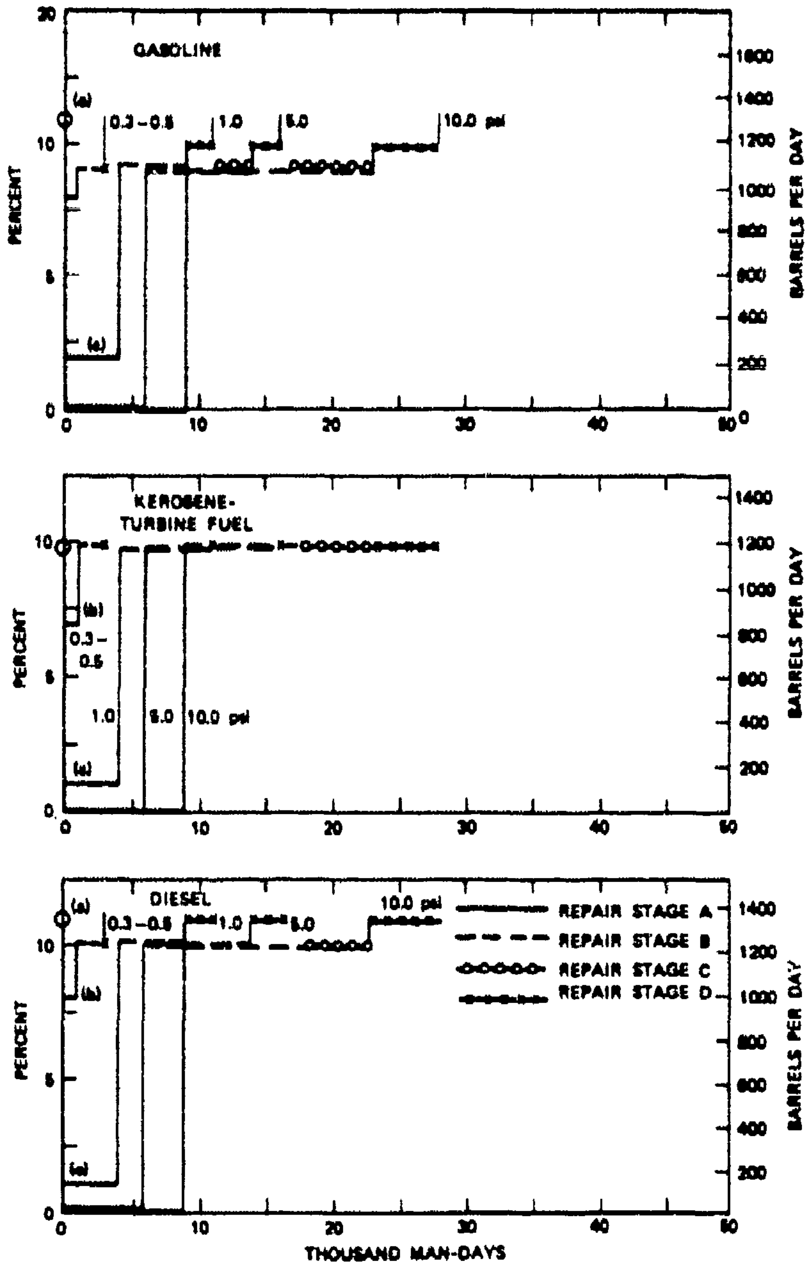
(a) UNDAMAGED CONDITION
(b) 70 PERCENT OPERATION AFTER 0.3–0.5 psi
(c) 50 PERCENT OPERATION AFTER 1.0 psi UNTIL STAGE B REPAIR

FIGURE 11 PRODUCT YIELD VERSUS REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: SMALL FUEL REFINERY; 24,000 BARRELS PER DAY CAPACITY



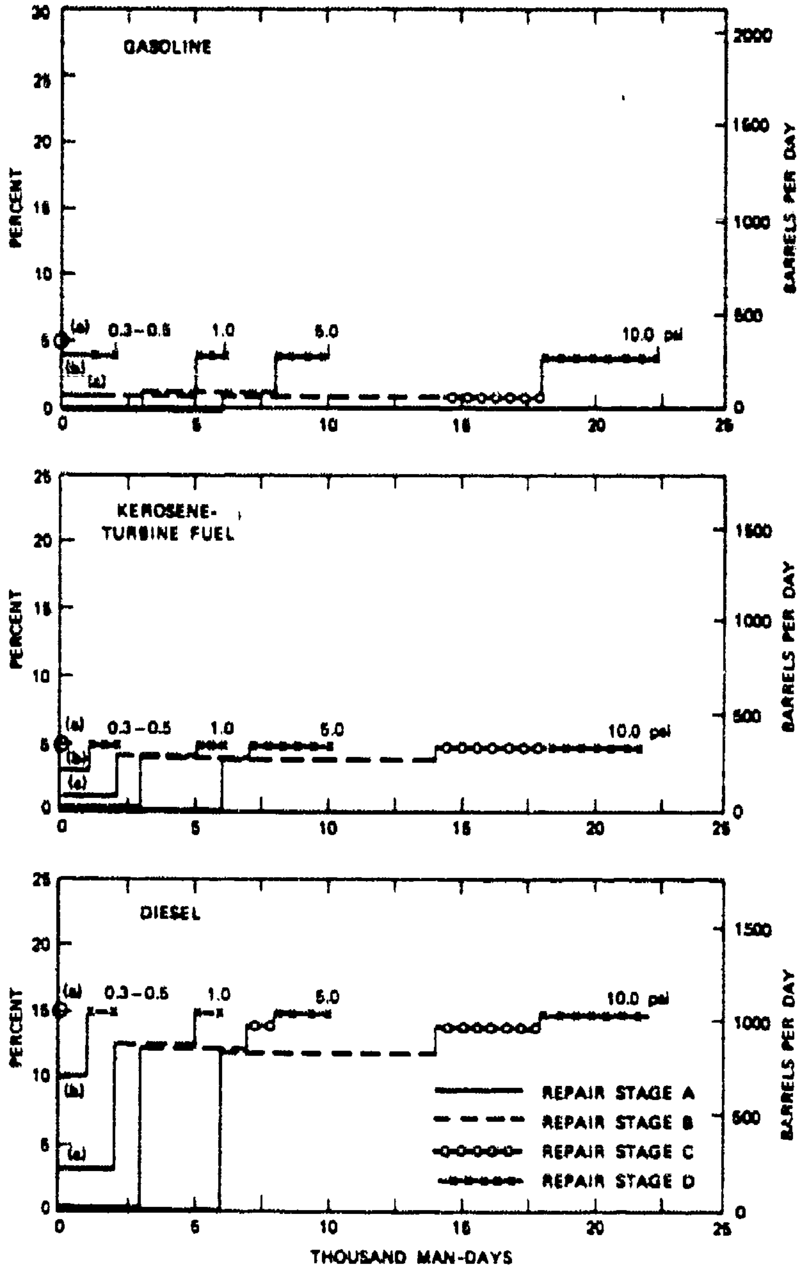
(a) UNDAMAGED CONDITION
(b) 70 PERCENT OPERATION AFTER 0.3–0.5 psi
(c) 50 PERCENT OPERATION AFTER 1.0 psi UNTIL STAGE C REPAIR

FIGURE 12 PRODUCT YIELD VERSUS REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: COMPLETE PROCESSING REFINERY; 194,000 BARRELS PER DAY CAPACITY



(a) UNDAMAGED CONDITION
(b) 70 PERCENT OPERATION AFTER 0.3 – 0.5 psi
(c) 50 PERCENT OPERATION AFTER 1.0 psi UNTIL STAGE A REPAIR

FIGURE 13 PRODUCT YIELD VERSUS REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: ASPHALT REFINERY; 12,000 BARRELS PER DAY CAPACITY



(a) UNDAMAGED CONDITION
(b) 70 PERCENT OPERATION AFTER 0.3–0.5 psi
(c) 50 PERCENT OPERATION AFTER 1.0 psi UNTIL STAGE A AND B REPAIR

FIGURE 14 PRODUCT YIELD VERSUS REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: ASPHALT AND LUBE REFINERY; 7,000 BARRELS PER DAY CAPACITY

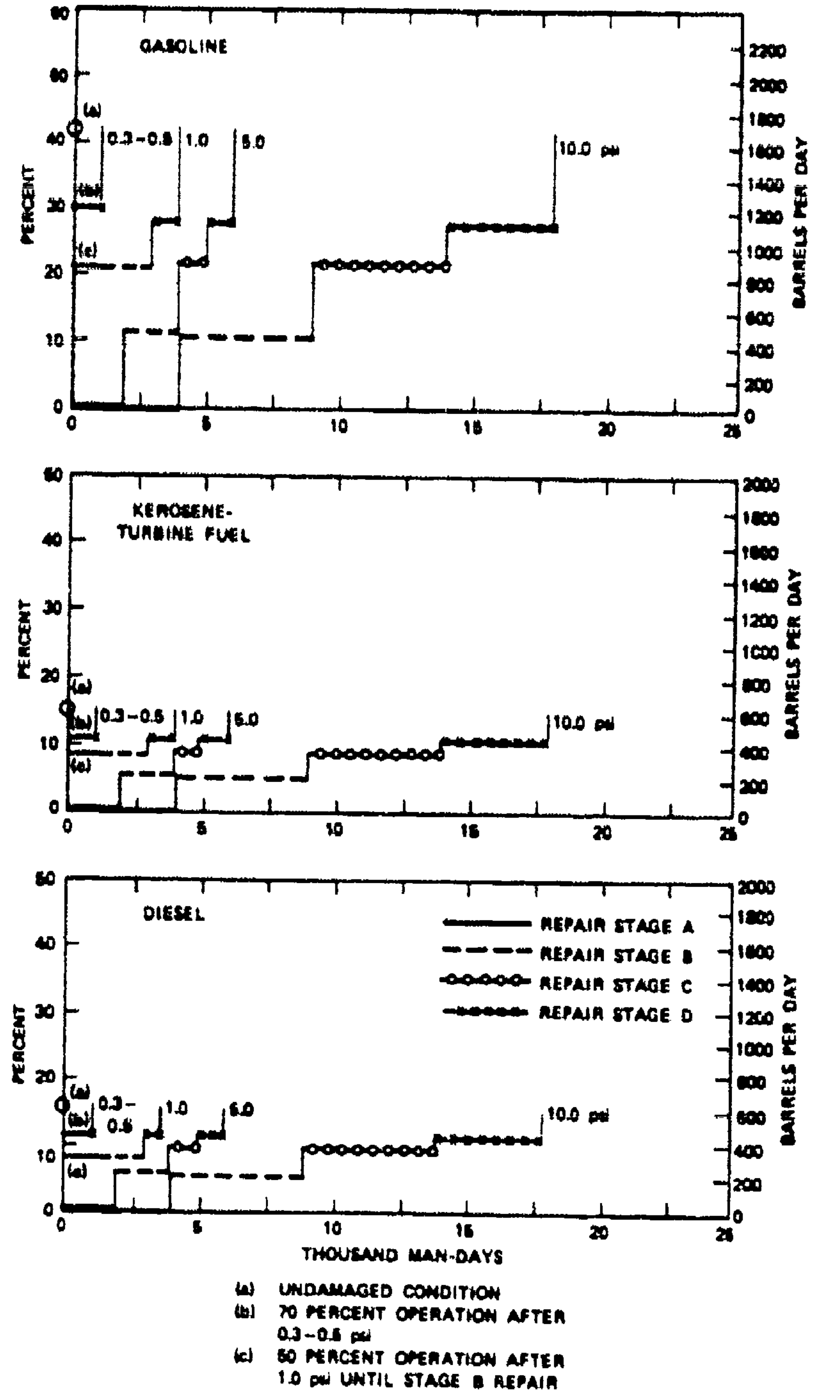


FIGURE 15 PRODUCT YIELD VERSUS REPAIR EFFORT AT SELECTED BLAST OVERPRESSURES: LUBE REFINERY; 4,000 BARRELS PER DAY CAPACITY

be more advantageous not to repair the specialty refineries, but instead to use the repair effort in the fuel and complete processing refineries.

Assuming gasoline as the product in greatest demand, Figure 13 shows that to restore an average asphalt refinery to 100 percent of initial capacity after 1.0 psi would require 11,000 man-days, and an increment of 1,320 B/D of gasoline would result. Application of the 11,000 man-days, instead, to any repair stage for a large fuel refinery, would yield more gasoline. The increments of repair labor and gasoline production capability for a 165,000 B/D refinery can be shown as:

Repair Stage	Labor in 000's of Man-Days		Gasoline Production in 000's of B/D	
	Increment	Cumulative	Increment	Capability
A	101-118	101-118	42.9	42.9
B	84- 98	185-216	0.	42.9
C	53- 61	238-277	11.6	54.5
D	2- 3	240-280	34.6	89.1

The repair stages must be completed in sequence. From this, it can be seen that if the example refinery has repair labor sufficient only to complete stages A, B, and C, it would be advantageous for gasoline supply to apply the 2,000-3,000 man-days of repair labor to the example refinery, instead of to an asphalt refinery. The asphalt refinery gasoline would only go up to 1,200 B/D instead of 1,320 B/D, a decrease of 120 B/D (Figure 13). However, the example refinery gasoline would increase by 34,600 B/D (from 54,500 to 89,100 B/D), giving a net gain in gasoline of 34,480 B/D.

In general, for the fuel and complete processing refineries, Repair Stages A and B result in distinct increments of gasoline, kerosene, and diesel production. However, when further repair is planned, it should be noted that the combined labor of Repair Stages C and D makes a significant production increase over that from Repair Stage C effort alone. This results from the emphasis on light fuels production (i.e., gasoline). When nonfuels-producing processes are returned to operation, normal routing of process flows within a refinery is permitted. The heavy components of crude oils that normally produce fuel oils and asphalt are removed from the gasoline producing processes, so that these processes have a lighter petroleum fraction that can produce a greater amount of gasoline. Similar relationships are evident for kerosene and diesel production.

Relationships of this nature may also be developed, as required, using alternative crude oils.

