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CRITICAL INDUSTRY REPAIR ANALYSIS
PETROLEUM INDUSTRY

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OCTOBER 1965



ADVANCE RESEARCH, INC.

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1

SUMMARY

BACKGROUND

Because three-quarters of all energy consumed in the United States comes from petroleum fuels, the industry is essential, yet petroleum refining is vulnerable to nuclear attack, due to geographical concentration and to the highly combustible nature of its raw materials and products. The assessment of this vulnerability, and the development of an appropriate methodology for preattack damage estimation and postattack repair allocations in this industry is the chief purpose of Critical Industry Repair Analysis: Petroleum Industry.

The work on this report was begun under Contract OCD-OS-62-257 by the Office of Civil Defense, Department of the Army; the latter part of the work was completed under B-70916(4949A-33)-US, a subcontract from Stanford Research Institute, Menlo Park, California.

SCOPE

The heart of the petroleum industry is the refineries which transform crude oil into fuels, lubricants, waxes, and petrochemicals, and the major effort of this project has been directed at analysis of vulnerability and post-attack repair of refineries, during the survival period.

While many peripheral areas may merit investigation, it is nonetheless true that the oil fields and the pipelines, carriers, storage terminals, and retail distributors are far less vulnerable than the refineries. However, key inputs to the various plants are also examined. Crude oil production is not studied because of its wide dispersion; TEL is studied and production analyzed at a Dupont plant.

Three refineries are analyzed in detail, to assess their vulnerability and the probable damage from attack by megaton-range weapons. The post-attack repair times are based on these damage estimates.

A Baton Rouge refinery—the nation's largest—was selected because it underwent an emergency shutdown caused by electric power failure. A Whiting, Indiana refinery was chosen because of a major process unit explosion which caused widespread fire damage. A refinery in Pascagoula, Mississippi was studied because it has modern features, representing future trends, such as isocracking.

Costs and repair efforts are analyzed based on the damage sustained. Labor inputs are documented for a number of specific cases using a CPM technique; material requirements, repair equipment requirements, and various alternative possibilities were analyzed.

Considerations of the methodology of the damage estimates and repair led to construction of flow charts, showing generalized damage analysis methodology and a generalized repair chart.


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Some substitutes for gasoline are studied. The recommendation of techniques for hardening the weak links are left to the future.

CONCLUSIONS

Calculations indicate that any refinery within a 10-mile radius of a 1-MT weapon's ground zero, where the overpressure will be 1.5 psi or greater, will suffer heavy damage resulting in forced shutdown for several months. This high vulnerability is due to the cooling towers and controlhouse roofs, which are heavily damaged. With the exception of a crude still, a modern refinery cannot operate without the instruments in a controlhouse and repair of the controlhouse complex, in particular, is lengthy. Without cooling towers, it is impossible to operate a refinery.

A minimum of 163 weapons, properly placed, could severely damage all U.S. refineries, but one weapon can similarly affect 10 per cent of all refining capacity, three can seriously affect 25 per cent, and nine can account for 51 per cent. The industry is vulnerable on a national basis because of both the vulnerability of individual refineries and the geographical concentration, particularly in populous urban areas. Therefore, an attack on population centers would destroy much of the national refining capacity.

Distribution

Locations of the world's known crude oil reserves are: United States, 11 per cent; Middle East, 62 per cent; U.S.S.R. and bloc, 10 per cent; South America, 7 per cent; Africa, 4 per cent; and other, 6 per cent. United States consumption of petroleum products is divided between commercial-industrial users, 48 per cent; personal (autos, home fuel) 38 per cent; farm, 10 per cent; and military, 4 per cent. Most U.S. crude oil is transported by pipeline, although the east coast is entirely ship-supplied, while trucks and ships are leading transporters of refined products. The best substitute for gasoline is liquid petroleum gas (LPG) which can successfully run gasoline and diesel engines after a somewhat complicated engine conversion. While pipelines are not vulnerable, their pumping stations largely depend on electricity; electrical failure will shut down both the stations and refineries. The total amount of stored crude oil in the U.S. is only eight days' supply at current refinery consumption rates, not a meaningful postattack reserve.

Refinery vulnerability

The most vulnerable components of a refinery are the controlhouse and cooling towers, as noted above. Replacement of wooden cooling towers is relatively easy, but controlhouse repair is time-consuming. With the possible exception of the crude still, operation without automatic controlhouse instruments is impossible because refining is a highly complex, automated operation. Storage units can cause severe damage through spilled gases and liquids from blast-ruptured tanks flowing into the refining area, finding an ignition source, and burning. Empty cylindrical tanks fail by uplift at 1.5 psi; when full, at 6.5 psi. Spherical tanks are less vulnerable, failing by

overturning at 9.0 psi. Many tank areas are diked so as to retain contents of only the largest tank; if more than one tank ruptures, overflow will result. Tanks and contents are not of great importance in the refining operation, which does not depend as much on storage as on processing units.

Weak links

The refineries are the weak link of the industry. Controlhouses and cooling towers are the weak links of the refineries, because they are essential to operation and fail at very low overpressures. Another weak link is tetraethyl lead (TEL), which is necessary to get high octane gasoline in appreciable quantities, and there are only seven TEL plants in the United States.

Blast damage

The failure of the controlhouse roof and cooling towers due to blast are discussed above. Blast will overturn the pipe still at 7.5 psi, due to anchor bolt failure. The fractionator tower will fail for the same reason, at 7.0 psi. The two cat crackers analyzed will fail at 12 and 16 psi; and their regenerators will overturn at 7.0 and 16 psi respectively. Other points of collapse: deisobutanizer tower, 9.5 psi; furnace stacks, 6.0 psi; maintenance building, 6.0 psi; tower-supported flares, 3.0 psi. Collapse of high structures will cause great damage to equipment beneath and adjacent. These figures apply to a shut down refinery and most are irrelevant in the case of probable total destruction of an operating refinery by fires and detonations when pipes are broken and major units displaced at 5.0 psi.

The methodology for blast damage calculations involves the following assumptions: "table top" conditions, front-face orientation, equivalent triangular representation of the blast loading, bilinear resistance function, single-degree-of-freedom system and high-megaton-range weapons.

Fire damage

Fire due to thermonuclear attack is similar to a "normal" fire, except that fallout arrival may curb firefighting. Because they contain volatile combustibles, the greatest fire danger exists in the operating processing units. If the refinery is shut down and the units are emptied of all combustibles, then the maximum fire danger is transferred to the storage tanks. Gases in process that are heated above their autoignition temperatures will immediately ignite upon being released into the air; otherwise, an ignition source is needed and spilled stored fuels need not necessarily ignite, particularly if the refinery is shut down. However, blast-produced metal missiles can produce incendiary sparks upon striking other metal. Thermal radiation is an unlikely ignition source. Fire weakens critical steel such as tower supports beyond repair and, while water cannot extinguish petroleum fires, it can cool metal to prevent weakening. Other firefighting techniques include foam, air agitation, and emergency diking with sand. Firefighting strategy is generally to contain the fire and let it burn itself out.

Shutdown

As noted, shutdown can make the difference between a refinery totally destroyed at 5.0 psi and one still repairable after a 12.0 psi blast. A few minutes warning time can permit significant measures, while four hours permit a relatively normal shutdown with minimal damage. Proper preplanning and personnel training are essential. But shutdown is costly in terms of lost production. The report gives two case histories of emergency shutdowns, based on power failure and fire. In the former, shutdown was immediate and successful, with no warning time; in the latter, poor procedures may have contributed to major devastation.

Repair

The speed and effectiveness of postattack repair of refineries will depend on the level of damage, availability of construction equipment, replacement parts and materials, labor, blueprints, and salvageability of damaged equipment. Actual case histories of construction and repair projects at refineries are given, and the repair estimates are largely based on these data.

Critical path scheduling techniques provide a valuable tool for planning repair effort. The most critical components, from the standpoint of lead time are turbines and compressors, slide valves, pressure vessels, and heat exchangers.

The order in which processing units should be repaired will depend upon minimum postattack fuel requirements. A typical example might be: first, the crude oil still for straight run gasoline, jet, diesel, and furnace fuel; second, the catalytic cracker for high octane gasoline and light naphtha; then vapor recovery units for butane and propane; and lastly, the alkylation plant for high octane alkylate. Refineries should be rebuilt generally close to preattack design, to save months of additional repair time due to major redesign. Field fabrication, substitutions, and cannibalization will be advantageous. Because cone roof tanks are easier to repair than floating roof tanks, they might replace the latter for gasoline storage. Gin poles and cranes, possibly brought in from a neighboring refinery, will be needed for reconstruction of towers. Long-lead-time items include compressors, slide valves, pressure vessels, and heat exchangers.

A number of typical repair schedules are given, compiled from detailed damage calculations; they are scheduled by means of the critical path technique. Labor requirements are broken down into 12 basic categories. Typical repair times (assuming no labor shortages) range from 188 eight-hour calendar days for controlhouse damage at 1.5 psi, to a maximum of 277 days to repair a crude still damaged at 7.0 psi.

Techniques for scaling, applicable to lengths of postattack repair times, are briefly outlined. A conclusion involves an average scaling exponent of 0.75 as in the following formula:

$$\frac{\text{Labor time for postattack repair of A}}{\text{Labor time for postattack repair of B}} = \left[\frac{\text{Capacity A}}{\text{Capacity B}} \right]^{0.75}$$

This 0.75 exponent would apply to high damage levels and was determined by averaging exponents for individual processing and storage units. An exponent of 0.35 seems more appropriate at low damage levels.

RECOMMENDATIONS FOR FURTHER STUDY

Repair times in this study are based, out of necessity imposed by limitation of scope, on the assumptions that replacement parts, materials for repair, and trained operators and repair personnel are all available. There are no criteria as yet to indicate the probable postattack availability of these essential inputs to repair. In particular, repair charts should be prepared for those industries specializing in, and essential to, reconstruction of refineries.

A similar advantage could be obtained in updating prior studies on petroleum products distribution.

This petroleum study points out the dependence of many refineries on electricity from outside power plants. Conversely, many electric power generating plants depend upon petroleum products. In connection with the Critical Industry Repair series, of which this report is a part, it may prove beneficial to reexamine electric power. Critical Industries Repair Analysis: Electric Power, by Advance Research, used earlier techniques which have become somewhat outdated by advances in the state of the art in the more than three years since it was published.

The identification of the controlhouse and cooling tower as the refinery weak links is one of the most significant findings of this study. Because they fail at low overpressures, thereby destroying the automatic instrumentation and cooling capacity without which most of the refinery processing units cannot operate, they present an excellent opportunity for hardening. A controlhouse hardening study could use techniques employed in prior industrial hardening studies by this corporation.

Key essential chemical inputs to petroleum, including tetraethyl lead and chlorine, merit further study. Resonant periods of vibration of buildings deserve further investigation because of insufficient data, at present, to obtain precise results. Failure of concrete slabs, such as the administration building floor merit further investigation.

In connection with these projected studies, it is anticipated that the computer program for the analyses of structures subjected to blast loading will be improved and published.

ADVANCE RESEARCH, INC.

**CRITICAL INDUSTRY REPAIR ANALYSIS:
PETROLEUM INDUSTRY**

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ABSTRACT

The American petroleum industry is analyzed in terms of vulnerability to megaton-range weapon attack and of postattack repair, with particular emphasis on refineries, based on three operating refineries which were visited and studied in detail.

An appropriate methodology for damage analysis is developed. Results include the first application of CPM charts to the repair analysis, the generation of a generalized model for damage analysis, and the development of a preliminary repair model.

Significant findings: Two critical refinery elements are especially vulnerable to blast, controlhouse roofs at 1.5 psi, and cooling towers at 3.5 psi. Repair times are lengthy, with a minimum of 188 eight-hour calendar days for the controlhouse, and up to 277 days if a crude still collapses (at 7.0 psi). Shutdown is essential to avoid destruction of processing units by fire due to moderate blast overpressures, and rapid shutdown can be accomplished in less than 15 minutes with less damage than that which would result from a moderate blast striking an operating refinery.

Controlhouses are the weak links of the refineries, and the refineries are the weak links of the petroleum industry. Because of geographical concentration, one properly-placed weapon can seriously damage 10 per cent of U. S. refining capacity; three weapons, 25 per cent; and nine weapons, 51 per cent.

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October, 1965

CRITICAL INDUSTRY REPAIR ANALYSIS
PETROLEUM INDUSTRY
TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	
1. INTRODUCTION	1-1
1.1 Background	1-1
1.2 Scope	1-1
1.3 Approach	1-2
2. SUMMARY	2-1
2.1 National vulnerability evaluation	2-1
2.2 Distribution	2-1
2.3 Refinery vulnerability	2-2
2.3.1 Storage tank vulnerability	2-2
2.4 Blast damage	2-3
2.5 Fire damage	2-3
2.6 Shutdown	2-4
2.7 Repair	2-4
2.7.1 Repair procedures	2-5
2.7.2 Repair schedules	2-5
2.7.3 Generalized repair estimates	2-5
2.8 Conclusions	2-6
3. NUCLEAR ATTACK DAMAGE ANALYSIS	3-1
3.1 General refinery vulnerability	3-1
3.2 Hypothetical nuclear attack pattern	3-1
3.2.1 Methodology	3-3
3.2.2 Findings	3-3
3.3 Geographical locations	3-4
3.4 Crude oil reserves, sources, and classifications of products	3-13
3.5 Major users of petroleum products	3-18
3.6 Distribution of crude and refined products	3-19
3.7 Vulnerability	3-21
3.7.1 General	3-21
3.7.2 Blast damage to refinery process units	3-23
3.7.2.1 Controlhouses	3-23
3.7.2.2 Crude units	3-27
3.7.2.3 Fluid catalytic crackers	3-27
3.7.2.4 Light ends units	3-34
3.7.2.5 Water cooling tower	3-34
3.7.2.6 Furnaces	3-35
3.7.2.7 Miscellaneous structures	3-35
3.7.3 Blast damage to tetraethyl lead (TEL) building	3-40
3.7.4 Blast damage to storage facilities	3-40
3.7.4.1 Storage tanks	3-43
3.7.4.2 Study of the vulnerability of a tank farm	3-47
3.7.4.3 Bulk terminal	3-52
3.7.5 Texas City disaster	3-53

3.8	Fire damage	3-57
3.8.1	Physical and chemical aspects	3-58
3.8.2	Whiting experiences	3-62
3.8.3	Signal Hill experience	3-69
3.8.4	Firefighting methods	3-70
3.8.5	Fire conclusions	3-73
3.9	Fallout	3-74
3.10	Refinery shutdown and startup	3-74
3.10.1	General discussion	3-74
3.10.2	Normal shutdown and startup	3-75
3.10.3	Rapid shutdown	3-76
3.11	Precatack damage estimation method	3-81
3.12	Weak links	3-84
4.	POSTATTACK REPAIR	4-1
4.1	Refinery repair	4-1
4.1.1	General	4-1
4.1.2	Minimum postattack process requirements for balanced operation	4-4
4.1.3	Examples of balanced postattack operations	4-5
4.1.4	Repair procedures	4-8
4.1.5	Materials	4-9
4.1.6	Repair schedules	4-12
4.2	TEL plant repair	4-29
4.3	Storage tank repair	4-30
4.4	Generalization of repair estimates	4-30
5.	ESSENTIAL POSTATTACK FUELS, SUBSTITUTE FUELS AND ADDITIVES	5-1
5.1	Essential postattack fuels and their quality requirements	5-1
5.2	Essential raw materials	5-4
5.3	Antiknock additives	5-5
5.3.1	Applications	5-5
5.3.2	Antiknock additives production	5-6
5.4	LPG as a substitute fuel	5-7
6.	RECOMMENDATIONS FOR FUTURE STUDY	6-1
APPENDIX A Plant descriptions		
APPENDIX B Glossary and list of symbols		
APPENDIX C References		
APPENDIX D Effect of variations in overpressure duration on structural vulnerability		

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
3.1	Simplified Flow Diagram of Inputs and Outputs	3-2
3.2	Effects of Nuclear Weapons on Refineries, National Production Capacity Losses	3-10
3.3	Effects of Nuclear Weapons on Refineries The Ten most Destructive Weapons	3-11
3.4	Map of Refinery Vulnerability to Hypothetical Attack, The Ten most Destructive Weapons	3-12
3.5	Simplified Flow Plan Showing Locations of Major Units Analyzed	3-24
3.6	Controlhouse	3-28
3.7	Damage to Controlhouse at 1.5 psi	3-29
3.8	Crude Unit	3-30
3.9	Damage to Crude Unit at 6.0 psi	3-31
3.10	Fluid Catalytic Cracker	3-32
3.11	Damage to Catalytic Cracker at 7.0 psi	3-33
3.12	Light Ends Unit	3-36
3.13	Damage to Light Ends Unit at 4.0 psi	3-37
3.14	View of Pascagoula Refinery	3-48
3.15	The Fluid Hydroformer before the Explosion	3-66
3.16	The Fluid Hydroformer after the Explosion	3-67
3.17	Recovery from the 1955 Whiting Fire	3-68
3.18	Block Diagram of the Analysis of Structures Subject to Blast Loading	3-83
4.1	CPM Repair Chart - Controlhouse	4-20
4.2	CPM Repair Chart - Attendant Structure of Crude Still	4-21
4.3	CPM Repair Chart - 80,000 b/d Crude Still	4-22
4.4	CPM Repair Chart - 31,000 b/d Cat. Cracker	4-23
4.5	CPM Repair Chart - 20,000 b/d Cat. Cracker	4-24
4.6	CPM Repair Chart - Vapor Recovery Unit	4-25
4.7	CPM Repair Chart - 9-Cell Water Cooling Tower	4-26
4.8	CPM Repair Chart - Atmospheric Furnace of Crude Still	4-27
4.9	CPM Repair Chart - Floating Roof Storage Tank	4-28
4.10	Generalized CPM Repair Chart	4-34
5.1	Octane Envelope of LPG	5-9

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
3.1	Refinery Capacities Lost by 1 MT Weapons	3-5
3.2	Number of Refineries with over 10,000 B/CD Capacity and Total Capacity by Areas	3-14
3.3	Number and Capacity of Refineries, by States, January 1, 1964	3-15
3.4	Refineries with over 100,000 B/D Capacity, January 1, 1964	3-16
3.5	Crude Oil Production and Number of Producing Oil Wells, by States, 1962	3-17
3.6	Total Crude Oil and Refined Products Transported in U.S., by Method of Transportation, 1961	3-20
3.7	Summary of Blast Damage to Structures	3-25
3.8	Storage Capacity at Refineries, Gasoline Plants, Bulk Terminals and Tank Farms, by Refinery Districts, April 1, 1963.	3-42
3.9	Vulnerability of Tankage Areas to Flooding	3-50
3.10	Accumulated Tank Leakage	3-51
3.11	Parameters used in Blast Damage Analysis	3-55
3.12	Significant Temperatures associated with Fire Hazards in Straight Chain Hydrocarbons	3-60
3.13	Typical Operating Temperatures	3-63
3.14	Shutdown-Startup Data at Baytown Refinery	3-78
4.1	U.S. Refineries with over 100,000 B/D Capacity, by States	4-2
4.2	Summary of Repair Estimates	4-19

1. INTRODUCTION

1.1 Background

Approximately three-quarters of all energy currently consumed in the United States comes from petroleum, and its associated fuel, natural gas;⁵ this in itself, illustrates the essentiality of the industry in the pre-attack environment. In addition, petroleum refining is especially vulnerable to nuclear attack because of its geographical concentration, as well as its combustible materials. The assessment of this vulnerability, and of the postattack repair problems associated with it, is the purpose of Critical Industry Repair Analysis: Petroleum Industry. This is the fourth in a continuing series by Advance Research on problems of post-attack repair of United States industries. Its predecessors include the steel industry,¹ electric power,² and food.^{3*} This current study is a logical sequel to the food industry study, which demonstrated that while postattack food stocks appear adequate under most circumstances, the weak link could be transportation of food, in turn, directly dependent upon petroleum products.

The work on this report started under contract OCD-OS-62-257, by the Office of Civil Defense, Department of Defense, and is being completed under B-70916(4949A-33)-US, a subcontract from Stanford Research Institute, Menlo Park, California under contract OCD-PS-64-201.

1.2 Scope

The heart of the petroleum industry, both in the preattack context and particularly in terms of postattack repair, is the refineries, which transform crude oil into its many essential end products: fuels, lubricants, waxes, and petrochemicals. (See figure 3.1.) While many peripheral areas offer themselves as worthwhile areas of investigation, it is generally true that the original producers (the oil fields) and the distribution network (the pipelines, carriers, storage terminals, and retail distributors) are far less vulnerable than the refineries, which are relatively few in number and somewhat geographically concentrated. Therefore,

the major effort of this project is directed at vulnerability and postattack repair of refineries, as dictated both by their importance to the industry and by the necessarily limited scope of the investigation.

1.3 Approach

Accordingly, three refineries are examined and analyzed in detail, in order to estimate their vulnerability, and, based on this, the probable damage calculated to result from attack with megaton-range weapons. The postattack repair times and schedules are based on such damage estimates. It should be pointed out, however, that repair is obviously in part a function of priorities assigned on the basis of knowledge of essential oil refining processes, as well as on the extent of damage as a whole.

The three refineries are described in detail in appendix A: The 362,000 b/cd Baton Rouge (Louisiana) refinery of Humble Oil & Refining Company, the 207,000 b/cd Whiting (Indiana) refinery of American Oil Company, and the 100,000 b/cd Pascagoula (Mississippi) refinery of Standard Oil Company of Kentucky.

The Humble refinery is selected because of its size—it is the nation's largest—and because it has a wide range of processes and products. Of particular interest is an actual emergency shutdown caused by electric power failure, described in chapter 3. Whiting is chosen primarily because it underwent a major process unit explosion in 1955, which caused widespread fire damage due to secondary missiles. The Pascagoula refinery is designated because it is modern, completed in 1963. Modern features of particular importance, probably representing future trends, include the use of hydrocracking to provide unusual flexibility in the percentage yield of light or heavy refined products, flexibility in the overall throughput rate, the use of a highly automated in-line blending system, and innovations in cooling tower and air-cooled heat exchangers.

The obverse of essential processes is essential products, which were examined, and are discussed in some detail. Essential post-attack fuels are designated as diesel fuel; motor gasoline for automobiles,

trucks, and certain tractors; aviation gasoline or "avgas"; tractor fuel, a low octane gasoline; jet aircraft fuel, a kerosine derivative; and furnace fuel.

In addition to the refineries, and their essential processes and products, a tetraethyl lead (TEL) plant is analyzed, and the applications of TEL evaluated, since without it most of the gasoline produced would be either useless or damaging in today's high compression gasoline engines.

While these refineries are described individually in some detail in the appendix, it is felt to be neither desirable nor necessary to do so in the main body of the report; rather, their salient features are introduced where pertinent to the general topic, particularly in terms of significant processes, equipment, and actual histories of forced shutdowns, fires, explosions, and like phenomena which could be expected to result from nuclear attack as well as from "normal" preattack causes.

Four principal steps are involved in the investigative approach:

1. Analysis of processes and operations, to determine critical, essential processes and their vulnerability in general.
2. Evaluation of selected items of plant equipment and structures, to determine response and damage resulting from blast and thermal radiation at varying levels of intensity. Secondary effects, such as those caused by missiles and inadequate shutdown (which may cause greater damage than primary effects) are also estimated.
3. Estimates of repair and reconstruction efforts required to return damaged facilities to full operating condition, for various levels of blast overpressure. Methodology for the repair estimates involved the use of the Critical Path Method.
4. Analysis of qualitative fuel requirements, in the postattack situation, and means by which surviving

facilities can be returned to production in the shortest possible time. This includes the possible elimination of certain processes, the combining of facilities, and the interchangeability of equipment and crews, consistent with balanced refinery operations.

There are several important differences between the current study and prior studies, ^{8,9} of the effects of nuclear weapons on the petroleum industry, as follows:

1. A point-by-point analysis is made of specific units, and the weak links in the entire manufacturing process are identified.
2. Apart from higher yield, the effects of weapons in the megaton range, as compared to the kiloton range at the same range of overpressure, differ primarily in the former's much greater positive phase duration of blast pulse and the greater intensity and duration of the thermal radiation pulse. In the petroleum industry, this has a particular significance in the response of storage tanks and refinery towers and structures subject to blasts. In the kiloton range, the duration would be only about one-tenth that of the megaton range for the same overpressure. At this same overpressure, the equivalent static stress in a structure would be substantially greater in the megaton range because the ratio of pulse duration to natural period of the structure influences its ability of absorb suddenly-applied loads.
3. Because of the great fire hazard in the industry, the effects of actual fires and disasters on petroleum industry facilities are cited in some detail to arrive at estimates of fire damage resulting from nuclear attack.
4. Repair estimates, using CPM, are made for a range of damage levels corresponding to the findings of blast damage calculations.

The majority of the data in the report derives from three refinery visits. The results of an extensive review of existing literature and meetings with trade associations and Government agencies are likewise included.

2. SUMMARY

2.1 National vulnerability evaluation

The vulnerability of the United States' crude oil refining industry to a hypothetical attack pattern is evaluated on the basis of weapons of one megaton (1-MT), exploded at optimum burst height. Calculations indicate that any refinery within a 10-mile radius of ground zero, where the overpressure is 1.5 psi or greater, will suffer heavy damage resulting in forced shutdown for several months.

This high degree of vulnerability at a relatively low overpressure is due to the controlhouses, which would be heavily damaged in the 1.0 - 1.5 psi range. With the exception of the crude stills, the refineries cannot operate without them, and repair of controlhouses is lengthy.

The results of the analysis indicate that a minimum of 163 weapons, placed so as to avoid overlapping and to damage the controlhouses severely, are required to shut down all 288 refineries, but one weapon properly placed can disrupt 10 per cent of the total U.S. refining capacity, three can disrupt 25 per cent, and nine can account for 51 per cent. The industry, then, is quite vulnerable on a national basis, both because of the inherent vulnerability of individual refineries and because they tend to be concentrated geographically, particularly near populous urban areas. Therefore, an attack directed at population centers could automatically bring about the loss of a large portion of the national refining capacity and conversely, a refinery-oriented attack could entail large population losses.

2.2 Distribution

The principal locations of the world's known crude oil reserves are the United States, with 11 per cent of the supply; the Middle East, 62 per cent; the U.S.S.R. and bloc, 10 per cent; South America, 7 per cent; Africa, 4 per cent; and other, 6 per cent. United States consumption of petroleum products is divided between commercial-industrial users, 48 per cent; personal (autos, home fuel), 38 per cent; farm, 10 per cent; and military, 4 per cent. Most U.S. crude oil is transported by pipeline, although the east coast crude is entirely ship-supplied, with trucks and

ships the loading--and roughly equal--transporters of refined products. While pipelines are not particularly vulnerable, their pumping stations largely depend on electricity. Electrical failure will shut down both the stations and the refineries.

2.3 Refinery vulnerability

Estimates for both vulnerability and repair are based on calculations made in the course of visiting three operating U.S. refineries, that are described in some detail in appendix A. Refineries are the most vulnerable segment of the petroleum industry, and the most vulnerable components of refineries, as noted, are the controlhouses and cooling towers. Replacement of wooden cooling towers is relatively easy, but controlhouse repair is time-consuming. Operation without a controlhouse is virtually impossible because refining is a highly complex, automated operation. Both practicality and safety considerations preclude hand operation of most processing units such as catalytic crackers and ultraformers, although there is some possibility of the manual operation of a crude still.

2.3.1 Storage tank vulnerability

The significance of storage units lies in the damage caused by spilled combustible gases and liquids from blast-ruptured tanks which can flow into the refining area, find an ignition source, and burn. Many tank areas are diked so as to retain contents of only the largest tank; if more than one tank ruptures, overflow will result.

Empty cylindrical tanks fail by uplift at 1.5 psi; when full, at 6.5 psi. Spherical tanks are less vulnerable, failing by overturning at 9.0 psi.

Tanks and contents are not of great importance in the refining operation, which does not depend on storage. As a result (section 3.7.4.3), the total amount of stored crude oil in the U.S. represents approximately eight days' supply at current refinery consumption rates, not a meaningful postattack reserve.

2.4 Blast damage

The failure of the controlhouse roof due to blast is discussed above. Blast also overturns the pipestill at 7.5 psi, due to anchor bolt failure. The fractionator tower fails at 7.0 psi, for the same reason. The two cat crackers analyzed fail at 12 and 16 psi, and their regenerators overturn at 7.0 and 16 psi respectively. Miscellaneous points of collapse include the deisobutanizer tower at 9.5 psi, furnace stacks at 6.0 psi, maintenance building at 6.0 psi, and tower-supported flares at 3.0 psi. Collapse of high structures will cause great damage to equipment beneath and adjacent.

As mentioned previously, blast indirectly causes fire by rupturing tanks, breaking pipes, and generally promoting leakage of combustibles. It should be noted, therefore, that the above overpressure figures apply to a refinery which has been shut down; many are irrelevant in the case of an operating refinery whose heated, pressurized combustibles could bring about total destruction by fires and detonations when pipes are broken and major units displaced at 5.0 psi.

The methodology for blast damage calculations involves the following assumptions: "table top" conditions, front-face orientation, equivalent triangular representation of the blast loading, bilinear resistance function, single-degree-of-freedom system, and megaton-range weapons.

2.5 Fire damage

Fire due to thermonuclear attack is similar to a "normal" fire, except that fallout may curb firefighting. The extent of fire damage is governed by the amounts of fuel in process and stored, and by its volatility, which depends on the temperature and the degree of refinement. Because they contain volatile combustibles, the greatest fire danger exists in the operating processing units; if the refinery is shut down and the units are emptied of all combustibles, then the maximum fire danger is transferred to the storage tanks. Gases in process that are heated above their auto-ignition temperatures will immediately ignite upon being released into the air; otherwise, an ignition source is needed and spilled storage fuels need not necessarily ignite, particularly if the refinery is shut down.

Blast-produced metal missiles can produce incendiary sparks, however, upon striking other metal. Thermal radiation, preceding blast, is a negligible ignition source.

Fire consumes stored fuels, can cause explosions in vessels, and weakens critical steel such as tower supports beyond repair. While water cannot extinguish petroleum fires, it is useful in reducing metal temperatures to prevent weakening. Other techniques include foam, air agitation, and emergency diking with sand. Firefighting strategy is generally to contain the fire, and let it burn itself out.

2.6 Shutdown

Shutdown can make the difference between a refinery totally destroyed at 5.0 psi and one still repairable after a 12.0 psi blast. Even 15 minutes warning time can permit significant measures while 4 hours permit a relatively normal shutdown with minimum damage. Proper pre-planning and personnel training are essential.

The report gives two case histories of emergency shutdowns, based on power failure and fire respectively. In the former, shutdown was immediate and successful, with no warning time; in the latter, slipshod procedures are believed to have contributed to major devastation.

2.7 Repair

The speed and effectiveness of postattack repair of refineries depend on the level of damage, as well as the availability of construction equipment, replacement parts and materials, labor, blueprints, and salvageability of damaged equipment. Some actual case histories of construction and repair projects undertaken at refineries are given, and the repair estimates are largely based on these data.

Critical path scheduling techniques have been used to provide a valuable tool for planning repair effort. The most critical components, from the standpoint of lead time, are turbines and compressors, slide valves, pressure vessels, and heat exchangers. The availability of additional labor or employment of crash programs will not materially

affect the procurement phase, but can substantially shorten the reconstruction phase.

Those processing units most essential, and the order in which they should be repaired, will depend upon minimum postattack fuel requirements. A typical example might be: first, the crude oil still for straight run gasoline, jet, diesel, and furnace fuel; second, the catalytic cracker for high octane gasoline and light naphtha; then vapor recovery units for butane and propane; and lastly, the alkylation plant for high octane alkylate.

2.7.1 Repair procedures

Refineries should be rebuilt generally close to preattack design, to save months of additional repair time due to major redesigning. Field fabrication, substitutions, and cannibalization will be advantageous. Because cone roof tanks are easier to repair than floating roofs, they might replace the latter for gasoline storage. Gin poles and cranes, possibly brought in from a neighboring refinery, will be needed for reerection of towers. Long lead-time items include compressors, slide valves, pressure vessels, and heat exchangers.

2.7.2 Repair schedules

A number of typical repair schedules are given, compiled from detailed damage calculations; they are scheduled by means of the critical path method (CPM), a technique widely used by petroleum industry designing firms. Labor requirements are broken down into 12 basic categories. Typical repair times (assuming no labor shortages) range from 188 (eight hour) days for controlhouse damage at 1.5 psi, to a maximum of 277 calendar days to repair a crude still damaged at 7.0 psi.

2.7.3 Generalized repair estimates

Certain generalized conclusions are drawn, based on repair data. Techniques for scaling, applicable to lengths of postattack repair times, are briefly outlined. A conclusion involves an average scaling exponent of 0.75 as in the following formula:

$$\frac{\text{Labor time for Postattack Repair of A}}{\text{Labor time for Postattack Repair of B}} = \frac{\text{Capacity A}^{0.75}}{\text{Capacity B}}$$

This 0.75 exponent applies to high damage levels and is determined by averaging exponents for individual processing and storage units.

2.8 Conclusions

As has been shown, the petroleum industry is vulnerable on a national scale, because nine thermonuclear weapons can severely damage half of the U.S. refinery production for at least nine months, even assuming optimum availability of parts and labor.

The refineries are the weak link of the industry; controlhouses and cooling towers are the weak links of the refineries, because they are essential to operation and fail at very low overpressures. Other weak links are additives such as tetraethyl lead (TEL), and possibly chemical inputs, principally H_2SO_4 . The TEL is necessary to get high octane gasoline in appreciable quantities, and there are only seven TEL plants in the United States. The chemical industry supplying the H_2SO_4 may be vulnerable to attack, although this has not been ascertained as yet and is recommended for further study (see chapter 6).

Shutdown can be accomplished quite rapidly, with damage less than the cost of lost production. Shutdown is vital: typically, an operating refinery can be destroyed by a 5.0 psi blast but, if shut down, is still repairable after a 12 psi blast.

Blast is the most damaging of nuclear effects, even at moderate overpressures, because it directly affects weak but essential structures, and indirectly threatens the more rugged ones by creating conditions under which ruinous fires can break out. Fire in the storage areas, if contained by dikes, is far less serious than fire in the processing areas, because storage is not particularly essential to operation and because tanks are largely interchangeable and are more easily repaired than processing units. Thermal radiation does not appear to present any great hazard, although it could possibly serve as an ignition source for vapors emitting from storage tank vents.

Threshold of recovery operations, if gasoline is needed in quantity without major repair, require repair of controlhouse instrumentation, cooling towers, pipe stills, and cat crackers, in that order.

The best substitute for gasoline is liquid petroleum gas (LPG), which can successfully run gasoline and diesel engines after a somewhat complicated engine conversion.

3. NUCLEAR ATTACK DAMAGE ANALYSIS

3.1 General refinery vulnerability

It should be self-evident that the most vulnerable elements in many industries are the manufacturing plants themselves, for it is at the plants that the many lines of inputs—labor, raw materials, and utilities—come together, and it is out of the plants that the different products and many lines of distribution radiate. The point at which all of these inputs and outputs converge is, in effect, the industry's bottleneck. To the extent to which this bottleneck is vulnerable to attack—as refineries are—it is also a weak link. For these general reasons, the petroleum industry's manufacturing plants—the refineries—are also one of that industry's most vulnerable points. Figure 3.1 shows, in a greatly simplified manner, the pivotal nature of the refinery in terms of its principal inputs and outputs.

Refineries, in turn, have a weak link of their own, the controlhouses, described at the end of this chapter. Still another weak link in the industry is the manufacture of additives such as tetraethyl lead (TEL) and tetramethyl lead (TML), because there are only seven TEL plants in the United States, and their product is essential for production of adequate amounts of usable grades of gasoline, as described below in chapter 4.

3.2 Hypothetical nuclear attack pattern

Because petroleum production hinges on the industry's refineries, the following hypothetical thermonuclear attack is designed to be of optimum efficiency in destroying the United States' refining capacity through attacks on the 288 operating crude refineries.⁶ The pattern bears no relation to any other attack patterns, nor has any consideration been given to targets other than petroleum refineries in formulating this pattern. The attack pattern is entirely arbitrary, solely to illustrate the vulnerability of the refining industry.

Based on calculations, it is assumed for the purpose of this analysis that a blast incident overpressure of 1.5 psi or greater is sufficient to cause severe damage, resulting in the refineries being shut down for extended

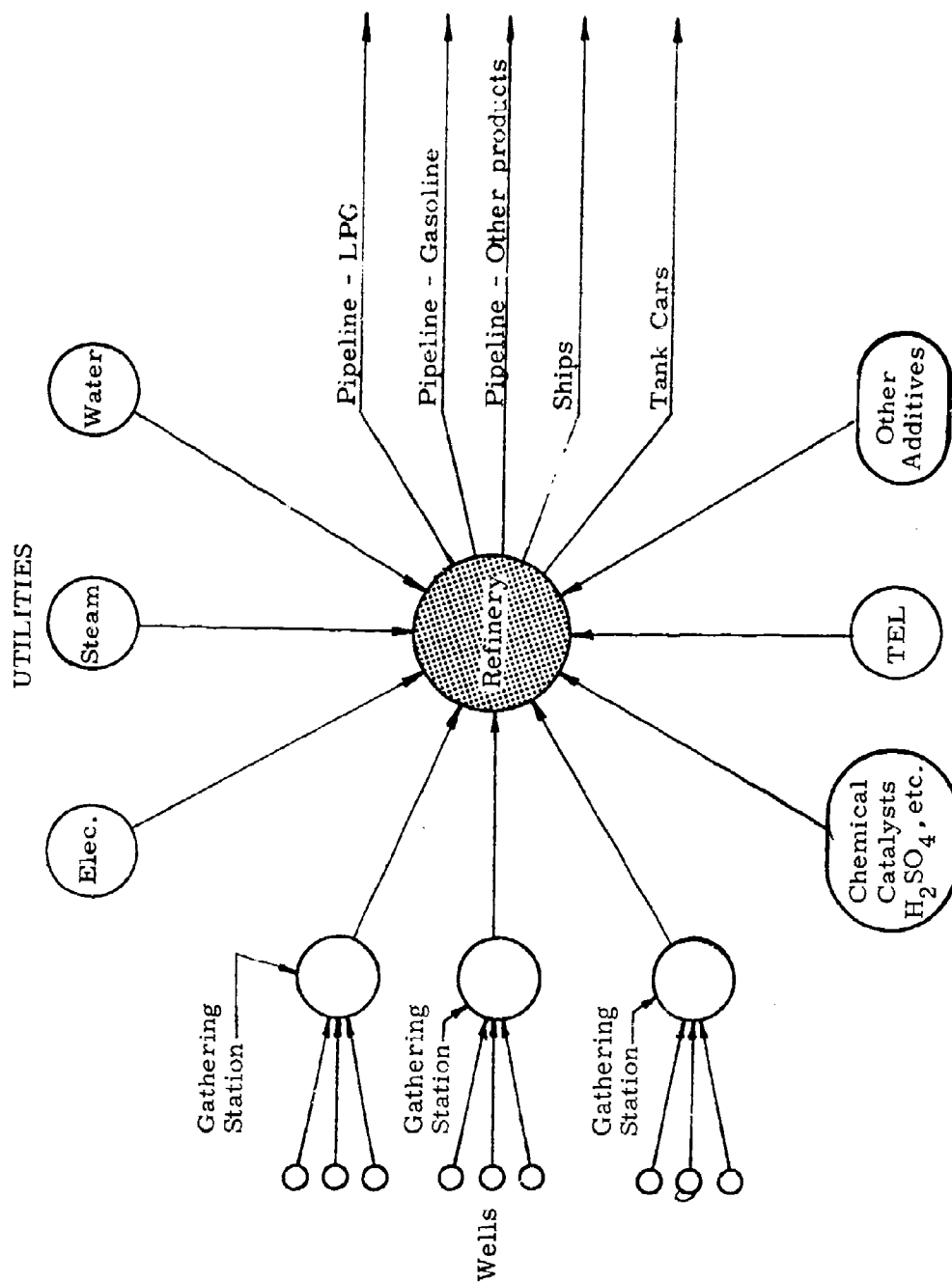


Figure 3.1 Simplified Flow Diagram of Inputs and Outputs

Source: Advance Research, Inc.

periods. The reason for this extensive damage at a relatively low blast overpressure is that the precast concrete controlhouse roofs will collapse, with consequent heavy damage to controls by secondary missiles, for which repair could require as many as from 150 to 200 eight-hour days. In the case of a steel deck with a built-up roofing, controlhouse collapse can come at an even lower overpressure, at from 1.0 to 1.5 psi. A weapon yield of 1 MT at optimum burst height is used in the hypothetical attack pattern because this gives a circle of about 10 miles radius within which the overpressure is 1.5 psi or greater. The overpressure duration makes little difference in this case (see appendix D).