It is recognized that many variations of refineries exist. In some instance, a refinery that is being investigated may vary by a large degree from the average six types considered in this study. In this event, the correct equipment characteristics of numbers and sizes may be substituted in Appendix A. The seven parameters (Table 9) would then be applied to the modified sizes and numbers to yield corrected equipment repair.

It is also recognized that the sequence of repair stages and the repair of process units in each stage can vary, depending on which products are in demand in the postattack period. Repair effort has been detailed in Appendix D so that resequencing may be easily done. It is necessary for the estimator to recalculate production capabilities with each sequence selected. It is also necessary for the estimator to select an alternative sequence of repair and calculate the products that could be produced with the operable equipment at each repair stage. The summary of this effort for this study is shown in Appendixes B and C. Details of this effort have not been included.

Appendix A

EQUIPMENT SIZES AND NUMBERS

Appendix A

EQUIPMENT SIZES AND NUMBERS

The equipment that would be necessary for each processing unit within each type of refinery is detailed in Tables A-1 through A-17. These data are used to develop representative processing units and refinery categories, based on equipment data that reflect known or calculable vulnerability and blast damage reclamation requirements.

These equipment data are used in determining refinery vulnerability to low overpressure levels and resultant product capacities and the reclamation requirements and correlated production capacities after higher blast overpressures (see Sections IV and V of the main text).

Refinery Equipment

Selected items of refinery processing equipment that represent an overall average of that type of equipment in the petroleum refining industry are described in terms of general characteristics. For refineries that include equipment that does not match the average given, the specific comparable characteristics of individual refinery equipment may be substituted. Although a particular type of equipment performs a specific function regardless of the refinery category, its size and therefore its reclamation requirements are direct functions of the refinery capacity and processing requirements. All pieces of equipment are individually sized for each processing unit in each refinery category. Individual equipment numbers and sizes for each processing unit are detailed below. Units of size measurement are kept consistent with data from which vulnerability and reclamation information are drawn.

Although these units of size in some instances are not the usual ones encountered in petroleum refining, they can be easily converted, if desired.

Control Room

In some instances the control room roofs will be of steel construction that has been calculated to be damaged after 1.0 psi, instead of reinforced concrete construction which has been calculated to collapse after 1.5 psi overpressure. The steel construction is characteristic of older refineries, smaller refineries, simpler processing units not requiring structural strength for "double-decking," or those refineries where construction was strongly influenced by minimum investment principles. This steel control house roof could be anticipated in the process units of the following types of refineries:

- Crude oil topping
- Vacuum flashing
- Light oil treating
- Asphalt

Of these, the first process is essential to all processing of crude oil; the second to separation of stocks for midbarrel and asphalt production and for feed preparation for cracking; the third is essential to all light products being on-grade; and the last is essential only to asphalt and road oil production. Emergency repairs to some of these as needed, would be expected before the refinery could be operated. Repairs would be in the above sequence, but only to the extent that they would then match the remaining refinery capacity.

The size of a particular processing unit control room is a function of both the capacity and the complexity of the processing unit. Larger capacity units tend to have a greater number of and more precise instrument controls, and more complex units require a greater number of control points. Control room size may be expressed as a linear function of processing unit capacity as:

$$v = a \times c,$$

where v = control room size in cu ft (minimum = 2,000 cu ft)

c = processing unit capacity in B/D

a = a constant dependent on the processing unit complexity.

For each of 16 selected types of processing units, the corresponding values of the complexity "a" are as follows:

Processing Unit	Constant "a" (cu ft per B/D)	Processing Unit	Constant "a" (cu ft per B/D)
Crude topping	0.374	Alkylation	1.667
Thermal cracking	0.746	Hydrogen treating	0.900
Thermal reforming	0.746	Vacuum flashing	0.374
Vis breaking	0.746	Vacuum distillation	0.900
Coking	1.667	Lube and specialties	3.122
Catalytic cracking	0.900	Asphalt	0.571
Catalytic reforming	0.746	Light oil treating	0.374
Polymerization	0.900	Naphthenic lube and specialties	2.565

Example: for a 90,000 B/D crude topping processing unit, control room

$$\text{size} = 90{,}000\ \text{B/D} \times 0.374\ \frac{\text{cu ft}}{\text{B/D}}$$

$$= 33{,}660\ \text{cu ft}$$

Fired Heater

Many designs of fired heaters are in operation in various refineries. In addition to size variations, there are variations in burner location (floor, sides, ends, or top); in heat recovery (successive passes, steam generation, or waste heat recovery); and in construction design (to permit ease of maintenance). A box-type fire box with floor mounted burners was selected as a representative fired heater. Heater volume approximates 0.8 cu ft per B/D capacity of the heater. Maximum heater sizes considered are as follows:

Refinery Type	Maximum Heater Size (cu ft)
Large fuel	40,000
Small fuel	30,000
Complete processing	50,000
Asphalt	20,000
Asphalt and lube	20,000
Lube	20,000

In instances where a processing unit capacity requires greater than the above sizes, multiple heaters are considered.

Fractionation Column (Distillation Towers)

Separation of petroleum into two or more parts is accomplished in fractionation columns by the different boiling temperatures of those parts. The heated petroleum enters the fractionation column where the liquid part (which has a higher boiling temperature) flows downward, and the vapor part (which has a lower boiling temperature) flows upward. For adequate separation of the petroleum parts there must be intimate contacting of liquid and vapor throughout the height of the column.

Actual design of any one fractionation column reflects the complex relationships of the characteristics of the petroleum materials entering and leaving the tower. This study made simplifying assumptions and calculated the size of each column separately as a function of quantity of petroleum separated, type of separation, and the percentage that remains as a liquid. This relationship is:

1. $c = 220 \times D^2 \times R,$

where D = column diameter in ft

R = fraction of residual liquid

c = column input in B/D.

2. Height required for one unit of intimate mixing (one "tray") is 22 in.

3. Number of trays required for types of separation are as shown below.

Separation Type	No. of Trays = c
Stripping	10- 20
Primary fractionation	20- 40
Secondary fractionation	40- 50
Splitting	50- 70
Super fractionation	70-100

Fractionation column sizes are expressed in cu ft.

Extraction Columns

These are vessels used for separation of portions of petroleum liquids through use of selective solvents or immiscible chemical solutions, followed by a settling type of separation. Extraction column sizes are essentially the same as the distillation towers with which they are used.

Cooling Tower

Extraction of heat is requisite to the operation of every refinery. This is usually accomplished by heat exchange with water and water evaporation, although air cooling systems with radiation exchanger coils with fans are also used. Deciding factors are equipment economies, climatic conditions, operational requirements, and water availability.

This study considers as representative equipment the extraction of heat by cooling towers using induced draft fans for evaporative cooling of a circulating water system. The basic system is of a module construction with a volume approximating 18,000 cu ft. The outer surface has louvers of redwood or cement-asbestos, and the inner framework includes baffles and splash decks as needed for adequate evaporation. Modules are additive as required for refinery cooling. Cooling capacity required is considered to be 4.0 cu ft of cooling tower volume per B/D throughput capacity of each processing unit.

Reactor

Those vessels in which petroleum fractions change structurally are characteristically termed reactors. In most instances a catalyst is present. These vessels are in two groups, based on operational characteristics. One group includes those that normally operate at high temperature and pressure, such as catalytic cracking reactors. These would be of thick-walled construction and are expected to be relatively insensitive to blast conditions. In the study, this group was referred to as "cracking" reactors. The other group normally operates at a relatively low pressure and does not require as great a structural strength for normal operation. Examples are alkylation process reactors. This group was labeled "chemical" reactors. In either instance, the study assumed that reactor volume is essentially a straight-line function of reactor total throughput, which includes reactor fresh feed plus recycled material. This relationship is:

$$v = 0.1725 \times c,$$

where v = reactor volume in cu ft

c = processing unit capacity in B/D.

Minimum volume is considered to be 600 cu ft.

Regenerator

In some catalytic processes the catalyst is regenerated, or returned to its active state, by transferring it from the reactor to a separate regeneration vessel, where it is properly processed by steam, air, and so forth. This study also relates sizes of these vessels to the totaled process unit throughput. This relationship is:

$$v = 0.380 \times c,$$

where v = regenerator volume in cu ft

c = processing unit capacity in B/D.

Minimum regenerator volume is considered to be 600 cu ft.

Pressure Vessels

At several points in every processing unit, pressure vessels are needed for segregation of liquid and vapor phases, elimination of water, or separation of waste material. Pressure vessels are normally of heavy walled steel construction. While the vessel shells are relatively insensitive to blast, they may be displaced from their footings or foundations by blast. Differentiation is made between vertical and horizontal vessels, because of differing difficulties in handling during reclamation. Thus, this study considered only the numbers of pressure vessels of these two types that would be representative of each processing unit.

Pipe Support

Economics of modern refining dictate conditions of ease of piping maintenance and simple flow modifications consistent with ease of operations. These factors have resulted in much of the process unit piping being supported on overhead framework. The amount of overhead pipe support in a process unit is a function of both the capacity and the complexity of the processing unit. The linear feet of overhead pipe support may be expressed as a function of processing unit capacity as:

$$\ell = a \times c,$$

where ℓ = linear feet of pipe support

c = capacity of processing unit in B/D

a = a constant dependent on the processing unit complexity.

The 16 selected types of processing units and the corresponding values of their complexity constant "a" are:

Processing Unit	Constant "a" (ft per B/D)	Processing Unit	Constant "a" (ft per B/D)
Crude topping	0.0049	Alkylation	0.0490
Thermal cracking	0.0143	Hydrogen treating	0.0200
Thermal reforming	0.0143	Vacuum flashing	0.0049
Vis breaking	0.0143	Vacuum distillation	0.0200
Coking	0.0490	Lube and specialties	0.1250
Catalytic cracking	0.0200	Asphalt	0.0093
Catalytic reforming	0.0143	Light oil treating	0.0049
Polymerization	0.0200	Naphthenic lube and specialties	0.0806

Example: for a 90,000 B/D crude topping processing unit, pipe support is

$$= 90{,}000 \text{ B/D} \times 0.0049 \frac{\text{ft}}{\text{B/D}} = 441 \text{ ft}$$

Pipe supports are also used in the moving of intermediate products between processing units. This study weighted the complexity of the units included in a refinery and estimated the pipe supports between process units in the same manner as that for individual process units, but using the refinery capacity as throughput. Exceptions exist at either end of the scale; a minimum of 400 ft of pipe support is estimated for the smallest lube refinery, and a maximum of 2,000 feet for any refinery, no matter how large.

Tankage

Tankage is one of the major items of investment in a petroleum refinery and it is essential to refinery operation. In addition, tankage is vulnerable to relatively low blast overpressure, and it has major reclamation requirements.

At the input to a refinery for the crude oil topping unit alone, a minimum of four large tanks are required: one being filled from the supply system, one full and ready to use, one supplying the crude topping unit, and one empty ready to be filled. If there is a secondary crude oil supply, additional tanks are required, as they are for each processing unit; the movement of intermediate products from one processing unit to the next normally requires segregation and blending of products and storage or residence time to accommodate process unit shutdowns for repairs. Seldom can only one tank be used between processing units as a surge vessel. If this is done, a shutdown of one unit forces the next processing unit also to shut down in a short time. At the point of product completion, much storage is needed--products are delivered to their respective markets in large quantities, and enough storage is needed to satisfy required shipment schedules.

The tankage volume requirement in terms of each processing unit capacity approximates a logarithmic relationship:

$$a \log v = \log c + b,$$

where

v = tankage volume in cu ft

c = processing unit capacity in B/D

$a = 0.807$

$b = 0.842$

Example: for a 90,000 B/D crude topping unit, tankage required

$= 15.2 \times 10^6$ cu ft

Reclamation effort after blast damage will vary with the type of tank. This study considered three types of tankage:

- Cone roof tanks for those materials that are relatively nonvolatile
- Floating roof tanks for those materials that could potentially vaporize
- Spherical (and semi-spherical) tanks for those materials that must be stored under pressure.

Each representative processing unit was examined and the appropriate amount of each type of tankage designated.

Pumps

The pump requirements for each representative processing unit were investigated. The requirements include pumps that are needed for processing reasons within the process unit and pumps required for feed to the unit and for delivery of products from the unit to storage. Pump requirements are expressed as:

$$\text{Capacity} = \text{GPM} \times \text{TDH},$$

where GPM = gallons per minute

TDH = total dynamic head (in ft)

Tables A-1 through A-17 list the number of pumps required at each capacity in each process unit. The minimum capacity (GPM × TDH) value is 10,000.

Pump Drives; Electric Motors and Steam Turbines

Pump drives are frequently divided into two groups. One group, electric drive, is subject to electric power failure and is normally in service that is not critically affected by immediate and unscheduled shutoff. The other group, steam turbine drive, is normally supplied by steam generated within the refinery, and thus is not subject to immediate shutoff. The latter drive is used to power the more critical services in process units. Steam drive pumps are normally in service that is critical to at least partial pumping capacity, i.e., charge to a cracking unit fired heater. There is an approximately even division between these two groups.

Within each group, each pump drive was sized for horsepower requirement at 80 percent efficiency:

$$HP = \frac{GPM \times TDH \times \text{Specific Gravity}}{3{,}960} \times \frac{80}{100},$$

and the number of pump drives within standard power ratings available were detailed.

Centrifugal Blowers

In some catalytic processes, the regeneration of catalyst is accomplished by passage of large quantities of air through the catalyst in a regeneration vessel at relatively low pressure. Blowers and their required drivers for this service are sized, based on the relationship of 0.112 HP per B/D of catalytic cracking process plant capacity.

Heat Exchangers

Heat exchangers are treated in a manner similar to pressure vessels. Studies have shown them to be relatively insensitive to low blast overpressure effects, but they may be displaced from their footings or foundations. This study considered only the number of sets of heat exchangers, since repair primarily consists of righting them.

Filters

These are relatively small in number, but they are included because they are requisite to product finishing in some instances and because they are vulnerable to damage at low blast overpressure. They are essentially a fabric-covered rotating cylindrical drum with valving arrangements to permit vacuum and pressure to be applied from within at different points during rotation. This study assumed that a representative filter has a canvas-covered 6-ft diameter drum.

Instrument Cubicles

In large size and complex processing units, refiners have found it expedient to have a portion of the control instrumentation located in an instrument cubicle near the operating equipment, rather than in the central control room. This study assumed that a cubicle consists of a small weather-shield type of enclosure housing six to ten instruments. Although the cubicles represent only a small investment, the contained instruments are a part of the control system of a processing unit, and they are vulnerable to damage at low blast overpressure (glass front breakage, instrument damage, or wiring breakage).

Utilities

Equipment necessary to bring in energy from outside the refinery is also considered. These pieces of equipment represent relatively small investments, but they are vulnerable to low blast overpressure damage. The fuel gas flows through a meter and a pressure regulator valve, both of which are normally unprotected. Every refinery requires at least one meter and one regulator valve. Electrical energy is received through electri transformers, also unprotected and vulnerable. This study assume at every refinery requires at least one transformer, and large refin s require at least three transformers to operate.

On the above bases, the equipment that would be necessary for each processing unit within each category of refinery is detailed in Tables A-1 through A-17.

Notes to Tables A-1 through A-17

1. About 5 percent of time is usual for shutdown and repair. Capacities for operating time only (excluding down time) would be higher by a factor approximating 100/95.

2. Single units of equipment are shown with only the size of the single unit in the "Size" column (the numeral 1 in the "Numbers" column is omitted); modular types of equipment have only a number in the "Numbers" column, showing the equivalent number of modules. The size module is reflected in the value of C_0 shown in Table 9. Fractional modules in the case of cooling towers reflect combined use of a cooling tower by more than one processing unit. The number of fractional modules shown for any one process unit is that unit's minimum requirement (i.e., a crude topping process unit in a 24,000 B/D refinery requires 5.3 of the selected size cooling tower modules (see Table A-1).

Table A-1

EQUIPMENT SIZES AND NUMBERS: CRUDE TOPPING P

Equipment	Unit of Measure	Equipment by Re — Large Fuel 78,000 No.	Size	Large Fuel 150,000 No.	Size	Small Fuel 24,000 No.	Size	Complete Processing 194,000 No.	Size
Control house, steel rf.	1,000 ft^3		30.0		57		8		73
Control house, concr. rf.	1,000 ft^3								
Fired heater	1,000 ft^2	3	21.0	3	40	2	15	3	60
	1,000 ft^3		16.0	1	30			1	44
Fractionation column	1,000 ft^3	4	20.3	4	39	2	22.3	4	50.4
	1,000 ft^3	8	1.8	8	3.5	4	1.1	8	4.5
	1,000 ft^3								
	1,000 ft^3								
	1,000 ft^3								
	1,000 ft^3								
Extraction column	1,000 ft^3								
	1,000 ft^3								
Cooling tower	No.	17.0		33		5.3		43	
Reactor, cracking	1,000 ft^3								
	1,000 ft^3								
Reactor, chemical	1,00^ ft^3								
Regenerator	1,000 ft^3								
Pressure vessel, horiz.	No.	4		4		2		4	
Pressure vessel, vert.	No.	8		8		4		8	
Pipe support	ft		380		740		120		960
Storage tank, cone rf.	1,000 ft^3		15,600		30,000		3,000		40,500
Storage tank, fltg. rf.	1,000 ft^3								
Storage tank, spherical	1,000 ft^3								
Pumps	1,000 GPM X TDH*	8	160	8	300	4	90	8	400
	1,000 GPM X TDH*	12	80	12	150	6	50	40	200
	1,000 GPM X TDH*	28	90	28	180	14	60		
Electric motor	Hp	4	50	4	100	2	30	4	125
	Hp	6	25	6	50	3	15	20	60
	Hp	14	30	14	50	7	20		
Steam turbine	Hp	4	50	4	10.	2	30	4	125
	Hp	6	25	6	50	3	15	20	60
	Hp	14	30	14	50	7	20		
Centrifugal blower	Hp								
Heat exchanger	No.	72		72		36		72	
Filter	No.								
Instrument cubicle	No.								

* Gallons per minute X total dynamic head.

A

Table A-1

NUMBERS: CRUDE TOPPING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Fuel	Complete Processing		Asphalt				Asphalt and Lube		Lube			
,000	194,000		12,000		14,000		7,000		4,000		27,000	
Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
8		73		4.3		5		3		2.0		10
15	3	50		9.6		11		7	?	1.5	2	10
	1	44										
22.3	4	50.4		6.3		7.4		3.2		4.1	2	13.5
1.1	8	4.5		0.7		0.8	2	0.3	2	0.4	4	1.3
				0.9		1.0						
	43		2.6		3.1		1.6		0.91		6.1	
	4		1		1		1		1		1	
	8		2		2		2		2		2	
120		960		70		80		40		20		140
3,000		40,500		1,290		1,500		660		513		3,450
90	8	400	2	90	2	100	2	60	2	30	2	200
50	40	200	3	40	3	50	10	30	3	20	3	100
60			7	60	7	70			7	20	7	120
30	4	125		30		30		20	5	10		60
15	20	60		15		15		5				30
20			3	20	3	20					3	40
30	4	125		30		30		20	7	10		60
15	20	60	2	15	2	15	5	10			2	30
20			4	20	4						4	40
	72		18		10		18		18		18	

Table A-2

EQUIPMENT SIZES AND NUMBERS: THERMAL CRACKING PROCESSING

Equipment	Unit of Measure	Large Fuel 75,000 No.	Large Fuel 75,000 Size	Large Fuel 150,000 No.	Large Fuel 150,000 Size	Small Fuel 24,000 No.	Small Fuel 24,000 Size	Complete Processing 194,000 No.	Complete Processing 194,000 Size	12,000 No.	12,000 Size
Control house, steel rf.	1,000 ft^2										
Control house, concr. rf.	1,000 ft^2		10.0		20		2		7		2.0
Fired heater	1,000 ft^2	4	4.9	4	9.4		7.7		31		5.4
	1,000 ft^2										
Fractionation column	1,000 ft^3	4	7.8	4	15		6		24		4.3
	1,000 ft^3	4	5.9	4	11		4.6		18		1.3
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	3.2		6.1		0.67		2.6		0.45	
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.										
Pressure vessel, vert.	No.	12		12		3		3		3	
Pipe support	ft		210		400		40		180		20
Storage tank, cone rf.	1,000 ft^3		1,330		2,550		150		750		10
Storage tank, fltg. rf.	1,000 ft^3		620		1,200		80		450		50
Storage tank, spherical	1,000 ft^3										
Pumps	1,000 GPM X TDH	8	280	8	550	2	220	2	850	2	15
	1,000 GPM X TDH*	20	30	20	55	5	25	5	90	5	20
	1,000 GPM X TDH*										
Electric motor	Hp	4	100	4	175		60		250		50
	Hp	10	10	10	20	2	10	2	30	2	10
	Hp										
Steam turbine	Hp	4	100	4	175		60		250		50
	Hp	10	10	10	20	2	10	3	30	3	10
	Hp										
Centrifugal blower	Hp										
Heat exchanger	No.	24		24		6		6		6	
Filter	No.										
Instrument cubicle	No.	4		4		1		1		1	

* Gallons per minute × total dynamic head.

Table A-2

...S AND NUMBERS: THERMAL CRACKING PROCESSING UNIT

Small Fuel 24,000		Complete Processing 184,000		Asphalt 12,000		Asphalt 14,000		Asphalt and Lube 7,000		Lube 4,000		Lube 27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	2		7		2.0		2		2		2.0		2
	7.7		31		3.4		6.3		3.2		0.9		6.3
	6		24		4.3		5		2.5		0.8		5
	4.6		18		1.3		1.5		0.8		0.8		3.2
0.67		2.8		0.45		0.53		0.27		0.079		0.53	
		3		3		3		3		3		3	
	40		180		20		20		20		20		40
	150		750		100		120		50		20		120
	80		450		50		60		30		10		60
	220	2	850	2	150	2	180	2	90	2	30	2	180
	25	5	90	5	20	5	20	5	10	5	10	5	20
	60		250		50		50		30		10		50
	10	2	30	2	10	2	10	2	10	2	5	2	10
	60		250		50		50		30		10		50
	10	3	30	3	10	2	10	3	10	3	5	3	10
		6		6		6		6		6		6	
		1		1		1		1		1		1	

B

Table A-3

EQUIPMENT SIZES AND NUMBERS: THERMAL REFORMING PROCESSING UN

		Equipment by Refinery Type an									
		Large Fuel				Small Fuel		Complete Processing		A	
		75,000		150,000		24,000		194,000		12,000	
Equipment	Unit of Measure	No.	Size	No.	Size	No.	Size	No.	Size	No.	Si
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3		2.0		2				6		2.0
Fired heater	1,000 ft^3		1.5		2.9				7.8		0.19
	1,000 ft^3										
Fractionation column	1,000 ft^3		3.1		5.9				16		0.4
	1,000 ft^3		0.5		0.9				2.4	2	0.1
	1,000 ft^3		0.2		0.3				0.8		
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	0.41		0.78				2.2		0.052	
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.										
Pressure vessel, vert.	No.	2		2				2		2	
Pipe support	ft		20		40				120		20
Storage tank, cone rf.	1,000 ft^3		40		80				600		10
Storage tank, fltg. rf.	1,000 ft^3		70		50				390		10
Storage tank, spherical	1,000 ft^3										
Pumps	1,000 GPM X TDH*	2	70	2	140			2	740	2	30
	1,000 GPM X TDH*	4	10	4	20			4	80	4	20
	1,000 GPM X TDH*										
Electric motor	Hp		20		40				250	3	10
	Hp	2	5	2	10			2	15		
	Hp										
Steam turbine	Hp		20		40				250	3	10
	Hp	2	5	2	10			2	25		
	Hp										
Centrifugal blower	Hp										
Heat exchanger	No.	5		5				5		5	
Filter	No.										
Instrument cubicle	No.	1		1				1		1	

* Gallons per minute X total dynamic head.

A

Table A-3

...ES AND NUMBERS: THERMAL REFORMING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		194,000		12,000		14,000		7,000		4,000		27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
			6		2.0		2		2		2.0		2
			7.8		0.19		0.23		0.11		0.22		1.5
			16		0.4		0.5		0.3		0.5		3
			2.4	2	0.1	2	0.1	2	0.1	2	0.1		0.5
			0.8										0.2
		2.2		0.052		0.061		0.031		0.062		0.42	
		2		2		2		2		2		2	
			120		20		20		20		20		20
			600		10		10		10		10		80
			390		10		10		10		10		60
		2	740	2	30	2	40	2	40	2	20	2	150
		4	80	4	20	4	20	4	20	4	10	4	20
			250	3	10		15		15		10		50
		2	15			2	10	2	10	2	5	2	10
			250	3	10		15		15		10		50
		2	25			2	10	2	10	2	5	2	10
		5		5		5		5		5		5	
		1		1		1		1		1		1	

Table A-4

EQUIPMENT SIZES AND NUMBERS: VIS BREAKING PROCESSING UNI

Equipment	Unit of Measure	Equipment by Refinery Type (									
		Large Fuel				Small Fuel		Complete Processing			
		75,000		150,000		24,000		104,000		12,000	
		No.	Size	No.	Size	No.	Size	No.	Size	No.	Si
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3		3.1		6		2	2	6		
Fired heater	1,000 ft^3	2	6.8	2	13		4		13		
	1,000 ft^3										
Fractionation column	1,000 ft^3		2.8		5.2		0.8		5		
	1,000 ft^3		7.3		14		2.2		14		
	1,000 ft^3		0.7		1.4		0.3		1.3		
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	1.0		2.0		0.31		1.9			
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.										
Pressure vessel, vert.	No.	3		3		3		3			
Pipe support	ft		60		120		20		100		
Storage tank, cone rf.	1,000 ft^3		390		750		80		690		
Storage tank, fltg. rf.	1,000 ft^3		80		150		20		170		
Storage tank, spherical	1,000 ft^3										
Pumps	1,000 GPM x TDH*	2	210	2	410	2	70	2	400		
	1,000 GPM x TDH*	3	40	3	70	3	20	3	70		
	1,000 GPM x TDH*	4	20	4	40	4	10	4	40		
Electric motor	Hp		60		125		20		125		
	Hp		15		20		10		20		
	Hp	2	10	2	15	2	5	2	15		
Steam turbine	Hp		60		125		20		125		
	Hp	2	15	2	20	2	10	2	20		
	Hp	2	10	2	15	2	5	2	15		
Centrifugal blower	Hp										
Heat exchanger	No.	8		8		8		8			
Filter	No.										
Instrument cubicle	No.	1		1		1		1			

* Gallons per minute x total dynamic head.