3.2.1 Methodology

The geographic locations of the 288 operating refineries are plotted on a map of the United States, and circles with 10-mile radii are then drawn on the map, to include as much refining capacity as possible within each circle, without overlapping, until each of the refineries plotted is so enclosed. This results in 163 circles, containing from one to thirteen refineries each. The refining capacities within the circles naturally vary widely. The greatest capacity in any circle is in Port Arthur, Texas: 1,017,500 b/cd produced by six refineries. The smallest is 200 b/cd produced by one refinery in Lusk, Wyoming.

The groups or circles are listed in order of decreasing refining capacity in table 3.1, which likewise details the refining capacity that would be destroyed by each of 163 weapons of 1 MT each, on a weapon-by-weapon cumulative basis.

3.2.2 Findings

The petroleum refining capacity in the United States has only a few significant groups of closely spaced refineries, but these large concentrations must be considered because a few 1 MT weapons, carefully placed, will seriously damage or destroy a high percentage of the national refining capacity. To illustrate the vulnerability of these concentrations, one weapon placed strategically at Port Arthur, Texas, could seriously damage approximately 10 per cent of the industry's capacity. Three weapons carefully placed could seriously damage 25 per cent, and nine

weapons 51 per cent, of total capacity. Beyond this, however, the additional damage per weapon declines rapidly:

25 weapons seriously damage	74 % of capacity
50 weapons seriously damage	88 % of capacity
75 weapons seriously damage	94 % of capacity
100 weapons seriously damage	97 % of capacity
125 weapons seriously damage	99.1% of capacity
150 weapons seriously damage	99.8% of capacity
163 weapons seriously damage	100.0% of capacity

In fact, it requires over 40 weapons to seriously damage the final 1 per cent, as may be seen in table 3.1.

Two-thirds of the weapons account for the destruction of only a single refinery per weapon. These are generally, but not always, the smaller refineries in remote locations. A significant exception is the Baton Rouge refinery of Humble Oil & Refining Company, with 3.3 per cent of the U.S. capacity, and the only refinery destroyed by weapon number eight.

These results have been plotted in the graphs of figures 3.2 and 3.3, and illustrated in the map of figure 3.4. It is significant that a majority of the ten most destructive attacks occur in or near large cities and population centers, Los Angeles, San Francisco, Houston, St. Louis, Chicago, Philadelphia, and New York. This means that considerable damage to population, industry, and transportation would occur along with the destruction of these refineries located in these areas. Conversely, an attack directed in part or whole against population centers would in all probability result in the loss of a very high percentage of petroleum refining capacity.

3.3 Geographical locations

There are four areas with concentrations of refining capacity, California, Texas-Louisiana, Chicago-Midwest, and the Middle Atlantic States. Their combined capacity represents 69 per cent of the United States total capacity, and the Texas-Louisiana area alone accounts for 33 per cent of the national capacity, as shown in table 3.2. The large refineries--those of over 100,000 b/cd capacity--are identified by owner and location in table 4.1, in the discussion of repair in the following chapter. As noted earlier, this

Table 3.1

REFINERY CAPACITIES LOST BY 1 MT WEAPONS

<u>Weapon Order</u>	<u>Target Location</u>	<u>No. of Refineries</u>	<u>Refinery Capacity Losses b/cd</u>	<u>Total Accumu- lated Losses b/cd</u>	<u>Percent of National Capacity</u>
1	Texas, Port Arthur	6	1,017,500	1,017,500	10
2	California, Los Angeles	13	776,140	1,793,640	17.5
3	Pennsylvania, Philadelphia	6	752,000	2,545,640	25.0
4	Texas, Houston	7	733,250	3,278,890	32.2
5	Indiana, Whiting	7	477,700	3,756,590	36.7
6	California, San Francisco	4	428,000	4,184,590	41.0
7	New Jersey, Linden	6	397,550	4,582,140	45.0
8	Louisiana, Baton Rouge	1	365,000	4,947,140	48.3
9	Illinois, E. St. Louis	4	340,500	5,287,640	51.5
10	Texas, Texas City	3	254,350	5,541,990	54.0
11	Louisiana, Lake Charles	2	240,000	5,781,990	56.5
12	Texas, Corpus Christi	6	227,250	6,009,240	58.5
13	Ohio, Toledo	4	226,950	6,236,190	61.0
14	Delaware, Delaware City	1	140,000	6,376,190	62.1
15	Missouri, Kansas City	2	135,000	6,511,190	63.5
16	Oklahoma, Tulsa	2	126,000	6,637,190	65.0
17	Illinois, Robinson	2	125,800	6,762,990	66.0
18	Illinois, Lockport	2	125,000	6,887,990	67.0
19	Louisiana, Norco	1	116,000	7,003,990	68.3
20	Washington, Anacortes	2	113,500	7,117,490	69.5
21	Oklahoma, Ponca City	2	110,000	7,227,490	70.5
22	Utah, Salt Lake City	4	100,750	7,328,240	71.5
23	Mississippi, Pascagoula	1	100,000	7,428,240	72.5
24	Montana, Billings	3	95,500	7,523,740	73.5
25	Texas, Sweeny	1	95,000	7,618,740	74.3
26	California, Bakersfield	8	91,750	7,710,490	75.2
27	Texas, El Paso	2	91,000	7,801,490	76.0
28	Michigan, Detroit	4	88,880	7,890,370	77.0
29	Texas, Borger	1	85,000	7,975,370	77.8
30	Kansas, El Dorado	3	81,900	8,057,270	78.0
31	Minnesota, St. Paul	3	81,800	8,139,070	79.3
32	Arkansas, El Dorado	4	81,700	8,220,770	79.9
33	Kentucky, Catlettsburg	1	75,000	8,295,770	80.9

Table 3.1

REFINERY CAPACITIES LOST BY 1 MT WEAPONS

<u>Weapon Order</u>	<u>Target Location</u>	<u>No. of Refineries</u>	<u>Refinery Capacity Losses b/cd</u>	<u>Total Accumu- lated Losses b/cd</u>	<u>Percent of National Capacity</u>
34	Louisiana, Chalmette	2	70,000	8,365,770	81.3
35	Kansas, Wichita	2	66,500	8,432,270	82.0
36	New York, Buffalo	2	61,900	8,494,170	82.8
37	Wyoming, Casper	3	61,300	8,555,470	83.3
38	Ohio, Cleveland	1	56,000	8,611,470	83.8
39	Ohio, Cincinnati	2	51,500	8,662,970	84.2
40	Ohio, Lima	1	48,000	8,710,970	84.8
41	Illinois, Pana	1	47,000	8,757,970	85.3
42	Oklahoma, Duncan	1	44,000	8,801,970	85.8
43	North Dakota, Mandan	1	42,500	8,844,470	86.2
44	Washington, Ferndale	1	39,000	8,883,470	86.5
45	Colorado, Denver	4	38,200	8,921,670	86.3
46	Virginia, Yorktown	1	38,000	8,959,670	87.2
47	Hawaii, Honolulu	1	35,000	8,994,670	88.0
48	Ohio, Canton	1	34,000	9,028,670	88.8
49	Kansas, Chanute	2	33,450	9,062,120	88.2
50	Oklahoma, Enid	1	31,680	9,093,800	88.4
51	Kansas, McPherson	1	31,000	9,124,800	88.7
52	Texas, Big Spring	1	29,600	9,154,400	89.2
53	Maryland, Baltimore	3	28,900	9,183,300	89.4
54	Michigan, Alma	3	27,750	9,211,050	89.6
55	Texas, Sunray	1	27,500	9,238,500	89.9
56	California, Santa Maria	2	26,000	9,264,550	90.2
57	Kansas, Arkansas City	1	25,000	9,289,550	90.4
58	Kansas, Coffeyville	1	24,500	9,314,050	90.6
59	Wyoming, Sinclair	1	24,000	9,338,050	90.8
60	Ohio, Newark	1	24,000	9,362,050	91.0
61	Oklahoma, Wynnewood	1	24,000	9,386,050	91.3
62	Texas, Tyler	1	24,000	9,410,050	91.5
63	Oklahoma, Admore	1	23,750	9,433,800	91.8
64	Michigan, Muskegon	2	23,300	9,457,100	92.0
65	Indiana, Rock Island	1	22,000	9,479,100	92.3
66	Michigan, Bay City	1	22,000	9,501,100	92.5

Table 3.1 REFINERY CAPACITIES LOST BY 1 MT WEAPONS

<u>Weapon Order</u>	<u>Target Location</u>	<u>No. of Refineries</u>	<u>Refinery Capacity Losses b/cd</u>	<u>Total Accumu- lated Losses b/cd</u>	<u>Percent of National Capacity</u>
67	Texas, Odessa	1	21,500	9,522,600	92.8
68	Oklahoma, Cushing	2	20,640	9,543,240	93.0
69	Pennsylvania, Warren	2	20,600	9,563,840	93.2
70	Wyoming, Cheyenne	1	20,500	9,584,340	93.4
71	Tennessee, Memphis	1	20,300	9,604,640	93.6
72	Alaska, Nikiski	1	20,000	9,624,640	93.8
73	Wisconsin, Superior	1	20,000	9,644,640	94.0
74	Louisiana, Shreveport	2	19,400	9,664,040	94.2
75	Kentucky, Louisville	1	19,000	9,683,040	94.4
76	Texas, Mt. Pleasant	1	19,000	9,702,040	94.5
77	Texas, Amarillo	1	19,000	9,721,040	94.7
78	Oklahoma, Okmulgee	1	19,000	9,740,040	94.9
79	Mississippi, Purvis	1	18,600	9,758,640	95.0
80	Minnesota, Wrenshall	1	16,000	9,774,640	95.2
81	New Mexico, Artesia	1	15,500	9,790,140	95.3
82	Ohio, Findlay	1	15,000	9,805,140	95.7
83	Rhode Island, Providence	2	14,500	9,819,640	95.9
84	Pennsylvania, Franklin	3	13,950	9,833,590	96.0
85	Kansas, Phillipsburg	1	13,000	9,846,590	96.2
86	Washington, Tacoma	1	12,500	9,859,090	96.3
87	Texas, Colorado City	1	12,500	9,871,590	96.4
88	Indiana, Mt. Vernon	1	12,200	9,883,790	96.5
89	Oklahoma, Cyril	1	12,000	9,895,790	96.6
90	Alabama, Tuscaloosa	2	10,770	9,906,560	96.8
91	New Mexico, Ciniza	1	10,700	9,917,260	96.9
92	Texas, Ft. Worth	2	10,500	9,927,760	
93	Massachusetts, Everett	1	10,000	9,937,760	97.0
94	California, Hanford	1	10,000	9,947,760	97.1
95	California, Oxnard	3	9,625	9,957,385	97.2
96	Texas, Wichita Falls	1	9,500	9,966,885	97.3
97	Texas, Pettus	1	9,500	9,976,385	97.4
98	Wyoming, Cody	1	8,500	9,984,885	97.5

Table 3.1

REFINERY CAPACITIES LOST BY 1 MT WEAPONS

<u>Weapon Order</u>	<u>Target Location</u>	<u>No. of Refineries</u>	<u>Refinery Capacity Losses b/cd</u>	<u>Total Accumu- lated Losses b/cd</u>	<u>Percent of National Capacity</u>
99	Texas, San Antonio	3	8,125	9,993,010	
100	South Carolina, Charleston	1	8,000	10,001,010	97.6
101	Texas, Winnie	1	7,600	10,008,610	97.7
102	Wyoming, Newcastle	1	7,500	10,016,110	
103	Montana, Cut Bank	3	7,200	10,023,310	97.8
104	Washington, Richmond Beach	2	7,200	10,030,510	97.9
105	Georgia, Savannah	1	6,600	10,037,110	98.0
106	Oregon, Portland	1	6,400	10,043,510	
107	Michigan, Carson City	1	6,200	10,049,710	98.1
108	Alabama, Mobile	1	6,000	10,055,710	
109	Mississippi, Sandersville	1	5,800	10,061,510	98.2
110	Texas, Abilene	2	5,730	10,067,240	98.3
111	Kansas, Shallow Water	1	5,700	10,072,940	
112	Pennsylvania, Freedom	1	5,500	10,078,440	98.4
113	Illinois, Pana	1	5,000	10,083,440	98.5
114	Michigan, West Branch	1	5,000	10,088,440	
115	Wyoming, Thermopolis	1	5,000	10,093,440	98.6
116	Texas, Edinburg	3	4,855	10,098,295	
117	Louisiana, Cotton Valley	1	4,750	10,103,045	98.7
118	California, Huntington Beach	1	4,750	10,107,795	
119	Wisconsin, Sheboygan	1	4,700	10,112,495	98.8
120	Montana, Great Falls	1	4,500	10,116,995	98.9
121	Indiana, Laketon	1	4,500	10,121,495	
122	Indiana, Princeton	1	4,500	10,125,995	99.0
123	Michigan, Kalamazoo	1	4,275	10,130,270	
124	West Virginia, Falling Rock	1	4,200	10,134,470	99.1
125	Pennsylvania, Farmers Valley	1	4,000	10,138,470	
126	Oklahoma, Stroud	1	4,000	10,142,470	99.2
127	Pennsylvania, Farm City	2	3,890	10,146,360	
128	Delaware, Claymont	1	3,500	10,149,860	99.3
129	Texas, Brownsville	1	3,400	10,153,260	
130	Texas, Longview	1	3,400	10,156,660	

Table 3.1 REFINERY CAPACITIES LOST BY 1 MT WEAPONS

<u>Weapon Order</u>	<u>Target Location</u>	<u>No. of Refineries</u>	<u>Refinery Capacity Losses b/cd</u>	<u>Total Accumu- lated Losses b/cd</u>	<u>Percent of National Capacity</u>
131	California, Newhall	1	3,400	10,160,060	
132	Arkansas, Waterloo	2	3,300	10,163,360	99.4
133	New Mexico, Bloomfield	2	3,150	10,166,510	
134	Florida, St. Marks	1	2,950	10,169,460	
135	Indiana, Ft. Wayne	1	2,850	10,172,310	
136	Montana, Wolf Point	1	2,850	10,175,160	99.5
137	Nebraska, Scotts Bluff	1	2,800	10,177,960	
138	West Virginia, St. Marys	1	2,650	10,180,610	
139	Texas, Carrizo Springs	1	2,500	10,183,110	99.6
140	Mississippi, Yazoo City	1	2,500	10,185,610	
141	Michigan, Reed City	1	2,500	10,188,110	
142	North Dakota, Williston	1	2,400	10,190,510	
143	Louisiana, Jennings	1	2,375	10,192,885	99.7
144	Alabama, Cordova	1	2,200	10,195,085	
145	Illinois, Colmar	2	2,200	10,197,285	
146	Georgia, Douglasville	1	2,000	10,199,285	
147	Alabama, Moundville	1	2,000	10,201,285	
148	Texas, Bryson	1	2,000	10,203,285	
149	Texas, Waskom	1	2,000	10,205,285	
150	Texas, Gainesville	1	1,900	10,207,185	99.8
151	Louisiana, Church Point	1	1,700	10,208,885	
152	New Mexico, Monument	1	1,675	10,210,560	
153	Colorado, Rangely	1	1,500	10,212,060	
154	Texas, Three Rivers	1	1,500	10,213,560	
155	Kentucky, Somerset	1	1,425	10,214,985	99.9
156	Indiana, Troy	1	1,425	10,216,410	
157	Louisiana, Ida	2	1,400	10,217,810	
158	Texas, Tucker	1	1,000	10,218,810	
159	Montana, Kalispell	1	1,000	10,219,810	
160	Montana, Chinook	1	1,000	10,220,810	
161	Montana, Mosby	1	1,000	10,221,810	
162	Colorado, Alamosa	1	715	10,222,525	
163	Wyoming, Lusk	1	200	10,222,725	100%

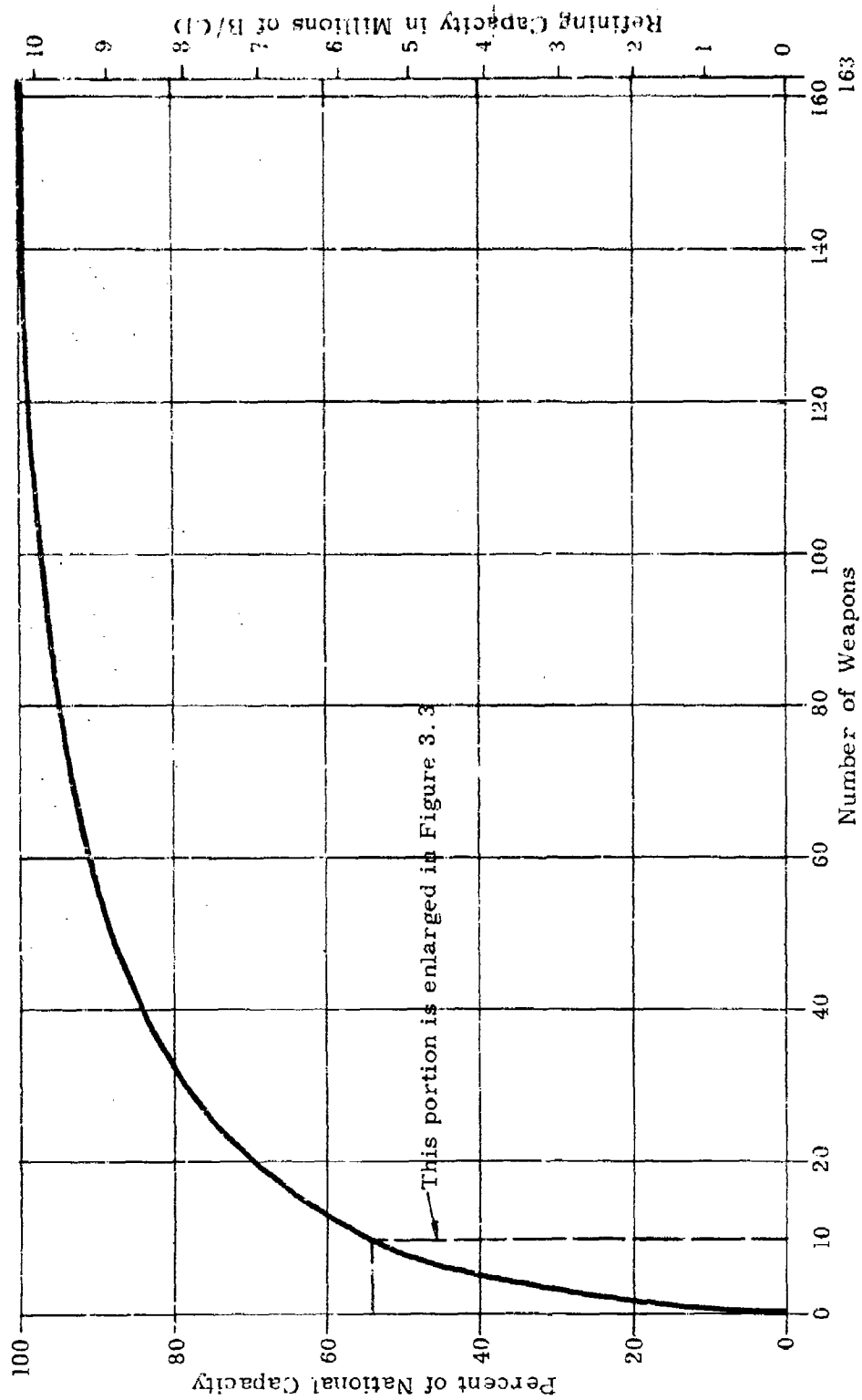


Figure 3.2 Effects of Nuclear Weapons on Refineries
National Production Capacity Losses

Source: Advance Research, Inc.

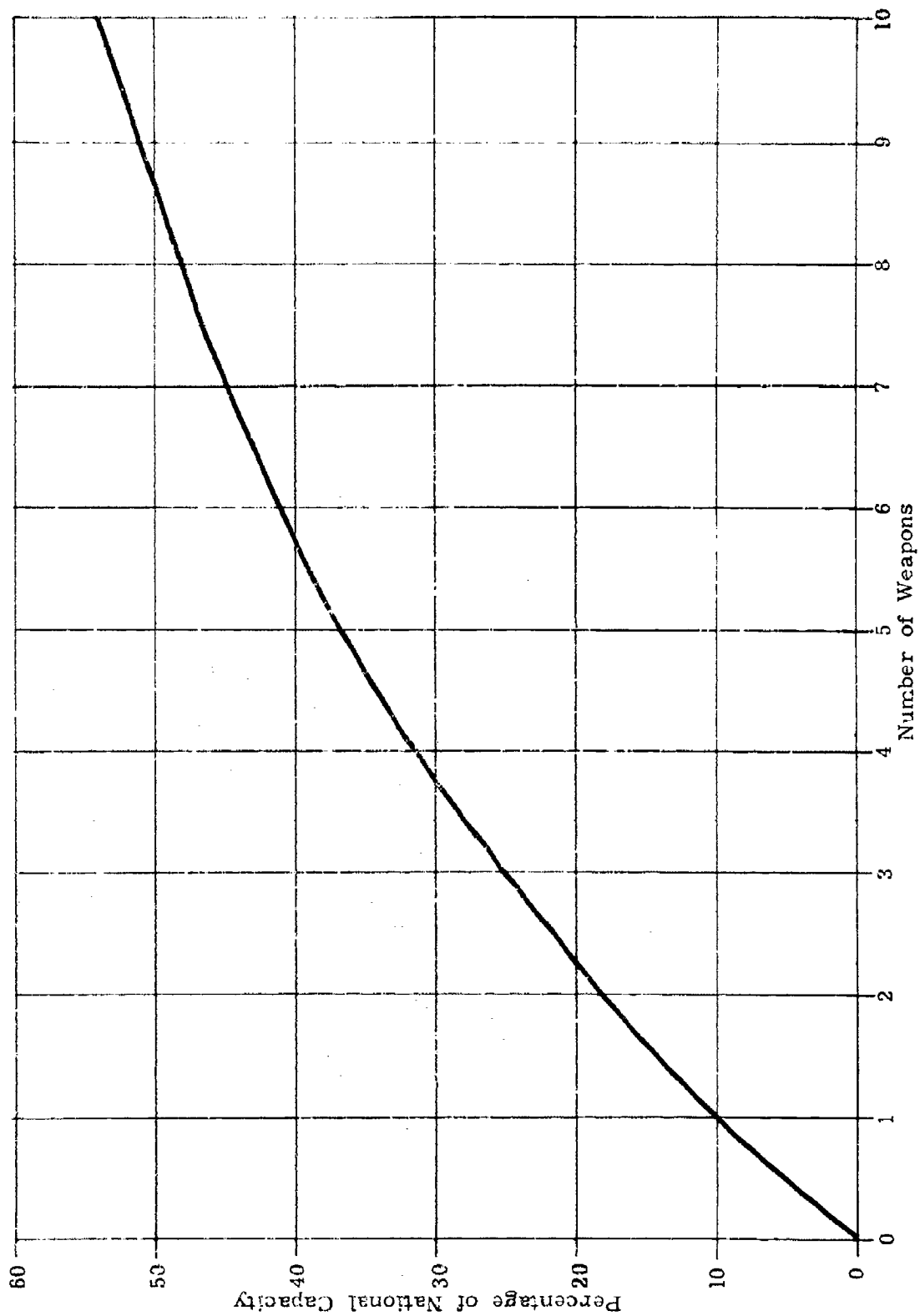
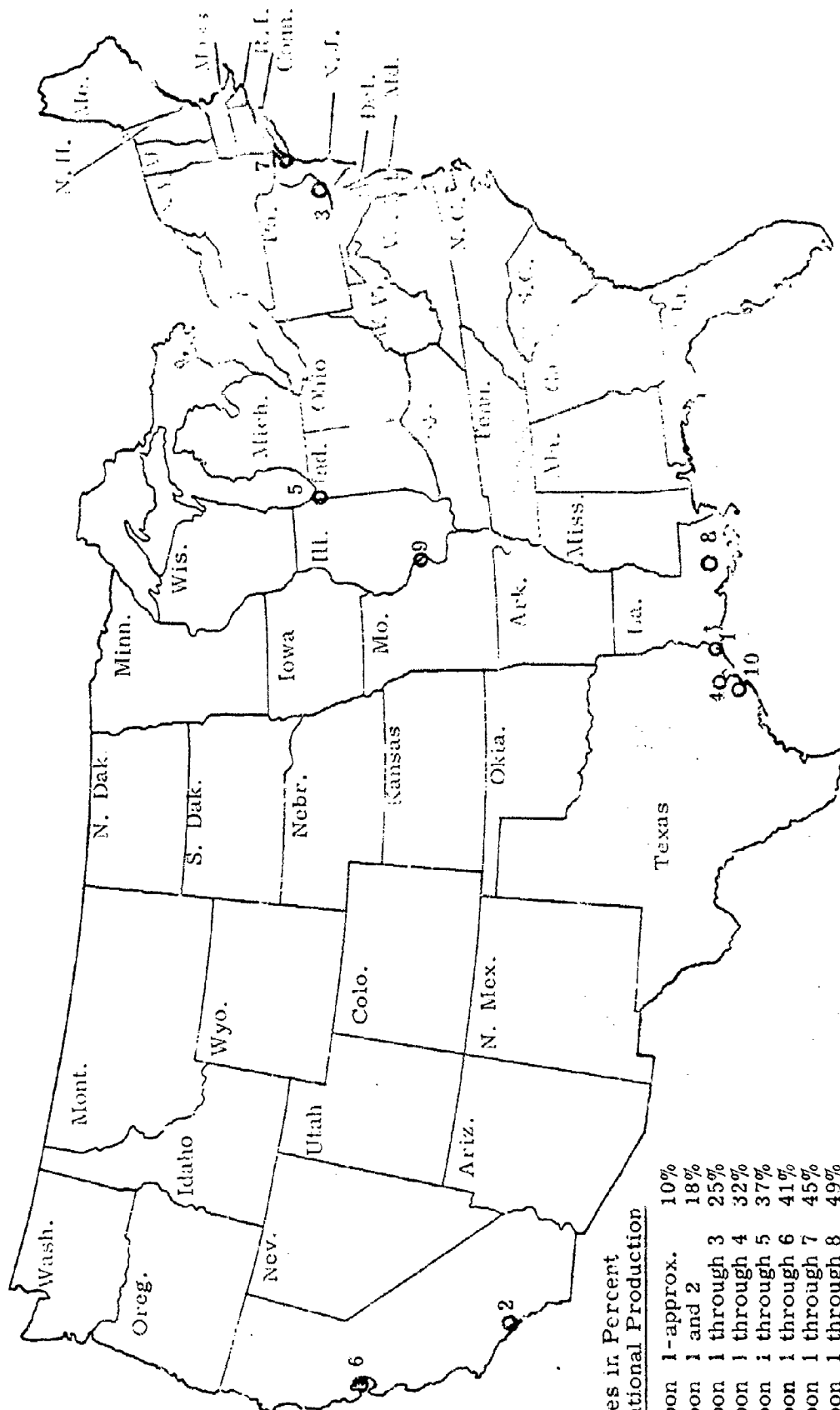


Figure 3.3 Effects of Nuclear Weapons on Refineries
The Ten Most Destructive Weapons

Source: Advance Research, Inc.



MAP OF REFINERY VULNERABILITY TO HYPOTHETICAL ATTACK
THE 10 MOST DESTRUCTIVE WEAPONS

Figure 3.4

Source: Advance Research, Inc.

tendency toward geographical concentration not only accentuates vulnerability, but also assumes even more serious proportions because the big refineries are usually found in or near large population targets. Because of the economy of water transportation, refineries are usually located on the coasts, Great Lakes, and rivers, which raises the possibility of vulnerability of coastal installations to tsunamis. Table 3.3 gives the numbers of refineries, and their capacities by states, and table 3.4 lists the refining companies with capacities exceeding 100,000 b/d.

Oil fields are reasonably dispersed and not particularly vulnerable. Newer wells are under pressure, and blowout could result from attack, causing extensive local damage and fire, but having little effect on the overall supply. There are almost 600,000 producing oil wells scattered throughout 31 of the states, as shown in table 3.5.

Although offshore drilling activity has been increasing in recent years, and its share of the total at present is still relatively small, it does indicate a trend, and in years to come this may very well be the major source of crude oil. In 1962, California's offshore wells produced only 6 per cent of that state's total of 296.6 million barrels.¹² In Louisiana, however, offshore production is 18 per cent of the total,¹¹ and the proposed construction of the Red Snapper pipeline in the Louisiana offshore field by 1967, can be expected to boost this still further. As of June, 1964, there were 90 wells capable of producing in offshore Louisiana, though many of these were "shut in" (capped).¹³

3.4 Crude oil reserves, sources, and classifications of products

With the possible exception of some experimental processing of coal into gasoline by the U. S. Bureau of Mines,¹⁴ petroleum products are all derived from gas and crude oil. The estimated world crude oil reserves in 1962 were as follows:¹⁵

U. S. A.	11%
Middle East	62%
U. S. S. R. and Satellites	10%
South America	7%
Africa	4%
Other	6%

Table 3.2

NUMBER OF REFINERIES WITH OVER 10,000 B/CD CAPACITY
AND TOTAL CAPACITY BY AREAS ⁶

Area	Number of refineries	Total crude capacity	Percentage of U. S. total
California	19	1,272,265	12%
Texas-Louisiana	38	2,644,950	33%
Chicago-Midwest	15	1,093,800	11%
Middle Atlantic	15	1,295,250	13%
Other Areas			<u>31%</u>
Total			100%

Table 2.3

NUMBER AND CAPACITY OF REFINERIES, BY STATES, JANUARY 1, 1964⁶

States	No. of refineries	Crude capacity b/cd
Alabama	5	20,970
Alaska	1	20,000
Arkansas	6	85,000
California	33	1,349,665
Colorado	6	40,415
Delaware	2	143,500
Florida	1	2,950
Georgia	2	8,600
Hawaii	1	35,000
Illinois	13	634,000
Indiana	12	489,775
Kansas	13	351,050
Kentucky	3	95,425
Louisiana	14	820,625
Maryland	3	28,900
Massachusetts	1	10,000
Michigan	14	179,905
Minnesota	4	97,800
Mississippi	4	126,900
Missouri	1	65,000
Montana	11	113,050
Nebraska	1	2,800
New Jersey	7	529,250
New Mexico	5	31,025
New York	3	89,200
North Dakota	2	44,900
Ohio	11	455,450
Oklahoma	13	415,070
Oregon	1	6,400
Pennsylvania	13	640,940
Rhode Island	2	14,500
South Carolina	1	8,000
Tennessee	1	20,300
Texas	54	2,730,210
Utah	4	100,750
Virginia	1	38,000
Washington	6	172,200
West Virginia	2	6,850
Wisconsin	2	24,700
Wyoming	9	127,000
Total	288	10,176,075

Table 3.4

REFINERS WITH OVER 100,000 B/D CAPACITY, JANUARY 1, 1964⁶

Refineries	Number
1. Humble	8
2. Texaco	13
3. Standard (Calif.)	14
4. American	12
5. Mobil	12
6. Shell	6
7. Gulf	6
8. Sinclair	5
9. Cities Service	4
10. Phillips	6
11. Tidewater	2
12. Continental	9
13. Sun	2
14. Atlantic	2
15. Pure	4
16. Union	6
17. Sunray	3
18. Ashland	6
19. Richfield	1
20. Standard of Ohio	3
21. Marathon	4
22. Hess	<u>2</u>
Total	130

Table 3.5
CRUDE OIL PRODUCTION AND
NUMBER OF PRODUCING OIL WELLS BY STATES, 1962 ¹²

State	Thousands of barrels	Number of Wells as of December 31
Alabama	7,493	449
Alaska	10,260	52
Arizona	43	4
Arkansas	27,585	5,918
California	296,572	39,265
Colorado	42,460	2,110
Florida	418	11
Illinois	77,325	30,174
Indiana	11,709	5,607
Kansas	112,076	46,750
Kentucky	18,122	19,448
Louisiana:		
Gulf Coast	-----	13,813
Northern	-----	12,569
Total	483,101	26,382
Michigan	17,117	4,282
Mississippi	54,471	2,560
Missouri	108	105
Montana	31,648	3,692
Nebraska	24,850	1,764
Nevada	137	4
New Mexico	108,708	16,102
New York	1,789	13,537
North Dakota	25,164	1,794
Ohio	3,066	16,867
Oklahoma	198,563	80,799
Pennsylvania	5,225	59,673
South Dakota	170	18
Tennessee	18	40
Texas:		
Gulf Coast	-----	19,491
East Texas	-----	19,424
West Texas	-----	65,236
Rest of State	-----	93,508
Total	936,508	197,659
Utah	30,964	852
Virginia	3	5
West Virginia	3,345	12,880
Wyoming	145,167	7,581
U.S. Total	2,676,185	596,385

The United States sources of crude, for 1962, were 2.7 billion barrels from domestic production, and 0.4 billion barrels imported.¹¹ Imports of foreign oil are limited by the import control program which became effective in March, 1959.

Crudes are generally classified either "sweet" or "sour", depending on hydrogen sulfide (H_2S) content. When dissolved H_2S content exceeds 0.95 cu. ft. per 100 gallons of oil, the oil is considered sour.¹⁹ The oils from West Texas, New Mexico, and some fields of Kansas, Wyoming, Arkansas, and the Middle East, are sour oils, but most of the crude runs to refineries in the United States are sweet. Sour oils generally present three problems.

- 1) Their corrosive action requires that refining equipment be constructed of special corrosion-resistant alloy steels. A refinery designed to handle only sweet crude would be seriously damaged by corrosion from a sour crude after about six months of operation.
- 2) The toxicity of H_2S makes its presence in the free state a hazard.
- 3) The presence of sulfur in gasolines greatly affects their lead susceptibility and therefore their ability to be raised in octane number by tetraethyl lead antiknock additives.

Sweetening treatments are widely used to convert and treat refined products to modify objectionable compounds and various other undesirable impurities. A "sour" refinery could handle a sweet crude without difficulty, but a "sweet" refinery would be susceptible to appreciable corrosion damage if required to process "sour" crude.

3.5 Major users of petroleum products

There are four major U.S. consuming sectors, or markets, for petroleum products: personal, commercial-industrial, agriculture, and government-military. Personal consumption, consisting chiefly of gasoline, motor lubes, and home fuel oil, accounts for about 38 per cent of United States consumption. The commercial-industrial area accounts for almost

one-half, 48 percent, and includes land, air, marine public transportation, public utilities, mining, and manufacturing. The farm market takes 10 percent, and the balance, 3.5 percent, goes to the government-military market.¹⁶ In the event of a postattack fuel shortage, it is a reasonable assumption that the personal market would be the first to have its consumption restricted. Postattack petroleum demand and restrictions of petroleum supplies are speculative questions at best, and depend upon specific scenarios, including attack patterns. For this reason, these questions presently lie beyond the scope of this study.

3.6 Distribution of crude and refined products

Crude oil within the U.S. is principally transported by pipelines, and trucks and ships are the leading carriers of refined products, as shown in table 3.6, which summarizes the relative importance of the various means of transportation. The trend toward pipelines received its impetus in the construction of the "Big Inch" and "Little Big Inch" lines, during World War II, as a countermeasure against U-boat attacks on tankers. Since then, pipeline use has increased rapidly; for example, in the 1951-61 decade, the capacity for products grew by 232 percent, and for crude oil, 51 percent.¹⁷

Crude oil pipelines run from oil producing areas to refineries, and the majority of U.S. refineries depend on them. Most of their pumps use diesel drives, whereas product lines generally use electric motor drives.

Other types of drives used are natural gas and gas turbine.¹⁷ In 1961, there were 3,588 pumping units in 1,169 crude pumping stations, of which 233 were standby. For product pumping stations, in 1961, there were 606 pumping stations with 1,519 pumping units, of which 91 were standby.¹⁷ Pumping stations are generally in rural areas not likely to be near targets. Their dependence on electricity, however, means that a power failure would interrupt the flow, and in addition, such a power failure would also shut down many refineries.²

Pipelines are not vulnerable because they are buried and well dispersed, although for many refineries cutting one or two key pipelines would cause shut-down. Tank trucks, tank cars, ships, and natural gas pipelines, if modified,

Table 3. 6

TOTAL CRUDE OIL AND REFINED PRODUCTS TRANSPORTED IN U. S.,
BY METHOD OF TRANSPORTATION, 1961¹²

Method of Transportation	Crude Oil		Refined Products	
	Thousand tons	Percent of total	Thousand tons	Percent of total
Pipelines	333,319	75.5	150,852	22.5
Water Carriers	78,297	17.5	244,400	37.0
Trucks	28,177	6.5	245,441	36.5
Railroads	2,027	0.5	27,937	4.0
Total	441,820	100	668,630	100

present alternate forms of transportation. River crossings are generally on river bottoms and are therefore not vulnerable. Of 742 crude pipeline river crossings, in 1961, only 70 were overhead, and of 813 product pipeline river crossings, only 54 were overhead.¹⁷

Interchangeability between product lines and crude lines is fairly easy to accomplish, providing the flow rate is not critical and something can be run through the crude line to clean it out when switching from crude to refined products. For example, after the war the "Little Big Inch" was converted to natural gas transmission, and still later was converted to a product line, in which capacity it currently serves between Baytown, Texas, and Lebanon, Ohio. Product lines can also be converted to natural gas pipelines if modifications are made. On the east coast, for instance, refineries receive their crude oil by ship, and if this were lost by damage to shipping or port facilities it might be necessary to convert a natural gas transmission line to crude service.

3.7 Vulnerability

3.7.1 General

The method of analyzing a structure subject to blast loading follows the procedure outlined in the "Professional Guide on Reducing the Vulnerability of Industrial Plants to the Effects of Nuclear Weapons", prepared by Advance Research for the Office of Civil Defense. The sequence of operations in the analysis by this method is given in figure 3.18 of section 3.11, and is described in detail in reference 69.

However, for those familiar with the state of the art, the basic methodology involves the following assumptions:

a) "Table Top" conditions

Topography is considered to be flat which gives ideal conditions consisting of a smooth, plane, rigid surface.

b) Front Face orientation

Structures and their components are analyzed for their most critical orientation to a blast without

regard to the orientation of other structures which may be in the immediate vicinity.

c) Equivalent Triangular representation

In order to use overpressure-time curves in computations of structural response to blast loading, triangular representations equivalent to the actual overpressure-time functions are used.

d) Bilinear Resistance function

The resistance function is assumed to have an ideal elasto-plastic relation, i. e., the resistance of the elements remains constant after the material reaches the yield point.

e) Single-Degree-of-Freedom system

A single-degree-of-freedom system is assumed wherein the period of the structure is calculated for its fundamental mode only. Higher resonant frequencies involving more complicated deflections and stress patterns are not considered.

f) Megaton-Range Weapons

A 20-MT weapon is assumed in the analyses. In the megaton range, damage is caused at lower incident overpressures than in the kiloton-range, because of the significantly longer duration of the positive phase. A discussion of the effect of overpressure duration is included in appendix D.

Using the above assumptions and the maximum static resistance of the structure or component, a dynamic load is determined. The level of the peak incident overpressure, measured at the ground surface under "table top" conditions, is found, with which this dynamic load is associated. This

analysis is repeated for various elements in a structure to determine what element fails first.

Table 3.11, at the end of section 3.7, summarizes the various parameters used, the blast analyses, and the resulting pressures for the various units investigated in this study.

3.7.2 Blast damage to refinery process units

At the end of each of the following damage summations is a unit number corresponding to the unit number in table 3.11. Blast damage calculations can be found in reference 69.

Figure 3.5 illustrates a simplified flow plan of a refinery showing the areas where the major units which were analyzed are located.

Table 3.7 summarizes in chart form the damage described below.

3.7.2.1 Controlhouses

The steel roof decking of the controlhouse for the FCC Unit will collapse at 1.0 psi in the switchgear room from a blast from any direction. The roof decking of the adjacent control room will collapse at 1.5 psi from a westerly blast, but will survive the same overpressure from the east because pressure will be relieved by the shattering of the glazed wall at the east end of the building (picture window). A blast from the north or south will start the roof at the west end of the control room collapsing until the pressure has been relieved by this partial roof collapse and the shattering of the glazed wall by side-on pressure. The concrete block walls will fail at 3.5 psi in both rooms (3.11-1a). Figures 3.6 and 3.7 show a controlhouse before and after a 1.5 psi blast.

The steel frame of the controlhouse for the pipe still will show deformation at 1.0 psi from blast striking the windward wall at the end of the frame. The precast concrete slabs will collapse in bending at 1.5 psi from a blast in any direction because of the small percentage of openings in any of the walls. The concrete block walls will fail at 3.5 or 4.0 psi, depending upon the direction of the blast. The steel frames will collapse in bending at 10 psi (3.11-1b).

TABLE 3.7 SUMMARY OF BLAST DAMAGE TO STRUCTURES

Over-pressures (psi)	CONTROL HOUSES			CRUDE UNITS			FLUID CATALYTIC CRACKING UNITS (FCCU)				
	Steel Roof Decking and No Frame	Precast Concrete Roof and Steel Frame	Steel Frame bet. Vessels	Atmos. / Vacuum Towers	Fractionator Tower	Regenerator Tower	Reactor Tower	Fractionator Tower			
	Windows shatter	Windows shatter		Rectangular (Conc. Frame)	Rectangular (Conc. Frame)	Rectangular (Conc. Frame)	Rectangular (Conc. Frame)	Rectangular (Conc. Frame)			
0.5	Windows shatter	Windows shatter									
1.0	Roof collapse (switchgear room)	Frame deformation									
1.5	Roof collapse (control room)	Roof collapse (all rooms)									
	West Blast Partial roof collapse (control room) North and South blast			Note: Atmospheric & Vacuum Towers	Note: Vacuum Towers only			Note: Reactor & Fractionator supported by same frame			
3.5	Conc. block walls fail	Conc. block walls fail	Conc. brackets fail causing frame collapse								
4.5											
5.0					Anchor bolts yielding						
5.5				Conc. frame cracking		Leeward columns buckle East or West blast		Anchor bolts yielding			
7.0				Conc. frame collapse	Conc. frame cracking	Overturns Easterly blast		Leeward coils buckle, East blast			
					Conc. frame collapse	Vessel & foundation overturn		Leeward coils buckle, West blast			
8.0						Overturns Westerly blast					
8.5								Concrete frame cracking			
10.0		Steel frame collapse				Conc. frame cracking					
12.0											
16.0								Steel frame overturns			
								Conc. frame collapse			
								Conc. frame collapse			

Source: Advance Research, Inc.

TABLE 2.7 SUMMARY OF HEAT DATA FOR STRUCTURES

OVER- PRESSURE (psi)	LIGHT TANK UNITS		FURNACE PIPE TALL		MAINTENANCE BUILDING	WATER TOWER	PLANTS		PISTON RINGS		NUMBER STAIN P.C.C. UNIT	TIL BUILDING	BICK TERRACE	STADIUM LANE	
	Domestic Federal and Large Post	Rectangular Steel Frame	Atmospheric	Vacuum			Tower Supported	Day	Steel frame	Concrete frame				Time Mon.	Spinning
0.3					Corrugated Aluminum Siding fails	Corrugated Aluminum Louvers fail									
1.5															
2.0															
3.0															
3.5															
4.0															
5.0															
6.0															
6.5															
7.0															
7.5															
8.0															
9.5															
10.0															
10.5															
11.0															
12.0															
20.0															

Source: Advance Research, Inc.

3.7.2.2 Crude units

The crude unit with a steel platform structure between the vessels will exhibit the collapse of this platform structure at an overpressure of 3.5 psi, due to the bond failure of the reinforcing steel in the concrete brackets which support the structure. Depending on the direction of the blast, this structure will fall on either the atmospheric or vacuum furnaces, and destroy them. Cracking of the rectangular concrete frames supporting the atmospheric and vacuum vessels will occur at 5.5 psi, with complete collapse of the frames in bending at 7.0 psi. Figures 3.8 and 3.9 show the effect of 6.5 psi (3.11-2a).

The other pipe still, which has the vacuum tower on an octagonal reinforced concrete frame and the fractionator on a concrete pedestal and footing, will show cracking of the concrete frame at 7.0 psi, accompanied by the yielding of the vessel's anchor bolts in tension. At 7.5 psi, these anchor bolts will fail in shear, which will cause the vessel to overturn and thereby increase the load of the leeward columns. The columns cannot take this load and bending stress, and the frame will also collapse at 7.5 psi. The anchor bolts of the fractionator tower will start yielding in tension at 4.5 psi, and the vessel, together with its foundation will overturn at 7.0 psi (3.11-2b).

3.7.2.3 Fluid catalytic crackers

The first unit described is the steel-supported cat cracker. The wind bracing at ground level of the reactor and fractionator supporting frame will fail in shear of the end welds at 3.5 psi, from an easterly or westerly blast. The outer columns will buckle at 7.0 or 7.5 psi, depending on direction of the blast, with the results as shown in figures 3.10 and 3.11. The entire structure with the reactor and fractionator vessels will overturn from the tensile failure of the anchor bolts on the windward side at 12 psi (3.11-3a).

The leeward columns for the regenerator vessel will exhibit buckling at 5.0 psi, from an easterly or westerly blast. The entire structure will overturn through anchor bolt failure in tension on the

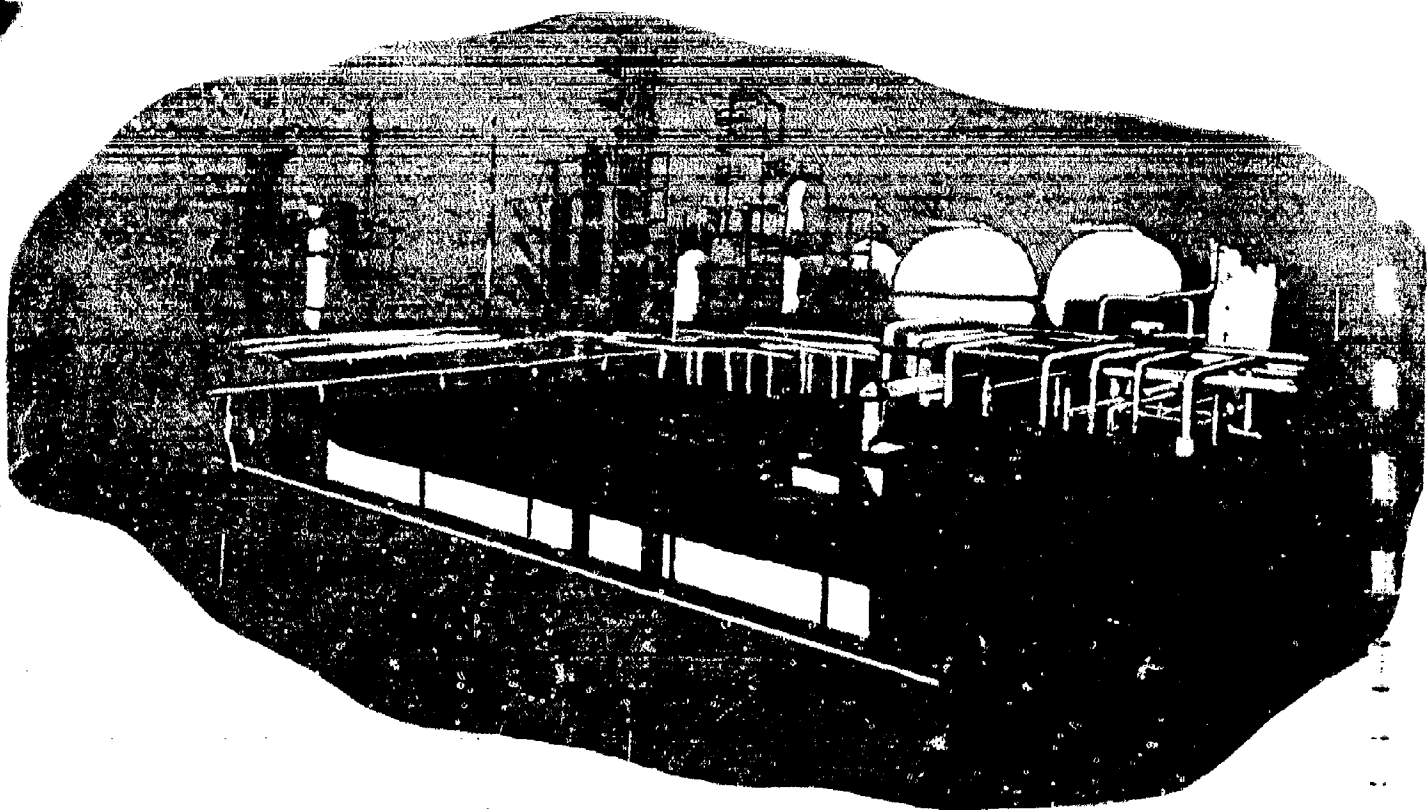


Figure 3.6 Controlhouse



Figure 3.7 Damage to Controlhouse at 1.5 psi

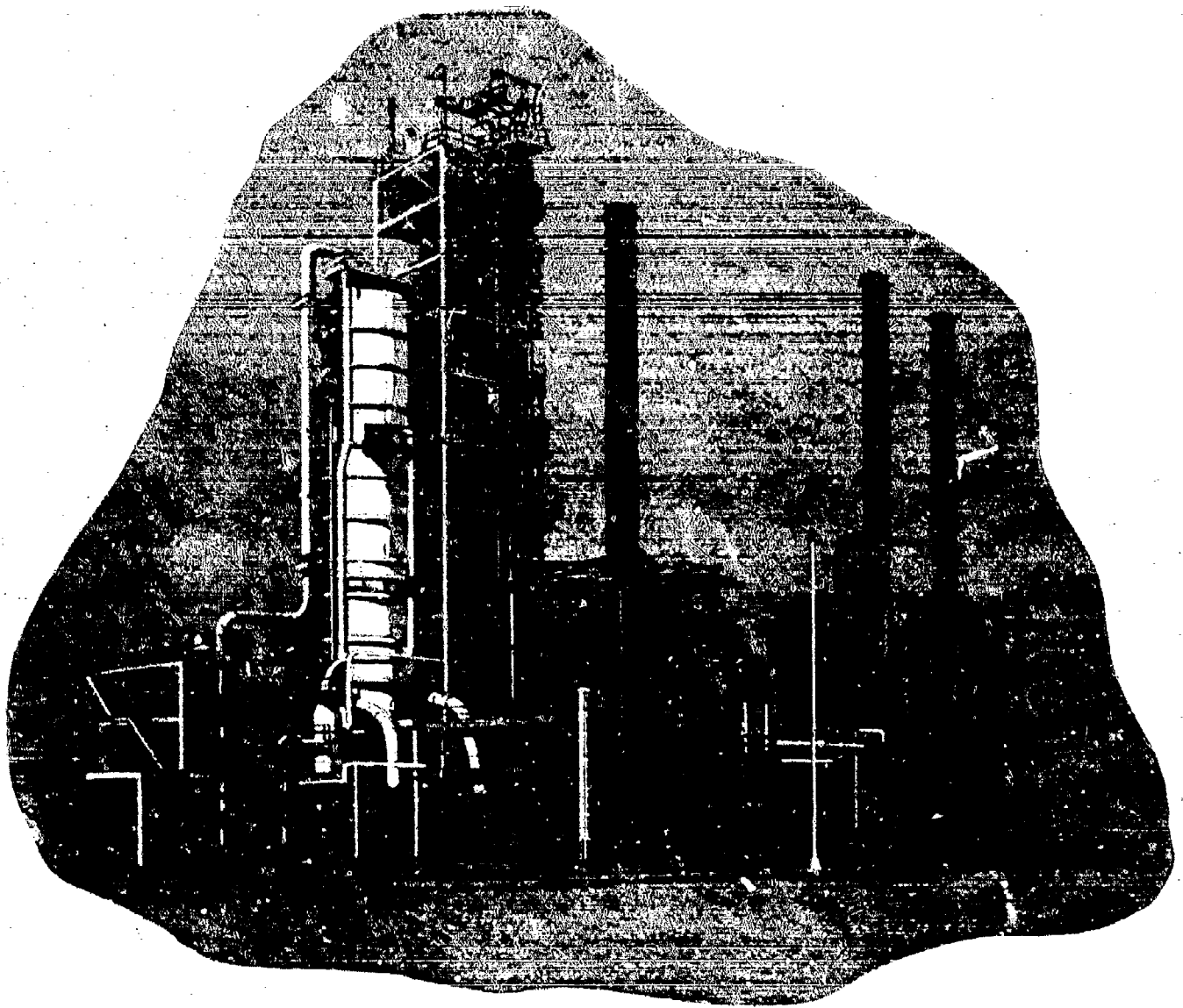


Figure 3.8 Crude Unit

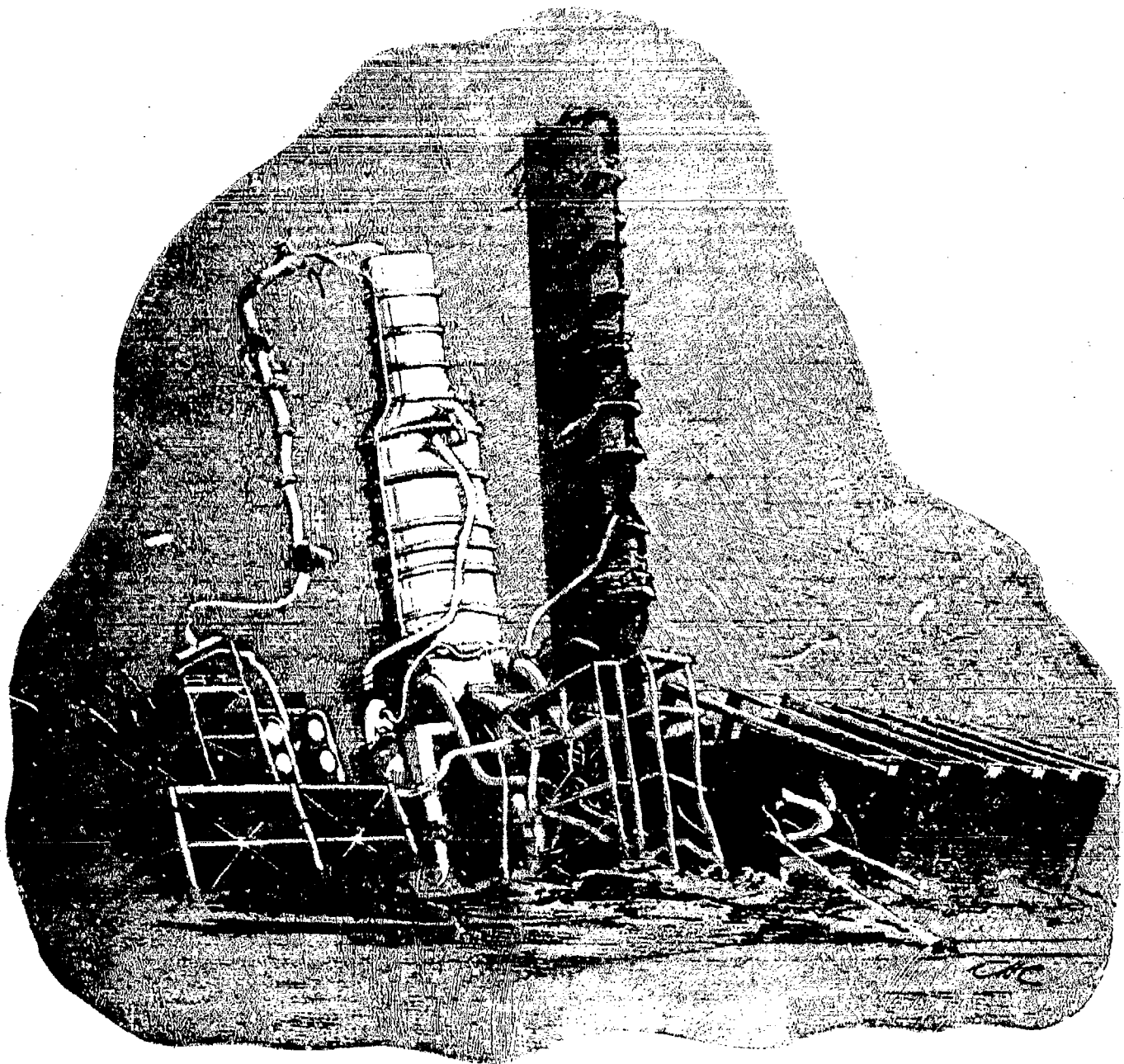


Figure 3.9 Damage to Crude Unit at 6.5 psi

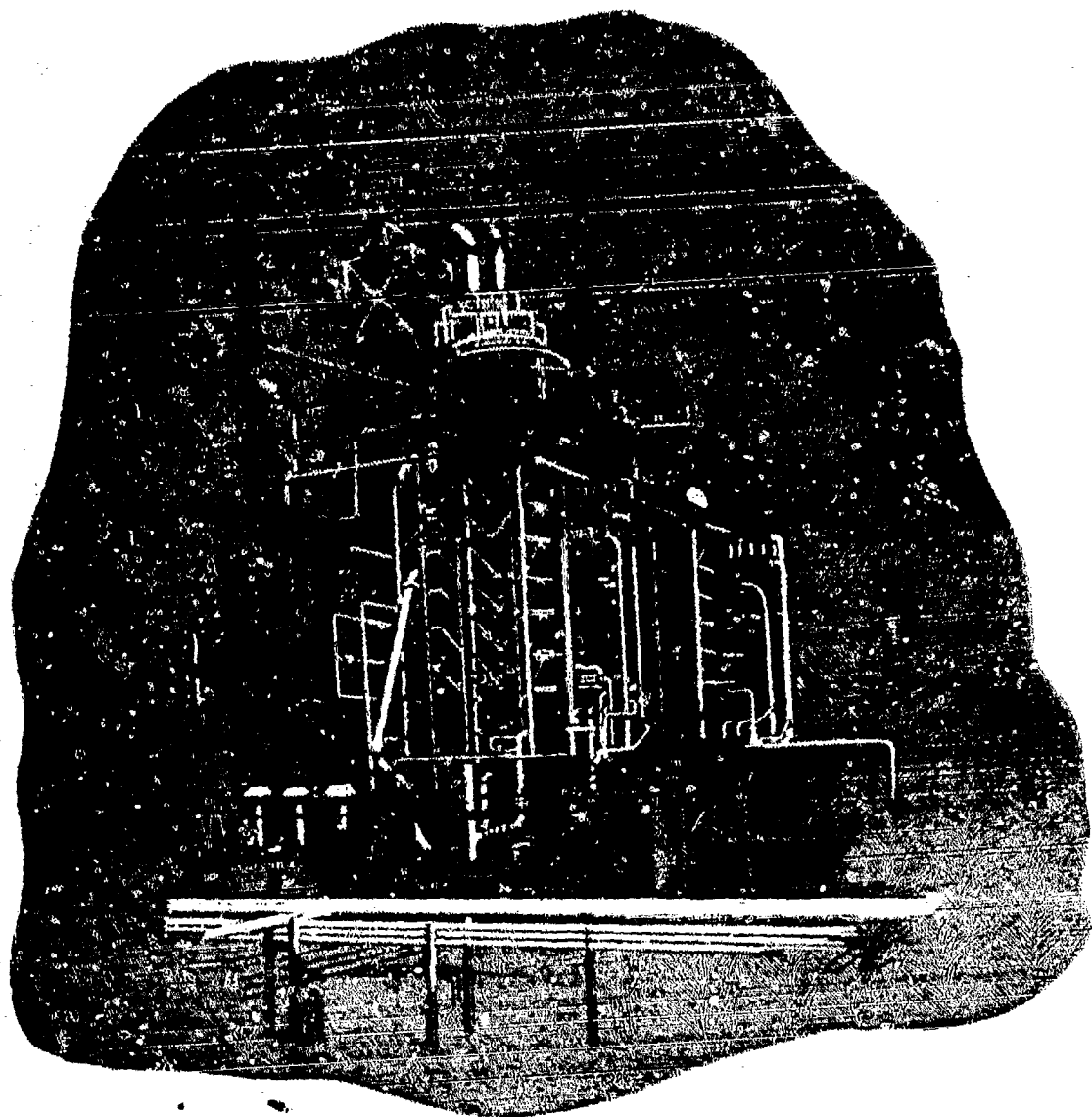


Figure 3.10 Fluid Catalytic Cracker

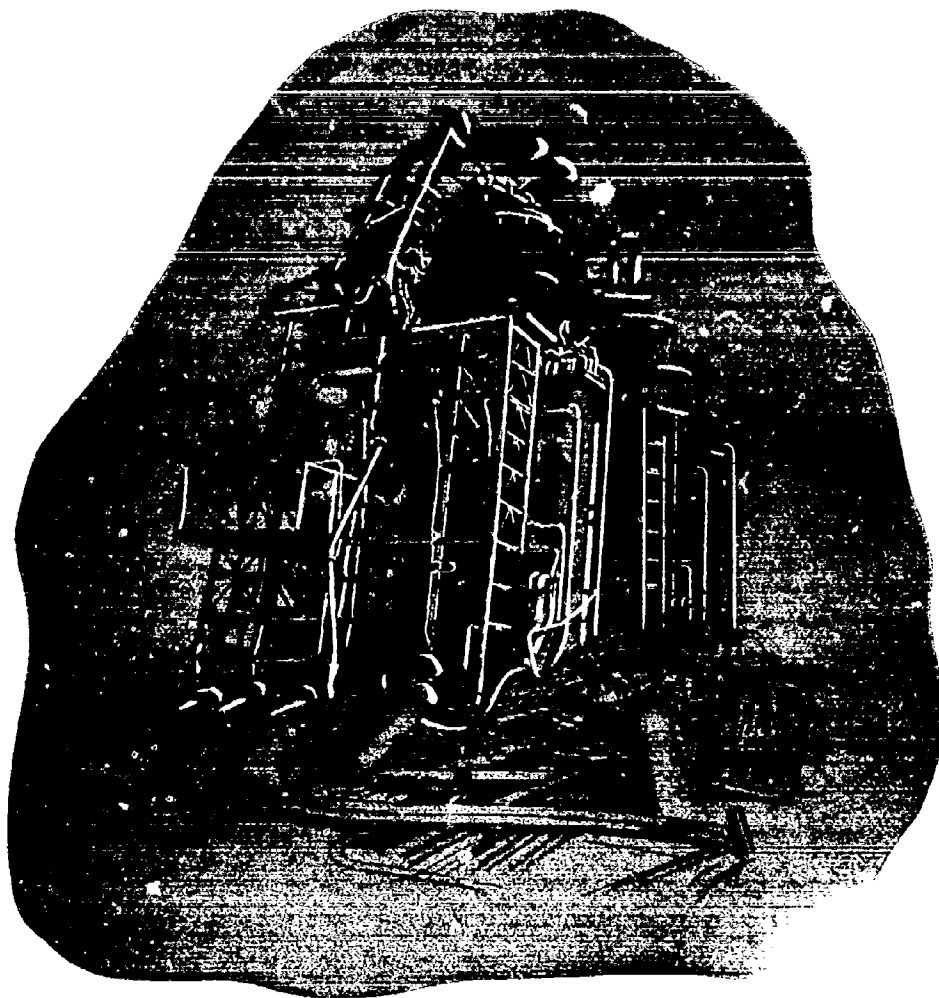


Figure 3.11 Damage to Cat Cracker at 7.0 psi

windward side at 7.0 to 8.0 psi, depending on the direction of the blast (3.11-3a).

The other cat cracker analyzed had the regenerator and the reactor supported on individual reinforced concrete frames. The concrete frame for the regenerator starts cracking at 8.5 psi, and collapses through column bending at 16 psi. The reactor frame exhibits cracking of the concrete frame at 8.0 psi, and complete frame collapse at 12 psi from column bending (3.11-3b).

The fractionator for the cat cracker which is mounted on a pedestal footing with steel pipe piles, exhibits anchor bolt yielding in tension at 5.0 psi, and overturning of the vessel through anchor bolt failure at 7.0 psi. Failure of the piles is not expected before failure of the anchor bolts (3.11-3b).

3.7.2.4 Light ends units

A deisobutanizer tower supported on a pedestal of mass concrete will overturn from the failure of anchor bolts in tension at 9.5 psi. The foundation is large because it also supports two other horizontal vessels and therefore failure of the footing is not expected before anchor bolt failure. Figures 3.12 and 3.13 show partial damage to another light ends unit (3.11-4).

A vapor recovery unit, with an absorber and lean oil still towers supported by steel frames, will partially overturn at 4.0 psi, but will be prevented from completely overturning by the restraint offered by the low level structures connected to each side of the main vessel frames. The vessels themselves will overturn from the tensile failure of their anchor bolts—the absorber tower at 5.5 psi, and the lean oil still at 6.0 psi. The overturning of the vessels will then cause complete collapse of the structures (3.11-4).

3.7.2.5 Water cooling tower

The corrugated asbestos louvers on the windward side will shatter at 0.3 psi, and their fragments will be blown into the interstices

of the tower, with little or no damage to the internal parts of the structure. Stripped of its siding, the structure will become sensitive to drag loading.

The transverse timber frames between the center and end shear walls will collapse into the concrete water basin at an overpressure of 3.5 psi. Associated with this overpressure is a wind velocity of 140 mph which creates a dynamic pressure of approximately 46 psf over the entire structure, resulting in the shear failure of the wind diagonals at the exterior columns and the bending failure of the interior columns.

The fan motors are not expected to suffer any damage, but the collapse of the tower will damage the fan blades beyond repair (3.11-5).

3.7.2.6 Furnaces (pipe still)

The atmospheric and vacuum furnaces for a pipe still will be shifted slightly from their original positions at 1.5 psi, by the shearing of the anchor bolts. The stacks will collapse at 6.0 psi from plate buckling. The furnace and its frame will overturn at 6.5 psi from anchor bolt failure resulting from a combination of drag and reflected pressures (3.11-6).

3.7.2.7 Miscellaneous structures

a) Maintenance building

The corrugated asbestos siding will shatter at 0.3 psi, thereby relieving the pressure on the roof, which will survive until the steel frame collapses. The frame, with the roof and brick walls intact, will suffer deformation at 3.0 psi, and will be permanently deformed when the brick walls fail at 5.0 psi. The cranes would then be inoperable because of deformed rails, if they were at the ends of the buildings at the time of the blast. The frame will collapse in column bending at 6.0 psi.

The frames will survive a higher overpressure, if the three overhead cranes are located at the

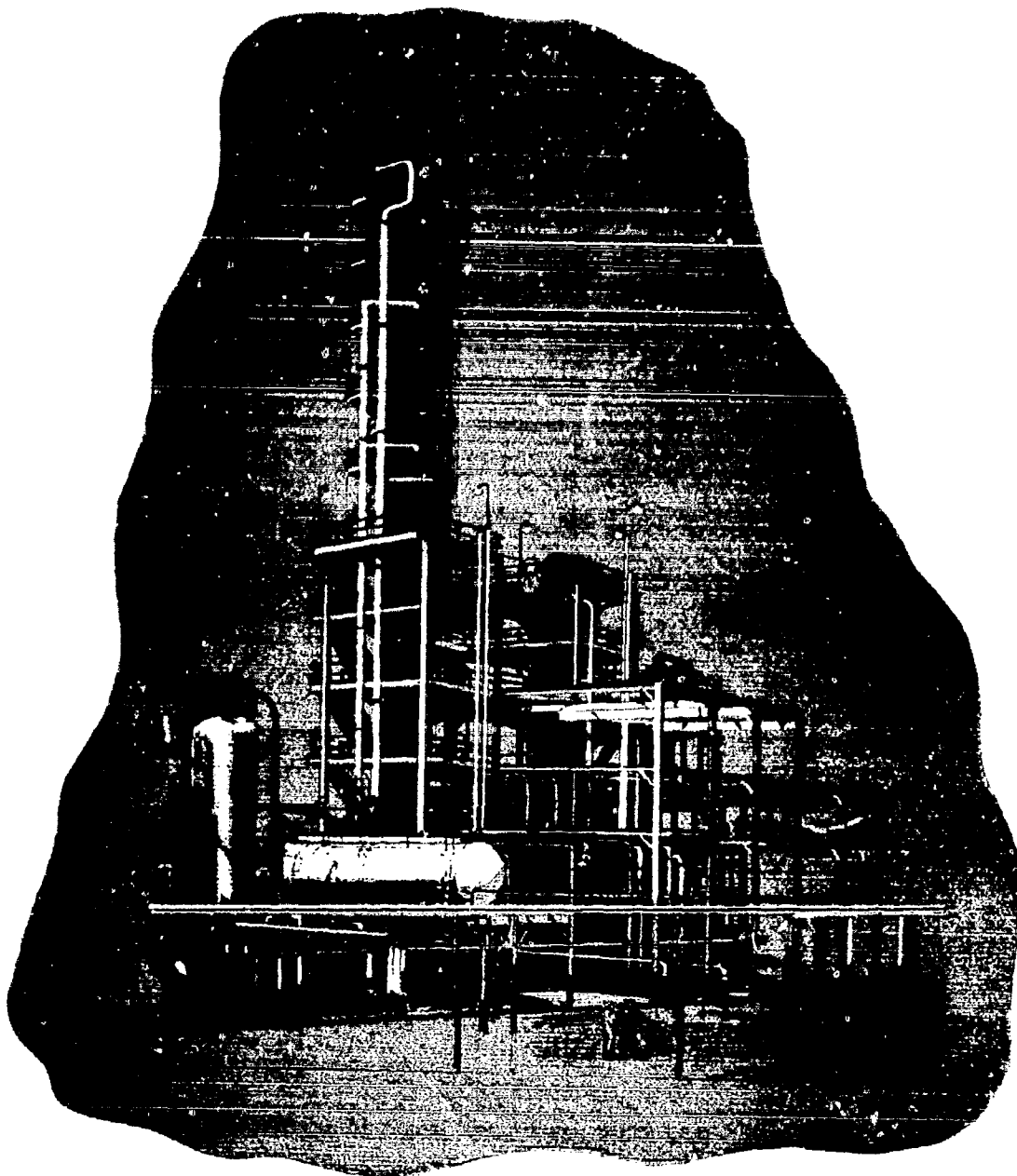


Figure 3.12 Light Ends Unit

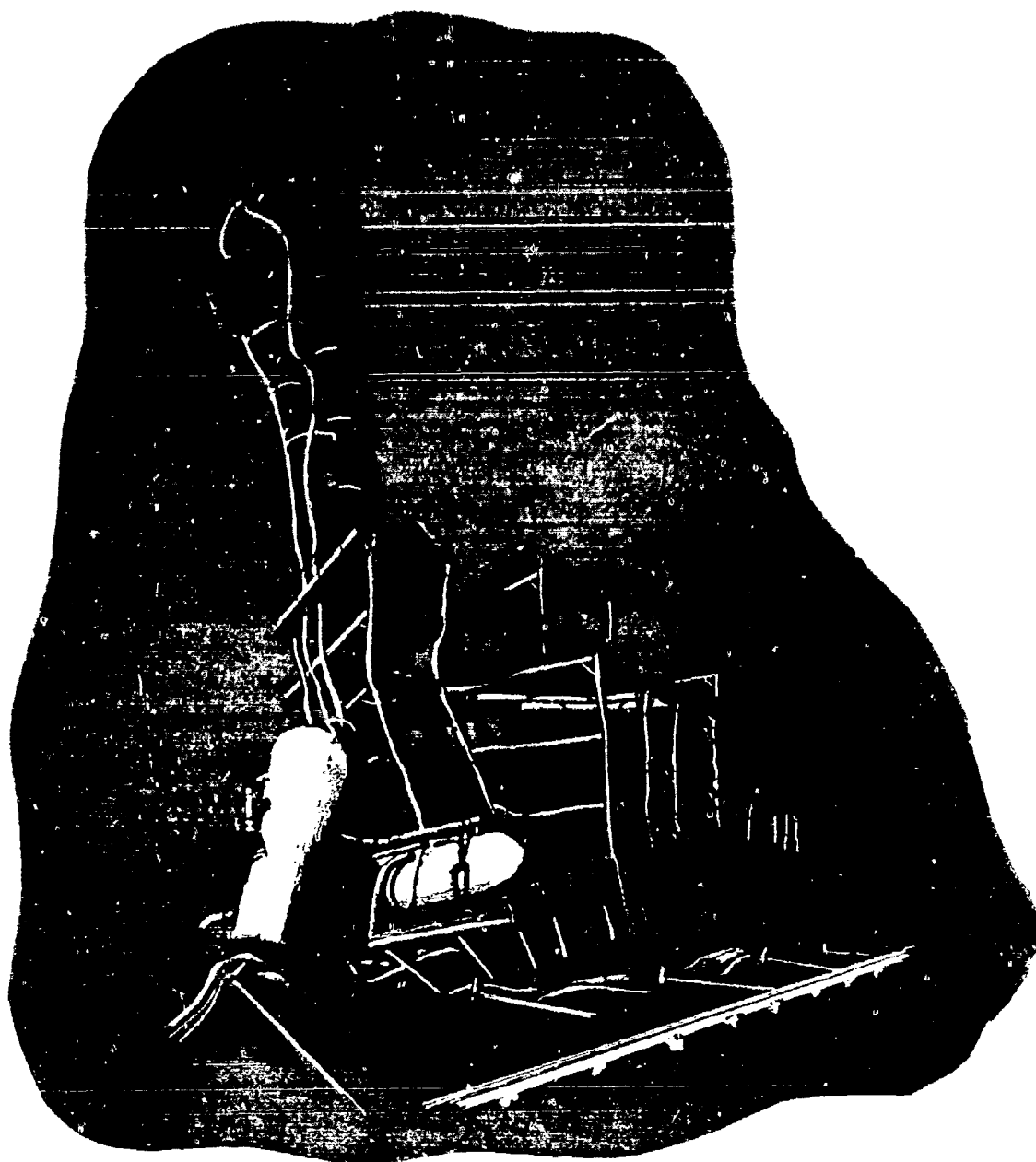


Figure 3.13 Damage to Light Ends Unit at 4.0 psi

quarter, half, and three-quarter points between the ends of the building. There is always the possibility that the cranes would be dislodged from their rails, however, when the frame is deformed, thereby destroying otherwise salvageable equipment below (3.11-7).

b) Flare stacks

The tower-supported flare, when oriented squarely to the blast, will overturn at 4.0 psi, by uplifting of the foundations on the windward side and column buckling on the leeward side. The same mode of failure will occur at 3.0 psi when the tower is oriented diagonally to the direction of the blast (3.11-8a).

The guyed flare stack has three sets of guys. The stack above the middle collar will collapse by the shear failure of the collar connection pin of the upper collar at 11.0 psi. Complete collapse of the stack will occur at 15.0 psi from the shear failure of the pin connections of the upper and lower connections (3.11-8b).

It should be pointed out here that the analysis of the guyed flare stack results in a very approximate solution because such a structure has marked nonlinear characteristics. The analysis then becomes complicated because of the difficulty in obtaining the correct solution to the nonlinear equations which govern the behavior of the structure. For example, a major factor which contributes to this nonlinear behavior is the displacement of the collar end of the guys. Another difficulty is the combination of periods of vibration of the guys and the stack.

c) Pipe bands

Steel-supported pipe bands will start deforming at 3.5 psi, and will collapse in column bending at 6.0 psi (3.11-9a).

The analysis of the reinforced concrete-supported pipe band is predicated on the assumption that it carried the same loading as that carried by the steel-supported pipe band. This procedure was necessitated by the fact that plans showing the sizes and locations of the pipes were not obtainable. On this premise, the concrete columns start cracking at 3.5 psi, and will collapse in bending at 5.0 psi (3.11-9b).

d) Boiler stack

This self-supporting steel stack and its concrete foundation will overturn at 6.5 psi, without anchor bolt failure, because of the number and size of bolts (3.11-10).

e) Administration building

A previous case study by Fernald, et al.,⁶³ of an existing electronics plant contains an analysis of a first-floor slab which is the roof of a shelter in the basement of the building. The purpose of this analysis was to determine the critical overpressure for slab failure.

This analysis can be applied to first-floor slabs in administration buildings where a shelter area has been designated in the basement.

The results of this analysis show that if existing windows act effectively as inlet openings, the

possibility of a complete collapse of the building on top of the slab is remote and the slab may be assumed to withstand 5.5 psi overpressure (3.11-11).

3.7.3 Blast damage to tetraethyl lead (TEL) building

The vulnerability of the TEL building which houses the batch process is determined by referring to calculations for other similar buildings which were analyzed in a previous report by Advance Research for the Office of Civil Defense. This report is entitled, "Critical Industry Repair Analysis, Food Industry", and can be obtained through the Defense Documentation Center, DDC No. AD-614-908.