A

Table A-4

SIZES AND NUMBERS: VIS BREAKING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		154,000		12,000		14,000		7,000		4,000		27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	2	[illegible]	5										
	4		13										
	0.8		5										
	2.2		14										
	0.3		1.3										
0.31		1.9											
3		3											
	20		100										
	80		690										
	20		170										
2	70	2	400										
3	20	3	70										
4	10	4	40										
	20		125										
	10		20										
2	5	2	15										
	20		125										
2	10	2	20										
2	5	2	15										
8		8											
1		1											

Table A-5

EQUIPMENT SIZES AND NUMBERS: COKING PROCESSING UNIT

Equipment	Unit of Measure	Equipment by Refinery Type								
		Large Fuel				Small Fuel		Complete Processing		
		75,000		150,000		24,000		194,000		12,00
		No.	Size	No.	Size	No.	Size	No.	Size	No.
Control house, steel rf.	1,000 ft^3									
Control house, concr. rf.	1,000 ft^3		6.2		12		2		10	
Fired heater	1,000 ft^3		3.4		6.5		0.23		4.8	
	1,000 ft^3									
Fractionation column	1,000 ft^3		4.2		8		0.4		5.7	
	1,000 ft^3		0.6		1.1		0.1		0.8	
	1,000 ft^3									
	1,000 ft^3									
	1,000 ft^3									
	1,000 ft^3									
Extraction column	1,000 ft^3									
	1,000 ft^3									
Cooling tower	No.	0.94		1.8		0.067		1.3		
Reactor, cracking	1,000 ft^3									
	1,000 ft^3									
Reactor, chemical	1,000 ft^3									
Regenerator	1,000 ft^3									
Pressure vessel, horiz.	No.	3		3		3		3		
Pressure vessel, vert.	No.	3		3		3		3		
Pipe support	ft		210		400		100		300	
Storage tank, cone rf.	1,000 ft^3		280		530		10		350	
Storage tank, fltg. rf.	1,000 ft^3		140		270		10		170	
Storage tank, spherical	1,000 ft^3									
Pumps	1,000 GPM X TDH*	2	70	2	130	6	10	2	90	
	1,000 GPM X TDH*	4	30	4	60			4	50	
	1,000 GPM X TDH*									
Electric motor	Hp		20		40	3	5		30	
	Hp	2	10	2	20			2	15	
	Hp									
Steam turbine	Hp		20		40	3	5		30	
	Hp	2	10	2	20			2	15	
	Hp									
Centrifugal blower	Hp									
Heat exchanger	No.	4		4		4		4		
Filter	No.									
Instrument cubicle	No.	1		1		1		1		

* Gallons per minute X total dynamic head.

A

Table A-5

MENT SIZES AND NUMBERS: COKING PROCESSING UNIT

	Equipment by Refinery Type and Capacity (B/D)													
	Small Fuel 24,000		Complete Processing 194,000		Asphalt 12,000		Asphalt 14,000		Asphalt and Lube 7,000		Lube 4,000		Lube 27,000	
ze	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
		2		10										
		0.23		4.6										
		0.4		5.7										
		0.1		0.8										
	0.067		1.3											
	3		3											
	3		3											
		100		300										
		10		350										
		10		170										
	6	10	2	90										
			4	50										
	3	5		30										
			2	15										
	3	5		30										
			2	15										
	4		4											
	1		1											

B

Table A-6

EQUIPMENT SIZES AND NUMBERS: CATALYTIC CRACKING PROCESSING

		Equipment by Refinery Type									
		Large Fuel				Small Fuel		Complete Processing			
		78,000		150,000		24,000		194,000		12,000	
Equipment	Unit of Measure	No.	Size	No.	Size	No.	Size	No.	Size	No.	[illegible]
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3		56.0		70		11		77		2.
Fired heater	1,000 ft^3	2	11.0	2	20		10	4	22		0.
	1,000 ft^3	2	10.0	2	19						
Fractionation column	1,000 ft^3	4	16.6	4	31.7		21	4	35		0.
	1,000 ft^3	4	1.3	4	2.5		1.6	4	2.7	3	0.
	1,000 ft^3	4	0.7	4	1.8		0.9	4	1.8		0.
	1,000 ft^3	4	0.6	4	1.2		0.8	4	1.4		0.
	1,000 ft^3	4	5.4	4	10.3		6.8	4	11.5		
	1,000 ft^3	4	2.9	4	4.8		3.6	4	5.3		
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	8.8		17		2.9		19		0,10	
Reactor, cracking	1,000 ft^3	4	2.1	4	4		2.5	4	4		0.6
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3	4	6.8	4	13		8	4	14		0,6
Pressure vessel, horiz.	No.	28		28		7		28		7	
Pressure vessel, vert.	No.	24		24		6		24		6	
Pipe support	ft		810		1,560		260		1,760		20
Storage tank, cone rf.	1,000 ft^3		3,350		6,450		710		7,500		10
Storage tank, fltg. rf.	1,000 ft^3		1,640		3,150		350		3,750		10
Storage tank, spherical	1,000 ft^3		1,640		3,150		360		3,750		10
Pumps	1,000 GPM X TDH*	8	160	8	300	2	200	8	300	16	10
	1,000 GPM X TDH*	40	120	40	230	10	150	40	230		
	1,000 GPM X TDH*	16	50	16	90	4	60	16	100		
Electric motor	Hp	4	50	4	100		60	4	100	8	5
	Hp	20	40	20	75	5	50	20	75		
	Hp	8	15	8	30	2	20	8	30		
Steam turbine	Hp	4	50	4	100		60	4	100	8	5
	Hp	20	40	20	75	5	50	20	75		
	Hp	8	15	8	30	2	20	8	30		
Centrifugal blower	Hp	8	600	8	1,200	2	700	8	1,200		75
Heat exchanger	No.	96		96		24		96		24	
Filter	No.										
Instrument cubicle	No.	12		12		3		12		3	

* Gallons per minute X total dynamic head.

A

Table A-6

ND NUMBERS: CATALYTIC CRACKING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)													
mall Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		194,000		12,000		14,000		7,000		4,000		27,000	
o.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	11		77		2.0		2		2		2.0		6
	10	4	22		0.38		0.45		0.39		1.0		7.3
	21	4	35		0.8		0.9		1		1.8		12
	1.6	4	2.7	3	0.1		0.3		0.3		0.2		0.9
	0.9	4	1.8		0.3		0.2		0.2	2	0.1	2	0.5
	0.8	4	1.4		0.2	3	0.1	3	0.1		0.6		3.8
	6.8	4	11.5								0.3		2
	3.6	4	5.3										
9		19		0.10		0.12		0.11		0.24		1.6	
	2.5	4	4		0.6		0.6		0.6		0.6		1.5
	8	4	14		0.6		0.6		0.6		0.7		5
		28		7		7		7		7		7	
		24		6		6		6		6		6	
	260		1,760		20		20		20		20		160
	710		7,500		10		10		10		50		350
	350		3,750		10		10		10		30		170
	360		3,750		10		10		10		30		180
	200	8	300	16	10	16	10	16	10	2	20	2	110
	150	40	230							14	10	10	80
	60	16	100									4	30
	60	4	100	8	5	8	5	8	5		10		30
	50	20	75							7	5	5	25
	20	8	30									2	10
	60	4	100	8	5	8	5	8	5		10		30
	50	20	75							7	5	5	25
	20	8	30									2	10
	700	8	1,200		75		75		60	2	75	2	400
		96		24		24		24		24		24	
		12		3		3		3		3		3	

B

Table A-7

EQUIPMENT SIZES AND NUMBERS: CATALYTIC REFORMING PROCESSING UNIT

Equipment	Unit of Measure	Equipment by Refinery Type and									
		Large Fuel				Small Fuel		Complete Processing		As	
		78,000		180,000		24,000		194,000		12,000	
		No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3		13.0		25		4		25		2.0
Fired heater	1,000 ft^3	4	3.6	4	7		4.6	4	7		0.29
	1,000 ft^3										
Fractionation column	1,000 ft^3	4	17.6	4	33.8		22.8	4	34.2		1.4
	1,000 ft^3	4	0.6	4	1.2		0.8	4	1.2	2	0.1
	1,000 ft^3	4	1.7	4	3.2		2.2	4	3.3		
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	4.1		7.8		1.3		7.8		0.081	
Reactor, cracking	1,000 ft^3	16	0.8	16	1.5	4	1	16	1.5	4	0.6
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.										
Pressure vessel, vert.	No.	12		12		3		12		3	
Pipe support	ft		260		500		100		500		20
Storage tank, cone rf.	1,000 ft^3		390		750		90		750		10
Storage tank, fltg. rf.	1,000 ft^3		1,640		3,150		330		3,300		10
Storage tank, spherical	1,000 ft^3		390		750		90		750		10
Pumps	1,000 GPM X TDH*	8	70	8	130	2	90	8	130	12	10
	1,000 GPM X TDH*	24	50	24	100	6	70	24	100		
	1,000 GPM X TDH*	16	20	16	40	4	30	16	40		
Electric motor	Hp	4	20	4	40		30	4	40	6	5
	Hp	12	15	12	30	3	20	12	30		
	Hp	8	10	8	15	2	10	8	15		
Steam turbine	Hp	4	20	4	40		30	4	40	6	5
	Hp	12	15	12	30	3	20	12	30		
	Hp	8	10	8	15	2	10	8	15		
Centrifugal blower	Hp	8	250	8	500	2	350	8	500		50
Heat exchanger	No.	48		48		12		48		12	
Filter	No.										
Instrument cubicle	No.	4		4		1		4		1	

* Gallons per minute X total dynamic head.

A

Table A-7

…IZES AND NUMBERS: CATALYTIC REFORMING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

	Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
	24,000		194,000		12,000		14,000		7,000		4,000		27,000	
ze	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
		4		25		2.0		2		2		2.0		3
		4.6	4	7		0.29		0.34		0.17		0.49		3.3
		22.8	4	34.2		1.4		1.6		0.8		2.4		16
		0.8	4	1.2	2	0.1		0.15	2	0.1		0.1		0.6
		2.2	4	3.3				0.1				0.2		1.6
	1.3		7.8		0.081		0.094		0.047		0.13		0.89	
	4	1	16	1.5	4	0.6	4	0.6	4	0.6	4	0.6	4	0.8
	3		12		3		3		3		3		3	
		100		500		20		20		20		20		80
		90		750		10		10		10		10		60
0		330		3,300		10		10		10		30		210
		90		750		10		10		10		10		60
	2	90	8	130	12	10	12	10	12	10	12	10	2	70
	6	70	24	100									6	50
	4	30	16	40									4	20
		30	4	40	6	5	6	5	6	5	6	5		20
	3	20	12	30									3	15
	2	10	8	15									2	10
		30	4	40	6	5	6	5	6	5	6	5		20
	3	20	12	30									3	15
	2	10	8	15									2	10
	2	350	8	500		50		50		30		75	2	250
	12		48		12		12		12		12		12	
	1		4		1		1		1		1		1	

Table A-8

EQUIPMENT SIZES AND NUMBERS: POLYMERIZATION PROCESSING UNIT

Equipment	Unit of Measure	Equipment by Refinery Type and									
		Large Fuel				Small Fuel		Complete Processing		A	
		78,000		150,000		[illegible]4,000		194,000		12,000	
		No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3		2.0		2		2		5		2.0
Fired heater	1,000 ft^3										
	1,000 ft^2										
Fractionation column	1,000 ft^3		0.7		1.4		0.23		2.1		0.1
	1,000 ft^3		0.8		1.5		0.3		2.6		0.2
	1,000 ft^3		4.9		9		1.6		16		0.9
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	0.29		0.56		0.01		0.94		0.057	
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3	2	0.6	2	0.6	2	0.6	2	1	2	0.6
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.	3		3		3		3		3	
Pressure vessel, vert.	No.			40		20		40			
Pipe support	ft		20								20
Storage tank, cone rf.	1,000 ft^3										
Storage tank, fltg. rf.	1,000 ft^3		40		80		20		120		10
Storage tank, spherical	1,000 ft^3		60		110		20		210		10
Pumps	1,000 GPM X TDH*	2	40	2	80	6	20	2	130	6	20
	1,000 GPM X TDH*	4	20	4	30	2	10	4	50	2	10
	1,000 GPM X TDH*	2	10	2	10			2	20		
Electric motor	Hp		15		25	3	10		40	3	10
	Hp	2	10	2	10		5	2	15		5
	Hp		5		5				10		
Steam turbine	Hp		15		25	3	10		40	3	10
	Hp	2	10	2	10		5	2	15		5
	Hp		5		5				10		
Centrifugal blower	Hp										
Heat exchanger	No.	9		9		9		9		9	
Filter	No.										
Instrument cubicle	No.	1		1		1		1		1	

* Gallons per minute X total dynamic head.

A

Table A-8

PMENT SIZES AND NUMBERS: POLYMERIZATION PROCESSING UNIT

	Equipment by Refinery Type and Capacity (B/D)															
	Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube					
000	24,000		184,000		12,000		14,000		7,000		4,000		27,000			
Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size		
2		2		5		2.0		2		2		2.0		2		
1.4		0.23		2.1		0.1		0.15	2	0.1	2	0.1	2	0.2		
1.5		0.3		2.6		0.2		0;2		0.4				1.2		
9		1.6		18		0.9		1				0.3				
	0.01		0.94		0.057		0.067		0.024		0.011		0.072			
0.6	2	0.6	2	1	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6		
	3		3		3		3		3		3		3			
	20		40				20		20			20	20			
						20										
0		20		120		10		10		10		10		10		
10		20		210		10		10		10		10		10		
0	6	20	2	130	6	20	6	20	6	20	8	10	6	30		
0	2	10	4	50	2	10	2	10	2	10			2	10		
0			2	20												
5	3	10		40	3	10	3	10	3	10	4	5	3	10		
0		5	2	15		5		5		5				5		
				10												
5	3	10		40	3	10	3	10	3	10	4	5	3	10		
0		5	2	15		5		5		5				5		
				10												
	9		9		9		9		9		9		9			
	1		1		1		1		1		1		1			

B

Table A-9

EQUIPMENT SIZES AND NUMBERS: ALKYLATION PROCESSING UNIT

		Equipment by Refinery Type									
		Large Fuel				Small Fuel		Complete Processing			
		78,000		150,000		24,000		194,000		12,000	
Equipment	Unit of Measure	No.	Size	No.	Size	No.	Size	No.	Size	No.	Si
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3		13.0		25		4		24		
Fired heater	1,000 ft^3		11.0		22		3		22		
	1,000 ft^3										
Fractionation column	1,000 ft^3		8.9		17		2.3		17		
	1,000 ft^3		14.6		29		3.8		28		
	1,000 ft^3		6.0		12		1.5		11		
	1,000 ft^3		5.2		10		1.3		9.4		
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.	1.6		3.1		0.42		3.0			
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3	4	0.6	4	1	2	0.6	4	0.9		
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.	6		6		6		6			
Pressure vessel, vert.	No.	4		4		4		4			
Pipe support	ft		360		700		100		680		
Storage tank, cone rf.	1,000 ft^3		330		630		60		600		
Storage tank, fltg. rf.	1,000 ft^3		120		240		20		240		
Storage tank, spherical	1,000 ft^3		330		630		60		600		
Pumps	1,000 GPM X TDH*	2	60	2	110	11	20	2	100		
	1,000 GPM X TDH*	9	80	9	160	4	10	9	150		
	1,000 GPM X TDH*	4	40	4	70			4	70		
Electric motor	Hp		20		30	5	10		30		
	Hp	4	25	4	50	2	5	4	50		
	Hp	2	15	2	20			2	20		
Steam turbine	Hp		20		30	6	10		30		
	Hp	5	25	5	50	2	5	5	50		
	Hp	2	15	2	20			2	20		
Centrifugal blower	Hp										
Heat exchanger	No.	15		15		15		15			
Filter	No.										
Instrument cubicle	No.	1		1		1		1			

* Gallons per minute x total dynamic head.

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Table A-9

IZES AND NUMBERS: ALKYLATION PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Small Fuel 24,000		Complete Processing 194,000		Asphalt 12,000		Asphalt 14,000		Asphalt and Lube 7,000		Lube 4,000		Lube 27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	4		24								2.0		6
	3		22								0.46		3.1
	2.3		17								0.4		2.4
	3.8		28								0.7		4.1
	1.5		11							2	0.2		1.6
	1.3		9.4										1.4
0.42		3.0								0.065		0.44	
2	0.6	4	0.9							2	0.6	2	0.8
6		6								6		6	
4		4								4		4	
	100		680								20		100
	60		600								10		60
	20		240								10		30
	60		600								10		60
11	20	2	100							16	10	11	20
4	10	9	150									4	10
		4	70										
3	10		30									5	10
2	5	4	50							7	5	2	5
		2	20										
6	10		30							8	5	6	10
2	5	5	50									2	5
		2	20										
15		15								15		15	
1		1								1		1	

Table A-10

EQUIPMENT SIZES AND NUMBERS: HYDROGEN TREATING PROCESS

Equipment	Unit of Measure	Equipment by Refinery Ty[pe]								
		Large Fuel				Small Fuel		Complete Processing		
		75,000		150,000		24,000		194,000		12,[illegible]
		No.	Size	No.	Size	No.	Size	No.	Size	No.
Control house, steel rf.	1,000 ft^3									
Control house, concr. rf.	1,000 ft^3		13.0		25		2		25	
Fired heater	1,000 ft^3		13.0		25		1.2		25	
	1,000 ft^3									
Fractionation column	1,000 ft^3		5.4		10		0.5		10	
	1,000 ft^3		11.4		22		1.1		22	
	1,000 ft^3									
	1,000 ft^3									
	1,000 ft^3									
	1,000 ft^3									
Extraction column	1,000 ft^3									
	1,000 ft^3									
Cooling tower	No.	3.2		6.1		0.31		6.1		
Reactor, cracking	1,000 ft^3	4	1.0	4	2	2	0.6	4	2	
	1,000 ft^3	2	0.5	2	1			2	1	
Reactor, chemical	1,000 ft^3									
Regenerator	1,000 ft^3									
Pressure vessel, horiz.	No.	3		3		3		3		
Pressure vessel, vert.	No.									
Pipe support	ft		290		560		20		560	
Storage tank, cone rf.	1,000 ft^3		940		1,800		50		1,800	
Storage tank, fltg. rf.	1,000 ft^3		470		900		30		900	
Storage tank, spherical	1,000 ft^3		470		900		20		900	
Pumps	1,000 GPM X TDH*	2	310	2	600	2	30	2	600	
	1,000 GPM X TDH*	4	170	4	320	4	20	4	320	
	1,000 GPM X TDH*	2	70	2	130	2	10	2	130	
Electric motor	Hp		100		175	3	10		175	
	Hp	2	50	2	100			2	100	
	Hp		20		40		5		40	
Steam turbine	Hp		100		175	3	10		175	
	Hp	2	50	2	100		5	2	100	
	Hp		20		40				40	
Centrifugal blower	Hp									
Heat exchanger	No.	12		12		12		12		
Filter	No.									
Instrument cubicle	No.	1		1		1		1		

* Gallons per minute X total dynamic head.

A

Table A-10

ZES AND NUMBERS: HYDROGEN TREATING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)													
Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		184,000		12,000		14,000		7,000		4,000		27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	2		25										
	1.2		25										
	0.5		10										
	1.1		22										
0.31		6.1											
2	0.6	4	2										
		2	1										
3		3											
	20		560										
	50		1,800										
	30		900										
	20		900										
2	30	2	600										
4	20	4	320										
2	10	2	130										
3	10		175										
		2	100										
	5		40										
3	10		175										
	5	2	100										
			40										
12		12											
1		1											

B

Table A-11

EQUIPMENT SIZES AND NUMBERS: VACUUM FLASHING PROC[…]

Equipment	Unit of Measure	Equipment by Refinery […]								
		Large Fuel				Small Fuel		Complete Processing		
		75,000		150,000		24,000		194,000		
		No.	Size	No.	Size	No.	Size	No.	Size	No.
Control house, steel rf.	1,000 ft³		8.3		18		3		11	
Control house, concr. rf.	1,000 ft³									
Fired heater	1,000 ft³	4	4.2	4	6		5.4	4.	4.8	
	1,000 ft³									
Fractionation column	1,000 ft³		8.6	4	16		11	4	11.5	
	1,000 ft³	2	1.3	6	2.5	2	1.7	8	1.8	2
	1,000 ft³									
	1,000 ft³									
	1,000 ft³									
	1,000 ft³									
Extraction column	1,000 ft³									
	1,000 ft³									
Cooling tower	No.	4.9		9.4		1.5		6.7		1.9
Reactor, cracking	1,000 ft³									
	1,000 ft³									
Reactor, chemical	1,000 ft³									
Regenerator	1,000 ft³									
Pressure vessel, horiz.	No.									
Pressure vessel, vert.	No.	4		4		1		4		1
Pipe support	ft		110		220		40		160	
Storage tank, cone rf.	1,000 ft³		3,120		6,000		620		3,750	
Storage tank, fltg. rf.	1,000 ft³									
Storage tank, spherical	1,000 ft³									
Pumps	1,000 GPM X TDH*	16	40	16	80	4	50	16	60	4
	1,000 GPM X TDH*									
	1,000 GPM X TDH*									
Electric motor	Hp	8	15	8	15	2	15	8	20	2
	Hp									
	Hp									
Steam turbine	Hp	8	15	8	25	2	15	8	20	2
	Hp									
	Hp									
Centrifugal blower	Hp									
Heat exchanger	No.	20		20		5		20		5
Filter	No.									
Instrument cubicle	No.									

* Gallons per minute X total dynamic head.

A

Table A-11

SIZES AND NUMBERS: VACUUM FLASHING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		194,000		12,000		14,000		7,000		4,000		27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	3		11		3.4		4						
	5.4	4.	4.8		6.9		8						
	11	4	11.5		5.4		6.3						
2	1.7	8	1.8	2	1.4	2	1.6						
1.5		6.7		1.9		2.2							
1		4		1		1							
	40		160		50		60						
	620		3,750		880		1,020						
4	50	16	60	4	70	4	80						
2	15	8	20	2	20	2	25						
2	15	8	20	2	20	2	25						
5		20		5		5							

B

Table A-12

EQUIPMENT SIZES AND NUMBERS: VACUUM DISTILLATION PROCESSING

		Equipment by Refinery Type									
		Large Fuel				Small Fuel		Complete Processing			
		75,000		150,000		24,000		194,000		12,000	
Equipment	Unit of Measure	No.	Size	No.	Size	No.	Size	No.	Size	No.	Si
Control house, steel rf.	1,000 ft^3										
Control house, concr. rf.	1,000 ft^3								17		
Fired heater	1,000 ft^3							4	3.9		
	1,000 ft^3										
Fractionation column	1,000 ft^3							4	8		
	1,000 ft^3							12	0.8		
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.							4.3			
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.										
Pressure vessel, vert.	No.							12			
Pipe support	ft								100		
Storage tank, cone rf.	1,000 ft^3								2,400		
Storage tank, fltg. rf.	1,000 ft^3										
Storage tank, spherical	1,000 ft^3										
Pumps	1,000 GPM X TDH*							24	40		
	1,000 GPM X TDH*										
	1,000 GPM X TDH*										
Electric motor	Hp							12	15		
	Hp										
	Hp										
Steam turbine	Hp							12	15		
	Hp										
	Hp										
Centrifugal blower	Hp										
Heat exchanger	No.							28			
Filter	No.										
Instrument cubicle	No.							4			

* Gallons per minute X total dynamic head.

A

Table A-12

IZES AND NUMBERS: VACUUM DISTILLATION PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Small Fuel 24,000 No.	Small Fuel 24,000 Size	Complete Processing 194,000 No.	Complete Processing 194,000 Size	Asphalt 12,000 No.	Asphalt 12,000 Size	Asphalt 14,000 No.	Asphalt 14,000 Size	Asphalt and Lube 7,000 No.	Asphalt and Lube 7,000 Size	Lube 4,000 No.	Lube 4,000 Size	Lube 27,000 No.	Lube 27,000 Size
			17						5		2.0		8
		4	3.9						4		1.1		7.6
		4	8						2.1		0.9		6
		12	0.8					3	0.3	3	0.1	3	0.9
		4.3						1.1		0.31		2.1	
		12						3		3		3	
			100						40		20		60
			2,400						440		140		960
		24	40					6	40	6	10	6	70
		12	15					3	15	3	5	3	20
		12	15					3	15	3	5	3	20
		28						7		7		7	
		4						1		1		1	

Table A-13

EQUIPMENT SIZES AND NUMBERS: LUBE AND SPECIALTIES PROCESS

Equipment	Unit of Measure	Equipment by Refinery Type: Large Fuel 78,000 No.	Size	Large Fuel 150,000 No.	Size	Small Fuel 24,000 No.	Size	Complete Processing 194,000 No.	Size	12, No.
Control house, steel rf.	1,000 ft^3									
Control house, concr. rf.	1,000 ft^3								50	
Fired heater	1,000 ft^3							3	2.5	
	1,000 ft^3									
Fractionation column	1,000 ft^3								9	
	1,000 ft^3							4	1	
	1,000 ft^3								2.5	
	1,000 ft^3							2	1.3	
	1,000 ft^3								3.5	
	1,000 ft^3								6	
Extraction column	1,000 ft^3								1	
	1,000 ft^3								1.3	
Cooling tower	No.							3.6		
Reactor, cracking	1,000 ft^3									
	1,000 ft^3									
Reactor, chemical	1,000 ft^3									
Regenerator	1,000 ft^3									
Pressure vessel, horiz.	No.							12		
Pressure vessel, vert.	No.							7		
Pipe support	ft								2,000	
Storage tank, cone rf.	1,000 ft^3								1,350	
Storage tank, fltg. rf.	1,000 ft^3								360	
Storage tank, spherical	1,000 ft^3								90	
Pumps	1,000 GPM X TDH*							40	120	
	1,000 GPM X TDH*							20	40	
	1,000 GPM X TDH*									
Electric motor	Hp							20	40	
	Hp							10	15	
	Hp									
Steam turbine	Hp							20	40	
	Hp							10	15	
	Hp									
Centrifugal blower	Hp									
Heat exchanger	No.							50		
Filter	No.							6		
Instrument cubicle	No.							5		

* Gallons per minute X total dynamic head.

A

Table A-13

AND NUMBERS: LUBE AND SPECIALTIES PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)

Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		194,000		12,000		14,000		7,000		4,000		27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
			50								3.7		25
		3	2.5							3	0.15	3	1
			9								0.4		3
		4	1							7	0.1	4	0.4
			2.5								0.2		0.9
		2	1.3								0.3	2	0.5
			3.5										1.3
			8										2.1
			1							2	0.1		0.4
			1.3										0.5
		3.6								0.19		1.3	
		12								12		12	
		7								7		7	
			2,000								150		1,000
			1,350								60		410
			360								20		110
			90								10		30
		40	120							60	10	40	50
		20	40									20	20
		20	40							30	5	20	15
		10	15									10	10
		20	40							30	5	20	15
		10	15									10	10
		50								50		50	
		6								3		3	
		5								5		5	

Table A-14

EQUIPMENT SIZES AND NUMBERS: ASPHALT PROCESSING UNIT

		Equipment by Refinery Type and									
		Large Fuel				Small Fuel		Complete Processing		As	
		78,000		150,000		24,000		194,000		12,000	
Equipment	Unit of Measure	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
Control house, steel rf.	1,000 ft^3						2		2		2.0
Control house, concr. rf.	1,000 ft^3										
Fired heater	1,000 ft^3						0.7		3.1		2.9
	1,000 ft^3										
Fractionation column	1,000 ft^3						0.2		0.6		0.6
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
	1,000 ft^3										
Extraction column	1,000 ft^3										
	1,000 ft^3										
Cooling tower	No.					0.19		0.89		0.81	
Reactor, cracking	1,000 ft^3										
	1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.										
Pressure vessel, vert.	No.										
Pipe support	ft						20		40		30
Storage tank, cone rf.	1,000 ft^3						50		320		300
Storage tank, fltg. rf.	1,000 ft^3										
Storage tank, spherical	1,000 ft^3										
Pumps	1,000 GPM X TDH*					4	10	2	30	2	30
	1,000 GPM X TDH*							2	20	2	20
	1,000 GPM X TDH*										
Electric motor	Hp					2	5	2	10	2	10
	Hp										
	Hp										
Steam turbine	Hp					2	5	2	10	2	10
	Hp										
	Hp										
Centrifugal blower	Hp										
Heat exchanger	No.					3		3		3	
Filter	No.										
Instrument cubicle	No.										

* Gallons per minute X total dynamic head.