The walls of the TEL building are comparable to those of the warehouse of the sugar plant of the above-referenced report. The clearing distance of the TEL building is about twice that of the sugar warehouse and the panel sizes are similar; therefore, the walls can be expected to fail at an overpressure of 2 psi.

The steel frame of the TEL building and the frame loading are similar to the process building of the citrus juice plant in the Food Industry report. Therefore, the frame would suffer distortion at 7 psi., resulting in many process pipe failures. The frame will collapse at an overpressure of 10 psi. A more detailed analysis may be presented in a future report.

3.7.4 Blast damage to storage facilities

Refined petroleum products are chiefly stored at refineries and at bulk terminals located near markets. Cone roof tanks are generally for storage of less volatile liquids, and floating roof tanks are generally for more volatile products to reduce fire hazard and evaporation losses. LPG is stored under pressure in spheres and underground. It can also be stored in refrigerated tanks and spheroids.

Any discussion of blast effects must touch on fire, since the release of combustibles from blast-damaged tanks and processing equipment is a leading cause of fire. All that is needed is a source of combustion to ignite the fluids and gases.

Petroleum liquid storage tanks represent a serious fire hazard at a petroleum refinery because of the large quantities of fuel contained. Such fires might spread to processing areas, and cause interruption of production. Little storage tankage is required for emergency operations, and there is a wide range of possible substitutions of one tank for another. The U.S. Strategic Bombing Survey showed that large fires in refinery storage areas could have relatively little effect on oil production.⁷ Generally, then, loss of storage tanks will be far less serious than destruction of a refinery.

The vulnerability to fire is discussed in detail in connection with the Whiting, Texas City, and Signal Hill holocausts in section 3.8. As demonstrated in these cases, it is assumed that any spilled liquids will be ignited by sparks or by the ignition sources present around the plant.

The effects of thermal radiation are also discussed in section 3.8. This is a much more serious problem for weapons in the megaton range than for weapons in the kiloton range because of the former's much greater intensity and pulse duration, by an order of magnitude for equal overpressures. This section deals primarily with the analysis of the effect of blast on petroleum liquids storage tanks.

Two basic storage tank configurations are considered: (1) the cylindrical shell, welded steel tank with either a cone roof or floating roof used for storage of crude oil, gasoline, kerosine, diesel fuels, and other refined products, at atmospheric pressure, as described in API Standard 650,³⁹ and (2) welded steel storage spheres used for the storage of volatile gases and liquids under pressures up to 250 psi. LPG is also stored under pressure in spheres and underground. Table 3.8 gives data on storage capacity of refined products at refineries and bulk terminals.⁴⁰ The wide dispersion of facilities is indicated by the table. Although there appears to be a considerable amount of stored fuel, it represents only part of an eight-day supply.

Table 3.3 STORAGE CAPACITY AT REFINERIES, GASOLINE PLANTS, BULK TERMINALS
AND TANK FARMS, BY REFINERY DISTRICTS, April 1, 1963¹⁰
(Thousands of barrels)

Product	East Coast	Appalachian		Indiana Illinois Kentucky	Minnesota Wisconsin No. and So. Dakota		Oklahoma Kansas Missouri		Texas Inland		Texas Gulf Coast		Louisiana Gulf Coast		Arkansas Louisiana Inland		New Mexico	Rocky Mountain Basin	West Coast	Total United States
		No. 1	No. 2																	
Gasoline:																				
At refineries	25,750	2,734	1,517	40,366	3,990	19,154	11,195	41,359	19,041	2,310	515	9,646	40,047	218,324						
At bulk terminals	59,522	6,597	4,539	27,272	10,365	13,346	3,316	6,906	3,726	1,737	437	2,683	17,095	185,561						
Total	85,272	9,331	6,056	67,638	14,355	32,500	16,511	50,265	21,767	9,997	952	12,329	57,142	384,085						
Kerosine:																				
At refineries	3,816	280	209	5,421	586	1,396	653	5,589	2,717	209	67	426	1,654	35,283						
At bulk terminals	18,988	967	693	4,987	2,193	1,008	792	809	726	813	42	1,242	34,157	94,157						
Total	22,804	1,247	902	10,408	2,779	2,394	1,445	6,498	3,443	1,142	109	1,658	5,611	99,440						
Distillate fuel oil:																				
At refineries	21,155	1,334	487	19,019	2,245	10,797	3,001	21,537	7,281	1,100	128	2,160	18,273	110,507						
At bulk terminals	71,280	4,368	2,225	20,270	9,870	8,648	1,156	3,070	1,639	1,612	181	1,745	11,832	130,086						
Total	93,035	5,702	2,712	39,289	12,115	19,445	4,157	24,607	8,920	3,012	289	3,905	30,105	240,593						
Residual fuel oil:																				
At refineries	7,259	564	404	9,334	1,164	1,952	1,051	7,162	1,138	300	230	1,492	17,915	90,365						
At bulk terminals	17,738	393	67	1,703	327	21	0	226	556	10	0	2	12,710	33,785						
Total	24,997	957	471	11,037	1,491	1,973	1,051	7,398	1,694	310	230	1,494	30,625	94,130						
Military jet fuel:																				
At refineries	476	40	27	1,613	202	1,441	1,126	3,457	1,845	170	137	960	2,689	14,133						
At bulk terminals	665	0	169	697	63	361	404	0	0	243	60	93	119	2,896						
Total	1,141	40	196	2,310	265	1,802	1,530	3,457	1,845	313	197	1,053	2,808	17,029						
Liquefied gases:																				
Aboveground:																				
At plants and terminals	329	...	...	471	...	695	2,105	628	320	212	229	201	96	5,306						
At refineries	252	...	...	787	...	711	674	971	324	...	...	95	922	4,736						
Total	581	...	...	1,258	...	1,406	2,779	1,599	644	212	229	296	1,018	10,042						
Underground:																				
At plants, terminals and refineries	1,982	...	...	4,712	...	10,163	14,684	27,791	6,849	4,512	1,374	374	850	73,476						
District total	229,812	17,277	10,337	136,662	30,965	60,648	42,157	121,615	45,156	19,728	3,380	31,709	128,167	876,545						

3.7.4.1 Storage tanks

a) Cylindrical shell tanks

While a considerable amount of theoretical analysis has been done on the blast resistance of petroleum liquid storage tanks,^{41,42} this is reviewed to determine the pertinence of the results to the present study, particularly as they relate to the effects of weapons in the megaton range. The results of these studies are summarized, as follows:

The blast resistance of cylindrical storage tanks is independent of weapon yields, at the same overpressures for yields of 500 KT or greater.

The critical failure mode is caused by uplift of the base of the cylindrical shell, over a portion not exceeding one-half of its circumference. This uplift occurs before other possible failure modes, such as shell buckling or bending, become significant, and it induces strains both in the steel plates of the shell and in the joint between the shell and the tank bottom sufficient to cause rupture and loss of contents of the tank through leakage.

The effects of drag loading, sloshing and spilling of liquids, wind girders, and roof configurations do not require particular mention in the analysis of blast resistance.

Empty tanks can be expected to fail, by uplifting, at between 1.0 and 1.5 psi. Filled or partially-filled tanks can be expected to fail at overpressures ranging to 6.5 psi, depending on the extent of filling and height-to-diameter ratio of the tank.

Floating roofs fail at an overpressure of approximately 20 psi, and cone roofs fail at much lower overpressures. The referenced study estimates that cone roofs will fail at about 0.5 psi, and pieces will blow away at this overpressure.

Advance Research's investigations further lead to several additional conclusions.

Reference 69 contains calculations on a cone roof, supported by columns inside the tank and with rafters radially oriented for additional support and bracing. A typical cone roof on a tank at Baton Rouge conforms with API Standard 650. The calculations show that roof failure will occur at about 1.3 psi, at which time the columns fail in buckling. This will cause inward collapse of the roof, but will not necessarily lead to tank failure or loss of contents through leakage (3.11-12a).

The actual collapse of the cone roof will not appreciably affect the blast loading on the tank shell. If the tank is full, the roof collapse will allow the overpressure to become directly applied to the liquid surface, as in the case of a floating roof tank or a roofless one. This increases the radially-directed outward pressure on the inside of the shell, which helps the shell to resist the external, inwardly-directed overpressure. The magnitude of this additional pressure at 2.0 psi, however, is on the order of one-tenth of the hydrostatic pressure for a full tank, and is therefore not very significant in the overall tank blast resistance.

If collapse of the roof is the only tank damage, repair is made relatively easy by removing the old roof and replacing it with a temporary wooden cover or floating covers, such as circular plywood panels, where specific gravity characteristics permit. The presence of vapors at the top of a tank, if open to the atmosphere, can create a very dangerous situation because of the ease with which such vapors can be ignited, as in a lightning storm, and should be avoided. The danger from tank contents leakage is proportionate, of course, to the quantity leaked. An empty tank, although failing at relatively low overpressures, does not create a serious hazard. On the other hand, failure of a full tank, not individually diked, can

allow the spread of volatile and flammable liquids over a large area with consequent serious fire hazard.

Tanks are frequently not individually diked. At Pascagoula, tanks are grouped in ground basins capable of containing the contents of one full tank only. If more than one full tank fails, spillover could result. This is somewhat compensated by drains in each basin leading to an open canal emptying into the Gulf. The drains can be opened by locally-operated valves.

Another related problem is the spacing between tanks, which affects the likelihood of fire spread from tank to tank. This tank spacing has been found to vary from refinery to refinery, and a high percentage do not have adequate spacing between tanks; according to current definitions of "adequate" tankage subject to possible explosion hazard should be spaced by at least two tank diameters.⁶¹

b) Spherical shell tanks

Spherical tanks are used for the storage of volatile liquids, liquid petroleum gases such as propane and butane, and natural gas, under pressures up to 250 psig. Because they contain volatile liquids under pressure, spherical shell tanks are potentially more dangerous than cylindrical shell liquid petroleum storage tanks with cone or floating roofs. With few exceptions, such as methane and ethane, most petroleum gases are heavier than air, and are flammable. This means that either there will be an explosion at the tank or, failing that, the gas will flow down to and along the ground. If and when this drifting mass of gas finds a flame or spark, the explosion or fire can be extremely destructive and the scale of damage comparable to that of a mass refinery fire.

The sphere itself is made of welded steel plates and is designed to withstand the internal operating pressure with a safety factor of four.⁴⁴ The supporting columns, or legs, and foundations are normally designed to withstand wind loads to 100 mph and the dead load of the tank filled with water for hydrostatic test. Sphere diameters can range up to 76 feet, but are generally smaller. Columns are mounted on piers with individual footings.

Because of size and configuration, storage spheres are primarily drag-sensitive targets, and the sphere is a relatively low drag shape in the range of high Reynolds numbers, over 10^5 , which apply in cases of nuclear blast. Because of the potential hazard, they are designed for greater structural ruggedness, as pressure vessels, than are cylindrical storage tanks. The spheres are accordingly much less vulnerable to blast than cylindrical cone roof or floating roof tanks, being able to withstand overpressures up to 9.0 psi without overturning. At this overpressure, calculations on a 38-foot diameter butane sphere indicate that overturning would result from column bending. The sphere analyzed has a peak operative design pressure of 25 psig, which is somewhat below average for this type of vessel. The shell plates, and consequently vessel weight, are thus lighter than average. A vessel designed to operate at higher internal pressure would be heavier and would therefore have greater blast resistance because of the restraining moment of the weight (3.11-12b).

In conclusion, storage spheres, although potentially very hazardous because of the high internal pressures and volatility of the stored products, do not suffer major damage at overpressures up to 6.5 psi. The failure mode for spheres is

overturning, and for cylindrical tanks it is tank leakage resulting from uplift.⁶⁹ In the first case, volatile substances under pressure would be spread over a large area and would probably ignite, causing a serious fire. In the second case, spread of the liquid, and thus the relative fire danger, depend on the amount of diking around individual tanks.

Although generally more vulnerable than processing units, storage tanks can be repaired more easily and quickly. A refinery that suffers major damage to its storage capacity, but only light damage to operating units, can return to operating condition fairly soon, because refined products can be shipped to other installations for blending and storage. An example of this occurred after the Whiting fire,⁴⁵ where damage to storage tanks was extensive but damage to processing units was negligible, except for the fluid hydroformer unit that exploded.

3.7.4.2 Study of a tank farm vulnerability

This section describes a study of the vulnerability of the storage tank area at the Pascagoula, Mississippi, refinery of Standard Oil Company (Kentucky) (see figure 3.14). At Pascagoula, as at many other installations, the crude oil and product storage tanks are not individually diked, but are instead located together in groups of about 10 tanks in areas which have only dikes around their boundaries. The diking around each area is adequate for containment of the contents of the largest tank in the group when filled to capacity. In the course of normal operations this amount of diking is adequate for most situations apt to arise, because only one tank at a time is likely to spring a leak. In the event of a nuclear weapons attack, however, it is likely that several tanks would spring leaks at once, as the result of blast damage or damage resulting from secondary missiles, and this type of diking in groups would probably be insufficient to contain the resulting larger quantity of spilled liquids.

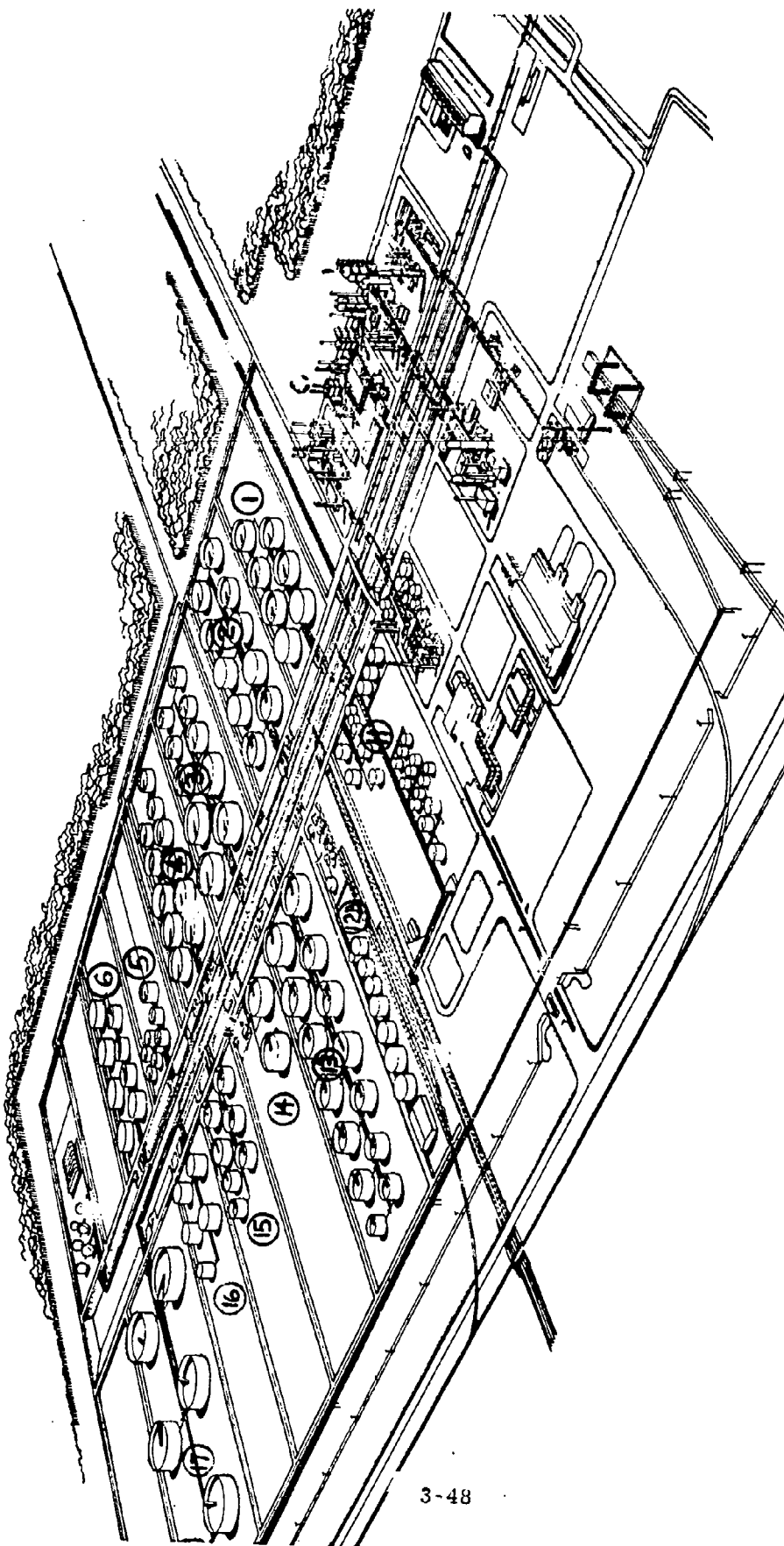


Figure 3.14 View of Pascagoula Refinery

In the present study an analysis has been made of the 13 diked areas, or groups of tanks, at the Pascagoula refinery, based on data of the contents of each tank on one particular day, February 8, 1965. It has been assumed that these data fairly represent a typical situation that could exist on any day, and that the results based on them would apply generally to the situation of the refinery at the time of an attack.

The tanks at the Pascagoula refinery are mostly floating roof welded steel tanks, conforming to API Standard 650. The mode of failure used for this analysis, as described in section 3.7.4.1, is uplift of the cylindrical shell of the tank along a portion of its circumference, not exceeding $1/2$ the circumference, causing rupture of the joint between shell plates and tank bottom with consequent loss of contents through leakage.

Using the refinery's stock report of February 8, 1965, which indicated a fuel storage of 3,448,613 bbl, table 3.9 shows the lowest incident blast overpressure that would cause flooding of each diked area. Area No. 14 is the most vulnerable, flooding at 2.3 psi incident blast overpressure, and Area No. 17 is the least vulnerable, flooding at 12.5 psi, at which pressure all tanks in all areas would fail. The flooding of any one area would cause hydrocarbon liquids to flow into adjacent areas, some of which would be processing areas where there are sources of ignition from the processing furnaces and other equipment. Thus, the probability of fire is high if storage areas are flooded and overflow their dikes. Area No. 14 is not located near the processing areas and, furthermore, it only contains two tanks. But Area No. 11, which would flood at 2.8 psi, is adjacent to the processing areas and contains 25 tanks. Its flooding, therefore, would result in a very hazardous situation.

In table 3.10, the quantities of liquids lost through tank leakage are shown for incident blast overpressures between 1.0 and 12.5 psi. The range of the overpressures listed is not intended to coincide with that in table 3.9, because the quantities listed are those which would leak from the tanks into the diked areas, regardless of whether or not the areas would be flooded and overflowing.

Table 3.9

VULNERABILITY OF TANKAGE AREAS TO FLOODING

Area No. *	Total Tanks	Tank Failures to cause Flooding	Blast Over-pressure at Flooding	Dike Capacities BBL
1	7	4	5.5	110,010
2	10	5	6.1	110,010
3	10	10	6.6	163,400
4	11	10	5.0	110,010
5	7	6	4.4	65,810
6	8	5	4.7	106,600
11	25	10	2.8	15,000
12B	9	6	4.2	26,700
13	14	9	5.0	110,010
14	2	2	2.3	110,010
15	7	7	5.0	65,810
16	5	3	5.0	106,600
17	6	6	12.5	274,000
Total Volume of Diked Areas				1,373,970 bbl

* Only those areas containing large diameter cylindrical shell storage tanks have been listed.

Table 3.10
ACCUMULATED TANK LEAKAGE

Pressure psi	Accumulated Losses BBL
1.0	116
1.4	5,077
2.0	96,604
2.5	179,114
3.0	288,271
3.5	372,266
4.0	505,124
4.6	721,528
5.0	1,344,726
5.5	1,617,716
6.1	1,838,513
6.6	2,838,914
7.7	2,917,415
12.5	3,448,613

In conclusion, it appears that an extremely hazardous situation could develop from leakage of petroleum liquids at overpressures below 3.0 psi. Since there is a strong probability of ignition, a devastating fire could result which would destroy a large part of the refinery.

3.7.4.3 Bulk storage

A large pipeline terminal located outside of Boston is comprised of a tank farm with cone roof tanks estimated to have a 50,000 bbl capacity, small administration building, truck loading dock, and various utility sheds.

Analyses made for other similar units in this study indicate that the cone roofs of the tanks will collapse at 1.3 psi, and if filled or partially filled, failure will occur at the base of the tank allowing the contents to leak out (section 3.7.4.1). The one-story administration building has the configuration and the construction of a typical refinery controlhouse. The roof, then, is expected to collapse at 1.0 to 1.5 psi, and the brick walls to collapse at 3.5 psi (section 3.7.2.1).

In general, storage areas—at refineries, bulk terminals, and tank farms—are well dispersed; many different tanks are readily interchangeable where substitution is needed; they are more easily repaired than most processing units; and relatively little storage is needed for petroleum production, because refinery operation depends upon a continuous inflow of crude oil, rather than on storage. The usable national supply of stored crude oil amounts to no more than eight day's worth, at the current rate of refinery consumption.⁵

This is because the growth of pipeline networks is effectively obviating the need for storage of crude oil as working stock for refineries. A five month's supply of stored crude was maintained in 1930; by 1963, this stock level had been reduced to 27 days. According to the Department of the Interior, less than one-third of this can be considered readily available in the preattack period, since the balance consists of pipeline fill, tank bottoms, and other relatively unavailable inventories.⁵ How much of this remainder could be recovered under postattack exigencies, and by what means, has not been determined, and could prove a worthwhile subject for further study.

3.7.5 Texas City disaster⁴⁶

This disaster is of particular interest in this study because the area affected contained petroleum refineries, tank farms, pipeline facilities, docks, and a styrene and polystyrene production plant of the Monsanto Chemical Company.

The disaster resulted from the explosions of two ships, which were tied up at piers, loading ammonium nitrate fertilizer. The explosions, a day apart, created extensive blast, missile, and fire damage, and were responsible for many deaths, injuries, and an estimated \$67 million of damage.

The Monsanto plant was located directly across the slip from the first ship which exploded, and most of its processing units were about 1/4 mile away. The plant was immediately engulfed in flames caused by ignition of combustible hydrocarbons in the polystyrene building, the ethylene purification units, the alkylation unit, the distillation towers, and storage tanks of benzol, fuel oil and other low vapor pressure hydrocarbons. The ship blast also caused extensive damage to Monsanto warehouses. Warehouses on the adjacent piers were badly damaged by blast and fire, there were fires on the water's edge from pipelines that had been split by missiles or blast, and six tanks in the Stone Oil Company farm (4000 feet away) ignited.

A day after the first explosion the other ship exploded and this second blast had about the same force as the first, completely disintegrating the ship and demolishing buildings and facilities already damaged by the first explosion. New fires were started by red-hot missiles in the Humble Pipe Line Company property (2800 feet away), the Stone Oil Company farm (4000 feet away), the Republic refinery (6700 feet away), and the Carbide and Carbon Chemical Company refinery (1200 feet away). Except for one slowly burning tank of bunker oil which was extinguished by foam, the tank farm fires were allowed to burn themselves out because all efforts were being devoted to rescue operations. Many other tanks were hit by missiles in both explosions but did not ignite.

From the estimated energy of the explosions (2-4 KT)⁴⁷ it is possible to make some estimates and comparisons with a hypothetical 20 MT air burst. Monsanto's alkylation and distillation units, structurally similar to those in petroleum refineries today, were about 1/4 mile from the first explosion and experienced about 12 psi incident overpressures with 0.3 second positive phase duration. The blast damage to controlhouses, instruments, piping and auxiliary equipment was extensive, and horizontal and vertical reactors, towers and their supports were extensively damaged by fire. Fractionating towers in the ethylene area were warped and leaning from fire damage, but much of the steel structures surrounding them remained intact.⁴⁸

For a 20 MT air burst, roughly the same amount of blast damage to refineries occurs at an overpressure of 5.5 psi (see table 3.7), and at a range of approximately 11 miles. This overpressure is much less than the 12 psi for the 2-4 KT blast, but the duration of the positive pressure is 7 seconds - an 18-fold increase over the 0.3 second duration of the kiloton blast.⁴⁷ The effects of overpressure duration are discussed further in appendix D.

Clearing Distance S (ft)	Shock Front Velocity U _s (ft)	Duration of Positive Phase t _p (sec)	Duration of Overpressure (Equiv. Triangular Load)			Resonant Period T _n (sec)	Time Ratio C _t	Resistance Ratio C _r	Peak Value of Dynamic Load (psi)	Incident Overpressure P _{ao}		Remarks
			Incident t _s (sec)	Reflected t _r (sec)	Trag t _d (sec)					For deformation (psi)	For collapse (psi)	
12.0	1210	10	7.5			0.12	62.5	0.98	P _{ao} = 1.64		1.6	Steel decking of the switch gear and control rooms collapses at 1.0 and 1.5 psi respectively, if wall openings are less than 30%. If the blast approaches in the direction of the glazed wall which is commonly found in control rooms, the roof is expected to survive until the frame collapses.
		10	7.5			0.18	41.7	0.96	P _{ao} = 1.15		1.1	
		8.5	6.4			0.10	61.3	1.16	P _{ao} = 1.54		1.5	Roof beams are not critical because the precast concrete planks fail at 1.5 psi, which is less than that for the beams (5.0 psi). The steel building frame suffers deformation at 1.0 psi, with the roof and walls intact. The brick walls collapse at 3.5 psi (see next sheet) precluding frame failure at 5.5 psi, thereby leaving a bare frame which collapses at 10 psi.
		6.4	4.8			0.07	71.6	0.99	P _{ao} = 5.13		5.1	
		8.4	6.3	0.006		0.74	0.076	0.186 = 1.31(0.01)(0.25)	P _{ao} = 2.22(3.4)	1.0	5.5	
		5.0			1.89	0.24	6.82	0.81	q _o = 2.31		10.0	
		5.2			1.95	0.46	42.3	1.78 = 1.31(0.03)(0.10)	q _o = 0.67(1.1)	5.5	3.4	The overpressure of 3.5 psi for the bond failure of the concrete bracket is assumed to be twice the resistance, i.e.
		5.0			1.89	0.55	3.4	1.46 = 1.31(0.01)(0.10)	q _o = 0.49(1.2)	5.5	7.0	The rectangular concrete frames of the vacuum and atmospheric towers exhibit cracking at 5.5 psi, and collapse at 7.0 psi.
		4.2			1.58	0.38	3.30	1.50 = 1.31(0.02)(0.10)	q _o = 1.34(5.17)	7.0	16	The octagonal concrete frame of the vacuum tower starts cracking at 7.0 psi. Before the frame is calculated to collapse at 10 psi from column bending, the vessel's anchor bolts shear causing the vessel to shift at 7.5 psi, thereby overloading the leeward columns of the frame. The frame will then collapse at the same overpressure as that causing the bolt shear - 7.5 psi.
		4.2			1.58	0.15	10.8	1.60 = 1.31(0.09)(0.26)	q _o = 1.35(2.40)	7.0	10	
		5.6			2.10	0.15	14.3	1.6	q _o = 1.39		7.5	
		5.8			2.10	0.94	2.32	1.40 = 1.31(0.60)(0.28)	q _o = 0.48(1.12)	4.5	7.0	
		5.8			2.18	0.94	2.32	1.4	q _o = 1.41		7.5	
		5.8			2.18	1.17	1.86	1.4	q _o = 1.19	7.0		Reactor & Regenerator - Although wind bracing fails at 3.5 psi, and the exterior columns on the leeward side buckle at 7.0 or 7.5 psi, depending on the direction of the blast, the steel frame is standing but in a deformed condition. The entire structure overturns from the tensile failure of the anchor bolts on the windward side at 12.0 psi. Regenerator - The wind bracing fails at 3.0 psi. The exterior and first interior columns on the leeward side buckle at 5.0 psi from a blast in either direction, however the frame stays intact but deforms. The entire structure overturns from the tensile failure of the anchor bolts on the windward side at 7.0 or 8.0, depending on the direction of the blast.
		5.2			1.95	1.17	1.67	1.4	q _o = 1.27	7.5		
		5.0			1.89	1.17	1.61	0.53	q _o = 3.06		12.0	
		7.0			2.62	1.17	2.24	1.4	q _o = 0.35	3.5		
		6.0			2.25	1.30	1.50	1.3	q _o = 0.64	3.5		
		6.4			2.40	1.30	1.50	1.35	q _o = 0.40	5.0		
		6.0			2.25	1.30	1.50	0.51	q _o = 1.33		7.0	
		6.0			2.25	1.50	1.50	1.3	q _o = 0.64	5.5		
		6.4			2.40	1.50	1.50	1.35	q _o = 0.60	5.0		
		5.2			1.95	1.30	1.30	0.48	q _o = 1.58		8.0	
		7.8			2.92	1.30	1.95	1.4	q _o = 0.26	3.1		
		5.8			2.18	0.81	2.69	1.50 = 1.31(0.76)(0.10)	q _o = 1.63(5.21)	8.0	12.0	
		5.7			2.10	0.49	4.3	1.50 = 1.31(0.72)(0.26)	q _o = 0.55(1.15)	4.8	7.0	Reactor & Regenerator - The rectangular concrete frames exhibit cracking at 8.0 and 7.5 psi respectively, and collapse from column bending at 12.0 and 10.0 psi respectively. Regenerator - The vessel anchor bolts start yielding at 4.5 psi, and with the tensile failure of anchor bolts at 7.0 psi, the vessel overturns. Since the vessel is founded on a pedestal and steel pipe piles, anchor bolt failure is expected before that of the piles.
		4.8			1.80	0.79	2.28	1.40 = 1.31(0.60)(0.10)	q _o = 2.54(4.88)	8.5	16.0	
		5.1			1.98	2.09	0.95	0.37	q _o = 2.08		9.5	Deisolutanizer - Vessel overturns from anchor bolt failure at 5.5 psi. The vessel is founded on a very large footing which supports other horizontal vessels. This foundation is not expected to fail before the anchor bolts. Vapor Recovery Unit - The anchor bolts of the frame supporting the absorber tower and the lean oil still fail at 4.0 psi, however, the frame is restrained from overturning by the low framing on each side of the vessel framing. The vessel's anchor bolts fail in tension at 5.5 psi for the absorber, and 6.0 psi for the lean oil still. The entire structure will collapse at 5.5 psi, if not already from the overturning of the vessels themselves.
		6.5			3.75	1.60	2.0	0.55	q _o = 1.17		6.5	
		6.5			3.58	1.60	2.23	0.60	q _o = 0.42	4.1	8.0	
		6.5			3.16	1.60	2.0	1.40 = 1.31(0.55)(0.26)	q _o = 0.57(1.32)	5.0	8.0	
		6.5			3.20	0.70	4.6	0.73	q _o = 0.75		5.5	
		8.0			3.60	0.55	5.45	0.77	q _o = 0.91		6.0	
		7.4			2.74	0.5 (assumed)	5.48	1.0	q _o = 0.32		3.7	The corrugated asbestos louvers on the windward side will shatter at 0.3 psi and their fragments will be blown into the interstices of the tower with little or no damage to the internal parts of the structure. Stripped of its siding, the structure becomes a drag structure. The transverse timber frames between the center and end shear walls collapse into the concrete water basin at 3.5 psi, from the bending failure of the columns and the failure of the wind diagonals.
17.7	C _{up} = 1025	5.7		0.52	2.15	0.20	C _{t1} = 0.25, C _r = 10.7	C _{r1} = 0.11, C _r = 0.88	P _{ao} q _o = 14.2		6.5	The frame anchor bolts fail in shear at 1.5 psi, causing the furnace to be shifted on its foundation and causing breakage of pipe between the furnace and the crude unit. At 6.0 psi the stack collapse from plate buckling and the furnaces overturn from anchor bolt failure at 6.5 psi.
17.7	C _{up} = 950	5.5		0.57	1.07	0.20	C _{t1} = 0.29, C _r = 15.3	C _{r1} = 0.68, C _r = 1.63	P _{ao} q _o = 2.55		1.5	
		6.4			2.40	0.27	8.9	0.95	q _o = 0.60		6.0	

TABLE 3.11 PARAMETERS USED IN BLAST DAMAGE ANALYSIS

Unit	Structure	Element	Failure Mode	Mass k	Effective Stiffness k _E (kips/ft)	Load-Mass Factor k _{lm}	Ductility u		Static Resistance R (psi)	Drag Area A _d (ft ²)	Drag Coefficient C _d	Pressure Sensitivity P _s	Clearing Distance S (ft)	Shock Front Velocity V _s (ft/sec)	Duration of Peak or Plateau T _p (sec)	Drain Incident T _a (sec)
							For deformation	For collapse								
Controlhouse (FCC Unit) (1a)	Control room Sw. gear room All rooms	Steel roof deck Steel roof deck Block walls	Bending Bending (see next sheet)	0.34 k 0.41 k	23.4 12.6	0.78 0.78	26 26	1.60 1.10				Incident Incident			10 10	7.5 7.5
Controlhouse (Crude Unit) (1b)	All rooms	Precast concrete roof panels Steel roof beams Block walls Steel frame (w/walls & roof) Steel frame (w/o walls or roof)	Bending Bending (see next sheet) Column bending Column bending	0.15 k/ft 1.83 k 43.4 k 2.97 k	11.3 395 68 68	0.78 0.78 1.0 & 0.33 1.0 & 0.33	10 26 26 26	1.77 5.06 0.40 1.87			Incident Incident Reflected Drag				8.3 8.4 8.4 5.0	6.4 4.8 6.4
Crude Unit (2a)	Attendant alcove Vacuum tower Atmospheric tower	Conc. bracket Conc. frame Conc. frame	Bond failure Column bending Column bending	800 k 480 k 480 k	4560 1070	1.0 1.0 1.0	1.3 1.3 1.3	10 10 10	1.7 1.14 1.0	2676 1441	1.0 & 2.0 1.0 & 2.0	Drag Drag Drag			5.2 5.0	
Crude Unit (2b)	Vacuum tower Fractionator Tower	Conc. frame Vessel A, B Vessel A, B Vessel A, B Vessel A, B	Column bending Tensile failure Shear failure Tensile failure Shear failure	1924 k 1924 k 1924 k 2428 k 2428 k	35800 35800 35800 1110 1110	0.33 0.33 0.33 0.33 0.33	1.3 1.3 1.3 1.3 1.3	10 26 26 26 1.97	4.23 2.16 2.22 0.67 2.572	5350 1803 1803 2572 2572	0.6 & 2.0 0.6 0.6 0.6 0.6	Drag Drag Drag Drag Drag			4.2 4.2 5.8 5.8 5.8	
Cat. Cracker (3a)	Reactor and Fractionator tower Regenerator tower	Steel frame Steel frame Frame A, B Frame bracing Steel frame Steel frame Frame A, B Steel frame Frame A, B Frame bracing	Forward col. buckle (E-W blast) Forward col. buckle (W-E blast) Tensile failure (E or W blast) Connection welds fail Forward col. buckle 1st interior col. buckle Tensile failure Forward col. buckle 1st interior col. buckle Tensile failure Shear failure of weldments				1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3 1.3	1.67 1.77 1.62 0.46 0.83 0.83 0.66 0.84 0.87 0.76 0.36	4403 4403 4403 4403 5028 5028 5028 5028 5028 5028 5028	0.8, 1.8, 2.0 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8	Drag Drag Drag Drag Drag Drag Drag Drag Drag Drag Drag			5.8 5.2 5.0 5.0 6.0 6.0 6.0 6.4 5.2 5.2 5.2		
Cat. Cracker (3b)	Reactor tower Fractionator tower Regenerator tower	Conc. frame Vessel A, B	Column bending Tensile failure	420 k 420 k	717		1.3 1.3 1.3	10 26 10	2.44 0.83 3.56	3473 1290 5273	0.6 & 2.0 0.6 0.6 & 2.0	Drag Drag Drag			5.8 5.0 4.8	
Light ends (4)	Deisobutanizer Absorber & Lean Oil still Absorber Lean Oil still	Vessel A, B Steel frame Frame A, B Frame bracing Vessel A, B Vessel A, B	Tensile failure Column bending Tensile failure Tensile failure Tensile failure Tensile failure	787 k 130 k 525 k 130 k 208 k 211 k	72.5 224 284	0.33 0.33 0.33	1.3 1.3 1.3 1.3 1.3 1.3	26 26 26 26 26 26	0.77 0.64 0.25 0.79 0.55 0.70	1452 594 1450 594 460 400	0.6 1.0 & 2.0 1.0 & 2.0 1.0 & 2.0 0.6 0.6	Drag Drag Drag Drag Drag Drag			5.2 5.2 5.2 5.2 5.2 5.0	
Water cooling tower (5)		Transverse frame	Column bending Wind bracing failure	27.6 k				5	0.32	380	0.4 & 2.0	Drag			7.5	
Furnaces (6)	Atmospheric & vacuum	Frame A, B Frame A, B Stacks	Tensile failure Shear failure Plate buckling	140 k 140 k 140 k	4290 4290		1.3 1.3 1.3	26 26 1.3	2.07 2.06 0.48	455 455	1.0 1.0 0.4	Drag & Reflected Drag	17.7 17.7	C _{sh} 1025 C _{sh} 1030	5.2 5.2 6.4	

Source: Advance Research, Inc.

2

Clearing Distance s (ft)	Shock Front Velocity C _s (ft/sec)	Duration of Positive Phase t _p (sec)	Duration of Overpressure (Equiv. triangular load)			Resonant Period T ₀ (sec)	Time Ratio C _t	Resistance Ratio C _r	Peak Value of Dynamic Load P _{max} (psi)	Incident Overpressure P _{ao}		Remarks
			Incident t ₀ (sec)	Reflected t ₁ (sec)	Drag t _d (sec)					For deformation (psi)	For collapse (psi)	
0.1	1152	10	7.5	0.11	—	0.026	4.23	1.5	P _{ao} = 0.58		0.29	Corrugated asbestos siding shatters at 0.3 psi, allowing roof to survive until collapse of frame. The building frame deforms at 3.0 psi, with the roof and walls intact. The frame is still standing but severely deformed when brick walls collapse at 5.0 psi. Frame and roof collapse at 6.0 psi.
35.8	1152	10	7.5	0.19	—	0.026	7.13	1.8	P _{ao} = 0.54		0.27	
10	C _{us} = 1000	6.4	—	0.03	2.4	0.29	C _{t1} = 0.10, C _{td} = 8.29	C _{r1} = 0.05, C _{rd} = 0.83	P _{ao} = 2.48	5.0		
10	C _{us} = 950	7.8	—	0.02	2.87	0.29	C _{t1} = 0.11, C _{td} = 8.89	C _{r1} = 0.25, C _{rd} = 1.65	P _{ao} = 1.49		3.1	
—	—	8.0	—	—	2.25	0.28	8.04	0.84	q _o = 0.91		6.1	
		6.4			2.4	1.56	1.54	1.3	q _o = 0.40		4.2	Tower-supported flange. With the blast squarely oriented to the tower, the tower overturns at 4.0 psi by the buckling of the two leeward columns and the uplifting of the windward footings. With the blast diagonally oriented to the tower, the tower overturns at 3.0 psi with the uplifting of the windward and the buckling of the leeward column.
		6.4			2.4	1.56	1.54	1.3	q _o = 0.33		4.0	
		6.4			2.4	1.56	1.54	1.3	q _o = 0.41		4.5	
		6.4			2.4	1.56	1.54	1.3	q _o = 0.22		3.0	
		3			106	0.096 (ave)	1.56	1.6	q _o = 2.83		11.0	Cylindrical Flange: The resistance of the pins and the guys are similar; however, the pins fail in shear before the guys fail in tension because $\sigma > 2\delta$ for tensile failure. At 11.0 psi the upper collar pin on the windward side fails in shear, resulting in the collapse of the flange above the middle collar. At 13.0 psi, the upper and lower collar pins fail in shear resulting in the complete collapse of the stack.
		3.7			1.09	0.091	15.3	1.6	q _o = 8.8		20.0	
		4.2			1.37	0.21 (ave)	6.83	1.6	q _o = 4.6		15.0	
		4.0			1.3	0.23 (ave)	6.53	1.5	q _o = 6.5		17.0	
		5.6			2.1	1.83	1.13	1.36u + 1.07d, 0.06u + 26d	q _o = 0.290, 36	3.5	6.1	Frame overturning and bolt shear are not critical because of their high resistances. The frame deforms at 3.5 psi, and collapses in column bending at 6.0 psi.
		6.4			2.4	0.58	4.2	1.56u + 1.31d, 0.05u + 10d	q _o = 0.32, 0.57	3.5	5.0	Frame exhibits cracking at 3.5 psi and collapses in column bending at 5.0 psi.
		6.4			2.4	0.72	3.35	0.95	q _o = 1.10		6.5	The stack and its foundation overturn at 6.5 psi. Failure of the anchor bolts at base of the stack is not expected before 6.5 psi because of their large size and number (32-2 # 3).
		2.7	2.0			0.55	36.4	0.95	P _{ao} = 3.5		3.5	First floor collapses from incident overpressure of 3.5 psi, in addition to collapse of floors above.
		11.3	6.65			0.1	0.51	0.96u + 1.30d, 22u + 26d	P _{ao} = 0.61, 2.50		2.5	The center column fails at 1.3 psi causing complete collapse of roof systems into tanks. The inner roof rafters fail at 2.5 psi which is less than the failure pressure of the outer rafters and girders because of their greater resistance.
		11.3	6.65			0.74	1.64	1.4	P _{ao} = 1.27		1.27	
		7.0		2.6	0.06	32.0	1.70u + 1.30d, 55u + 26d	1.13/1.85	q _o = 1.13/1.85	7.0	9.0	
		7.0		2.6	0.04	84.0	1.70u + 1.30d, 55u + 26d	1.32/2.36	q _o = 1.32/2.36	8.0	10.0	
		7.0		2.6	0.08	30.0	1.7	1.7	q _o = 9.5		21.0	
		7.0		2.6	0.03	90.0	1.7	1.7	q _o = 2.35		11.0	
		7.0		2.6	0.06	0.01						

Initial Pulse t ₀ sec/in ²	Value of $t_0 \left[\frac{21.3}{25 \times 10^6} \right]$	Value of $\left[\frac{21.3}{25 \times 10^6} \right] P_0$	P _{ao} psi	Incident Overpressure P _{ao} psi
0.066	0.1715	2.0	3.75	3.5
0.066	0.1715	2.0	3.75	3.5
0.06	0.111	1.00	3.97	3.5
0.066	0.1143	1.00	4.65	4.1
0.09	0.165	1.85	5.82	5.0

Source: Advance Research, Inc.

TABLE 3.11 (Continued)

Unit	Structure	Element	Failure Mode	Mass	Effective Stiffness k _E (kips/ft)	Load - Mass Factor k _{LM}	Ductility μ		Static Resistance R (psi)	Drag Area (ft ²)	Drag Coefficient C _d	Pressure Sensitivity	Clearing Distance S (ft)	Shock Front Velocity U	Duration of Positive Phase t _p	Dur (%)	
							For deformation	For collapse									
Maintenance Building		Corrugated Asbestos Siding	Fracture	1.8 #/inch	2,27	0.78	1.3	0.87							10	7.5	
(7)		Corrugated Ash. Siding	Fracture	1.8 #/inch	2,27	0.78	1.3	0.87							10	7.5	
		Brick Walls	(see below)														
		Steel frame (w/walls & roof)	Column bending	244k	3152	1.0 & 0.13	1.3	0.59	1572	1.0, 1.8, 2.0	Drag and Reflects	10	C _{up} = 1000	6.4			
		Steel frame (w/walls & roof)	Column bending	281k	3152	1.0 & 0.13	26	0.59	1572	1.0, 1.8, 2.0	Drag and Reflects	10	C _{up} = 950	7.8			
		Steel frame (w/roof only)	Column bending	215k	3152	1.0 & 0.13	26	0.76	1212	1.8 & 2.0	Drag	—	—	6.0			
Flare	Tower Supported	Tower frame	Leeward column buckling	72k	11,05	0.33	1.3	0.52	2416	0.4 & 2.0	Drag				6.4		
		Tower frame	Shear failure of leeward columns and tensile failure of diagonals				26	0.67									
		Tower A, B, Tower Edges, Tower frame	Tensile failure Windward footings uplift Leeward col. buckle				26	1.07									
		Tower frame	Shear failure of leeward columns and tensile failure of diagonals				26	0.88									
		Tower A, B Tower Edges	Tensile failure Windward footing uplifts				26	0.56									
Flare	Guyed	Upper guy	Tensile failure				26	4.1	160	0.1	Drag						
		Middle guy	Tensile failure				26	14.1									
		Lower guy	Tensile failure				26	7.5									
		Upper pin	Pin shear	14,11k	75%	0.23 & 0.66	1.3	4.2									
		Middle pin	Pin shear	14,11k	100%	0.66	1.3	13.8									
		Lower pin	Pin shear	45,8k	80%	0.66 & 0.78	7.4										
		Flare A, B, Base friction	Bolt shear	45,8k	80%	0.66 & 0.78	9.7										
Pipe head		Steel frame	Column bending	19k	7.13	1.0	1.3	0.36	157	0.1 & 2.0	Drag				5.8		
			Frame overturning	19k	7.13	1.0	1.3	1.06	157	0.1 & 2.0	Drag						
			Frame A, B	Bolt shear	19k	7.13	1.0	1.3	2.22	157	0.1 & 2.0	Drag					
			Concrete frame	Column bending	38,6k	119	0.33 & 1.0	1.3	0.40	160	0.1 & 2.0	Drag				6.4	
Cat Cracker	Steel Stack	Concrete fin.	Overturning				5	0.42		0.4	Drag				6.4		
Administration Building	Basement	1st floor slab	Slab collapse	1,42k	202.5		25	6.14			Incident			2.7	2.0		
Storage Tanks	Cone Roof	Roof						0.74									
		Outer roof rafters	Bending				1.3	26	3.33			Inc. load			11.5	8.85	
		Inner roof rafters	Bending						0.67								
		Girders	Bending						1.70								
		Center column	Buckling				1.3	26	1.73						11.5	8.85	
		Columns	Bending (full)				1.3	26	1.73						7.0		
	Spheres		Bending (empty)				1.3	26	2.24						7.0		
		Foundations	Footings uplift (full)				1.3	16.0							7.0		
			Footings uplift (empty)				1.3	3.5							7.0		
		Column A, B	Tensile failure (full)				26	19.3									
			Tensile failure (empty)				26	7.1									

3.8 Fire damage

At a refinery, the nature of fire due to thermonuclear attack is similar to that of a "normal" preattack fire with some special conditions superimposed, namely fallout, thermal radiation, and extensive blast damage. Normal firefighting activities may be quite severely restricted by the arrival of fallout, as discussed below in section 3.9.

The amount of fuel stored and in process in a refinery varies roughly in proportion to the size of the refinery. At the Baton Rouge refinery, production is 334,000 b/d, and fuels in storage tanks amount to a one-day supply. At any given time, the amount of fuel in process in the crude units is much smaller. Ideally, in shutdown, the units will be entirely emptied of fuel, but with a rapid shutdown some fuel may be left in the units.

The extent of fire damage, once started, is governed primarily by the amount of fuel in process or storage. The likelihood of a fire starting in case of attack damage, is much greater for an operating unit. Because of the quantity of fuel processed in the refinery, and the likelihood of fire, the greatest fire hazard is to be found in operating processing units. However, little or no fire hazard exists in units which have been properly shut down. In this case, the fire hazard only exists at the storage units. On the other hand, damage to storage units would be much less serious to the refinery operations than the loss of processing units, since storage is somewhat interchangeable, may not be essential to operation, and can be much more easily reconstructed or repaired.

For one weapon, the sequence of events is: first, the detonation, accompanied by the formation of the fireball and the shock front; second the emission of infrared thermal radiation from the fireball for the duration of its existence; and third, blast damage caused by the blast wave. The initial thermal radiation could provide some additional ignition sources around the plant. Some thermal radiation can arrive at a refinery after the blast wave, although not in sufficient quantities to cause ignition of spilled liquids and vapors, since much less energy is present after the blast for the overpressures considered important here. This is further analyzed in section 3.8.1.

Significant major differences in the repair problem are associated with the question of whether or not ignition occurs. In the Whiting, Indiana disaster, if no ignition had occurred there would have been a tremendous spillage of petroleum, but no fire. In the opinion of those who investigated, the ignition was caused by sparks from the impact of a piece of metal striking and piercing a tank.

The problems of repair, depend upon the nature and duration of the fire. Generally, an operating unit which has been exposed only to blast damage is repairable after sustaining relatively severe damage. For example, large reactor towers have been dropped in the course of construction, and it has been possible to straighten them out, raise them again, and put them into operation. However, a fire at the base of one of these towers would weaken the steel of the vessels themselves seriously and prevent their reuse. In short, the presence of a major fire at a particular location in a refinery can make the difference between an easy or possible repair operation and circumstances under which it would be simpler to reconstruct the unit completely.

Combustible liquids are generally in storage tanks individually surrounded by dikes designed to contain at least half of the volume of the tanks inside them. Hence, the excessive spread of fires from flooding is not likely. An exception is the Pascagoula refinery, which is discussed in section 3.7.4.2.

A brief discussion of the physics and chemistry of the fire problem at a refinery in the environment of a nuclear attack is given in the following section.

3.8.1 Physical and chemical aspects

Three things are required to cause fires: fuel, air or oxygen, and an ignition source. Technically, fires do not occur in liquids, but in their vapors. Hence, the temperature of potential ignition, the flash point of the liquid, the temperature at which appreciable quantities of the vapor

are present, is quite significant. A higher temperature at which the fuel gas will ignite spontaneously, the autoignition temperature, is also quite important.

Some controversy exists over the exact value of this temperature, since it depends to some extent on the technique used for measuring it.⁶² The temperatures listed in table 3.12^{55, 56} are generally derived from large area combustion tests, and represent minimum temperatures and optimum mixtures with air under essentially steady flow conditions. In the table, the broad minimum near C_{12} to C_{16} , characteristic of many of the heavier hydrocarbons present in crude oil, should be noted. More information on these characteristics, and the exact conditions of measurement are given in references 55 and 56.

To simplify the table greatly, petroleum gases released from processing units and exposed to air at temperatures above their autoignition temperatures, possibly from breakage of pipes due to nuclear blast, will undoubtedly ignite without another ignition source. On this account, released liquids and vapors at temperatures above the flash points represent a severe hazard to a refinery because there are many ignition points, particularly furnaces and flares. The heat content of the fluid at the autoignition temperature is the amount of heat energy which must be added to the fluid to cause it to ignite spontaneously. This could theoretically be used to determine the hazard to liquids exposed to the thermal radiation from a nuclear weapon. A gram of the material, absorbing the specified quantity of energy would reach its autoignition temperature, and ignite, in the presence of air.

In the event of a nuclear attack, the sequence of events noted above in the lower blast overpressure range, would involve thermal radiation arriving first, followed by the blast wave, and then more thermal radiation of much less intensity continuing for a period of up to a minute. Few petroleum fuels in a refinery would be exposed to air and thermal radiation prior to the arrival of the blast wave. On the other hand, many could be exposed as a result of the blast. Some fuels might be ignited by metal-to-metal impact as a result of the blast wave; it is doubtful, however, that

Table 3.12

SIGNIFICANT TEMPERATURES ASSOCIATED WITH
FIRE HAZARDS IN STRAIGHT CHAIN HYDROCARBONS^{55,56}

Compound	Autoignition temperature	Flash point	Heat content at autoignition (related to 100°F)	
Methane (C ₁)	999°F	-305°F	701-BTU/lb	391 Cal/gm
Ethane (C ₂)	959	-202°	560	311
Propane (C ₃)	871	-152°	575	319
n-Butane (C ₄)	761	-96°	410	228
n-Pentane (C ₅)	496	-54°	255	142
n-Hexane (C ₆)	433	-15°	—	—
n-Heptane (C ₇)	433	25°	—	—
n-Octane (C ₈)	428	56°	—	—
n-Dodecane (C ₁₂)	399	165°	—	—
n-Hexadecane (C ₁₆)	301	259°	—	—

enough thermal radiation would arrive after the blast to represent a significant hazard to fuels exposed by blast damage.

For example, a 10-MT weapon, at optimum burst height, will yield 5.0 psi overpressure at 9.3 miles.⁴⁷ The blast wave will arrive in about 39 seconds. Of the 70 cal/cm² radiated from the fireball at that radius, given near-perfect visibility, almost 90 per cent would have arrived prior to the blast wave. This only leaves 7 cal/cm² to arrive after the wave, and the rate of arrival would be quite slow, further reducing the incendiary effect. For autoignition, at least 142 calories per gram are required. Since the volume of a gram of liquid product is a little more than a cubic centimeter, it seems unlikely that sufficient energy, at 7 cal/cm², could be absorbed to cause ignition of any petroleum vapors. Further analysis is indicated.

Propane and butane are gases at ambient temperatures and pressures, but are liquids under the high pressures existing within pressure storage tanks. Physical damage to one or more tanks could result in the rapid spread of inflammable vapors over large areas of the plant. Methane is lighter than air, ethane (ethylene, acetylene) is very close to the density of air, but all other hydrocarbon gases are heavier than air and are therefore particularly hazardous, because they do not dissipate but spread along the ground. Ignition sources exist at many locations within the plant, primarily at furnaces, electrical equipment and flares, and when these fuels, mixed with air, reach the source of ignition, a conflagration usually results. If such gases had ignited at their source, a lesser hazard would have resulted, since the fire might have been more localized.

In almost all cases, the petroleum liquids inside the processing units are at temperatures exceeding their flash point, and rupture of one of these vessels is potentially very serious. Even below the autoignition temperature, a flammable mixture of air and fuel will probably come into contact with a source of ignition and ignite. The gaseous detonation at the Whiting, Indiana refinery hydroformer, described below, resulted from such a mixture.

Table 3.13 gives some representative temperatures and pressures present within certain operating units. In many of these units, the temperatures are above the autoignition temperature of the fuels and breakage of pipes by blast would result in an immediate fire. Fires could also be started by sparks generated during the blast by the friction between pieces of metal, as noted, and from electrical sources.^{54, 64}

In studying this problem, the examples of actual fires which have taken place are useful, because the damage from these fires does not differ appreciably from that which could be expected to be caused by nuclear weapons.

Examples of such disasters are the following:

- 1) The fire at the Whiting, Indiana, refinery of American Oil Company in 1955, caused by a detonation in the reactor of the fluid hydroformer.
- 2) The oil froth fire at the Signal Hill, California, refinery of Hancock Oil Company in 1958.
- 3) The explosion at Texas City, Texas in 1947, when two ships exploded in the harbor showering missiles and debris onto petroleum storage tanks, refinery process equipment, and the Monsanto Chemical Plant.
- 4) The earthquake at the Kenai, Alaska, refinery of Standard Oil Company of California on March 27, 1964.
- 5) The earthquake at the Niigata, Japan, refinery of Showa Oil Company on June 16, 1964.

Of the above, 1 and 2 are discussed in this section; item 3 in section 3.7; and items 4 and 5 in section 3.10.

3.8.2 Whiting experiences^{45, 54, 57, 58}

The Whiting fire, on August 27, 1955, started with a detonation in a fluid hydroformer unit. The unit was being brought on stream following

Table 3.13

REPRESENTATIVE OPERATING TEMPERATURES
PRESENT IN SELECTED UNITS

Unit	Operating temperature (maximum)	Pressure
Atmospheric Crude Unit	675 ^o F	7-8 psig
Vacuum Pipe Still	800 ^o F	Vacuum, $\approx$ 2 psia
Fluid Cat Cracker Unit		
Reactor	920 ^o	30 psig
Regenerator	920 ^o	10 psig
Fluid Hydroformer (Whiting Unit)	940 ^o F	225 psig
Ultraformer	920 ^o F	150 psig
Debutanizer	212 ^o F	120 psig
Alkylation Unit	35-40 ^o F	150-175 psig

a turnaround, but had not yet reached full operating temperature. An undetected air leak occurred between the regenerator and reactor via the catalyst circulating lines, when a valve failed to close. Since the temperature was below the autoignition point (about 350°F), the air circulated throughout the unit prior to explosive mixture detonation in the furnace.^{57, 58} After several hours, enough air had leaked into the unit's recycle gas system to form a flammable mixture with the inert gas and naphtha vapor present there. Ignition probably occurred in the furnace tubes developing into a detonation which shattered the 2-1/2-inch-thick walls of the reactor, sending missiles flying throughout the refinery for a distance up to a quarter of a mile.

The sequence of events which led to the detonation constitutes an ever-present hazard under conditions of emergency shutdown. The danger would be particularly severe if a blast wave arrived during the process of shutting down a unit.^{59, 60, 61}

The damage resulting from this detonation consisted of total destruction of the reactor and the regenerator of the fluid hydroformer unit, roof and wall collapse at the controlhouse, extensive damage to piping, but relatively little damage to other adjacent vertical towers in the unit (see figures 3.15 and 3.16). The 600-ton reactor unit broke into 13 major size pieces; one 60-ton fragment traveled 1200 feet. Other blast damage included broken glass and damage to some houses outside the refinery.

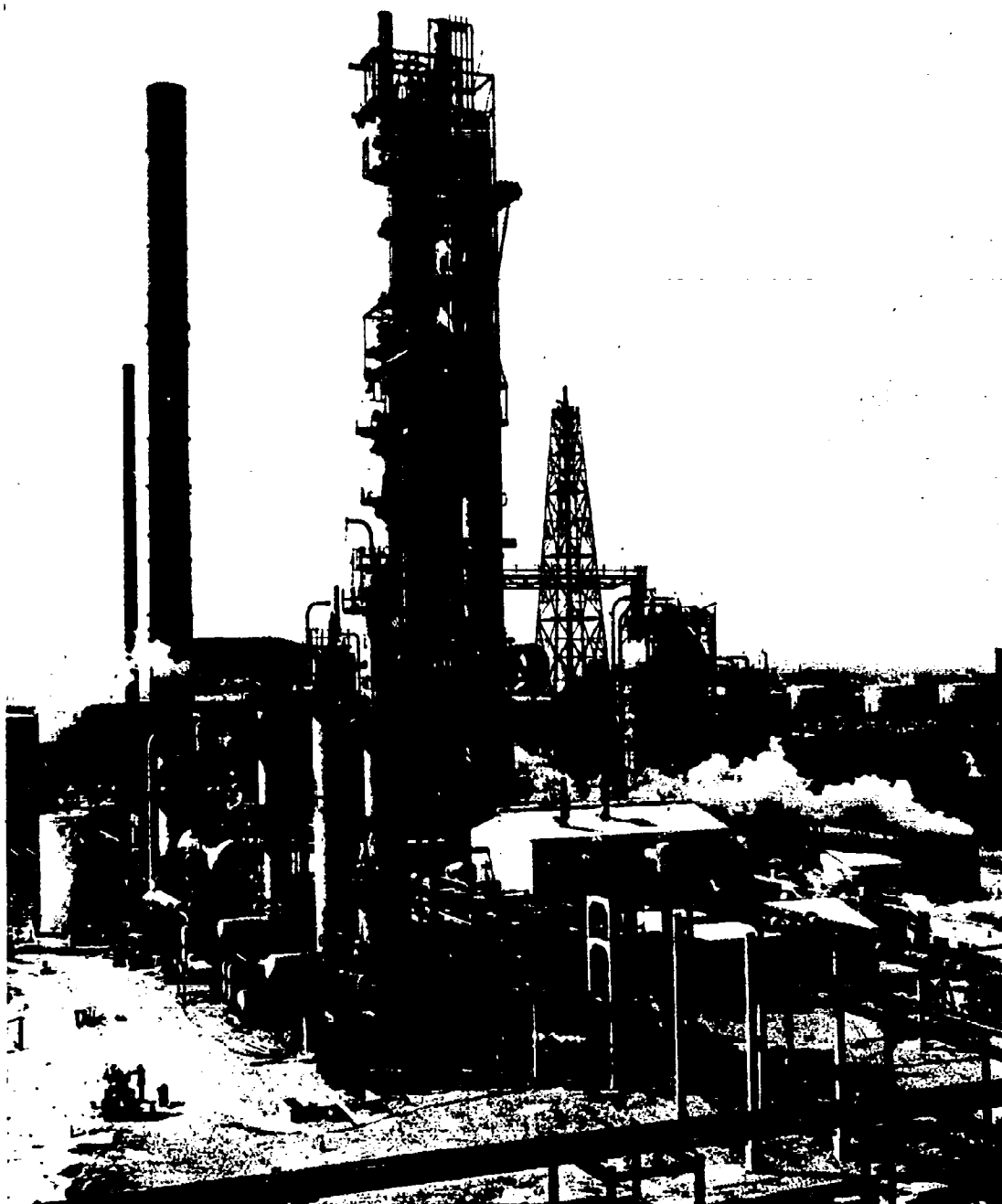
With the exception of the fluid hydroformer unit and one naphtha tank, no units would have required scrapping due to the blast damage alone. Most of the total damage, estimated at more than \$10 million, occurred as a result of the fire, caused by the missiles. The total valuation of the refinery approximated \$350 million, so the extent of damage could be expressed as between three and four per cent.⁵³

Missiles caused the immediate fire in the storage tanks to the north of the fluid hydroformer. Ignition of the oil was thought to have been caused by sparks from metal-to-metal impact.⁵⁴ About 20 tanks were pierced and immediately ignited, and the fire ultimately spread over 47

acres. Once started, the spread of the fire resulted from tanks boiling over, and spillage that could not be contained in dikes.

Firefighting strategy was to contain the conflagration, rather than try to extinguish it, which would have been impossible for such a large fire. Sand was brought in for diking, and water streams used for cooling. On the second day the burning area began to decrease, but it took eight days for the fire to burn itself out. Although 85 days were required to restore the refinery to full crude capacity operation, production reached 50 per cent of capacity less than four weeks after the start of the fire.⁴⁵ Storage tankage lost in the fire was replaced in another location five to eight months later. The fluid hydroformer unit was never rebuilt. Another unit, an ultraformer, was added later, coming on stream for the first time 11 months after the fire. A production recovery chart, showing the time required to resume full operation after the fire, is given in figure 3.17, and is indicative of postattack recovery time after a serious tank fire. Conclusions to be drawn from the Whiting fire are:

- 1) The fluid hydroformer unit explosion might be duplicated under some conditions of blast wave arrival during shut-down. The conditions required would include breakage of pipes or valves at some locations which would permit air to enter the system; presence within the unit of flammable vapors below their autoignition temperature; the development of an explosive mixture circulating within the unit, and its ignition.
- 2) Considerable damage to storage units can occur, but loss of production depends primarily on the extent of damage to operating units.
- 3) Advance planning and training of personnel for emergencies as was done at Whiting can do much to reduce loss of life and property and contribute to efficiency of action in a disaster.
- 4) Tank fields should be separated from process areas.



The Fluid Hydroformer Before the Explosion

Figure 3.15



The Fluid Hydroformer After the Explosion

Figure 3.16

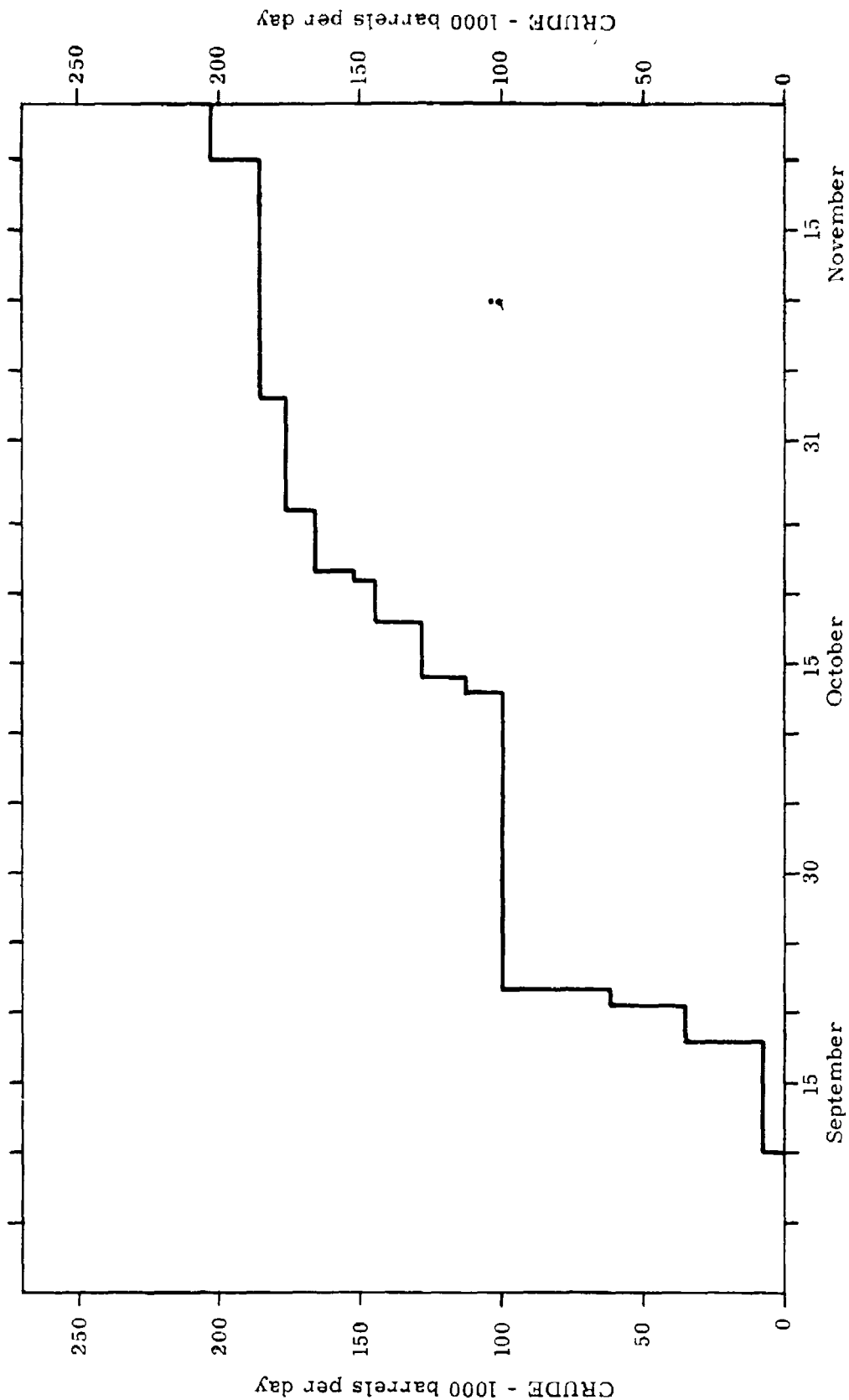


Figure 3.17 Recovery of production following the 1955 Whiting fire 45

- 5) Tanks should be adequately spaced, and each tank should be individually diked with no drains or connections through dikes.
- 6) If a tank fire cannot be extinguished, at least it must be contained.
- 7) Missile damage from blasts is more of a hazard to storage tanks than to process units.

3.8.3 Signal Hill⁶⁵

This fire started from an oil froth wave (or boilover) which emanated from a residual oil storage tank. The tank was normally maintained at 300°F by a hot stream of residual bottoms coming from the straight-run unit fractionating tower of 20,000 b/d capacity. Part of this stream was diverted to the tank in question, and the rest went to the thermal cracking unit. There were no steam coils in the tank. On the morning of the fire, the temperature in the tank was 315°F. The cause of the oil froth is not definitely known. It may have resulted from a layer of water in the bottom of the tank becoming overheated, a sudden disturbance of the water, or by pumping water into the tank by mistake. The tank capacity was 80,000 barrels, and was filled to about 50,000 barrels. It had a cone roof and a diked area capable of retaining 75 to 100 per cent of the tank's capacity. Because froth volume far exceeds the volume of the oil from which it is derived, the oil froth wave eventually spread out over an area of about 27 acres. It did not ignite at first, but a second froth wave about 8 or 10 minutes later did ignite, spreading burning oil from both waves throughout the processing area and into storm drains.

There was no time to shut down processing equipment, but depressurizing took place because of pipeline failures. There was no serious damage to major structures in the process areas, but piping, wiring, and instruments were extensively damaged. Insulated and fireproofed supports remained relatively undamaged, but unprotected steel buckled.

Within two hours the fire had been extinguished everywhere except in the tank farm section where it lasted 40 hours. The tetraethyl lead weigh tank building was dangerously exposed, but no damage was sustained at the building or at the tetraethyl lead tank where water was used to reduce the heat. The storage tanks did not have fixed foam chambers, but many were protected by water streams, and foam was used in the diked areas. The damage amounted to \$9 million, of which about half was outside the refinery. An interesting aspect of this fire is the relatively mild damage suffered by major processing structures. Most of the damage was to storage tanks, piping, and instruments.

3.8.4 Firefighting methods

Firefighting facilities presently installed at a refinery are generally inadequate in extinguishing a widespread fire in a tank farm and operating units as a result of an attack. Outside assistance will certainly be required in such circumstances. Nevertheless, fires started by an attack of the same magnitude as those heretofore experienced by refineries could be combatted with existing firefighting equipment, supplemented by outside help from local fire stations.

The methods and equipment currently used in fighting refinery fires are, as follows:

- 1) Application of foam.
- 2) The use of water to cool threatened steel equipment and retard the spread of fire.
- 3) Removal of the burning liquid.

Supplementary methods are carbon dioxide extinguishers and fog nozzles. Air agitation is sometimes used for storage tanks in some services, but this is not applicable everywhere or universally accepted.

The foam is a mixture of a foaming agent and water, containing carbon dioxide gas trapped in the form of bubbles. It floats on the surface of a burning liquid, excluding air, and thus smothers the fire.

Some storage tanks have foam pipes attached to their sides with foam chambers for inserting the foam into the tank interior mounted high up on the tank's walls. Pipes are run from a connection outside the dike, through the dike to the foam chamber. In case of fire a foam truck is brought to the scene, and one line from the foam truck is attached to this connection while another is connected to the nearest water hydrant.

Other tanks have no foam chambers or piping, and, for these, foam towers are erected next to the burning tank. The foam tower must be brought to the site with the foam truck and connected in the same manner as if there were a foam chamber and fixed piping. The height of the foam tower is varied either by a section of telescoping tubing and a hydraulic extending mechanism, or by the pressure of the foam itself.

Opinions of the effectiveness of foam systems vary. It is most effective for two-dimensional fires, where the liquid and fire are on a single plane. For three-dimensional fires, complicated by a stream, flow or free vapor, foam is not particularly effective and the way to fight the fire is by removing the fuel or letting it burn itself out.⁶⁶ Removal of fuel usually means closing a valve to interrupt the flow, then waiting for the fire to consume the remaining fuel and thus put itself out. Another possibility, in connection with storage tanks, is to pump the liquid out of the tank into a slop tank.

The use of water, or quenching, essentially removes heat from the fire. The most effective equipment are turret nozzles, which are located in key spots through the refinery, and can be put in operation by one man and left unattended thereafter.

Air agitation is sometimes used in fighting tank fires in conjunction with foam, although opinions vary as to its usefulness.⁶⁷ Its use is based on the fact that petroleum products or crudes will burn only when flammable vapors and air are present about the surface of the liquids in the correct proportions:

FLAMMABLE LIMITS
IN AIR
PERCENTAGE⁶⁰
(by volume)

	<u>Lower</u>	<u>Upper</u>	Flash Point OF <u>Closed Cup</u>
Butane	1.9	8.5	-76
Carbon Monoxide	12.5	74.0	gas
Gasoline	1.4	7.6	-50
Hydrogen	4.0	75.0	gas
Kerosene	0.7	5.0	115-150
Propane	2.2	9.5	gas

A change outside these limits will extinguish the fire. It is most effective if the surface temperature of the liquid can be reduced below the flash point. Air agitation rates vary, depending on viscosity, from 2 to 8 cfm/100 ft.² of liquid surface, for 50 centistokes or less, to 8 to 25 cfm/100 ft.² of liquid surface for more viscous liquids.

In crude oil fires, there is a heat wave which travels toward the bottom of the tank as the fire progresses. If a water bottom is present, this will cause a "boilover" when the heat wave reaches the water and causes it to "flash" to steam. Air agitation can cause a boilover by mixing the water with the hot oil and causing it to turn to steam. When foam is applied, on the other hand, a "slopover" can occur, but air agitation will prevent this by mixing and cooling the hot surface layer. Boilover can be prevented by starting the air agitation at a low rate and gradually increasing it.

Air agitation, based on tests made by Creole Petroleum Company, is most effective at oil depths ranging from full tank to six feet, while oil depths from six to three feet require progressively more air.⁶⁷ At depths of less than two feet of oil, it is essentially useless. It alone can extinguish fire only if the liquid temperature at the surface drops below the flash point.

It can also be used to hold fires in low flash products such as gasoline, jet fuel, or crudes at reduced intensity for long periods of time, thereby reducing the hazard and the damage to equipment.

High explosives are regularly and successfully used to extinguish oil fires, in the case of flowing oil wells. The technique involves, first, the removal of any hot metal pieces from the vicinity of the fire, using a crane, to prevent reignition. Next, the explosive is detonated to blow out the fire. Finally, the well is capped and the combustible liquids are removed. Explosives are not often used in refinery fires.

3.8.5 Fire conclusions

- 1) An operating refinery will probably burn and destroy itself at levels of blast which cause pipe breakage at approximately 5-7 psi.
- 2) Thermal radiation presents slight additional hazard. Ignition sources present are sufficient to cause a major fire. Fires could be worse in some cases if ignition is delayed. A few additional ignition points might result from thermal radiation, at the few places where petroleum vapors might be exposed to both air and the thermal radiation. Thermal radiation hazards merit further investigation.
- 3) Fire hazard to a shut down refinery exists primarily in storage tank areas. Such a fire, if it can be contained in the tank areas, would not result in the extreme repair problem of the damage to controlhouse instrumentation or damage to operating units.

3.9 Fallout

Fallout is essentially a hazard to personnel, rather than to crude oil or products, and the anticipated problems involved in refining clean-up of contamination are covered in prior studies.^{38, 39} The danger to personnel could result in a too-hasty shutdown, or no shutdown at all, in the face of imminent arrival of fallout. If this happened, improper shutdown could account for considerable damage at the refinery, even in the absence of blast or thermal radiation damage. The potential value of adequate fallout shelter protection, at least for essential shutdown personnel, requires little additional justification.

Shelter areas could be provided in the administration buildings at refineries. If there is a basement, it is possible to construct a shelter capable of withstanding an overpressure of 3.5 psi, in addition to the partial collapse loads of the floors above it, or 5.5 psi if there is no collapse of the floors above (see reference 69). In the event there is no basement in the building, as might be the case in an area where ground water is a problem, it is anticipated that interior corridors in the middle floors of the building may provide fallout protection factors of 100 or better. No stocked, marked fallout shelters were found at any of the refineries visited.

3.10 Refinery shutdown and startup

3.10.1 General discussion

Assuming a labor force that is adequate both in numbers and in degree of shutdown training, the extent of shutdown will depend on the time allotted to it—probably determined by the amount of warning time—or on estimates of the probability of attack directed at the particular refinery or its vicinity, or a combination of both.

Warning time could range from as little as 15 minutes up to days or even weeks. Shutdown operations should be performed on a pre-planned "first things first" basis, and even 15 minutes will permit a few important steps which could conceivably avoid widespread destruction as occurred at Niigata, Japan, in the June, 1964 earthquake, described below.

There is at least one example of virtually immediate, no-warning shutdown, afforded by the experience of the Baton Rouge refinery of Humble Oil, also described in this chapter.

If there were as much as 4 hours warning time, a relatively normal shutdown could be accomplished. At the Whiting fire, for example, this was done in spite of the major fire developing nearby. The fluid cat cracker was put through a safe, orderly shutdown, over the course of several hours.^{45, 54}

Fire is frequently a secondary, or indirect, effect of blasts of all kinds, and fire damage would probably be much less in the case of a shutdown refinery than in the case of an operating one. The quantities of volatile substances, under conditions of high temperatures and high pressures in furnaces, catalytic cracking reactors, regenerators, and light ends fractionating towers represent a considerable fire hazard under normal circumstances, and would be much more so under blast. A shutdown refinery would not be subject to these conditions and would obviously be much less subject to fire damage following blast.

3.10.2 Normal shutdown and startup

Normally it takes several hours to shut down a processing unit, because lines must be purged with steam and furnaces should be allowed to cool gradually. In the FCCU Units at the Baton Rouge refinery, for instance, shutdown normally requires 4 hours to prevent coking in the furnace coils. Equipment is turned off and emptied in a predetermined sequence and flushed out with steam and water during the shutdown period.

Normal startup of a crude unit involves leak tests, careful equipment checks, hydrostatic testing with water for leaks in vessels, and gradual heating with light oil to purge air from the system to avoid the formation of explosive mixtures.

In the fluid catalytic cracking units, the normal shutdown involves circulating and withdrawing the catalyst. If oil were lost before the catalyst could be removed, remedial action would be required to prevent slumping and plugging of lines. Steam injection automatically cuts in to prevent this and it also prevents excessive temperatures in the reactor (normally running at 900° - 950°F).

3.10.3 Rapid shutdown

Although normal shutdown requires several hours, an operating refinery can, if necessary, be shut down in a few minutes and there are instances when this has happened. Most refineries have some sort of procedure to be followed in an emergency if processing units have to be shut down rapidly.

Probably the best documented example of a rapid shutdown is in Esso's Report on Emergency Shutdown.³⁷ This describes the power failure at Humble's Baton Rouge refinery on April 29, 1960, which resulted in loss of steam and electric power throughout the entire refinery in a few minutes. The power failure occurred at Gulf States' Louisiana station, which at that time supplied almost all of the refinery's power and steam except for a small quantity of 200 psi pressure steam purchased from an adjacent chemical plant and a small amount of power generated at the refinery's own power station.