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Table A-14

…PMENT SIZES AND NUMBERS: ASPHALT PROCESSING UNIT

	Equipment by Refinery Type and Capacity (B/D)													
	Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
	24,000		194,000		12,000		14,000		7,000		4,000		27,000	
…e	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
		2		2		2.0		2		2				
		0.7		3.1		2.9		3.4		1.7				
		0.2		0.8		0.6		0.7		0.4				
	0.19		0.89		0.81		0.94		0.47					
		20		40		30		40		20				
		50		320		300		350		150				
	4	10	2	30	2	30	2	30	2	20				
			2	20	2	20	2	20	2	10				
	2	5	2	10	2	10	2	10		10				
										5				
	2	5	2	10	2	10	2	10		10				
										5				
	3		3		3		3		3					

Table A-15

EQUIPMENT SIZES AND NUMBERS: LIGHT OIL TREATING PROCESSING UNIT

Equipment	Unit of Measure	Equipment by Refinery Type and C…									
		Large Fuel				Small Fuel		Complete Processing		Asp…	
		75,000		150,000		24,000		194,000		12,000	
		No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
Control house, steel rf.	1,000 ft^3		14.0		27		3		27		3.0
Control house, concr. rf.	1,000 ft^3										
Fired heater	1,000 ft^3 1,000 ft^3	12	3.7	12	7.2	3	4.8	12	7.2	3	2.0
Fractionation column	1,000 ft^3 1,000 ft^3 1,000 ft^3 1,000 ft^3 1,000 ft^3 1,000 ft^3	12	1.5	12	2.9	3	1.9	12	2.9	3	0.8
Extraction column	1,000 ft^3 1,000 ft^3	12	1.5	12	2.9	3	1.9	12	2.9	3	0.8
Cooling tower	No.	8.8		17		2.7		17		1.1	
Reactor, cracking	1,000 ft^3 1,000 ft^3										
Reactor, chemical	1,000 ft^3										
Regenerator	1,000 ft^3										
Pressure vessel, horiz.	No.	80		80		20		80		20	
Pressure vessel, vert.	No.	40		40		10		40		10	
Pipe support	ft		200		380		80		380		30
Storage tank, cone rf.	1,000 ft^3		3,120		6,000		630		6,000		280
Storage tank, fltg. rf.	1,000 ft^3		3,120		6,000		640		6,000		330
Storage tank, spherical	1,000 ft^3										
Pumps	1,000 GPM X TDH* 1,000 GPM X TDH* 1,000 GPM X TDH*	40 40	100 40	40 40	200 80	10 10	90 50	40 40	200 80	10 10	30 20
Electric motor	Hp Hp Hp	20 20	30 15	20 20	60 25	5 5	30 15	20 20	60 25	10	10
Steam turbine	Hp Hp Hp	20 20	30 15	20 20	60 25	5 5	30 15	20 20	60 25	10	10
Centrifugal blower	Hp										
Heat exchanger	No.	80		80		20		80		20	
Filter	No.										
Instrument cubicle	No.										

* Gallons per minute X total dynamic head.

Table A-15

S AND NUMBERS: LIGHT OIL TREATING PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)													
Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		184,000		12,000		14,000		7,000		4,000		37,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
	5		27		2,0		2		2		3,0		5
3	4,8	12	7,2	3	2,0	3	2.3	3	2.2	3	0,55	3	3,7
3	1,9	12	2,9	3	0,8	3	0,9	3	0.5	3	0.2	3	1,5
3	1,9	12	2,9	3	0,8	3	0,9	3	0,8	3	0.2	3	1,5
2.7		17		1.1		1.3		0.61		0.31		2.1	
20		80		20		20		20		20		20	
10		40		10		10		10		10		10	
	80		380		30		40		20		20		60
	630		6,000		250		290		110		70		450
	640		6,000		230		270		110		70		460
10	90	40	200	10	30	10	40	10	20	20	10	10	70
10	50	40	80	10	20	10	20	10	10			10	40
	30	20	60	10	10	5	15	5	10	10	5	5	20
	15	20	25			5	10	5	5			5	15
	30	20	60	10	10	5	15	5	10	10	5	5	20
	15	20	25			5	10	5	5			5	15
0		80		20		20		20		20		20	

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Table A-16

EQUIPMENT SIZES AND NUMBERS: NAPHTHENIC LUBE AND SPECIALTIE

		Equipment by Refinery T								
		Large Fuel				Small Fuel		Complete Processing		
		75,000		150,000		24,000		104,000		1
Equipment	Unit of Measure	No.	Size	No.	Size	No.	Size	No.	Size	No.
Control house, steel rf.	1,000 ft²									
Control house, concr. rf.	1,000 ft³									
Fired heater	1,000 ft²									
	1,000 ft³									
Fractionation column	1,000 ft³									
	1,000 ft³									
	1,000 ft³									
	1,000 ft³									
	1,000 ft³									
	1,000 ft³									
Extraction column	1,000 ft³									
	1,000 ft³									
Cooling tower	No.									
Reactor, cracking	1,000 ft³									
	1,000 ft³									
Reactor, chemical	1,000 ft³									
Regenerator	1,000 ft³									
Pressure vessel, horiz.	No.									
Pressure vessel, vert.	No.									
Pipe support	ft									
Storage tank, cone rf.	1,000 ft³									
Storage tank, fltg. rf.	1,000 ft³									
Storage tank, spherical	1,000 ft³									
Pumps	1,000 GPM × TDH*									
	1,000 GPM × TDH*									
	1,000 GPM × TDH*									
Electric motor	Hp									
	Hp									
	Hp									
Steam turbine	Hp									
	Hp									
	Hp									
Centrifugal blower	Hp									
Heat exchanger	No.									
Filter	No.									
Instrument cubicle	No.									

* Gallons per minute × total dynamic head.

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Table A-16

AND NUMBERS: NAPHTHENIC LUBE AND SPECIALTIES PROCESSING UNIT

Equipment by Refinery Type and Capacity (B/D)													
Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
24,000		194,000		12,000		14,000		7,000		4,000		27,000	
No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
									5				
								3	0.7				
									0.4				
								7	0.1				
									0.2				
									0.3				
								2	0.1				
								0.18					
								12					
								7					
									200				
									30				
									20				
									10				
								60	10				
								30	5				
								30	5				
								50					
								3					
								5					

Table A-17

EQUIPMENT SIZES AND NUMBERS: PIPE SUPPORTS AND UTILITIES

Equipment	Unit of Measure	Equipment by Refinery Type and									
		Large Fuel				Small Fuel		Complete Processing		A	
		78,000		150,000		24,000		194,000		12,000	
		No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
Pipe supports	ft		1,040		2,000		880		2,000		210
Utilities, gas motor	No.	1		1		1		1		1	
Utilities, gas regulator	No.	1		1		1		1		1	
Utilities, electric transformer	No.	3		3		2		3		1	

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Table A-17

MENT SIZES AND NUMBERS: PIPE SUPPORTS AND UTILITIES

Equipment by Refinery Type and Capacity (B/D)

	Small Fuel		Complete Processing		Asphalt				Asphalt and Lube		Lube			
	24,000		194,000		12,000		14,000		7,000		4,000		27,000	
ze	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size	No.	Size
00		880		2,000		210		240		240		60		400
	1		1		1		1		1		1		1	
	1		1		1		1		1		1		1	
	2		3		1		1		1		1		1	

Appendix B

PRODUCT YIELD FROM CRUDE OILS
AFTER LOW BLAST OVERPRESSURE

Appendix B

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE

For each refinery, the equipment that remained operable and its degree of operability after low blast overpressure of 0.3-0.5 psi and 1.0 psi is determined.[9,10] Assumptions were made of rerouting process flows within each refinery, to bypass damaged or shutdown equipment. The product yields from both the normal crude oils and alternative crude oils were recalculated. In every instance, the reduced capacity of a process unit remaining operable after blast damage is reflected in the resultant limited product yields.

The combined effects of equipment shutdown, rerouting process flows, and limited capacities of remaining equipment reduces refinery throughput after 1 psi to about one-half to one-fourth of initial capacity. If a refinery must use alternative crude oils, the throughput is reduced further.

At the overpressure that reduces the cooling towers to 70 percent capacity (0.3-0.5 psi[9,10]), the capacities of all processing units is considered at 70 percent of initial capacity and the refinery production estimated for this condition.

At the 1.0 psi overpressure, the crude topping, vacuum flashing, light oil treating, and asphalt process units are considered shut down. Sufficient repair is made to the crude topping process unit to permit the refinery to operate at 50 percent of initial capacity. The vacuum flashing, light oil treating, and asphalt process units remain shut down. While the refinery is operating at 50 percent of initial capacity it is assumed that all light oils find a market, even though they do not meet normal specifications; vacuum distillation units are assumed to process topped crude in the production of specialty products; and thermal cracking and catalytic cracking units are assumed to use some topped crude oil as a part of their input.

The product yields in each instance are summarized in Tables B-1 through B-6 for the six types of refineries. Yields are developed at 100 percent capacity with undamaged conditions, 70 percent capacity after 0.3 to 0.5 psi blast damage, and 50 percent capacity with appropriate volume modifications required for partial shutdown of equipment after 1.0 psi.

Table B-1

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE: LARGE FUEL REFINERY

Blast condition	Undamaged	After 0.3-0.5 psi	After 1.0 psi*
	Production as a Percent of Initial Refinery Capacity		
Maximum capacity (%)	100%	70%	50%
Crude oils and products:			
Normal: 30°-40° API Gulf			
Gasoline	54%	38%	26%
Kerosene	15	10	8
Diesel	14	10	7
Lube	--	--	--
Fuel oil	13	9	7
Asphalt	--	--	--
Coke	4	3	2
Total	100%	70%	50%
Alternative: 20°-25° API West Coast			
Gasoline	12%	9%	6%
Kerosene	5	3	2
Diesel	6	4	3
Lube	--	--	--
Fuel oil	13	9	7
Asphalt	--	--	--
Coke	2	1	1
Total	38%	26%	19%
Alternative: 20°-25° API Midcontinent			
Gasoline	8%	6%	4%
Kerosene	4	3	2
Diesel	4	3	2
Lube	--	--	--
Fuel oil	13	9	7
Asphalt	--	--	--
Coke	2	1	--
Total	31%	22%	15%

* Emergency repairs made to crude topping process.

Table B-2

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE: SMALL FUEL REFINERY

	Production as a Percent of Initial Refinery Capacity		
Blast condition	Undamaged	After 0.3-0.5 psi	After 1.0 psi*
Maximum capacity (%)	100%	70%	50%
Crude oil and products:			
Normal: 30°-40° API Gulf			
Gasoline	50%	35%	26%
Kerosene	15	11	8
Diesel	15	10	7
Lube	--	--	--
Fuel oil	15	11	9
Asphalt	4	2	--
Coke	1	1	--
Total	100%	70%	50%
Alternative: 20°-25° API West Coast			
Gasoline	13%	10%	7%
Kerosene	5	4	3
Diesel	6	4	4
Lube	--	--	--
Fuel oil	15	11	9
Asphalt	2	1	--
Coke	1	1	--
Total	42%	31%	23%
Alternative: 20°-25° API Midcontinent			
Gasoline	8%	6%	3%
Kerosene	4	3	2
Diesel	4	3	2
Lube	--	--	--
Fuel oil	15	11	9
Asphalt	1	1	--
Coke	1	--	--
Total	33%	24%	16%

* Emergency repairs made to crude topping process.

Table B-3

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE: COMPLETE PROCESSING REFINERY

Blast condition	Production as a Percent of Initial Refinery Capacity		
	Undamaged	After 0.3-0.5 psi	After 1.0 psi*
Maximum capacity (%)	100%	70%	50%
Crude oils and products:			
Normal: 30°-40° API Gulf			
Gasoline	47%	33%	24%
Kerosene	15	11	7
Diesel	15	10	7
Lube	8	6	4
Fuel oil	11	8	7
Asphalt	2	1	--
Coke	2	1	1
Total	100%	70%	50%
Alternative: 20°-25° API West Coast			
Ga ine	10%	7%	6%
Kerosene	4	3	2
Diesel	5	4	3
Lube	3	2	2
Fuel oil	11	8	7
Asphalt	1	--	--
Coke	1	--	--
Total	35%	24%	20%
Alternative: 20°-25° API Midcontinent			
Gasoline	6%	4%	3%
Kerosene	3	2	2
Diesel	3	2	2
Lube	2	2	1
Fuel oil	11	8	7
Asphalt	1	--	--
Coke	1	1	--
Total	27%	19%	15%

* Emergency repairs made to crude topping process.

Table B-4

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE: ASPHALT REFINERY

Blast condition	Undamaged	After 0.3-0.5 psi	After 1.0 psi*
	Production as a Percent of Initial Refinery Capacity		
Maximum capacity (%)	100%	70%	50%
Crude oils and products:			
Normal: 10°-15° API Heavy-Asphaltic			
Gasoline	11%	8%	2%
Kerosene	10	7	1
Diesel	11	8	1
Lube	--	--	--
Fuel oil	2	1	11
Asphalt	66	46	--
Coke	--	--	--
Total	100%	70%	15%
Alternative: 30°-40° API Gulf			
Gasoline	11%	8%	2%
Kerosene	4	3	1
Diesel	4	2	1
Lube	--	--	--
Fuel oil	1	1	1
Asphalt	4	3	--
Coke	--	--	--
Total	24%	17%	5%
Alternative: 20°-25° API West Coast			
Gasoline	11%	8%	1%
Kerosene	5	4	--
Diesel	7	4	1
Lube	--	--	--
Fuel oil†	4	3	1
Asphalt	14	10	--
Coke	--	--	--
Total	41%	29%	3%
Alternative: 20°25° API Midcontinent			
Gasoline	11%	8%	1%
Kerosene	5	4	1
Diesel	6	4	1
Lube	--	--	--
Fuel oil†	9	7	2
Asphalt	13	10	--
Coke	--	--	--
Total	44%	33%	5%

* Emergency repairs made to crude topping process.

† Some asphalt equipment used for fuel oils.