The refinery's own power station picked up the load at the time of the failure at Gulf States but, although the load was diminished because of some equipment kicking out on low voltage, the power station was overloaded and forced to shut down. Shutdown of refinery processing units resulted primarily from loss of air pressure needed to operate vital instruments. This "instrument air" is supplied by several electric motor-driven air compressors scattered throughout the refinery, and almost all operating units depend on it for the controls. As previously noted, they are designed to "fail safe", that is to operate for maximum safety following air failure. Process furnace fires were put out as rapidly as possible. Large quantities of gas were burned in flare stacks and no serious injuries or fires occurred and no injuries to personnel resulted. The damage to refinery equipment was surprisingly small.

The total cost of the shutdown, including lost production of products, raw materials "flared" (deliberately burned), losses of process chemicals, and mechanical damage, has been estimated at slightly over \$1 million, or approximately the value of one days' supply of crude oil.

Since water was supplied by electric motor-driven pumps, there was a loss of water for processing, cooling towers, and firefighting. Although a tie-in was made to city water mains, this probably would not have been adequate if fire had broken out.

The most serious process equipment damage happened to the pre-heat furnaces at Nos. 1 and 2 catalytic cracking units, and the furnace at the No. 4 steam cracking unit. Some of the cyclones at No. 2 catalytic cracking unit were plugged with coke, and excessive catalyst losses limited production to 80% of normal, for several weeks following the shutdown.

Operations were resumed gradually, beginning 28 hours after the shutdown with the operation of the refinery boilerhouse, next with the large pipe stills, and then with light ends units, in that order.

Other instances of sudden shutdown have been analyzed at Creole Petroleum Company in Venezuela because of labor stoppages, and for Baytown refinery of Humble Oil & Refining Company in connection with radioactive fallout following a hypothetical attack.³⁸ It was assumed the refinery would be undamaged by blast and thermal radiation effects of nuclear explosion, and that it would remain shut down for two weeks. Table 3.14 summarizes the data. Because of lines plugged with catalyst, the catalytic crackers show the longest period (4 to 6 weeks) of repair prior to resumption of production. This estimate is in direct contradiction with what actually happened at Baton Rouge, where the three catalytic crackers were down only 60, 141, and 84 hours respectively. The difference can be explained in three ways: 1) the fact that at Baton Rouge, personnel stayed on the job and may have been able to take some measures which prevented most of the catalyst plugging and furnace coking, whereas it was assumed in the Walter Kidde study, that

Table 3.14

STARTUP AFTER SHUTDOWN DATA
AT BAYTOWN REFINERY
HUMBLE OIL & REFINING COMPANY³⁸

UNIT	FEEDSTOCK	STARTUP	
		Normal	After emergency shutdown and 2 week idleness
CRACKING AND POLYMERIZATION:			
Catalytic Light Ends Units #1 and 2	light ends fractions from catalytic cracking units	8 hrs.	4-5 days—check heater, pump seals, repair refractory
Catalytic Light Ends Unit #3	gas products from fluid catalyst cracking units	36-48 hrs.	4-5 days—repair refractories in heater
Catalytic Polymerization Unit	olefinic gases from catalytic light ends units	12 hrs.	4-5 days—check furnace, repair refractories, clean reactors where plugged, check pumps, recharge refrigerant
Fluid Catalytic Cracking Units #1, 2, and 3	gas oil feed from storage	48-60 hrs.	4-6 weeks—disassemble, clean and deplug all lines and equipment, replace catalyst
LIGHT ENDS:			
Alkylation Unit	olefin gases and isobutane feed from storage	16-24 hrs.	4-5 days—recharge reactors with acid
Light Ends Fractionating Unit	treated feed stock from catalytic light ends units and alkylation units	24-48 hrs.	4-5 days
Naphtha Fractionating Unit	treated feed from storage	18 hrs.	4-5 days—clean furnace, repair refractories, check pumps
Debutanizers	treated feed from storage	24-48 hrs.	2-3 days—check pump seals, instrumentation, relief and regulator valve

TABLE 3.14 (continued)

UNIT	FEEDSTOCK	STARTUP	
		Normal	After emergency shutdown and 2 week idleness
DISTILLATION: Booster Station #1	off gases from various processing units	several hrs.	24 hrs.—purge of air
Air Station #1	produce compressed air	immediate	immediate
Hydrodesulfurization Units #1 and #2	oil feed from storage	24-36 hrs.	6-7 days—check heaters, repair refractory, clean out coked up catalyst and product lines
Pipe Stills #3, #4, 5 and 6	crude petroleum from storage	12-18 hrs.	3-4 days—clean vacuum tower bottoms, tower bottom pump, and lines. Check heaters and repair refractories.
TREATING: Effluent Filtration Unit	filters waste to remove oil	6 hrs.	6 hrs.—clean filters
Girbotol Unit	gas feed from LEFU & CLEU	4-6 hrs.	48 hrs.—check unit
Hydrofiners #1, 2 and 3	feed from storage	16-20 hrs.	3-4 days—coked furnaces and reactors need cleaning, repair refractories
SOLVENTS: Benzene Unit	—	—	—
Hydroformer Units #1 and 2	desulfurized naphtha feed from storage	8-12 hrs.	5-7 days—regenerate coked catalyst. Descale heater tubes and decoke. Repair refractories
Naphtha Units	feed from pipe stills and storage	4-8 hrs.	4-5 days—decoke heaters and repair refractories

90 per cent of the operating personnel, after receiving the alarm and orders to shut down, would elect to return home to be with their families and would remain at the plant 10 minutes at the most, 2) the fact that at Baton Rouge the operating procedures and action taken at the time of the emergency were above average in effectively limiting the damage caused by catalyst plugging, and 3) the fact that any catalytic cracker can be operated at reduced capacity without the furnace, and that this was actually done at Baton Rouge for several weeks.

An example of the consequences of delayed shutdown may be afforded by the Niigata, Japan refinery fire, in which damage was far greater than that caused to an Alaskan refinery by a more severe earthquake.⁷⁰ There are two small refineries in Niigata, one owned by Nippon Oil Company, the other by Showa Sekiyu K. K. There was considerable damage at the 47,000 b/d Showa refinery, where crude oil and gasoline storage tanks caught fire and burned out of control for several days. Tetraethyl lead tanks nearby were threatened, and had they caught fire, a poisonous smoke would have been loosed over the city. A tsunami flooded the site and floating oil also ignited. By way of contrast, the Alaskan earthquake, three months earlier resulted in relatively minor damage to the Kenai (Alaska) refinery, even though the quake was more severe: 8.5 on the Richter scale vs. 7.5 for Niigata. The vastly smaller Kenai damage may have been due to better shutdown procedures, particularly in turning off certain critical feed lines. In Niigata, the feed lines were not cut off before the fire spread, and fire-fighting operations were further hampered because all main water lines were damaged and electricity cut off. The cut-off of these utilities may have led demoralized employees to abandon shutdown operations sooner than might otherwise have been the case.

3.11 Preattack damage estimation method

On the basis of the calculations of blast damage completed for this study, a list of generalizations can be made of the vulnerability of the critical units of a refinery.

- 1) The vulnerability of controlhouses is essentially the same at all refineries in that severe damage to instruments and controls will result at an extremely low overpressure by the collapse of roofs and masonry walls.
- 2) Water cooling towers at all refineries will suffer severe damage at a very low overpressure.
- 3) The blast vulnerability of processing units—crude stills, catalytic crackers, etc.—is less for newer units than for older ones. Newer units generally use reinforced concrete pedestals and structures for supporting large vessels and towers; older units use structural steel supports. Although designed for the same wind loads, the former are stronger in cases of high dynamic loading because design of newer units is cleaner and more compact. This reduces the projected area and also the drag coefficients at high Reynolds numbers. This condition is particularly marked in the case of fluid catalytic cracking units, where the older units have their vessels mounted in and surrounded by a massive steel structure.
- 4) The blast vulnerability is independent of the unit's capacity, except that smaller units will benefit from shielding more than large units.
- 5) Structural damage caused by blast is essentially the same whether the unit is operating or not. The fire hazard will be much greater if the unit is operating. An operating refinery will be severely damaged by fire at 5 psi, when blast causes pipe breakage.
- 6) Tower-supported flare stacks are more vulnerable to blast than guyed flare stacks, because the drag loading on guys is insignificant compared to that on tower supports.

A generalized method of analyzing a structure subject to blast loading is shown in figure 3.18, which is prepared in accordance with the method detailed in reference 69, and summarized as follows:

- 1) Determine the static structural resistance to a loading in the mode of the expected dynamic loads. In the usual case, where bending is involved, use plastic design principles to evaluate the plastic moment, M_p , of the structural sections, based on the appropriate bending formula for the type of member involved and solve for the allowable static loading. Subtract dead load, if any, from the allowable static loading to arrive at net resistance, R .
- 2) Determine the natural period of the structure or member: The weight of the structure or member (including the weight carried) must be computed. Calculate the effective stiffness k_E , and use the appropriate load-mass factor, k_{lm} .
- 3) Assume a loading configuration; based on the resistance calculated in step 1, assume an expected peak incident overpressure, p_{so} , and find the corresponding positive phase duration, calculate the appropriate duration of the loading function applying to the structure being investigated.
- 4) Find the capacity of the structure or element in terms of maximum overpressure which can be withstood: Assess a value of ductility, μ , based upon the use and nature of the structure, and the engineer's judgment. Calculate the time ratio, C_t , and find the corresponding value of the C_r factor. Use the relationship, $C_r = R/B$, to find peak load, B , from the computed resistance, R . Finally, find the level of peak incident overpressure, p_{so} , with which the drag or reflected pressure loading, $B = q_0$ or p_{ro} , is associated.
- 5) If the critical loading is a reflected pressure, the resistance can be checked using a polygonal loading diagram. The overpressure and reflected pressure calculated in step 4 above is used as an assumed loading and a required resistance computed for comparison with the furnished resistance.

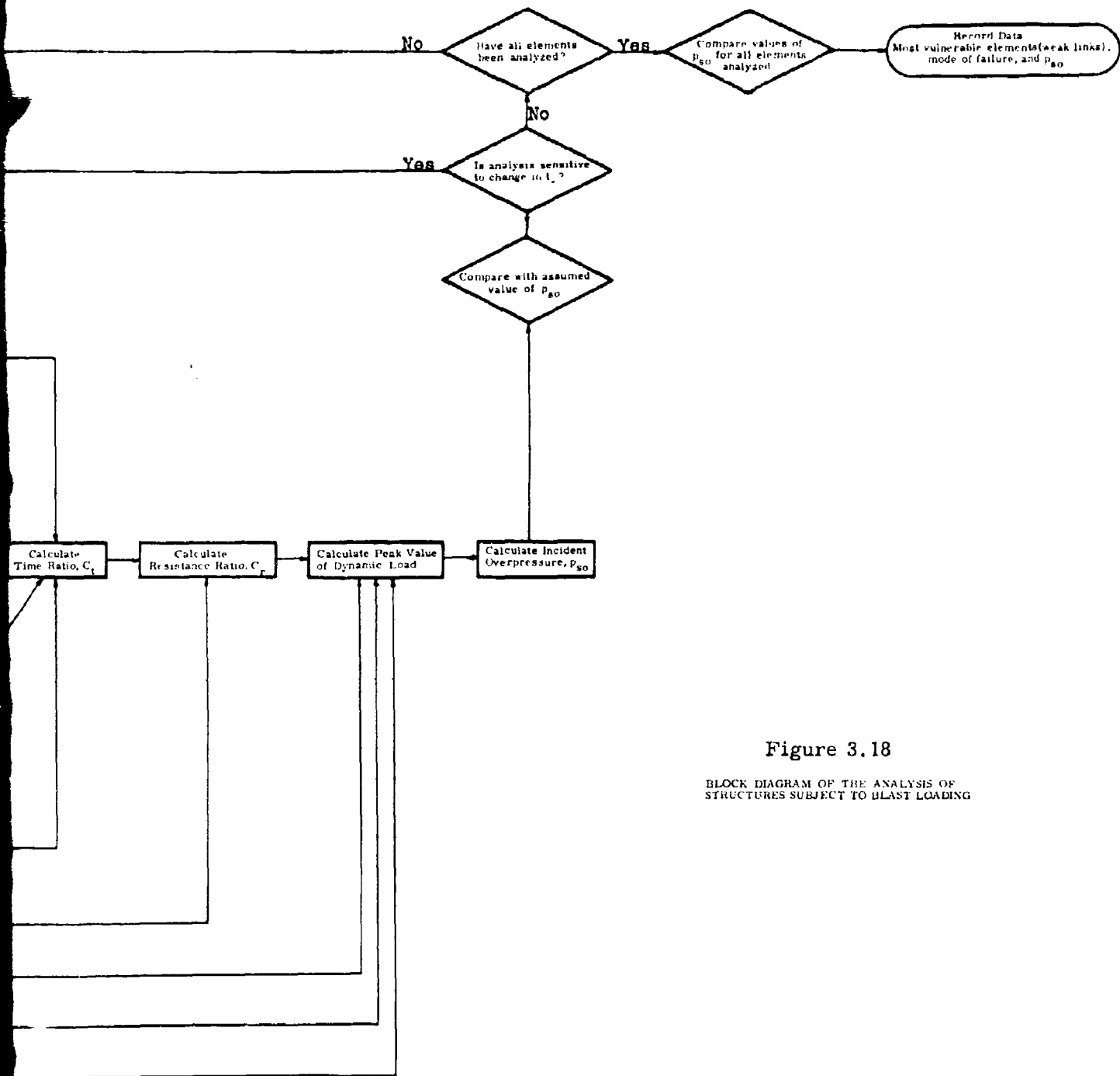
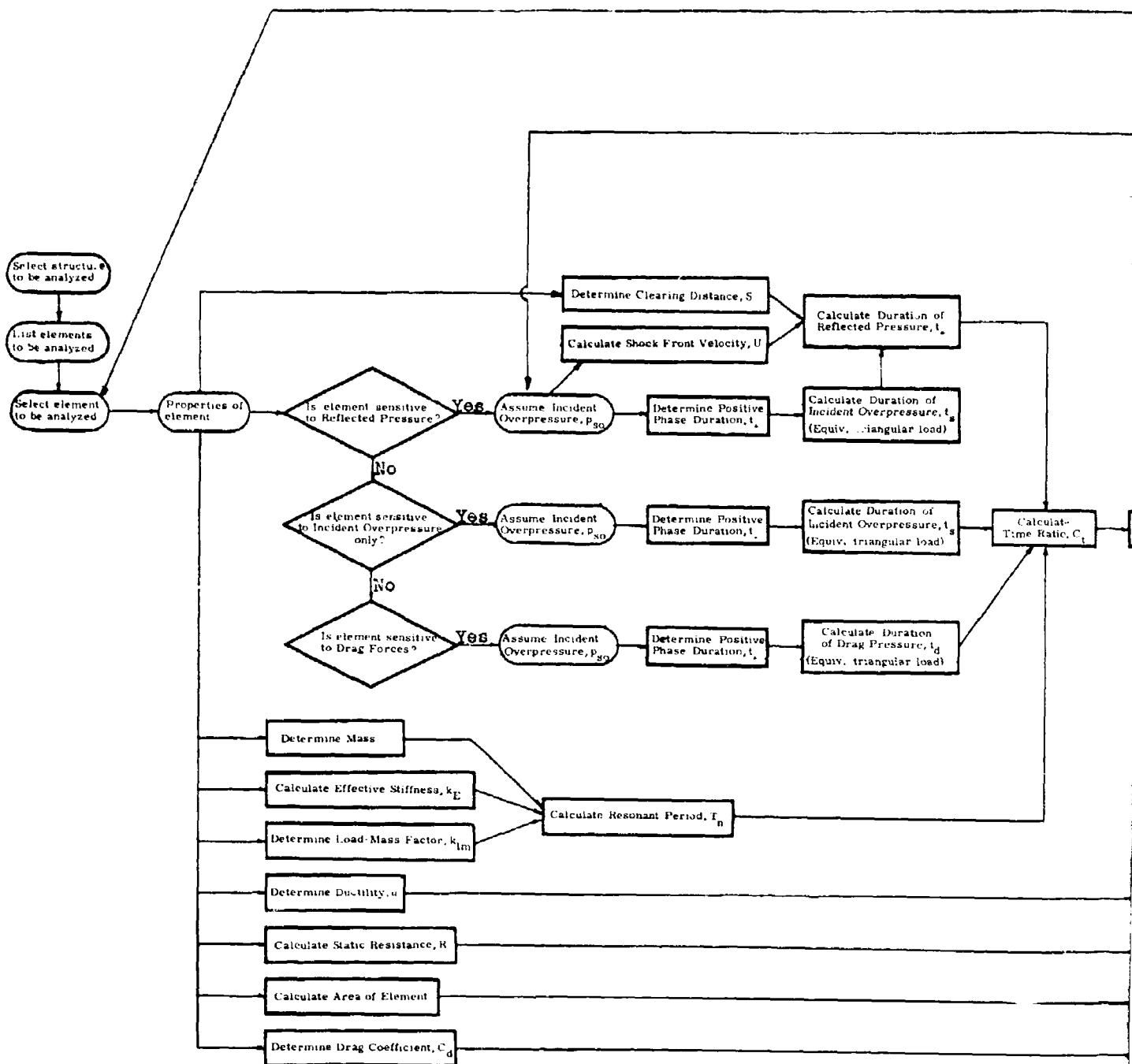


Figure 3.18

BLOCK DIAGRAM OF THE ANALYSIS OF
STRUCTURES SUBJECT TO BLAST LOADING



Source: Advance Research, Inc.

3.12 Weak links

The analysis of controlhouses and water cooling towers indicate they are the weak links and are extremely vulnerable at very low overpressures.

The collapse of controlhouse roofs between 1.0 and 1.5 psi, will cause considerable damage to instruments and switchgear, which means that the entire process system of the particular units is shut down. A process unit such as a cat cracker cannot be run manually and sectionalized, and still produce a consistently acceptable product, because there are too many valves to be opened, kept open for a certain period of time, and then closed again and because there is extreme danger of explosion when such a unit is run manually. A consistently acceptable product would be one which present-day engines could use without causing preignition, thereby ruining the engine. Missile damage from shattered glass at overpressures greater than 0.5 psi, would also compound the overall damage to instruments.

Although water cooling towers collapse at an overpressure of 1.5 psi, they would be repaired in less time than that required for the controlhouses. This does not mean that they are not important to oil refining, because without a water cooling process a refinery cannot operate. They are merely less of a weak link than controlhouses.

Another possible weak link is curtailment of tanker shipments or port facilities. For example, virtually all of the crude oil arriving at East Coast refineries—with 16 per cent of the nation's capacity—comes by ship, and none comes by pipeline. One possible solution would be to convert existing natural gas lines to crude oil.

4. POSTATTACK REPAIR

4.1 Refinery repair

4.1.1 General

Postattack repair of refineries depends on eight main considerations: (1) the products most needed in the survival period, (2) the requirement that a refinery operate as a unit, that is, the requirement for balanced operations, (3) the damage level at a particular refinery and the relative damage levels at other plants, (4) the availability of construction equipment and tools needed for repair, (5) the availability of replacement materials and parts needed for repair, (6) the salvage of damaged equipment, (7) the availability of labor with the skills needed for repair, and (8) the availability of blueprints and mechanical drawings both for repair and rebuilding.

The first and third considerations will determine which refineries and how much of them should be repaired first. For example, if aviation gasoline is in demand, given TEL availability, then those refineries with high alkylation capacities should be repaired first. In the event TEL is not available, aviation gas could be used for motor gasoline since the octane number of avgas without TEL is an adequate substitute for motor gas. A breakdown of the large refineries with capacities exceeding 100,000 barrels/day into the capacities of their principal processing units is given in table 4.1. A more complete list is given, for example, in reference 10. With a listing such as this, and an evaluation of the extent of damage suffered at each of these refineries, repair priorities can be determined in order to meet special postattack requirements for certain fuels. Reference to figure 3.5 in section 3.7.2 will locate the units which produce the products shown as headings in table 4.1.

The second consideration determines what units are required and the sequence in which they are placed "on stream." These minimum requirements are discussed in two specific areas in section 4.1.2.

The third largely determines feasibility of repair. Where damage is so widespread that major towers and structures have been overturned and destroyed, extensive fires have occurred, and there is little or

Table 4.1 U.S. REFINERIES WITH OVER 100,000 B/D CAPACITY, BY STATES¹⁰

Company and location	Crude capacity—		Vacuum distillation	Thermal operations	Catalytic cracking—		Hydrogen treating—		Alkylarion	Polymerization	Lubes	Coke (tons)	Asphalt
	b/cd	b/sd			Fresh feed	Recycle	Catalytic reforming	Unit						Feed
California													
Mobil Oil Co.—Torrance	110,000	114,000	42,000	23,500	32,700	23,400	20,000	24,400	SR&crkd. gaso.	4,200 (f)	800	.....	1,400
Richfield Oil Corp.—Watson	165,000	173,000	75,000	60,000	65,500	28,500	32,000	32,000	SR naph.	7,200 (s)	2,560	.....	3,500
Standard Oil Co. of California—El Segundo	150,000	NR	76,000	70,000	40,000	15,000	30,000	28,500	Other	5,400 (s)	.....	.....	8,325
Richmond	190,000	NR	50,000	57,500	40,000	15,000	40,000	40,000	Other	4,500 (s)	.....	10,000	11,100
Tidewater Oil Co.—Avon	135,000	142,000	74,500	20,000	47,000	.....	32,500	34,000	SR naph.	6,000 (s)	.....	1,670	1,200
Union Oil Co. of California—Wilmington	106,500	112,500	83,000	10,000	34,000	4,000	13,000	34,000	SR naph.	5,000 (s)	.....	.....	6,700
Delaware													
Tidewater Oil Co.—Delaware City	140,000	150,000	90,700	.....	62,000	44,000	45,000	30,000	SR naph. Mid. dist.	5,000 (f)	5,100	.....	1,200
Illinois													
Shell Oil Co.—Wood River	194,000	200,000	79,000	20,000	76,000	16,000	52,000	60,000	SR naph. Mid. dist. Lubes	13,500 (s)	.....	4,200	425
Indiana	207,000	215,000	113,000	.....	111,000	12,000	43,000	54,000	SR naph.	15,000 (s)	.....	7,400	1,470
American Oil Co.—Whiting	114,000	120,000	47,000	30,000	36,000	7,200	20,000	22,000	SR naph.	5,000 (f)	2,450	2,750	.....
Sinclair Refining Co.—East Chicago	.....	.....	.....	.....	.....	.....	.....	3,500	Lubes	.....	.....	.....	4,000
Louisiana													
Cities Service Oil Co.—Lake Charles	185,000	190,000	42,000	12,000	98,000	62,000	23,000	.....	.....	17,000 (s)	.....	.....	.....
Humble Oil & Refining Co.—Baton Rouge	362,000	375,000	141,600	40,000	175,400	11,700	38,000	3,800	Solvent	23,800 (s)	7,800	12,000	1,125
.....	.....	.....	.....	.....	.....	.....	.....	11,000	Lube oil	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	800	Wax	.....	.....	.....	.....
Shell Oil Co.—Norco	152,000	157,500	58,000	14,200	72,000	20,000	18,500	10,000	SR naph.	12,000 (s)	.....	.....	3,500
.....	.....	.....	.....	.....	.....	.....	.....	25,000	Cat. feed	.....	.....	.....	.....
Mississippi													
Standard Oil Co. (Kentucky)—Pascagoula	100,000	105,000	43,000	.....	26,000	25,000	32,000	18,000	SR naph.	6,000 (s)	.....	.....	.....
New Jersey													
Humble Oil & Refining Co.—(Bayway refinery)	168,000	177,000	73,800	12,500	95,000	45,000	22,000	35,000	SR naph. Mid. dist.	10,700 (s)	5,000	.....	15,000

Table 4.1 U.S. REFINERIES WITH OVER 100,000 B/D CAPACITY, BY STATES

Company and Location	Crude capacity— b/d		Vacuum distillation	Thermal operations	Catalytic cracking		Hydrogen treating		Production capacities, b/d			
	Feed	Resid.			Fresh feed	Recycle	Catalytic reforming	Unit	Feed	Alkylaromatics	Polymerization	Asphalt
Pennsylvania												
Atlantic Refining Co., Philadelphia	155,000	160,000	93,000	16,000	54,000	10,000	25,000	14,000 25,000 2,400 Wax	SR naph. Med. dist. Wax	1,500 (a)	1,100	12,000
Gulf Oil Corp., Philadelphia	107,000	192,000	82,000	22,500	60,000	20,000	32,000	30,000 52,000 15,000	Med. dist. SR naph. Lubricants	4,000 (a)	4,000	
Sinclair Refining Co., Marcus Hook	134,000	140,000	71,000	27,000	40,000	8,000	22,000	22,000 10,000	SR naph. Med. dist.		1,800	
Sun Oil Co., Marcus Hook	NR	154,000		24,000	151,000		35,000	15,000	Med. dist.	1,000 (d)	12,000	
Texas												
American Oil Co., Texas City	171,600	177,600	70,000		120,000	55,650	42,000	42,000	SR naph.	27,200 (e)	1,100	450
Gulf Oil Corp., Port Arthur	276,000	284,000	129,500	26,000	105,000	23,000	67,000	50,000 13,000 67,000	Med. dist. Lubes SR naph.	9,500 (a)	6,000	550
Humble Oil & Refining Co., Baytown	270,000	290,000	155,000		128,000	26,000	54,000	104,500 43,000 25,000 9,400	SR naph. Med. dist. Lubes Solvents	21,000 (a)	3,500	11,800
Mobil Oil Co., Beaumont	220,000	235,000	73,500	23,000	93,000	10,000	44,000	44,000 42,000	SR naph. Med. dist.		3,000	100
Shell Oil Co., Houston	138,000	142,000	60,400	21,000	32,000	21,000	35,000	36,000 40,000 7,000	SR naph. Med. dist. Lubes	8,000 (a)		1,300
Sinclair Refining Co., Houston	174,500	183,000	72,000	14,000	50,000	30,000	38,000	35,000 15,000 6,300	SR naph. Med. dist. Lubes		5,400	
Texaco Inc., Port Arthur	310,000	NR	108,000	54,000	135,000		60,000	60,000 12,000	SR naph. Med. dist.	13,600 (a)	1,800	200
Average of All	185,000	185,000	77,210	23,630	76,331	22,012	35,062	61,055		10,100		

Table 4.1 U.S. REFINERIES WITH OVER 100,000 B/D CAPACITY BY STATES¹⁰

Company and Location	Crude capacity— b/d		Charge capacity based—			Hydrogen treating—		Alkylar—		Polymer—		Coke (long)
			Vacuum distillation	Thermal operations	Catalytic Fresh feed	Recycle	Catalytic reforming	Unit	Feed	Alkylar ton	Polymer ton	Asphalt
Pennsylvania												
Atlantic Refining Co.— Philadelphia	155,000	160,000	93,000	16,000	54,000	19,000	25,000	14,000 24,000 2,400	SR naph. Mid. dist. Wax	7,300 (s)	1,300	12,000
Gulf Oil Corp.— Philadelphia	147,000	192,000	82,000	22,500	65,000	21,000	52,000	50,000 52,000 18,000	Mid. dist. SR naph. Fuel gas	4,000 (s)	4,800	
Sinclair Refining Co.— Marcus Hook	133,000	140,000	71,000	27,000	40,000	8,000	22,000	22,000 10,000	SR naph. Mid. dist.	1,000		
Sun Oil Co.— Marcus Hook	NR	151,000		24,000	151,000		35,000	15,000	Mid. dist.	7,300 (t)	12,800	
Texas												
American Oil Co.— Texas City	171,600	177,600	70,000		120,000	59,600	42,000	42,000	SR naph.	37,200 (s)	1,100	480
Gulf Oil Corp.— Port Arthur	276,000	284,000	129,500	25,000	105,000	23,000	67,000	50,000 13,000 67,000	Mid. dist. Lubes SR naph.	9,500 (s)	6,000	550
Humble Oil & Refining Co.— Baytown	275,000	290,000	159,000		128,000	26,000	54,000	104,300 48,000 25,000 9,400	SR naph. Mid. dist. Lubes Solvents	34,000 (s)	5,500	11,800
Mobil Oil Co.— Beaumont	220,000	235,000	73,500	24,000	93,000	19,000	44,000	44,000 42,000	SR naph. Mid. dist.	17,700	8,000	825
Shell Oil Co.— Houston	139,000	142,000	60,400	21,900	52,000	21,000	35,000	35,000 7,000 45,000	SR naph. Mid. dist. Lubes Cat. feed	6,000 (s)		1,800
Sinclair Refining Co.— Houston	174,500	183,000	72,600	14,000	50,000	30,000	38,000	35,000 35,000 6,800	SR naph. Mid. dist. Lubes		5,400	
Texaco Inc.— Port Arthur	310,000	NR	108,000	54,000	135,000		60,000	60,000 12,000	SR naph. Mid. dist.	13,800 (s)	1,800	200
Average of All		185,985	77,215	23,658	76,831	22,012	35,962	61,435		40,192		

no salvageable equipment, the entire refinery will probably have to be completely rebuilt except for foundations. Other, less badly damaged refineries would probably be repaired first.

The fourth through the eighth considerations determine the sequence, or the method of repair, under the specific postattack circumstances.

4.1.2 Minimum postattack processing requirements for balanced operation

Under postattack conditions, those processing units which are essential and the order in which they should be repaired and brought on stream are determined by the minimum fuel quality requirements discussed in section 5.1.

Refinery processing equipment varies in capacity and in processing details from one refinery to the next. There is so much complexity that it is difficult to define a "typical" refinery, but modern refineries have certain traits in common: they all have crude distillation and light ends recovery units; most have catalytic cracking of one form or another; and most use the alkylation process for production of high octane aviation gasoline.

The first unit to bring on stream is the crude oil still, with both atmospheric and vacuum fractionators, for the production of straight run gasoline, catalytic cracker feed, tractor fuel, jet aircraft fuel, diesel fuel, and furnace oil. Little or no further processing would be required except for straight run gasoline.

The next unit to bring on stream is the catalytic cracker and its fractionator, fed by gas oil from the pipe still. This unit would provide moderately high octane gasoline and light naphtha, cracked diesel fuel, furnace oil and fuel oil. The gasoline and light naphtha would require stabilization in the light ends recovery plant, but the diesel fuel, furnace oil and fuel oil could be used without further processing.

The vapor recovery units in the light ends plant would be needed for recovery of butane and propane from the stocks of naphtha from the pipe still and catalytic cracker, before the olefin stocks are fed into the alkylation unit or blended to make regular gasoline. Feedstocks for the light ends units must be brought up to pressures as high as 300 psi for absorption, and some gas compressor equipment would therefore be required with the light ends unit.

The butane recovered would be used for blending of motor gasolines, while the propane would be used as LPG, refinery gas, or as a substitute motor fuel.²⁰ Light gas oil for the absorption process would be available from the pipe still or catalytic cracker.

The alkylation plant with its reactors and fractionators would be brought on stream next for production of high octane alkylate. Its olefin feed, propylene, butylene, or amylene, comes from the vapor recovery units. Isobutane comes from the vapor recovery units or is purchased from natural gasoline plants. The precise choice of olefin feed would depend on the type of light ends unit available. The alkylation process is practically indispensable for the production of high octane alkylate required for aviation gasoline. It is theoretically possible, but not practical, to produce a small yield of aviation gasoline without alkylation by catalytic hydroforming, polymerization, or hydrogenation.¹⁸

4.1.3 Examples of balanced postattack operations*

For either normal or postattack refining, it is important that refining operations be balanced with processes, equipment, and demands, so that the incoming crude oil is converted into a maximum of needed refined products with a minimum of waste. This requires that each process unit be utilized to full capacity, and that everything produced be used, either as product or as feed for other units. Otherwise, part of the useful crude oil entering the refinery would be converted into surplus products which would have to be thrown away or stored. Disposal is difficult and storage capacity is limited.

Two examples of such balanced hypothetical postattack operations at the Baton Rouge, Louisiana, refinery of Humble Oil & Refining Company follow. In example I, only the 94,000 b/d crude still and one fluid catalytic cracking unit are available. In example II, available units include the equipment of example I, plus seven 600-HP gas compressors; light ends fractionators, one alkylation stirred reactor, and deisobutanizer, debutanizer, depropanizer and rerun towers for recovery of alkylate light ends.

The threshold operations described in these examples are only indicative, because the exact situation would depend upon a great many factors, and in any situation certain optimization should be possible.

BATON ROUGE LOUISIANA REFINERY
THRESHOLD OPERATION

Example 1—Available only a) 94,000 b/d Crude Still #9 or #10
b) Fluid Catalytic Cracker (FCCU) #2 or #3

Crude Stilling		
Product	Vol. %	b/d
Gas and Loss	3	2,800
350° End Point Naphtha	17	16,000
JP-4 Jet Fuel	10	9,300
Jet Fuel A	11	10,300
FCCU Feed	53	50,000
Residual Bottoms	6	5,600
Charge—South Louisiana Crude	100	94,000

Fluid Catalytic Cracking Unit (FCCU)		
(From correlation made from reviewing several operating report sheets, estimate 68% conversion on FCCU @ 50,000 b/d charge rate)		
Product	Vol. %	b/d
Gas, Coke* and Loss	28	14,000
15# Reid Vapor Press		
Fluid Cracked (FC) Naphtha	40	20,000
FC Cycle Gas Oil	27	13,500
Heavy Gas Oil Bottoms	5	2,500
FCCU Charge	100	50,000

Motor Gasoline				
Component	b/d	Vol. %	Research Octane w/3 cc TEL/gal	Research Octane clear
Straight Run (SR)				
Naphtha	16,000	44	87	70
FC Naphtha	20,000	56	94	85
	36,000	100	91	78

$$\text{TEL requirement} = \frac{36,000 \text{ b/d}}{169 \text{ c.c./lb.}} \times \frac{42 \text{ gals/barrel}}{1} \times \frac{3 \text{ c.c./gal}}{1} = 27,000 \text{ lbs/day}$$

* Coke consumed in regenerator of FCCU

Yield Summary

Product	Vol. %	b/d
91 O. N. Motor Gasoline	38	36,000
JP-4 Jet Fuel	10	9,300
Jet Fuel A	11	10,300
Diesel-Heating Oil	14	13,500
Residual Fuel	9	8,100
Fuel Gas, Coke, Loss	18	16,800
Total Crude Input	100	94,000

Diesel-Heating Oil yield can be increased at corresponding decrease in Jet Fuel A.

$$\text{FCCU Catalyst Requirement estimated } \frac{.25 \times 50,000}{2,000} = 6.25 \text{ tons/day}$$

Example II—Equipment available in example I, plus seven 600 HP gas compressors, light ends fractionation, one alkylation stirred reactor, and deisobutanizer, debutanizer, depropanizer, and rerun towers for recovery of alkylate light ends.

$$1) \text{ Estimate recovery } 0.2 \text{ Vol. \% of Crude as } iC_4 = 200 \text{ B/D}$$

$$2) \text{ FCCU } iC_4 \text{ yield estimated as } 6.3\% = 3150 \text{ B/D}$$

$$C_4 \text{ yield estimated as } 10.0\% = 5000 \text{ B/D}$$

$$3) \text{ Alkylation: Alkylate produced } = 3350 \times 1.53 = 5100 \text{ B/D}$$

$$C_4 \text{ consumed } = 5100 - 1,70 = 3000 \text{ B/D}$$

$$(\text{Excess } C_4 = 2000 \text{ B/D})$$

$$\text{Alkylation shrinkage } = 3350 + 3000 - 5100 = 1250 \text{ B/D}$$

$$\text{Aviation Alkylate } = 90\% \text{ of } 5100 = 4600$$

$$4) \begin{array}{l} 115/145 \text{ Aviation gasoline Aviation Alkylate} \\ \text{Light Straight Run (LSR) + } C_4 \end{array} \quad \begin{array}{l} 4600 \text{ } 90\% \\ 500 \text{ } 10\% \\ \hline 5100 \text{ } 100\% \end{array}$$

(In volume, alkylation rerun bottoms replaces 500 b/d LSR + C_4 from motor gasoline pool—no significant change in quality)

$$5) \text{ Aviation TEL requirement } \frac{5100}{169} \times \frac{42}{4.6} = 5800 \text{ lbs/day}$$

$$6) \text{ Sulfuric Acid Catalyst requirement } \frac{5100 \text{ b/d}}{2000 \text{ lbs/ton}} \times \frac{42 \text{ gals/barrel}}{0.3 \text{ lbs/gal}} = 32 \text{ tons/day}$$

Yield Summary

Product	Vol. %	b/d
91 O. N. Motor Gasoline	38	36,000
115/145 Aviation Gasoline	5	5,100
JP-4	10	9,300
Jet Fuel A	11	10,300
Diesel-Heating Oil	14	13,500
Residual Fuel	9	8,100
Fuel Gas, Coke, Loss	13	11,700
Total Crude Input	100	94,000

It would be impossible to operate any of the units without fairly extensive off-site facilities, such as utilities and feed and product tankage. Further, achievement of the conversion and production shown would require very extensive downstream processing equipment.

4.1.4 Repair procedures

In completely rebuilding a damaged plant, the simplest approach is to rebuild as it was from existing drawings. In a postattack environment, this could be impractical, if the obsolescence of some equipment makes procurement difficult, or the drawings are destroyed or lost. The policy of Standard Oil Company (New Jersey) is to microfilm the drawings and store them in locations remote from the refinery. Repair effort should generally be directed at rebuilding the essential units as they were before the attack. There are two reasons for this: first, the engineering-design cycle for a major redesign would add 8 to 9 months to the repair time, and, second, many engineering-design man hours would be required to handle the changes induced by shortage of materials, non-availability of critical items, and forced substitutions.

In postattack repair, more field fabrication and more scavenged components and materials would be used, since the normal fabricating shops, if extant, would probably be overstrained. It would be possible to use prefabrication techniques at an adjacent location, then move in a prepackaged assembly for erection. Reinforced concrete could be used to replace structural steel, and wooden handrails can be substituted for steel. Painting and some fireproofing could be done after unit startup. Temporary pipe hangers could be installed, to be replaced later.

If the towers overturn, they would cause widespread damage simply by falling on adjacent equipment, and the towers themselves might be badly damaged and dented, probably beyond repair. This would become apparent, of course, almost immediately at the start of the repair project, allowing early procurement of new towers. Internal parts would also be seriously damaged but still probably repairable. Large towers over 13 feet in diameter must be field fabricated—that is, shipped to the site in pieces and erected by a crane on their support structures—because they are too large to ship in one piece. They will be pressure tested at the site. Towers under 13 feet

in diameter, however, can be shipped to the site in one piece and can be erected by a crane and gin pole. They will probably be pressure tested at the fabricator's shop. As a last resort, the fallen towers might be re-used, if not exposed to fire.

Storage tanks should be repaired by removing damaged sections with acetylene torches, and then welding to install new sections. Replacement of storage tank cone roofs is easier than that of floating roofs, and it might be necessary to replace some floating roofs with cone roofs, although some products should not be stored in cone roof tanks because of the product losses and some possibility of fire or explosion. In general, storage tanks are easy to repair, requiring only welders and steel plate, which is normally in stock. Tank fabrication is normally subcontracted to specialists such as Chicago Bridge and Iron, Graver, Pittsburgh-Des Moines, and Horton.