Table B-5

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE: ASPHALT AND LUBE REFINERY

Blast condition	Production as a Percent of Initial Refinery Capacity		
Maximum capacity (%)	Undamaged 100%	After 0.3-0.5 psi 70%	After 1.0 psi* 50%
Crude oils and products:			
Normal: 10°-15° API Asphaltic-Lube			
Gasoline	5%	4%	1%
Kerosene	3	3	1
Diesel	15	10	3
Lube	12	8	3
Fuel oil	6	5	12
Asphalt	57	40	--
Coke	--	--	--
Total	100%	70%	22%
Alternative: 30°-40° API Gulf			
Gasoline	5%	4%	1%
Kerosene	2	2	--
Diesel	2	1	--
Lube	2	1	--
Fuel oil	--	--	--
Asphalt	2	2	--
Coke	--	--	--
Total	13%	10%	1%
Alternative: 20°-25° API West Coast			
Gasoline	5%	4%	1%
Kerosene	3	1	1
Diesel	3	2	1
Lube	3	1	1
Fuel oil	2	1	1
Asphalt	7	3	--
Coke	--	--	--
Total	23%	12%	5%
Alternative: 20°-25° API Midcontinent			
Gasoline	5%	4%	1%
Kerosene	3	3	1
Diesel	3	3	1
Lube	3	2	1
Fuel oil	4	3	2
Asphalt	8	6	--
Coke	--	--	--
Total	26%	21%	6%

* Emergency repairs made to crude topping process.

Table B-6

PRODUCT YIELD FROM CRUDE OILS AFTER LOW BLAST OVERPRESSURE: LUBE REFINERY

Blast condition Maximum capacity (%)	Production as a Percent of Initial Refinery Capacity Undamaged 100%	 After 0.3-0.5 psi 70%	 After 1.0 psi* 50%
Crude oils and products:			
Normal: 30°-45° API Lube			
Gasoline	42%	30%	21%
Kerosene	15	11	8
Diesel	15	10	7
Lube	17	12	8
Fuel oil	11	7	6
Asphalt	--	--	--
Coke	--	--	--
Total	100%	70%	50%
Alternative: 30°-40° API Gulf			
Gasoline	39%	26%	21%
Kerosene	14	10	7
Diesel	14	9	7
Lube	14	10	8
Fuel oil	11	7	6
Asphalt	--	--	--
Coke	--	--	--
Total	92%	62%	49%
Alternative: 20°-25° API West Coast			
Gasoline	7%	5%	4%
Kerosene	4	3	2
Diesel	5	3	3
Lube	7	4	4
Fuel oil	11	7	6
Asphalt	--	--	--
Coke	--	--	--
Total	34%	22%	19%
Alternative: 20°-25° API Midcontinent			
Gasoline	4%	3%	2%
Kerosene	3	2	2
Diesel	3	2	2
Lube	5	3	3
Fuel oil	11	7	6
Asphalt	--	--	--
Coke	--	--	--
Total	26%	17%	15%

* Emergency repairs made to crude topping process.

Appendix C

PRODUCT YIELD FROM CRUDE OILS AT FOUR STAGES OF REPAIR

Appendix C

PRODUCT YIELD FROM CRUDE OILS AT FOUR STAGES OF REPAIR

This appendix details the estimated product yields from each of the six types of refineries after each of the four stages of reconstruction summarized in Section V of this report. For the large and small fuel types and the complete processing refineries, these repair stages are:

A. Repair crude topping unit

B. Repair processing units utilized in cracking processes

C. Repair processing units utilized in upgrading of products

D. Repair all other processing units

Slight modifications of these stages are considered for the specialty refineries to permit the production of some of the necessary nonfuels products. The repair sequences are detailed in Table 7 in the main text.

In all instances, the repaired equipment is considered to be returned to initial capacity. At Repair Stages A, B, and C, it is necessary to reroute process flows within each refinery to bypass the process units not yet repaired. After Repair Stage D, all process units are at initial capacities.

A summary of the pertinent factors of the products produced after each repair stage is outlined below.

Large fuel refinery:

A. Low octane gasoline, kerosene, and diesel are produced as raw stocks. Balance of crude oil is produced as fuel oils.

B. Larger volume and improved quality gasoline is produced.

C. Light oil products are "on-grade."

D. Coke is produced.

Small fuel refinery:

A. Low octane gasoline, kerosene, and diesel are produced as raw stocks. Balance of crude oil is produced as fuel oils.

B. Larger volume and improved quality gasoline is produced.

C. Light oil products are "on-grade."

D. Asphalt is produced.

Complete processing refinery:

A. Low octane gasoline, kerosene, and diesel are produced as raw stocks. Balance of crude oil is produced as fuel oils.

B. Larger volume and improved quality gasoline is produced.

C. Light oil products are "on-grade."

D. Asphalt and coke are produced.

Asphalt refinery:

A. Low octane gasoline, kerosene, and diesel are produced as raw stocks. Balance of crude oil is produced as fuel oils.

B. Asphalt is produced.

C. Larger volume and improved quality gasoline is produced.

D. Light oil products are "on-grade."

Lube refinery:

A. Low octane gasoline, kerosene, and diesel are produced as raw stocks. Balance of crude oil is produced as fuel oils.

B. Lubes and greases are produced.

C. Larger volume and improved quality gasoline is produced.

D. Light oil products are "on-grade."

After each repair stage, the product yield for each refinery has been calculated by methods comparable to those indicated in Appendix B. The product percentages produced reflect both the availability of repaired equipment, the equipment capacities, and the composition of the crude oil used. The repair sequence selected results in the individual refinery product percentages summarized in Tables C-1 through C-6. In all cases, production is shown as the percentage of initial refinery capacity.

Table C-1

PRODUCT YIELD FROM CRUDE OILS AT FOUR REPAIR STAGES:
LARGE FUEL REFINERY

		Production as a Percent of Initial Refinery Capacity		
		Normal Crude Oil	Alternative Crude Oils	
Repair Stage	Product	30°-40° API Gulf	20°-25° API West Coast	20°-25° API Midcontinent
A	Gasoline	13%	4%	3%
	Kerosene	6	3	3
	Diesel	5	4	3
	Lube	--	--	--
	Fuel oil	13	13	13
	Asphalt	--	--	--
	Coke	--	--	--
	Total	37%	24%	22%
B	Gasoline	22%	7%	4%
	Kerosene	8	4	3
	Diesel	7	4	3
	Lube	--	--	--
	Fuel oil	13	13	13
	Asphalt	--	--	--
	Coke	--	--	--
	Total	50%	28%	23%
C	Gasoline	33%	10%	7%
	Kerosene	10	4	3
	Diesel	9	5	3
	Lube	--	--	--
	Fuel oil	13	13	13
	Asphalt	--	--	--
	Coke	--	--	--
	Total	65%	32%	26%
D	Gasoline	54%	12%	8%
	Kerosene	15	5	4
	Diesel	14	6	4
	Lube	--	--	--
	Fuel oil	13	13	13
	Asphalt	--	--	--
	Coke	4	2	2
	Total	100%	38%	31%

Table C-2

PRODUCT YIELD FROM CRUDE OILS AT FOUR REPAIR STAGES:
SMALL FUEL REFINERY

		Production as a Percent of Initial Refinery Capacity		
		Normal Crude Oil	Alternative Crude Oils	
Reconstruction Stage	Product	30°-40° API Gulf	20°-25° API West Coast	20°-25° API Midcontinent
A	Gasoline	15%	5%	4%
	Kerosene	7	4	3
	Diesel	7	4	3
	Lube	--	--	--
	Fuel oil	15	15	15
	Asphalt	--	--	--
	Coke	--	--	--
	Total	44%	28%	25%
B	Gasoline	29%	9%	6%
	Kerosene	9	4	3
	Diesel	9	5	4
	Lube	--	--	--
	Fuel oil	15	15	15
	Asphalt	--	--	--
	Coke	--	--	--
	Total	62%	33%	28%
C	Gasoline	40%	11%	8%
	Kerosene	12	5	4
	Diesel	12	6	4
	Lube	--	--	--
	Fuel oil	15	15	15
	Asphalt	--	--	--
	Coke	--	--	--
	Total	79%	37%	31%
D	Gasoline	50%	13%	8%
	Kerosene	15	5	4
	Diesel	15	6	4
	Lube	--	--	--
	Fuel oil	15	15	15
	Asphalt	4	2	1
	Coke	1	1	1
	Total	100%	42%	33%

Table C-3

PRODUCT YIELD FROM CRUDE OILS AT FOUR REPAIR STAGES: COMPLETE PROCESSING REFINERY

Reconstruction Stage	Product	Normal Crude Oil: 30°-40° API Gulf	Alternative Crude Oils: 20°-25° API West Coast	Alternative Crude Oils: 20°-25° API Midcontinent
		Production as a Percent of Initial Refinery Capacity		
A	Gasoline	11%	4%	3%
	Kerosene	5	3	2
	Diesel	5	3	2
	Lube	--	--	--
	Fuel oil	11	11	11
	Asphalt	--	--	--
	Coke	--	--	--
	Total	32%	21%	18%
B	Gasoline	14%	5%	3%
	Kerosene	6	3	2
	Diesel	6	3	3
	Lube	--	--	--
	Fuel oil	11	11	11
	Asphalt	--	--	--
	Coke	--	--	--
	Total	37%	22%	19%
C	Gasoline	29%	9%	4%
	Kerosene	10	4	3
	Diesel	10	5	3
	Lube	5	2	2
	Fuel oil	11	11	11
	Asphalt	--	--	--
	Coke	--	--	--
	Total	65%	31%	23%
D	Gasoline	47%	10%	6%
	Kerosene	15	4	3
	Diesel	15	5	3
	Lube	8	3	2
	Fuel oil	11	11	11
	Asphalt	2	1	1
	Coke	2	1	1
	Total	100%	35%	27%

Table C-4

PRODUCT YIELD FROM CRUDE OILS AT FOUR REPAIR STAGES:
ASPHALT REFINERY

Reconstruction Stage	Product	Production as a Percent of Initial Refinery Capacity: Normal Crude Oil 10°-15° API Asphaltic	Alternative Crude Oils: 30°-40° API Gulf	Alternative Crude Oils: 20°-25° API West Coast	Alternative Crude Oils: 20°-25° API Midcontinent
A	Gasoline	9%	11%	11%	11%
	Kerosene	10	5	8	8
	Diesel	10	5	9	9
	Lube	--	--	--	--
	Fuel oil / Asphalt	67	10	33	41
	Coke	--	--	--	--
	Total	96%	31%	61%	69%
B	Gasoline	9%	11%	11%	11%
	Kerosene	10	5	8	8
	Diesel	10	5	9	9
	Lube	--	--	--	--
	Fuel oil / Asphalt	67	10	33	41
	Coke	--	--	--	--
	Total	96%	31%	61%	69%
C	Gasoline	10%	11%	11%	11%
	Kerosene	10	4	6	6
	Diesel	11	4	7	6
	Lube	--	--	--	--
	Fuel oil / Asphalt	67	7	20	25
	Coke	--	--	--	--
	Total	98%	26%	44%	48%
D	Gasoline	11%	11%	11%	11%
	Kerosene	10	4	5	5
	Diesel	11	4	6	6
	Lube	--	--	--	--
	Fuel oil / Asphalt	68	5	19	22
	Coke	--	--	--	--
	Total	100%	24%	41%	44%

Table C-5

PRODUCT YIELD FROM CRUDE OILS AT FOUR REPAIR STAGES:
ASPHALT AND LUBE REFINERY

		Production as a Percent of Initial Refinery Capacity			
		Normal Crude Oil	Alternative Crude Oils		
Reconstruction Stage	Product	10°-15° API Asphaltic-Lube	30°-40° API Gulf	20°-25° API West Coast	20°-25° API Midcontinent
A	Gasoline	1%	5%	5%	5%
	Kerosene	4	2	4	4
	Diesel	12	2	4	4
	Lube	--	--	--	--
	Fuel oil / Asphalt	63	5	15	18
	Coke	--	--	--	--
	Total	80%	14%	28%	31%
B	Gasoline	1%	5%	5%	5%
	Kerosene	5	2	4	4
	Diesel	14	2	4	4
	Lube	11	2	3	4
	Fuel oil	9	--	3	5
	Asphalt	54	3	9	9
	Coke	--	--	--	--
	Total	94%	14%	28%	31%
C	Gasoline	4%	5%	5%	5%
	Kerosene	5	2	3	3
	Diesel	15	2	4	4
	Lube	12	2	3	3
	Fuel oil	7	--	2	4
	Asphalt	56	3	7	9
	Coke	--	--	--	--
	Total	99%	14%	24%	28%
D	Gasoline	5%	5%	5%	5%
	Kerosene	5	2	3	3
	Diesel	15	2	3	3
	Lube	12	2	3	3
	Fuel oil	6	--	2	4
	Asphalt	57	2	7	8
	Coke	--	--	--	--
	Total	100%	13%	23%	26%

Table C-6

PRODUCT YIELD FROM CRUDE OILS AT FOUR REPAIR STAGES:
LUBE REFINERY

		Production as a Percent of Initial Refinery Capacity			
		Normal Crude Oil	Alternative Crude Oils		
Reconstruction Stage	Product	30°-40° API Lube	30°-40° API Gulf	20°-25° API West Coast	20°-25° API Midcontinent
A	Gasoline	11%	11%	4%	3%
	Kerosene	5	5	2	2
	Diesel	5	5	3	3
	Lube	--	--	--	--
	Fuel oil	11	11	11	11
	Asphalt	--	--	--	--
	Coke	--	--	--	--
	Total	32%	32%	20%	19%
B	Gasoline	22%	21%	5%	4%
	Kerosene	9	9	4	3
	Diesel	9	9	5	3
	Lube	10	9	6	5
	Fuel oil	11	11	11	11
	Asphalt	--	--	--	--
	Coke	--	--	--	--
	Total	61%	59%	31%	26%
C	Gasoline	28%	27%	7%	4%
	Kerosene	11	10	4	3
	Diesel	11	10	5	3
	Lube	12	10	6	5
	Fuel oil	11	11	11	11
	Asphalt	--	--	--	--
	Coke	--	--	--	--
	Total	73%	68%	33%	26%
D	Gasoline	42%	39%	7%	4%
	Kerosene	15	14	4	3
	Diesel	15	14	5	3
	Lube	17	14	7	5
	Fuel oil	11	11	11	11
	Asphalt	--	--	--	--
	Coke	--	--	--	--
	Total	100%	92%	34%	26%

Appendix D

REPAIR REQUIREMENTS AT FOUR REPAIR STAGES AFTER BLAST OVERPRESSURE

Appendix D

REPAIR REQUIREMENTS AT FOUR REPAIR STAGES AFTER BLAST OVERPRESSURE

This appendix details the labor repair requirements for each of the six types of refineries after blast damage from overpressure of 1/2, 1, 5, and 10 psi, for each of the selected Repair Stages: A, B, C, and D. Calculations follow the method outline in Section V, "Refinery Repair," in this report. The mathematical model is:

$$Rs = L\left[1 - e^{-k(p-x)^{y}}\right]\left[m\left(\frac{C}{C_o}\right) + b\right],$$

where Rs = repair effort in man-days for each specified piece of equipment

p = overpressure in psi

C = size of equipment being investigated

L, k, x, y, m, C_o, and b are the parameters of the selected items of equipment as listed in Table 9 in the main text.