Refinery maintenance shops are limited by lack of "know-how" and heavy lifting capacity. They can undertake repair of damaged equipment, but fabrication must be done by specialized contract maintenance shops, for which long lead times are necessary. While many refineries do their own maintenance, the trend is increasingly toward contracting with refinery maintenance specialists to do the work. This means less and less "in-house" repair and fabrication capability at refineries, which is doubly disadvantageous in postattack terms: the refineries are less self-sufficient, and the maintenance specialists, being relatively few in number, are vulnerable to attack or, surviving, would be overtaxed in trying to meet the simultaneous needs of many refineries in a stricken industry.

Hydrostatic testing is sometimes done in the field, sometimes at the fabricator's shop. Field testing might be required for evaluation of damaged vessels, and pneumatic or steam testing, although less safe, could probably be substituted for hydrostatic testing. In hydrostatic tests of repaired vessels, however, the vessel's bubble trays and other internal structures must be removed to avoid damage, while steam testing does not require this.

4.1.5 Materials

Gin poles and 100- and 150-foot cranes with 100 tons or more capacity will be required for erection of towers, and would probably have to

be brought to the site from another refinery. If rubber-mounted, they could be driven on roads; otherwise rail transportation would be used. Major refinery constructors have a good deal of idle construction equipment—air poles, cranes, and piping in their own storage dumps, and this equipment would probably be available in an emergency.

Piping is not a critical supply item because standard sizes are in general use and are usually stocked at refineries. Needed sizes could probably be obtained by shopping around.

Items with long lead times include compressors, slide valves, pressure vessels, and heat exchangers. The normal lead time for a vessel of 13-foot diameter by 200-foot length, including testing, is sixteen weeks after receipt of steel. There are about 10 shops capable of fabricating such vessels, among them: Chicago Bridge & Iron in Birmingham and Milwaukee; Nooter Corporation in St. Louis; Wyatt Industries, Inc. in Houston; Sun Shipbuilding & Drydock Company in Chester, Pennsylvania.

Transporting such a vessel can be a problem. The limit for rail shipments of long vessels is a 13-foot diameter and 17 feet for short ones. A length of 200 feet or more could be a problem on curves, necessitating a dry run in advance of actual shipment to see if any telegraph poles or other obstructions should be moved. Other means of shipment are by barge or by towing the vessel afloat.

There are only one or two shops capable of fabricating the heavy walled reactors used on hydrocrackers, of which Struthers Wells Corporation, Warren, Pennsylvania, is one.

The principal suppliers of turbines and compressors are General Electric, Westinghouse, Ingersoll Rand, Clark, and Brown Boveri. They are located primarily in the East and Midwest. Emergency transportation by freight of heavy machinery could also be a problem since it normally takes 6 weeks to obtain the freight cars at the vendor's plant.

Heat exchangers are also a critical item because of high pressures and required corrosion resistance. For some types, lead times are 8 to 10 months.

Valves are less critical because a low-quality item can be substituted temporarily for a specialty valve in most cases. Instruments are less critical than fabricated items but more so than piping. The suppliers of electronic and pneumatic instruments, such as Foxboro and Bailey Meter, are concentrated primarily in New England and Cleveland. Opportunities for interchanging instruments are few because calibration would probably have to be changed, and because of the instrument's complexity it would probably have to be sent back to the vendor for alterations.

Mechanical components such as bearings are not normally stocked at refineries because local suppliers generally carry adequate inventories.

Cooling towers are fairly vulnerable to blast and, if destroyed, would take time to repair. Because of their wooden construction, however, there should be many opportunities for shortcuts.

Furnaces are generally not interchangeable because they are designed to operate at a specific temperature and flow rate. Varying this upward or downward can cause coking and other difficulties. Use of cast firebrick is becoming more common, and in that case, even refractories cannot be moved. The incoloy tubes in some furnaces are a critical item.

Instrument repairmen would be the most critical of the labor grades needed for the repair of the controlhouses in the low levels of blast damage. At higher levels of damage, pipefitter-welders would be the most critical, with electricians next, and both are in short supply even in normal times. In recruiting pipefitter-welders, the first to be recruited would be skilled welders who can pass the welder's qualification test or whose qualification on another job can be verified. If welders must be brought in from elsewhere they should be qualified where hired and not at the repair site. As a last resort, unskilled labor can be trained, but it takes 6 weeks to train a welder.

An actual example of a repair project is that of a fluid cat cracker unit after an explosion blew off the regenerator head and dropped the regenerator a few feet into the structure, cocking it about 20 degrees. The

rest of the unit was not seriously damaged. Repair took 110 days (including design of new vessel), and peak work force on any one day was 300 men. The decision was made to design a new vessel because the damaged one was obsolete, with a heavier wall, dating from 1942, which would have taken longer to fabricate at the time of repair (1963) than a vessel conforming to contemporary design standards. Other components that were damaged included the regenerator support structure, elevator, other vessels, and pumps. The dented vessels and the pumps were salvaged, the support structures were replaced, the cyclones were replaced by redesigned cyclones, and the silencers were repaired. The regenerator head, when it blew, fortunately landed clear of the main part of the unit, causing relatively little damage. For the new vessel, a 154-ton lifting crane was required.

Other examples include repair of a reactor head, which had blown off. It was decided to install a new reactor, and the two adjacent reactors as well, although it could have been repaired in 8 to 20 days by welding on a new head.

Past experience with new construction shows that 7 to 8 months are normally required for a typical unit from foundations to completion, preceded by 8 to 9 months for design.^{18, 71} With a crash program in the construction phase, the time to construct could be reduced by one-third at the most, so that a construction job normally requiring 7-1/2 months to complete could be done in 5 months on a three-shift basis or with full use of overtime.

4.1.6 Repair schedule

On the following pages a number of repair schedules are presented, together with estimates of labor requirements in man-days, by labor craft, for each project. These apply to the postattack repair of typical petroleum refinery processing units, and are compiled from the detailed damage calculations of particular units in reference 69. Repair is scheduled according to the critical path method (CPM), scheduling, in which arrow diagramming is used to illustrate the step-by-step progress of the job. This technique is widely used by design and engineering firms in the petroleum

and chemical industries and, although similar to PERT scheduling, is more adaptable to the particular requirements of this project.

A detailed description of the procedures to be followed in making CPM charts is contained in reference 50. In general, the method involves listing each job separately, in any order, then making a diagram in which each job is represented by an arrow. The sequence of the arrows is indicative of the order and priority in which the jobs are to be performed. The number in the box below the line indicates the estimated time to complete in project days. The numbers in the upper half of the circles at both ends of the arrow are the job identification numbers. The numbers in the lower half of the circles are the accumulated, or elapsed, time in project days from start of the project. The critical path is determined by finding the path through the arrow diagram giving the longest elapsed time at each junction. A one-shift day is assumed.

In scheduling an actual construction project, as much detail as possible, except for the obvious, is usually shown on the CPM schedule. Each job is broken down into as many smaller jobs as possible to permit easier analysis. For scheduling hypothetical postattack repair projects, however, it is not practical to show as much detail, because of the many uncertainties in accurately estimating the damage, the salvageability of components, and the extent of blast damage on supplier industries and the resulting effect on lead times.

Normally, these lead times are known quite accurately from past and current experience. The critical path can then be determined with a high degree of certainty. In postattack repair projects, however, lead times could vary widely from normal peacetime conditions, because of the above-mentioned difficulty in predicting the damage suffered by vendor's plants and transportation facilities, and the availability of labor.

The critical path in postattack repair can be almost anywhere, depending on the specific attack and resultant shortages of particular

items, destruction of suppliers plants, or nonavailability of certain types of personnel. For this study, sufficient human ingenuity is assumed for surmounting such shortages and averaging out the effects. Therefore, the critical path has not been identified in the CPM schedules presented here. Lead times can be shortened slightly or extended considerably during a wartime situation because of priorities and decreased manpower. This wide variation in lead times for purchased items can be seen in reference 18, pages 50 and 51; where, for example, heat exchangers which normally took 2 to 4 months to process in 1955 and 1958, had lead times of 10 to 12 months during the Korean crisis in August, 1952. Overall, lead times probably would be extended, however, depending on the magnitude of the attack damage to the entire country.

Priorities can influence greatly the repair effort as evidenced by a crash program in the construction of a TEL batch plant during World War II. To fill a sudden demand for TEL, a 16-unit batch plant was set up at the Chambers Works in an existing building. Top priority was obtained for procurement of autoclaves and other long-lead items, and the plant was finished in just 15 weeks, including design and the installation of new floors in the building. A work force of 300 to 350 was used on this project for field erection and equipment installation. The lead times used in making these repair schedules have been taken from the literature,¹⁸ and from experience in procurement. The basic data used in making these estimates--size of work force, days or man-days needed to accomplish specific tasks--have been reviewed by competent people in the industry and it is believed that these data are realistic for normal, preattack conditions, and that they would not be much shorter under postattack conditions.

Whether or not they apply in postattack repair schedules is a question that cannot be answered without a detailed knowledge of the scenario, such as a definite attack pattern and analysis of damage to all industries involved in repair, together with assuming specific allocations of material and labor. Since this is beyond the scope of the current study, normal (1965) preattack conditions are used as the basis for all repair estimates, with the understanding that these data are to be reviewed and revised in an actual postattack planning situation. By using 1965 conditions as the basis,

the data presented have a common and uniform basis with which postattack planners are expected to be familiar, and imminently more suitable than a basis already adjusted for some assumed, but probably incorrect, post-attack situation.

The labor requirements for the repair projects analyzed here are broken down by craft into 12 basic categories. These, with their standard ratios, are as follows:

Boilermakers	.12
Bricklayers	.02
Carpenters	.08
Electricians	.04
Common Labor	.18
Insulators	.07
Operating Engineers	.07
Millwrights	.01
Painters	.02
Pipefitters	.30
Ironworkers	.08
Guniting Men & Cement Finishers	.01
	1.00

These are the same categories and standard ratios used by a leading design engineering firm in accounting and estimating new refinery work.

The categories of boilermakers, pipefitters, and ironworkers also include welders. Operating engineers are the crane operators, vehicle operators, portable machinery operators, and their helpers. Roofers are included among the carpenters. Instrument men, whether or not specializing in electronic or pneumatic instruments, are included among electricians.

The standard ratios are those used on large field construction projects involving work by all crafts, and do not necessarily apply in the case of repair projects where not all types of equipment would suffer equal damage. In cases of postattack repair estimates, where the project involves most of the different crafts, the standard ratios are shown as a means of comparison with the estimated ratios. In some cases, there is considerable variation, as for instance in the repair chart of the 80,000 b/d crude still, at 3.5 psi, and at 7.0 psi. Since the furnaces collapse at 6.5 psi, and they can be analyzed as separate units, their repair is shown on a separate

CPM chart, and thus does not appear on the repair charts for 3.5 psi or 7.0 psi. This means that essentially no bricklayers would be used on the latter two jobs, and a preponderance of bricklayers appears on the furnace repair job. The standard ratios are therefore not a particularly useful guide in this case, although their application could be more useful at a later stage when a number of repair analyses are being combined to determine total repair effort for a complete plant or for an industry.

There are some labor categories required for field erection which do not appear in the labor estimates. These are primarily personnel doing office and engineering work—accountants, bookkeepers, timekeepers, clerks, guards, engineers, and secretaries. Also, no labor is included for erection of special shops, temporary buildings, offices and shacks.

Generally, the level of damage selected for these repair estimates is the lowest overpressure at which moderate-to-heavy damage would occur, involving prolonged unit shutdowns and repair times up to a year in duration. The damage level is not great enough, however, to make repair impractical. In most cases the collapse of major structures and overturning of towers and reactor vessels is involved. In the latter instances, it must be generally assumed that the unit is not operating at the time of the blast; otherwise there would be a fire and consequent damage serious enough to make repair unfeasible.

It is also assumed that there will be no redesign, i.e., that the unit is to be rebuilt essentially as it was, according to existing drawings, and that these drawings are readily available at the site. Although it simplifies the task of repair estimating, in some ways this assumption is not realistic. The company owning the plant may desire to redesign obsolete, or even slightly outdated, facilities in keeping with the latest developments in technology, for competitive and/or cost reasons. Some redesigning may also be required for expedience in repair, to provide shortcuts and the most rapid return possible to operating conditions.

An illustration of this situation arose recently in the above-mentioned repair of a fluid catalytic cracking unit, after a regenerator explosion had seriously damaged the regenerator and its support structure. Drawings were available for the regenerator vessel, but because it had been designed and built several years previously, the existing vessel was obsolete by current standards and fabricating techniques. The decision was made to redesign the regenerator according to current practice, simply because it would have taken much longer to fabricate the vessel as it was originally designed. Furthermore, although the original, damaged vessel could have been repaired, it was decided to build a new one because salvage and reuse would have involved lengthy inspection, and negotiations between the engineering and design contractor, the refining company, underwriters, and local government, concerning the structural safety of the salvaged vessel.

These considerations, then, illustrate the complexity and the type of problems likely to arise in connection with salvageability vs. rebuilding and redesigning vs. rebuilding as is. Each case must be decided on its own merits. In the present analysis, provision is made in the repair charts for both repair and salvage of damaged components, and also procurement of new components, as both will undoubtedly take place.

Table 4.2 is a summary of the repair estimates presented in the subsequent CPM charts, figures 4.1 - 4.9. At their request, company names have been withheld, but the units represent actual plants currently in operation. The units taken for analysis are of recent construction and contemporary design. It is assumed that there were no fires, as this would probably rule out any question of repair. Damage is listed for only the major items, in addition to extensive supplementary damage to instruments, piping, structure, electrical equipment, pumps, valves, heat exchangers, drums, etc. The repair time and estimated field labor in man-days to repair are taken from the CPM charts. The estimated field labor in

man-days to build a complete new unit, for purposes of drawing the chart, is computed from case histories of actual new-plant construction, and adjusted for the capacity of the unit in question. In the case of the atmospheric furnace on the crude unit, however, a slightly different procedure was followed. Cases of actual construction show that furnaces require about 8 per cent of the total field labor. Since there are two furnaces, the atmospheric furnace and the vacuum furnace, this 8 per cent was allocated according to their relative capacities, about three to one. Thus 6 per cent of the labor for the complete unit is allocated to the atmospheric furnace and 2 per cent is allocated to the vacuum furnace. Since the repair involves more labor (but not necessarily more expense) than a new furnace, the repair may not be worth undertaking. The decision in any specific case depends on the availability of supplies and the essentiality of the repair from a national survival or recovery standpoint.

Each of the repair problems analyzed involves some materials. Generally, the materials could be better and more efficiently fabricated outside the plant if the external situation permitted. In other cases, some of the materials could be obtained from various storage yards, or perhaps salvaged from other refineries.

Further work needs to be done to allocate the repair dollars to the industries required in the repair; and the translation of these dollars from preattack to postattack times could then perhaps be accomplished by techniques similar to those used in a study by the Institute for Defense Analyses.⁵²

The cost of materials for the repair is computed in terms of 1965 dollars, by using current wage rates of refinery construction labor⁵¹ and assuming that direct labor cost represents 1/3 of all direct costs of process units, and 1/2 for storage tanks. The actual hourly wage rate used is \$4.85.

Table 4.2 SUMMARY OF REPAIR ESTIMATES

Unit	Capacity b/d	Over- pressure psi	Principal Damage	Repair time project days	Estimated Field Labor man-days		Cost of repair materials 1965 dollars
					To repair	To build complete new unit	
Crude Still	80,000	3.5	Collapse of attendant structure	151	4,270	40,000	330,000
Crude Still	80,000	7	Collapse of atmospheric and vacuum towers and attendant structure	277	17,630	40,000	1,370,000
Atmospheric furnace: crude still	80,000	6.5	Collapse of furnace	163	3,170	2,400	246,000
Fluid cat cracker	31,000	12	Collapse of fractionator and reactor. Deformation of regenerator support	261	20,700	30,060	1,610,000
Vapor recovery unit	—	6	Overturn absorber and lean oil still towers and supports	204	7,630	7,000	592,000
Controlhouse: FCC and alky- lation units	—	1.0	Collapse switch gear roof, secondary missile damage to sw. gear and instruments	188	1,350	3,000	105,000
100' Dia x 48' high floating roof welded steel storage tank 50% to 90% filled	67,140 bbl	5	Leakage of contents into diked area. Rupture of bottom to shell joint. Roof jammed. Wind girders and stairs de- formed	39	160	300 (1 tank, exclusive of foun- dation)	6,200

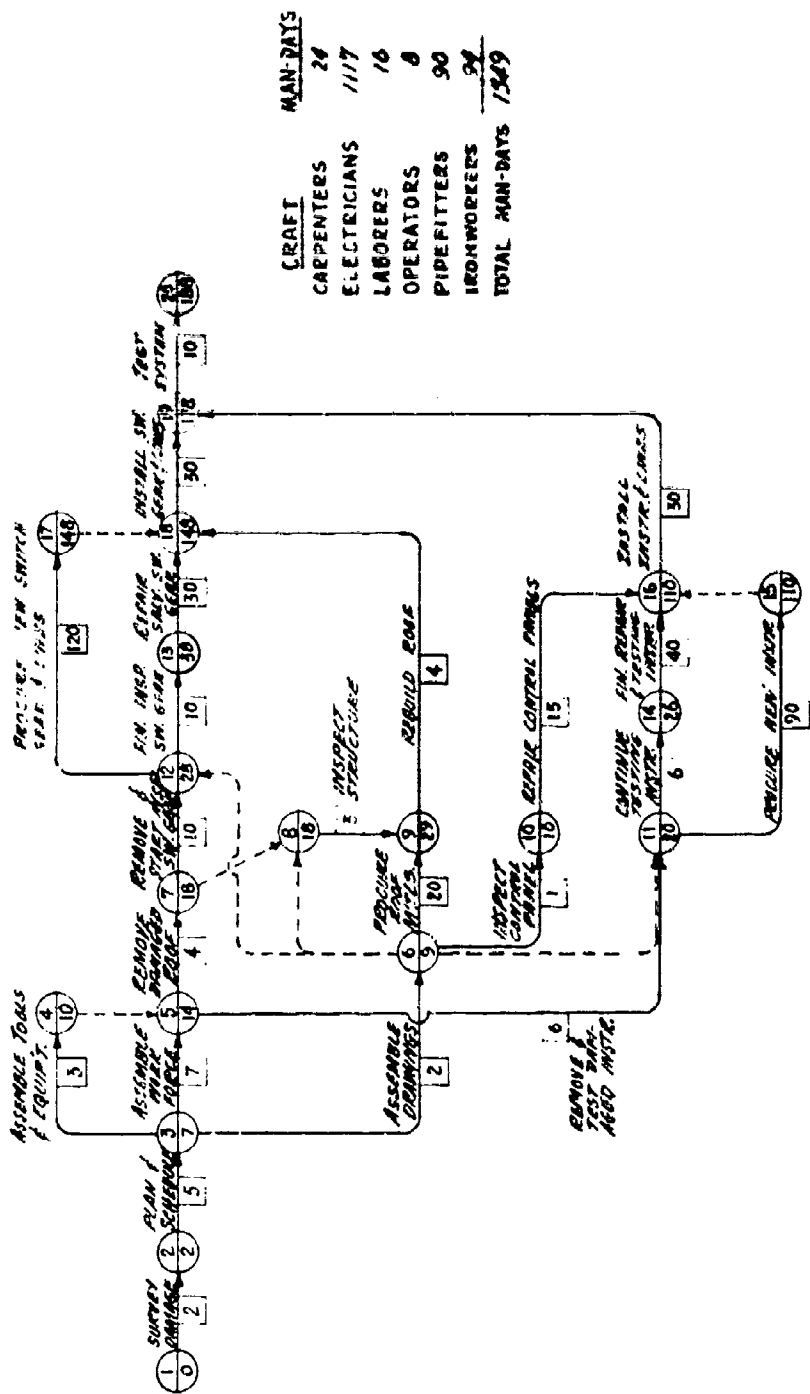
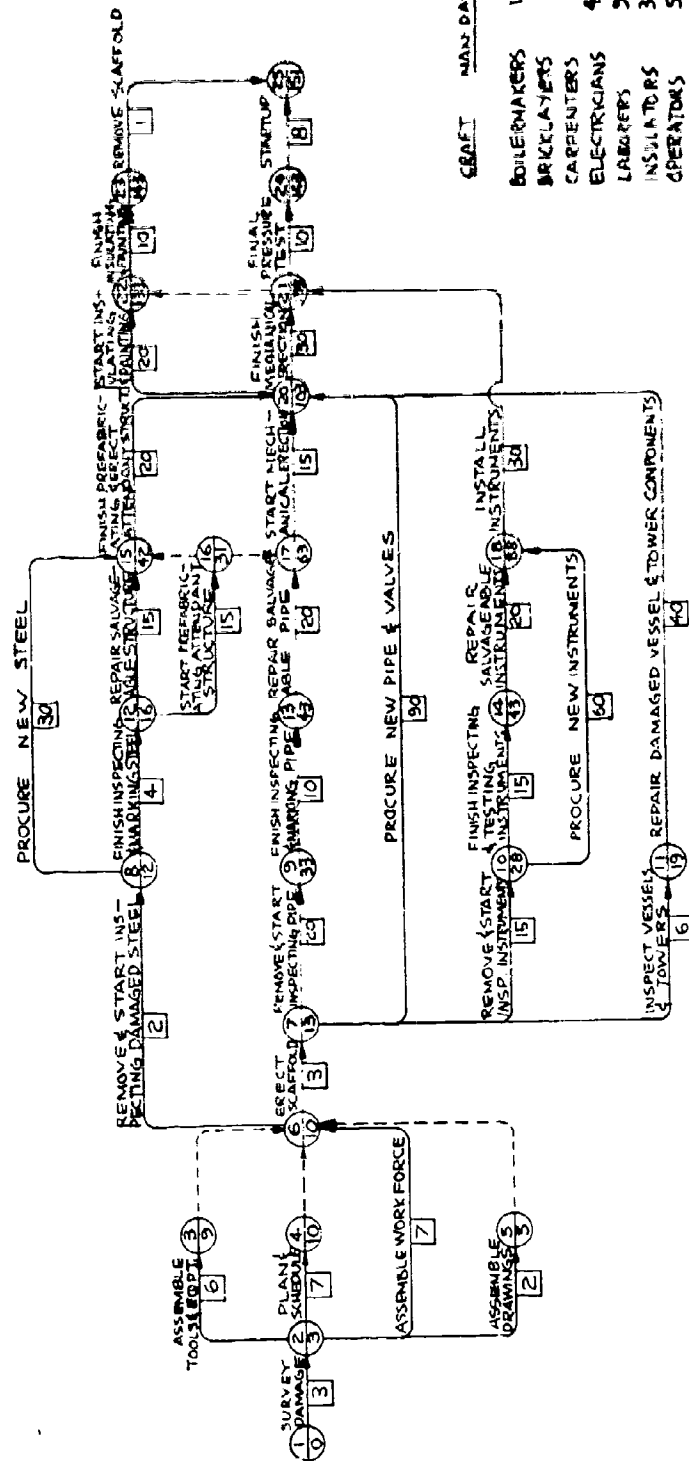


Figure 4.1 UNIT: CONTROLHOUSE - F.C.C. & ALKYLATION UNITS
OVERPRESSURE: 1.0 PSI
DAMAGE: SWITCH GEAR ROOF COLLAPSE, DAMAGE TO SWITCH GEAR.
DEFORMATION OF CONTROL PANELS, MISSILE DAMAGE TO CONTROL INSTR. & CONSOLES
AIR COND. UNIT ON ROOF DESTROYED
REPAIR: SWITCH GEAR ROOF, SW. GEAR, INSTR., CONSOLES, PANELS & LINES.



EST STD
CRAFT MAN DAYS RATE

BOILERMAKERS	156	.04	.12
BRICKLAYERS			.02
CARPENTERS	472	.11	.08
ELECTRICIANS	945	.22	.18
LABORERS	300	.07	.07
INSULATORS	510	.12	.07
OPERATORS			.01
MILLWRIGHTS	300	.07	.02
PAINTERS	1106	.26	.30
PIPEFITTERS	476	.11	.08
IRONWORKERS			.01
CONCRETE FIN.			

TOTAL MAN-DAYS 4265 100 1.00

Figure 4.2 UNIT: 80,000 ⁵/₈ CRUDE STILL
OVERPRESSURE: 3.5 PSI
DAMAGE: COLLAPSE OF ATTENDANT STRUCTURE
REPAIR: REBUILD ATTENDANT STRUCTURE, REPAIR PIPE, VESSELS, INSTRUMENTS, VALVES.

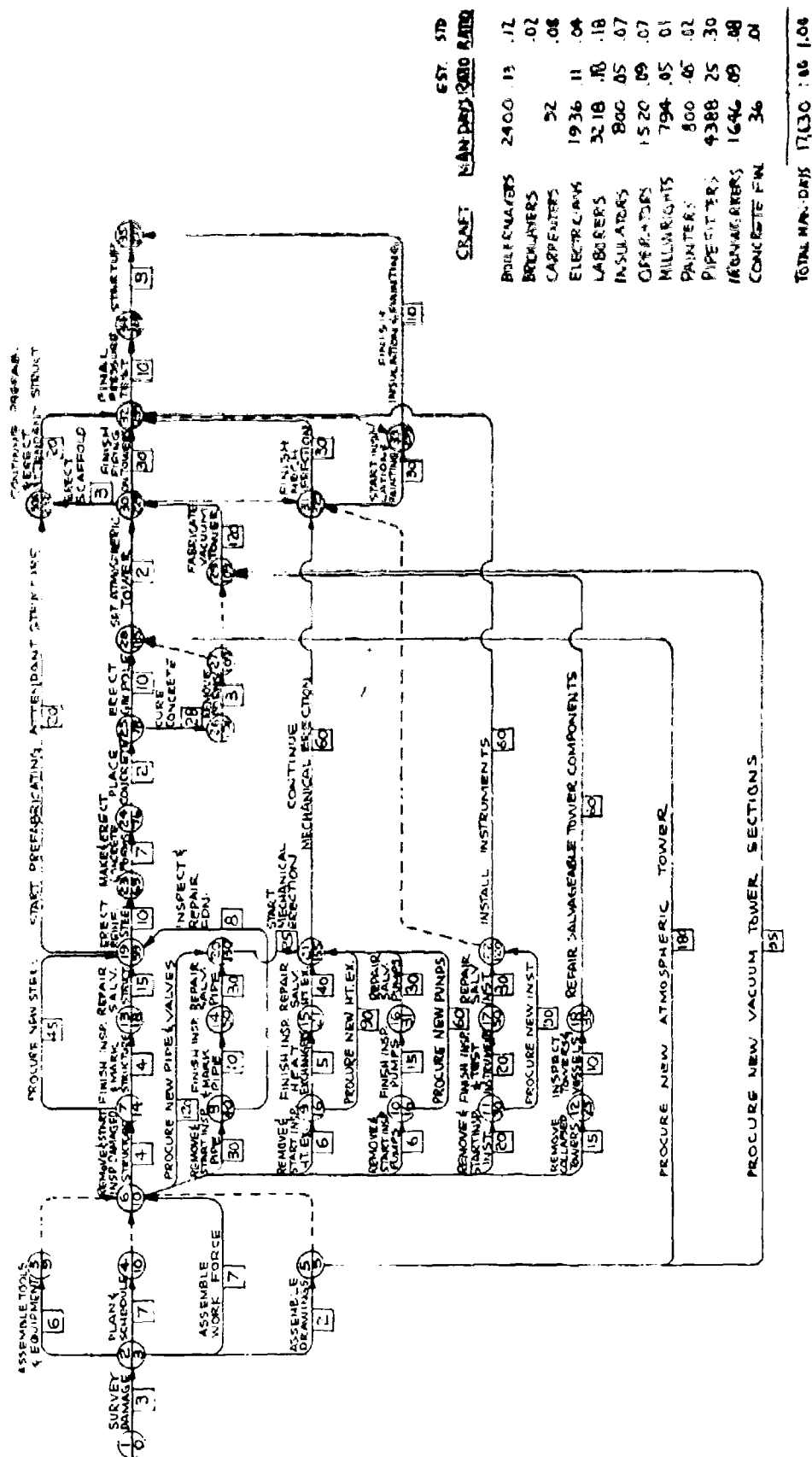


Figure 4.3 UNIT: 80,000 3/4 CRUDE STILL
OVERPRESSURE: 7.0 PSI

DAMAGE: COLLAPSE OF ATMOSPHERIC & VACUUM TOWER SUPPORTS & ATTENDANT STRUCTURE (3.5 PSI)
REPAIR: ERECT NEW ATM. & VACUUM TOWERS, SUPPORTS, ATTENDANT STRUCTURE, PIPING, VALVES, HEAT EX, ETC.

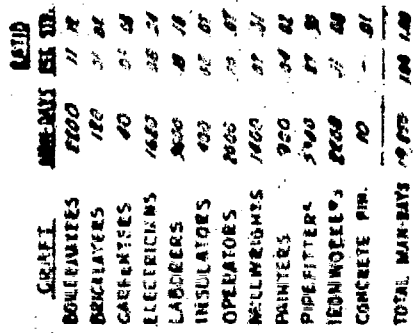


FIGURE 4.5 UNIT: 20,000 $\frac{\text{lb}}{\text{in}^2}$ FLUID CATALYTIC CRACKER (STEEL SUPPORTED)
OVERPRESSURE: 7.0 PSI

DAMAGE: REGENERATOR SUPPORT COLLAPSE S. FRACTIONATOR & REACTOR SUPPORT DEFORM. ELEVATOR DAMAGED.
REPAIR: REBUILD REGENERATOR & FRAME. REPAIR FRACTIONATOR & REACTOR, AUX. EQUIPMENT, ELEVATOR.

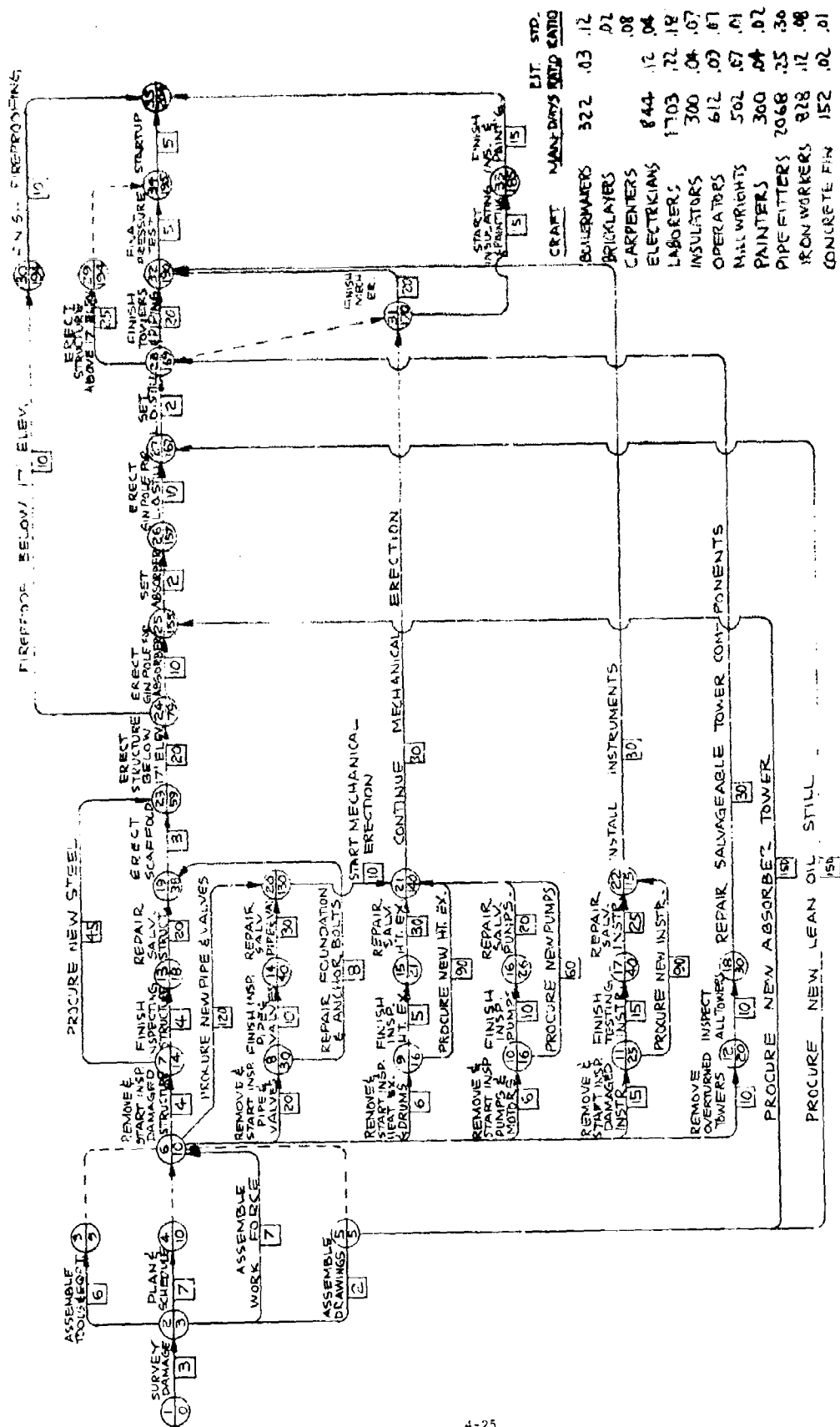


Figure 4.6 UNIT: VAPOR RECOVERY UNIT
 OVERPRESSURE: 6 PSI
 DAMAGE: OVERTURNING OF ABSORBER TOWER, LEAN OIL STILL, SUPPORT STRUCTURE & ATTENDANT STRUCTURE.
 REPAIR: REPLACE TOWERS, REBUILD STRUCTURES, REPAIR PIPING, HEAT EXCHANGERS, PUMPS & INSTRUMENTS.

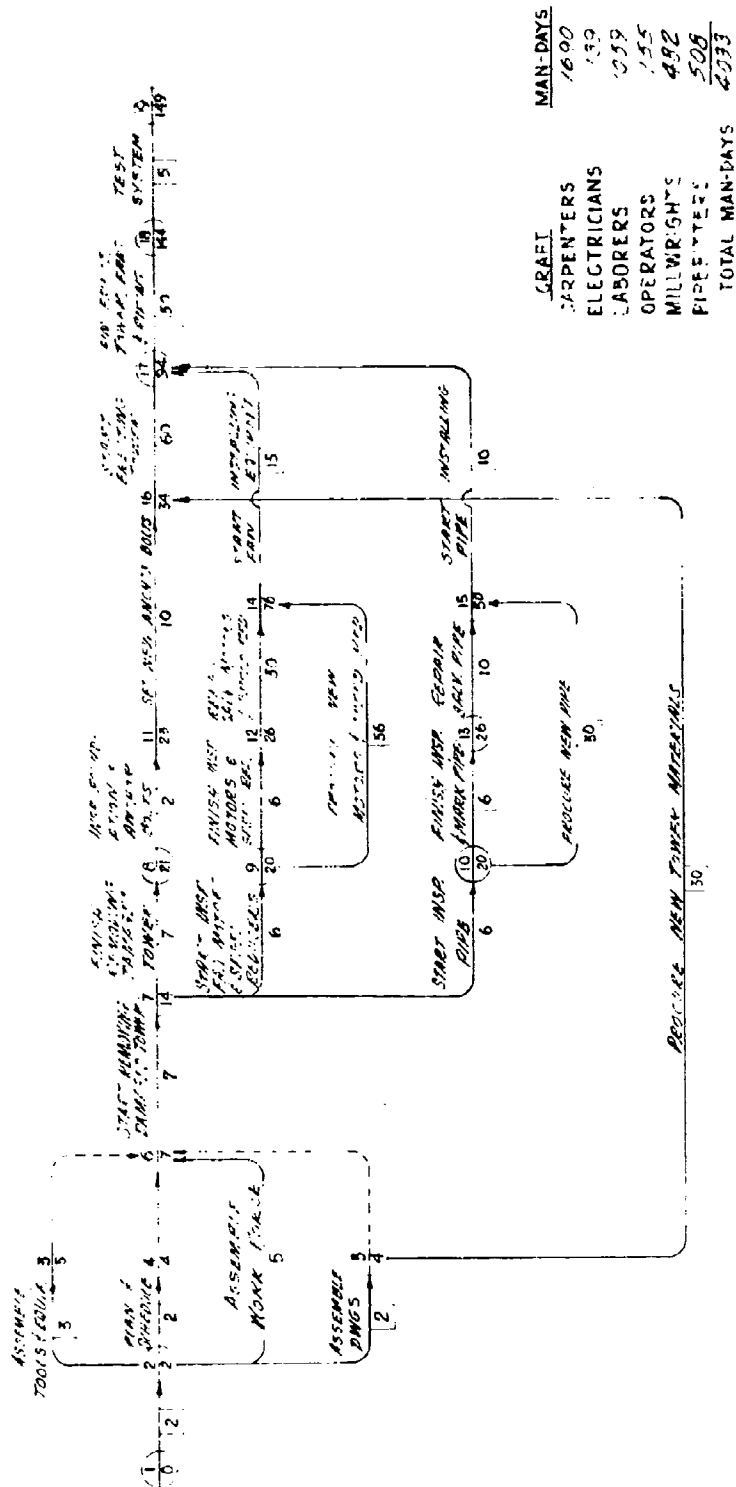


Figure 4.7 UNIT: 9-CELL WATER COOLING TOWER
OVERPRESSURE: 15 PSI
DAMAGED: TOWER COLLAPSED, FAN BLADES BROKEN, PIPING BROKEN
REPAIR: REBUILD TOWER

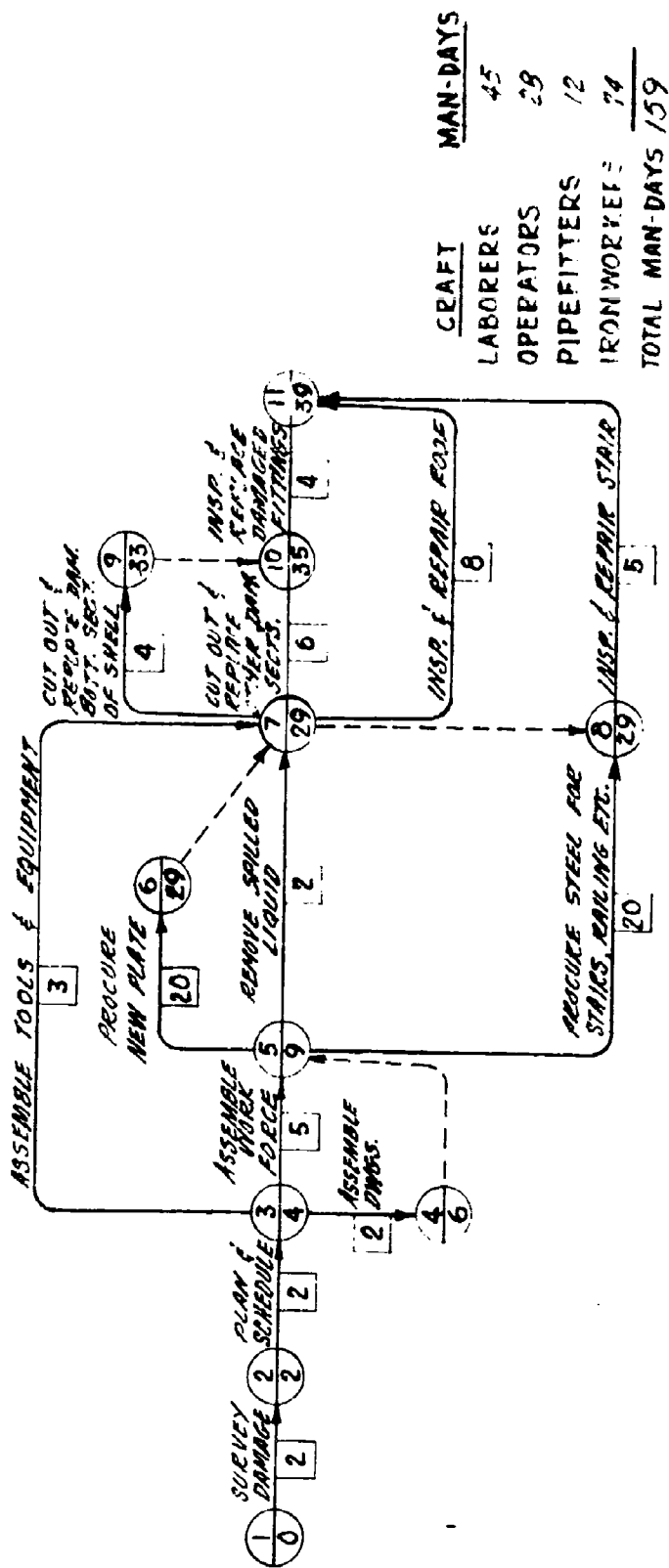


Figure 4.9 UNIT: 100' DIA. x 48' HIGH FLOATING ROOF, WELDED STEEL STIRGAGE
TANK - 0.5 TO 0.9 FILLED.