At each selected overpressure, the parameters are applied to each piece of equipment at the sizes (values of C) and total numbers detailed in Appendix A to yield the estimated labor repair required. The results are totaled to indicate the total labor requirement for each process unit, for each repair stage, for each select er pressure, and for each type of refinery.

The totaled repair requirements are summarized for the six types of refineries at average capacities. Similar results are included for the calculations that were used to determine the effect of refinery size on repair requirements.

Values included on these tables are shown as calculated (not rounded), to permit an estimator to resequence process unit repair. Totalled repair requirement after resequencing would be rounded.

Table D-1

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
LARGE FUEL REFINERY, 78,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days: 0.5 psi Each	0.5 psi Cumulative	1 psi Each	1 psi Cumulative	5 psi Each	5 psi Cumulative	10 psi Each	10 psi Cumulative
A	Crude topping	15,364		54,062		72,074		93,277	
	Utilities and pipe supports	0		0		841		3,942	
	Total	15,364	15,364	54,062	54,062	72,915	72,915	97,219	97,219
B	Vacuum flashing	3,076		10,826		14,609		17,736	
	Thermal cracking	1,923		6,778		9,524		21,137	
	Thermal reforming	70		247		435		1,457	
	Vis-breaking	464		1,646		2,410		4,912	
	Catalytic cracking	4,922		17,340		25,694		53,057	
	Catalytic reforming	2,003		7,056		10,391		27,986	
	Total	12,458	27,822	43,893	97,955	63,063	135,978	126,285	223,504
C	Polymerization	40		141		306		2,046	
	Alkylation	446		1,579		2,810		11,020	
	Hydrogen treating	1,392		4,907		7,232		11,781	
	Light oil treating	6,150		21,656		29,204		39,522	
	Total	8,028	35,850	28,283	126,238	39,552	175,530	64,369	287,873
D	Coking	415		1,461		2,267		3,922	
	Total	415	36,265	1,461	127,699	2,267	177,797	3,922	291,795

Table D-2

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
LARGE FUEL REFINERY, 150,000 B/D CAPACITY

Repair Stage	Process Unit	0.5 psi Each	0.5 psi Cumulative	1 psi Each	1 psi Cumulative	5 psi Each	5 psi Cumulative	10 psi Each	10 psi Cumulative
A	Crude topping	29,546		103,965		138,581		176,888	
	Utilities and pipe supports	0		0		1,554		7,209	
	Total	29,546	29,546	103,935	103,935	140,135	140,135	184,097	184,097
B	Vacuum flashing	5,915		20,819		28,085		44,999	
	Thermal cracking	3,698		13,034		18,231		39,297	
	Thermal reforming	129		458		758		2,435	
	Vis-breaking	889		3,152		4,602		9,049	
	Catalytic cracking	9,469		33,357		49,160		97,779	
	Catalytic reforming	3,849		13,555		19,813		51,719	
	Total	23,949	53,495	84,[illegible]	188,310	120,649	260,784	245,278	429,375
C	Polymerization	80		281		488		3,180	
	Alkylation	862		3,053		5,397		20,791	
	Hydrogen treating	2,666		9,396		13,814		22,068	
	Light oil treating	11,827		41,648		56,129		72,852	
	Total	15,435	68,930	54,378	242,688	75,828	336,612	118,891	548,266
D	Coking	790		2,783		4,298		7,248	
	Total	790	69,720	2,783	245,471	4,298	340,910	7,248	555,514

Table D-3

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
SMALL FUEL REFINERY, 24,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days							
		0.5 psi		1 psi		5 psi		10 psi	
		Each	Cumulative	Each	Cumulative	Each	Cumulative	Each	Cumulative
A	Crude topping	2,959		10,430		14,226		24,833	
	Utilities and pipe supports	0		0		701		3,269	
	Total	2,959	2,959	10,430	10,430	14,927	14,927	28,102	28,102
B	Vacuum flashing	612		2,158		2,999		5,993	
	Thermal cracking	227		808		1,232		3,542	
	Vis-breaking	99		352		581		1,612	
	Catalytic cracking	1,048		3,693		5,766		14,095	
	Catalytic reforming	416		1,465		2,306		7,899	
	Total	2,402	5,361	8,476	18,906	12,884	27,811	33,141	61,243
C	Polymerization	20		69		177		1,065	
	Alkylation	80		283		619		3,262	
	Hydrogen treating	79		280		499		1,338	
	Light oil treating	1,254		4,121		6,127		9,215	
	Total	1,433	6,794	5,053	23,959	7,422	35,233	14,880	76,123
D	Coking	20		70		234		808	
	Asphalt	50		175		293		531	
	Total	70	6,864	245	24,204	527	35,760	1,339	77,462

Table D-4

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
COMPLETE PROCESSING REFINERY, 194,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days: 0.5 psi		1 psi		5 psi		10 psi	
		Each	Cumulative	Each	Cumulative	Each	Cumulative	Each	Cumulative
A	Crude topping	39,884		140,330		186,789		235,472	
	Utilities and pipe supports	0		0		1,554		7,209	
	Total	39,884	39,884	140,330	140,330	188,343	188,343	242,681	242,681
B	Vacuum flashing	3,699		13,018		17,650		30,109	
	Thermal cracking	1,185		4,198		6,087		14,479	
	Thermal reforming	977		3,443		4,868		8,969	
	Vis-breaking	849		3,013		4,382		8,721	
	Catalytic cracking	11,094		39,079		57,089		110,421	
	Catalytic reforming	3,996		14,072		20,480		52,748	
	Total	21,800	61,684	76,823	217,153	110,556	298,899	225,447	468,128
C	Polymerization	120		422		769		5,157	
	Alkylation	832		2,949		5,214		20,041	
	Hydrogen treating	2,666		9,396		13,814		22,068	
	Vacuum distillation	2,367		8,335		11,621		20,904	
	Lube and specialties	1,702		5,969		10,611		23,581	
	Light oil treating	11,827		41,648		56,129		72,852	
	Total	19,514	81,198	68,719	285,872	98,158	397,057	164,603	632,731
D	Coking	514		1,810		2,887		5,095	
	Asphalt	316		1,115		1,583		1,953	
	Total	830	82,028	2,925	288,797	4,470	401,527	7,048	639,779

Table D-5

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES: ASPHALT REFINERY, 12,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days							
		0.5 psi		1 psi		5 psi		10 psi	
		Each	Cumulative	Each	Cumulative	Each	Cumulative	Each	Cumulative
A	Crude topping	1,273		4,484		6,144		8,467	
	Utilities and pipe supports	0		0		182		861	
	Total	1,273	1,273	4,484	4,484	6,326	6,326	9,328	9,328
B	Vacuum flashing	869		3,060		4,212		6,114	
	Asphalt	297		1,045		1,479		1,821	
	Total	1,166	2,439	4,105	8,589	5,691	12,017	7,935	17,263
C	Thermal cracking	148		529		826		2,176	
	Thermal reforming	20		70		173		614	
	Catalytic cracking	20		70		256		1,610	
	Catalytic reforming	20		70		240		1,140	
	Total	208	2,647	739	9,328	1,495	13,512	5,540	22,803
D	Polymerization	10		35		154		934	
	Light oil treating	474		1,672		2,337		4,129	
	Total	484	3,131	1,707	11,035	2,491	16,003	5,063	27,866

Table D-6

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
ASPHALT REFINERY, 14,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days							
		0.5 psi		1 psi		5 psi		10 psi	
		Each	Cumulative	Each	Cumulative	Each	Cumulative	Each	Cumulative
A	Crude topping	1,481		5,214		7,146		9,735	
	Utilities and pipe supports	0		0		205		963	
	Total	1,481	1,481	5,214	5,214	7,351	7,351	10,698	10,698
B	Vacuum flashing	1,007		3,547		4,883		7,050	
	Asphalt	346		1,220		1,723		2,111	
	Total	1,353	2,834	4,767	9,981	6,606	13,957	9,161	19,859
C	Thermal cracking	178		633		973		2,486	
	Thermal reforming	20		70		174		633	
	Catalytic cracking	20		71		258		1,630	
	Catalytic reforming	20		70		241		1,186	
	Total	238	3,072	844	10,825	1,646	15,603	5,935	25,794
D	Polymerization	10		35		137		881	
	Light oil treating	553		1,951		2,724		4,649	
	Total	563	3,635	1,986	12,811	2,861	18,464	5,530	31,324

Table D-7

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
ASPHALT AND LUBE REFINERY, 7,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days							
		0.5 psi		1 psi		5 psi		10 psi	
		Each	Cumulative	Each	Cumulative	Each	Cumulative	Each	Cumulative
A	Crude topping	652		2,299		3,203		4,701	
	Utilities and pipe supports	0		0		205		963	
	Total	652	652	2,299	2,299	3,408	3,408	5,664	5,664
B	Vacuum distillation	435		1,532		2,225		3,254	
	Asphalt	148		524		768		1,045	
	Naphthenic lube and specialties	56		191		686		3,689	
	Total	639	1,291	2,247	4,546	3,679	7,087	7,988	13,652
C	Thermal cracking	79		282		482		1,414	
	Thermal reforming	20		69		171		593	
	Catalytic cracking	20		70		256		1,645	
	Catalytic reforming	20		70		235		1,025	
	Total	139	1,430	491	5,037	1,144	8,231	4,677	18,329
D	Polymerization	10		35		134		741	
	Light oil treating	218		772		1,140		2,588	
	Total	228	1,658	807	5,844	1,274	9,505	3,329	21,658

Table D-8

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
LUBE REFINERY, 4,000 B/D CAPACITY

Repair Stage	Process Unit	Repair Requirements in Man-Days							
		0.5 psi		1 psi		5 psi		10 psi	
		Each	Cumulative	Each	Cumulative	Each	Cumulative	Each	Cumulative
A	Crude topping	503		1,771		2,417		4,049	
	Utilities and pipe supports	0		0		71		350	
	Total	503	503	1,771	1,771	2,488	2,488	4,399	4,399
B	Vacuum distillation	138		487		734		1,376	
	Lube and specialties	86		293		745		3,615	
	Total	224	727	780	2,551	1,479	3,967	4,991	9,390
C	Thermal cracking	30		105		225		810	
	Thermal reforming	20		70		174		633	
	Catalytic cracking	79		279		544		2,183	
	Catalytic reforming	40		140		335		1,436	
	Total	169	896	594	3,145	1,278	5,245	5,062	14,452
D	Polymerization	10		35		150		784	
	Alkylation	20		70		206		1,275	
	Light oil treating	138		488		720		1,852	
	Total	168	1,064	593	3,738	1,076	6,321	3,911	18,363

Table D-9

REPAIR REQUIREMENTS AFTER BLAST OVERPRESSURE, FOUR REPAIR STAGES:
LUBE REFINERY, 27,000 B/D CAPACITY

Repair Stage	Process Unit	0.5 psi Each	0.5 psi Cumulative	1 psi Each	1 psi Cumulative	5 psi Each	5 psi Cumulative	10 psi Each	10 psi Cumulative
		Repair Requirements in Man-Days							
A	Crude topping	3,403		11,978		16,243		23,274	
	Utilities and pipe supports	0		0		323		1,507	
	Total	3,403	3,403	11,978	11,978	16,566	16,566	24,781	24,781
B	Vacuum distillation	948		3,339		4,715		6,839	
	Lube and specialties	521		1,823		3,838		10,623	
	Total	1,469	4,872	5,162	17,140	8,553	25,119	17,462	42,243
C	Thermal cracking	178		633		987		2,862	
	Thermal reforming	139		488		747		1,753	
	Catalytic cracking	514		1,816		2,968		8,153	
	Catalytic reforming	267		943		1,538		5,666	
	Total	1,098	5,970	3,880	21,020	6,240	31,359	18,434	60,677
D	Polymerization	10		35		138		926	
	Alkylation	89		318		712		3,496	
	Light oil treating	899		3,170		4,408		7,019	
	Total	998	6,968	3,523	24,543	5,258	36,617	11,441	72,118

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13. ABSTRACT

This report details a method for estimating surviving petroleum refinery capability and repair effort needed to restore production capability following exposure to selected blast overpressures. The method addresses information required for post-attack decision areas. The results should facilitate decisions of which refineries should be restored and to what degree, based on products needed and repair effort available.

The many variations inherent in petroleum refining have been reduced to readily usable numbers: the total U.S. refineries are classified by six refinery types; crude oils are grouped into three major types and three specialty types; refining processes are typified by the 16 most prominent; all refinery equipment is represented by 25 items most vital to process operation, most susceptible to blast damage, and requiring largest labor input for repair; and petroleum products are represented by seven major groups.

In this context the method of estimating refinery production capability and repair requirements is detailed, and the application of the method to any individual refinery is illustrated.

Results indicate that production capability is reduced to about 70 percent after 0.3-0.5 psi, and to about 50 percent after 1 psi. After overpressure greater than 1.5 psi refineries are shut down and must be repaired in order to operate. Repair requirements and partial production are calculable by repair stage.

Additional potential areas of method application include petrochemical and natural gasoline industries.

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Repair stages						
Partial production						