OVERPRESSURE: 5.0 PSI

DAMAGE: LEAKAGE OF ENTIRE CONTENTS OF TANK INTO DIKE AREA.
NO FIRE. RUPTURE OF BOTTOM SHELL JOINT ALONG 1/3
OF TANK CIRCUMFERENCE. FLOATING ROOF JAMMED.

REPAIR: REPLACE DAMAGED PLATE, WIND GIRDERS, STAIRS,
FITTINGS. FREE ROOF.

4.2 TEL plant repair

Among the most critical items with respect to vulnerability and repair are the high pressure autoclaves used in the batch process. If the agitators are stopped while the reaction is in progress, there is a sudden buildup of temperature and pressure inside the autoclaves. They are protected against this by a rupture disc located in the overhead pipe. In case of emergency shutdown or power failure, the rupture disc fails, relieving the pressure in the autoclave and saving it from more serious damage. Of course, rupture of the disc allows the spread of hazardous chemicals and vapors throughout the area, and the hazard to personnel is intensified if the ventilation system has also been shut down by a power failure.

In 1962, there was such an emergency in a batch plant, when a power failure occurred. No serious damage was sustained, although three discs ruptured. Spare discs are normally maintained in stock at these plants and replacement was therefore not a problem.

Other repair items, which are not critical, are piping and steel plate. Alloy steel piping is normally used, and preferred, but plain carbon steel can be substituted temporarily without serious consequences. Instruments, gear boxes and drives, and heat exchangers would also not present critical repair problems because of adequate stocks and excellent nearby repair shops. The normal vendor's lead times on instruments and gear reducers is three months, and many are interchangeable.

The autoclaves themselves have 9 months' normal lead time, however, and would be a critical item if replacement were necessary. In postattack repair work, it would therefore be desirable to salvage as many autoclaves as possible rather than to procure new ones.

An example of rebuilding involving a batch plant, by salvaging equipment after a fire, occurred in 1935. In this case the autoclaves were salvaged and reused, when the batch plant was rebuilt, and are in operation today.

Fire is generally not a serious hazard in TEL manufacturing, at least compared to the petroleum refining industry. Sprinkler systems

are available in all buildings, primarily to keep steel vessels cool in a fire. Water is an effective extinguishant for TEL fires because TEL's 1.6 specific gravity permits the water to float on it and cut off its contact with the air. Ethyl chloride fires, on the other hand, are very difficult to extinguish. Foam is ineffective because the ethyl chloride vapors can penetrate the foam blanket and continue burning.

It can be said that the vulnerability of TEL and TML production facilities depends primarily on the buildings. The only outdoor equipment involved, the ethyl chloride fractionating columns, are not absolutely essential for operation if there is an adequate supply of ethyl chloride. The fire hazard is much less than in petroleum refining, and the repair problems, at least for batch plants, much less severe. The critical items are the autoclaves, and they lend themselves readily to repair, as illustrated in past experience. Although essential for high octane motor fuels production, TEL production facilities could probably be restored to operating condition sooner than the petroleum refining plants they serve.

4.3 Storage tank repair

The repair of storage tank shells is normally accomplished by welding. Epoxy plastics, however, are now in use for temporary and emergency repairs on leaky tanks, and their use under postattack conditions would be advantageous. Epoxies are widely accepted as a structural adhesive, but their use for repair of petroleum equipment is relatively new. Reference 43 describes methods, materials, and applications. There are two principal plastics described: the epoxies, used for light repairs and small leaks, and the isopolyester plastics, normally used for heavier jobs and the repair of metals damaged by corrosion.

4.4 Generalization of repair estimates

It can be seen in the repair estimates of major processing units that the form of the CPM charts for moderate-to-heavy damage does not vary appreciably. Specific tasks, however, the number of days and the man-days of labor, may be quite different. This is true

when comparing repair schedules of pipe stills, catalytic crackers, vapor recovery units, alkylation units, and hydrocrackers. If particular items of equipment are compared, such as a furnace vs. a fractionating column, the similarity obviously no longer exists for many types of equipment, and the labor categories involved in repair also vary widely. Since all processing units have furnaces, fractionators, pumps, heat exchangers, motors, drums, piping, and instruments, the form of the repair schedule remains unchanged as long as complete units or complete refineries are compared.

The repair effort required to return a plant to full operating condition depends on the damage, size of the plant, and type of equipment.

The first of these, damage, has already been discussed in section 3.7. The second, size of the plant, definitely affects the postattack repair effort. This assumes that the size of the plant is a function of capacity and that repair effort in man days is proportional to the field labor required in erection of new plants, other things being equal. In turn, this is a function of the capacity of the plant, and follows the so-called six-tenths power rule which applies to the overall cost of new plants. This rule states that, for two plants A and B,

$$\frac{\text{Cost A}}{\text{Cost B}} = \left[\frac{\text{Capacity A}}{\text{Capacity B}} \right]^n$$

where the exponent, "n" can range from 0 to slightly greater than 1. A value of $n = 0$ would make the right-hand side of the equation unity and Cost A would equal Cost B. This, then, corresponds to a fixed cost which does not vary with size; some of the engineering expenses, for example, or the instrumentation for a given process may be independent of size. From a repair standpoint, the survey of damage, and the planning and scheduling may be independent of size and would also have a value of "n" approaching 0.

On the other hand, the field fabrication of tanks and vessels causes the exponent to approach 1.0. The postattack repair of such units would also have the same value of exponent. The exponent is greater

than one for equipment which operates under high pressures such as vessels and piping and require greater thicknesses for strength.

The postattack repair requirements for plants suffering equal damage, as a function of the capacity of the unit, are generally expected to represent a proportion of the new cost of the specific units and a value of $n = 0.75$ is recommended for high damage levels. This value was determined by averaging exponents for units considered in this study as follows:

<u>Equipment</u>	<u>Cost Exponent</u>
Cracking, catalytic	0.83
Cracking, thermal (and refining)	0.51 to 0.70
Topping stills	0.62
Vacuum distillation	0.57
Cooling towers	0.64
Storage tanks:	
Cone roof	0.70
Floating roof	0.73
Spherical:	
15 psi	0.63
100 psi	0.56
Steam generation:	
Large, 200 psi	0.61
Large, 1000 psi	0.81
Power generation	0.88
Furnaces	0.66
Towers:	
Constant diameter	0.88
Constant height	1.56
Average Exponent	0.75

At low damage levels, up to 2.0 psi, the primary damage occurs to controlhouses, instrumentation and water cooling towers. The controlhouses and instrumentation are independent of size of plant and " n " approaches 0. Cooling towers are affected by size, however, and " n " for towers has a value of 0.64. Therefore, it seems reasonable that for low damage levels, an average of these two values resulting in an exponent of about 0.3 should be used.

To summarize, it appears that the exponential relationship, known as the six-tenths rule, and used for estimating the cost of building complete

refineries as a function of capacity, can be extended to apply in the case of estimating field man-days of labor in postattack repair projects by making the proper choice of exponent.

The equation then becomes:

$$\frac{\text{Labor time for postattack repair of unit A}}{\text{Labor time for postattack repair of unit B}} = \left[\frac{\text{Capacity A}}{\text{Capacity B}} \right]^n$$

A generalized CPM repair chart is shown in figure 4. 10.

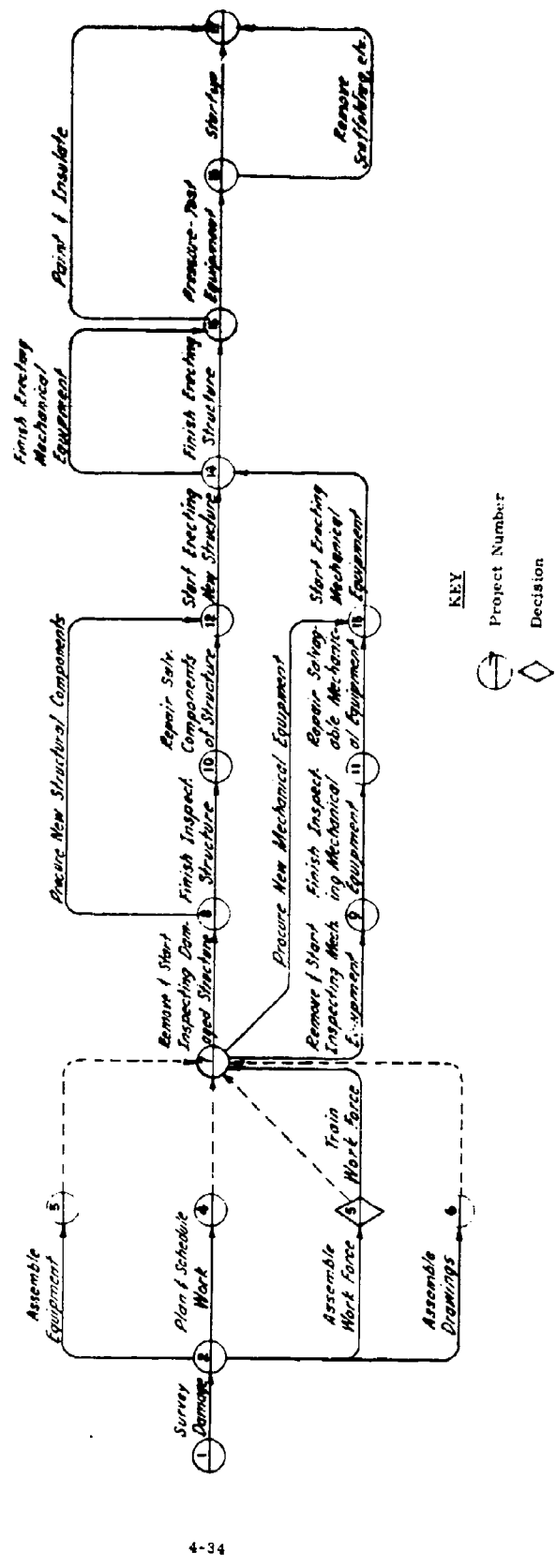


Figure 4.10 Generalized CPM Repair Chart

5. ESSENTIAL POSTATTACK FUELS, SUBSTITUTE FUELS, AND ADDITIVES

5.1 Essential postattack fuels and quality requirements

The following petroleum fuels are considered essential for recovery in the postattack environment, exclusive of natural gas, which is beyond the scope of this study:

- 1) Motor gasoline for automobiles and trucks (regular grade)
- 2) Aviation gasoline for piston aircraft
- 3) Jet aircraft fuel
- 4) Diesel fuel
- 5) Furnace fuel

Motor gasoline¹⁸ is usually a blend of straight cut (virgin) gasoline direct from the crude still; cracked gasoline, naphtha produced by catalytic reforming, alkylate, and butane to give it the proper Reid vapor pressure. One or more of these ingredients can be eliminated, depending on the grade of product required. Other desirable additives for quality improvement are antioxidants, metal deactivators, corrosion inhibitors, preignition preventers, anti-icing, upper cylinder lubricants, dyes, and decolorizers.¹⁹ Tetraethyl lead, which raises the octane number of gasoline, is the only essential additive; without it motor gasoline would have to be blended entirely from high octane ingredients, which would drastically reduce production.

Freedom from water, gum, and sulfur comprise the most significant quality requirements of motor gasoline are, as follows:

Water produces carburetor difficulties. Gum can be tolerated in small amounts, and is not a major problem unless the gasoline is stored for a long time. Corrosive sulfur adversely affects carburetor performance and corrodes the muffler and tailpipe over a period of time; noncorrosive sulfur affects lead susceptibility. The maximum permissible sulfur content

is about 0.40 per cent; 0.25 per cent was the maximum permissible during World War II. and no trouble developed.¹⁹

Freedom from vapor lock. This is governed by the boiling range and indicated by the Reid vapor pressure, ranging from 12.7 psi allowable maximum at 60 F to 5.3 psi at 120 F,¹⁹ although authorities disagree. Some upward revision of these values is possible at the expense of added inconvenience.

Warmup and acceleration. These are also governed by boiling range, and would not be critical performance characteristics for post-attack fuel requirements.

Antiknock quality. Modern automobile engines require increasingly higher octane numbers in order to reduce knocking. Mild knocking causes no harm, and has little effect on performance, but severe knocking can cause power loss and damage to pistons and bearings. L-head engines tend to knock at high speeds, and overhead valve engines at low speeds.¹⁹ The octane number is generally used as an indication of antiknock capability, although it does not correspond perfectly to road performance. The systems commonly used today for rating antiknock values are the Research and the Motor methods for automobiles; and the Aviation and the Supercharge methods for aircraft engines.¹⁹

The lead susceptibility of gasoline can vary. For example, 3 cc. of tetraethyl lead per gallon will raise a 60-MON typical straight run gasoline to 79 MON if sulfur content is below 0.1 per cent, and will raise an 80-MON catalytically cracked gasoline to 85 MON. The effect of tetraethyl lead is greater if the original octane number, the sulfur content, and the percentage of cracked gasoline are all low.¹⁹

Because of the importance of tetraethyl lead, this antiknock additive is discussed separately in section 5.3.

Crankcase dilution. This is also governed by boiling range, and would not be a critical characteristic for postattack requirements.

Aviation gasoline's important characteristics are antiknock rating under both lean and rich mixture conditions, cleanliness, chemical stability, and boiling range. There are four grades, ranging in octane up to 115/145

grade. The blend normally contains at least 85 percent iso-octane (the standard by which 100 MON is measured) produced by the alkylation process, plus virgin (straight run) gasoline, isopentane, butane for quick starting, and aromatics such as toluene.¹⁸ Tetraethyl lead is used for improving anti-knock characteristics in quantities up to 4.6 cc/gal. Its effectiveness is limited, and it cannot eliminate the need for alkylate.

Tractor fuel: Tractors are able to burn a lower octane gasoline without difficulty, and other specifications normally considered critical for automobile engines are not critical for tractors. Straight run gasolines or kerosine can be used without further treating and without antiknock additives. Specifications vary because of the need for cheapness and variety of engines. ASTM (American Society for Testing Materials) D1215 specifies 1.0 percent maximum sulfur and this could be even higher.¹⁹ Many tractors are also equipped for operation on L.F.G.

Jet military aircraft fuel (JP-4) is a relatively wide boiling range volatile distillate and is made by blending heavy virgin naphtha with kerosine of approximately 550° end point.¹⁸ It could be made from a single side stream of a pipe still. Domestic airline jet fuel (K-40 or Avjet A) is pure kerosine. The only treating involves caustic wash or sweetening and in some cases hydrotreating, which could be eliminated in an emergency.

Diesel fuel is obtained as cracked materials, as virgin side streams of a pipe still, or as a blend of the two. The important characteristics are cleanliness, ignition quality, fluidity and atomization, and volatility.¹⁹ Sulfur content is not critical. Additives normally used in diesel fuels could be omitted in an emergency without serious consequences. The relaxation of cleanliness specifications would have to be coordinated with the design of filters for fuel lines or else removal of the filters. Nozzles would have to be overhauled more frequently, and in extremely cold weather the pour point might be a problem, requiring some means of warming up the fuel.

Furnace fuel: Heating oils and industrial fuels are generally made from distillates such as kerosine and gas oil and residual fuels. The use of cracked distillates leads to problems of instability, normally corrected by treating or additives. Although customers would have to accept annoying

smells and the need for more frequent cleaning, such fuels would function without additional treating. The heavier fuels are residual fuel oils and are used for refinery fuel, as Bunker "C" or Navy Special. Indiscriminate blending of different residual fuel oils and cracked oils might lead to problems of separation or settling out of the heavier fractions. This, like the odor, is also in the nuisance category.

5.2 Essential raw materials

For the refinery to operate properly, certain essential raw materials are required. The postattack need for these will depend on the level of activity at the refinery during the reconstruction period, and the units being brought on stream. The essentiality of crude oil as a raw material input is manifest. TEL and TML, important additives for the production of gasoline, are discussed in section 5.3. The raw materials for TEL production include lead, sodium, chlorine, and ethylene; the ethylene alone is produced at the oil refinery.

The fluid catalytic cracker units require a fluidized silica-alumina catalyst, and although most of the catalyst is regenerated and reused, a substantial quantity is lost and must be replaced daily.

The alkylation process, used in the Baton Rouge threshold of recovery schedule (section 4.3.2) uses substantial quantities of sulfuric acid; typical alkylation yield data might require 0.5 to 2 pounds of sulfuric acid for every gallon of alkylate. The spent acid is returned to the supplier. In addition, some of the isobutane used is purchased in the form of a saturated compound from natural gasoline plants.

Most of the other processes referred to in the various sections of this report use some form of catalyst. For example, platforming and ultraforming use a platinum catalyst, which may require replacement at rates of one pound per 100 barrels of feed, with the used catalyst returned to the supplier for credit.

The bulk of the essential inputs described above come from the chemical industry and, although beyond the scope of the current study, these and other essential chemicals are recommended for further investigation.

5.3 Antiknock additives

This discussion of additives is limited to tetraethyl lead, $(C_2H_5)_4Pb$, "TEL", and tetramethyl lead, $(CH_3)_4Pb$, "TML", because other additives are primarily for convenience, and could be eliminated under emergency conditions without seriously affecting engine performance.

A detailed description of the facilities and operations at DuPont's Chambers Works TEL plant is presented in appendix A.

5.3.1 Applications

Regular gasoline today averages 93 RON (Research Octane Number), and premium averages over 100 RON. Regular is adequate for about 63 per cent of the cars on the road without excessive knocking; premium satisfies about 95 per cent. At 80-85 RON all cars on the road would be knocking severely enough to do engine damage and drastically limit performance. If 80-85 RON were the only gasoline available, one solution would be to limit speed and motor rpm, by some kind of a carburetor adaptation such as a restriction in the fuel intake line. Another partial solution would be to retard the spark. This change in timing could be done at any service station. Its effectiveness is limited by the fact that engine performance is drastically affected beyond a 2 or 3-degree change in timing. Since a 1-degree change in timing corresponds to 1 octane number, the difference between 93 and 83 octane would require a 10-degree compensation in timing, which is more than can be tolerated from an engine performance standpoint.

Modern automobile and truck engines, gasoline and diesel, are designed for maximum performance using the best grade of fuels commercially available. This is particularly true in the case of high-horsepower truck engines, and any deterioration in octane number would seriously affect truck engine performance. For this reason, the best fuels available for non-military postattack purposes should be reserved for trucks, because of their importance in transporting critical materials and food.

The products marketed as antiknock additives are actually blends of TEL or TML, scavenging compounds, stabilizers, and dye. The

scavengers are added to prevent the buildup of lead compounds in the cylinder or spark plug fouling.

5.3.2 Antiknock additives production

The following plants in the western hemisphere produce TEL or TML:

Ethyl Corporation

Baton Rouge, Louisiana	batch process	} →	400 million lbs/yr
Pasadena, Texas	batch process		(both plants combined)
Pittsburg, California	batch process		shut down
Sarnia, Ontario	batch process		

E. I. duPont deNemours Company

Deepwater, New Jersey	batch & continuous	} →	350 million lbs/yr
Antioch, California	continuous process		(both plants combined)
Maitland, Ontario	batch process		25 million lbs/yr
Coatzacoalcas, Mexico	batch process		40 million lbs/yr

Houston Chemical Company

Beaumont, Texas	batch process
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Nalco Chemical Company

Freeport, Texas	electrolytic process	40 million lbs/yr
-----------------	----------------------	-------------------

There are only three processes in commercial use at this time: (1) the batch process,²³ by which the first TEL was manufactured and which still accounts for the bulk of production, and in which ethyl chloride is reacted with lead sodium alloy in autoclaves, followed by steam distillation; (2) the continuous process, employing the same reaction between ethyl chloride and lead sodium alloy, but on a continuous throughput basis; and (3) the Nalco electrolytic process, in which magnesium chips are reacted with ethyl chloride to produce magnesium ethyl chloride, followed by a continuous electrolysis with ether solvent, in which lead pellets are the anode and the vessel's steel walls are the cathode.

The DuPont continuous process is about ten years old, and is commercially feasible only in large quantity throughput. The Nalco process has been in commercial use only about one and one-half years, and accounts for 5 per cent of the U.S. production.

TML is essentially interchangeable with TEL. It is made by the batch process only, using methyl chloride instead of ethyl chloride. The process is basically the same as the TEL batch process, with a few differences, primarily the use of higher autoclave pressures and mixing a dry graphite lubricant with the reactants to prevent paddle binding in the autoclave.

With a moderate amount of equipment modification, a TML batch plant could be converted to a TEL batch plant. The reverse is not true, however, because of the greater pressure needed for TML.

A more detailed discussion of the TEL and TML manufacturing processes is found in "Plant Descriptions" (appendix A).

5.4 LPG as a substitute fuel

In the event that supplies of gasoline and diesel fuel were reduced by an attack, liquid petroleum gases (LPG) could be substituted to an extent if conditions warranted. LPG, a mixture predominantly of propane with propylene and butane gases, currently enjoys limited use in internal combustion engines, particularly in large company-owned car and truck fleets, and in tractors. There are 839 natural gas processing plants scattered throughout 23 states, and 810 of them produce LPG as well as, in most cases, natural gasoline and/or gasoline-LPG combinations. Their locations and specific capacities are detailed in reference 25. Production of propane at these plants in 1965 averaged 12,232,105 gal/day. The extent to which this production can be increased or the extent to which the 18,343,495 gal/day of combined gasoline-LPG can be converted to straight LPG at the gas plants are beyond the scope of the present study, but merit further investigation. In any event, the large number of natural gas plants and their geographical dispersion suggest that, under most foreseeable conditions—including the hypothetical attack on refineries

detailed in chapter 3, LPG production capability will survive, and that LPG will be available in good supply, and perhaps in surplus. It therefore represents an excellent potential substitute for gasoline, far superior to any previously used, such as charcoal as a petroleum substitute in Europe in World War II. In addition to the gas plants, liquid petroleum gases are produced at cycling plants and refineries, but the great majority is produced at the gas plants.

The Research Octane Number of LPG ranges from 94 for butane to 110 for propane, and the Motor Octane Number ranges from 85 for propylene to 94 for propane.²⁶ This constitutes the "octane envelope" of LPG, shown in figure 5.1. It can be increased by using TML, which will vaporize with the propane.²⁷ In 1931, regular gasoline averaged about 64 RON, and LPG offered a substantial octane advantage. With the gradual increase in octane of regular gasoline, and the increase in compression ratios, this advantage has been whittled away, so that in 1965, regular gasoline at 93 RON entered the LPG octane envelope. The use of LPG is now justified economically by savings in maintenance, engine life, and operating costs, rather than in octane.

Most manufacturers of trucks, buses, and farm tractors, are prepared to supply either gasoline, diesel, or LPG engines as required by the customer. Farm tractors are a major user of LPG: in 1963, 9,588 LP gas tractors were produced, compared to 98,198 diesel tractors and 96,235 gasoline tractors. Also, over 20,000 LPG carburetors were sold for field conversion of tractors to LPG.²⁹ A good example of the use of LPG is in the fleet of 800 repair trucks and passenger cars operated by a telephone company in Florida.³⁰ Conversion was done on a production line basis by eight mechanics who completed the conversion from gasoline to LPG in 6 months. This is about 18 conversions per man-month. Most of the required tools and equipment would be found in any well-equipped auto repair shop.

Parts for LPG conversion are supplied by most of the engine manufacturers such as GMC, John Deere, International Harvester, and Ford, and also by companies specializing in carburetors.

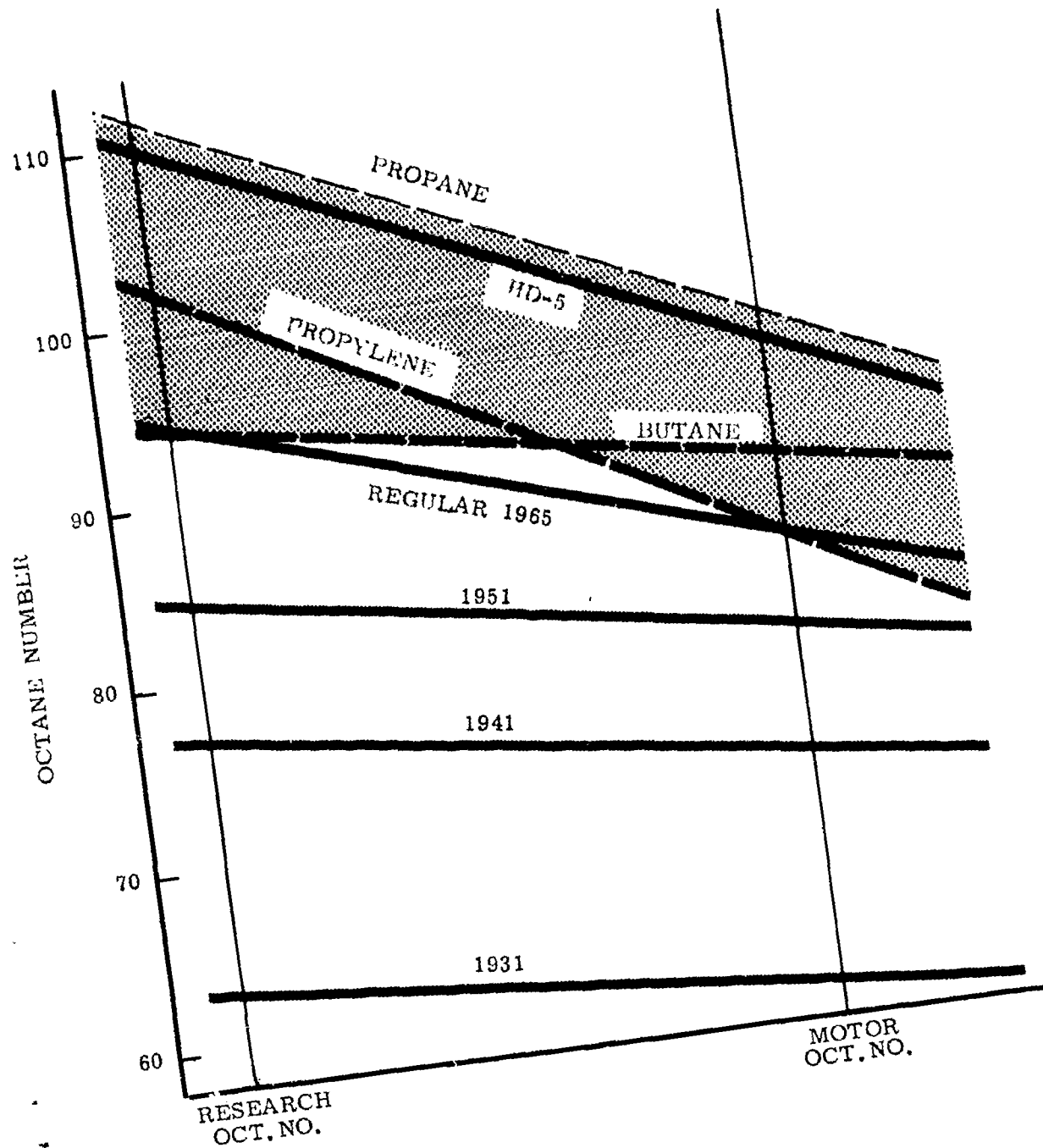


Figure 5.1 Octane Envelope of LPG 26

The Chicago Transit Authority provides an example of the use of propane in buses. Of 2661 motor buses as of June 7, 1962, 1549 were propane fueled.³¹

The feasibility of converting diesel locomotives to LPG has been studied, and, although technically possible, it is probably not practical to do so because the conversion problem grows with the size of the engine.³² Practical operating problems in railroad operation would probably limit conversion to LPG to yard and switching engines involved in "captive" service. Other "captive" service applications where LPG conversion is feasible are in industrial lift trucks and stationary engines.

Operations of engines on LPG have not been entirely trouble free. There have been some premature engine failures, burned valves, burned pistons, and cracked cylinder heads blamed on LPG. The situation has been greatly improved with the adaptation of a uniform fuel specification, as many of these failures were caused by too much butane or propylene in the fuel, resulting in a lower octane number. Other causes of engine failure are due to improper conversion.^{33, 34, 35}

In conclusion, LPG can be used as a fuel in gasoline and diesel engines in passenger cars, trucks, buses, and farm tractors in the post-attack period, if conversion is done properly.

Further study is recommended, particularly on the vulnerability of propane production facilities at gas plants, and the vulnerability of LPG carburetor suppliers.

6. RECOMMENDATIONS FOR FURTHER STUDY

Repair times in this study are based, out of necessity imposed by limitation of scope, on the following assumptions:

1. Replacement parts are available or substitutes could be fabricated.
2. Materials for repair are available.
3. Trained operators and repair personnel are available.

These assumptions are probably unrealistic for many postattack environments, but there are no criteria as yet to indicate the probable postattack availability of these three essential inputs to repair. Further analysis of these inputs in connection with specific attack patterns is recommended, particularly the preparation of repair charts for those industries essential to refinery repair. Analyses of items 1 and 3 (above) require a specific attack scenario, and coordination with other research by the Office of Civil Defense. Prior studies on petroleum products distribution should be updated in the same connection.

The scope of this project was limited to the survival period. Extension of the work into the recovery period is recommended.

This study of the petroleum industry points out the reliance of many refineries on electricity from outside power plants. Conversely, of course, many electric power generating plants depend upon petroleum products. In connection with the Critical Industry Repair series, of which this report is a part, it may prove beneficial to reexamine electric power. The original Critical Industries Repair Analysis: Electric Power, used earlier techniques which have become somewhat outdated by the advances in the state of the art in the more than three years since it was published.² Such advances, embodied in the current report, include a generalized vulnerability model with efforts started to program it; application of CPM techniques to repair problems in specific cases; and a generalized repair model, drawn in CPM format. New information generated would include damage and repair data for power plants designed to conform to an earthquake code, such as the one supplying San Jose.

While this power plant is technically outside the San Jose area, it should nevertheless be analyzed because it will be a critical postattack input. New Orleans has an "outdoor" generating plant, which could yield new data if analyzed.

The identification of the controlhouse and cooling tower as the refinery weak links is one of the most significant findings of this study. Because they fail at low overpressures, 1.0 - 1.5 psi, thereby destroying the automatic instrumentation and cooling capacity without which the refinery cannot operate, they present an excellent opportunity for hardening. Relatively little effort should be required to strengthen the controlhouse, particularly the roof, so as to reduce vulnerability to a level more consistent with that of the processing units whose operation largely depends upon the controlhouse. Failure of the controlhouse and cooling tower—if accompanied by failure of processing units—would probably not lengthen the total refinery repair time since processing units have longer repair times. A controlhouse hardening study could use techniques employed in prior industrial hardening studies.⁷²

Key essential inputs to petroleum merit further study. These are primarily within the chemical industry and include sulfuric acid, tetraethyl lead, and chlorine.

Resonant periods of vibration of buildings deserve further investigation because of insufficient data, at present, to obtain precise results. Failure of concrete slabs, such as the administration building floor, merit further investigation. In connection with these projected studies, it is anticipated that the computer program for analysis of structures subjected to dynamic loading will be improved and published.

Less than a third of the above-ground crude oil supply is readily available using conventional techniques, because most of this crude is line fill in pipelines, or in tank bottoms, or otherwise unavailable. Techniques for its postattack recovery could be analyzed or, if no such techniques are known, perhaps they could be developed.

Liquid petroleum gas appears to be the most feasible substitute for petroleum and, as such, merits further and more detailed consideration. Specific areas of interest include the possibility of increasing production of LPG's principal component, propane, and the conversion of combined natural gasoline - LPG to straight LPG.

APPENDIX A
PLANT DESCRIPTIONS

APPENDIX A

TABLE OF CONTENTS

A.1	Baton Rouge Refinery: Introduction	A-1
	A.1.1 General	A-1
	A.1.2 Operation and flow	A-4
	A.1.3 Utilities	A-14
A.2	Whiting Refinery: Introduction	A-19
	A.2.1 General	A-19
	A.2.2 Operation and flow	A-19
	A.2.3 Utilities	A-22
A.3	Pascagoula Refinery: Introduction	A-26
	A.3.1 Operation and flow	A-26
	A.3.2 Utilities	A-28
	A.3.3 Emergency repairs and procedures	A-29
A.4	DuPont's Chambers Works (TEL Plant)	A-33
	A.4.1 Plant and equipment	A-33
	A.4.2 Utilities	A-34

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
A. 1	Simplified Petroleum Products Flow Plan	A-5
A. 2	Crude Desalting Unit Flow Diagram	A-6
A. 3	Atmospheric Pipe Still Flow Diagram	A-7
A. 4	Vacuum Pipe Still Flow Diagram	A-8
A. 5	Catalytic Cracking Units Flow Diagram	A-11
A. 6	Light Ends Unit Flow Diagram	A-13
A. 7	Alkylation Plant - Stirred Reactor Section Flow Diagram	A-15
A. 8	Alkylation Plant - Fractionation Section Flow Diagram	A-16
A. 9	Superfractionator Flow Diagram	A-17
A. 10	Steam Generating Schematic Whiting Refinery	A-24

APPENDIX A PLANT DESCRIPTIONS

A.1 Baton Rouge Refinery: Introduction

The refinery of Humble Oil and Refining Company at Baton Rouge is studied in some detail because, while no single refinery can be considered typical, it is the largest in the United States and has process units covering a wide range of products and processes. The portions of the refinery devoted to the production of motor fuels—motor gasoline, aviation gasoline, jet turbine fuels, and middle distillates—are singled out for emphasis because of their pertinence to the current study. Lubricating oils and petrochemicals will be covered in a later phase of the program.

A.1.1 General

Layout

The Baton Rouge refinery is on the east bank of the Mississippi River, about two miles upstream from the state capital. It employs about 4,300 people. The plot plan is roughly square, about 1 1/2 miles on a side extending to the banks of the river if the dock area is included. Additional facilities are the Anchorage tank farm across the river and the Maryland tank farm at North Baton Rouge. There are also extensive storage facilities at the refinery itself, and natural gas liquids, (ethylene, propane, isobutane) are stored under pressure at the Sorrento salt dome storage area, about 30 miles away. The process units are, in general, grouped at the center of the plot, with the storage tanks and blending fields surrounding them to the north and south. The administrative and maintenance buildings are on the east, and the dock area, including the Plantation Pipeline Company pumping station facilities, are on the west.

Buildings

The principal buildings are grouped along the eastern side of the plot facing Scenic Highway. They are the main office building, the cafeteria behind it, the Esso laboratories just to the west, the employee relations and medical building just to the south, and the Central Mechanical Building south of all these and also facing Scenic Highway. The old boilerhouse was shut down in 1960 and is scheduled for demolition. Throughout the refinery there are also numerous one-story brick control centers and light framed shed style buildings covering certain items of process equipment. The tetraethyl lead plant weigh building is a one-story brick structure located on the northern edge of the plot connected by pipeline to the Ethyl Corporation manufacturing facilities which are just north of the refinery.

Central mechanical building

This is primarily a maintenance and repair shop and spare parts storage warehouse, serving the entire refinery. Because of its size and the excellence and completeness of its facilities, it would be a factor of major importance in the postattack recovery of the refinery and even for other plants in the area. The structure is really two buildings, one built in 1948, the other in 1956. Both are steel frame structures with brick walls extending ten feet up and transite panels above this. Facilities include the

machine shop, pipe shop, boiler shop, welding shop, sheet metal shop, electrical shop, heat exchanger repair shop (retubing, converting, cleaning), automotive and motorized equipment maintenance shop, paint shop and spray booth, carpenter shop, instrument shop, and spare parts storage with automatic conveyor. There are three 15-ton overhead traveling cranes, one in each bay, and lifting derricks at each column location. The slightly pitched roof is corrugated metal covered with insulation, tar and gravel.

Process equipment

The principal processing units at the refinery are separated into two main division, chemical and petroleum.

Chemical: These consist of the Butyl Department, Cracking Department, and Alcohol Department.

Petroleum: These consist of the Distillation and Cracking Department, with eight crude stills of which six are normally operated, and two fluid catalytic crackers, the Light Ends Department, with three alkylation units, with one stirred reactor (H_2SO_4) alkylation unit, the gas compression and light ends recovery units, one powerformer, one polymerization unit, one delayed coking unit, the treating facilities, and the Lube and Wax Department. These petroleum units are described more fully in section A.1.2.

The processing equipment associated with these units groups into the following categories:

- Vertical reactors and pressure vessels
- Vertical fractionating towers
- Heat exchangers and condensers
- Furnaces
- Horizontal drums and reactors
- Piping
- Controls
- Pumps, compressors, turbines and motors
- Attendant structures

Other equipment which is indirectly associated with processing units consists of storage tanks, pipe bands and pipelines, and flare stacks supported by either steel towers or guy wires.

Vertical reactors and pressure vessels

The most important of these are the reactor and regenerator in fluid catalytic cracking units 2 and 3. They are massive vessels, supported by the attendant structure. The regenerator is located high up in the unit, and is rather vulnerable to blast damage.

Vertical fractionating towers

In the pipe stills, both the atmospheric fractionating tower and the vacuum fractionating tower are supported at their bases independently of the attendant structure which surrounds them. They are retained by anchor bolts at their bases imbedded in a 35-foot-high reinforced concrete foundation frame.

In the light ends units the absorbing, debutanizing, and stripping towers are mounted free-standing, either on a reinforced concrete pedestal or a reinforced concrete foundation frame.

The fractionating towers in the three alkylation units are similarly mounted. The 205 foot superfractionating, or deisobutanizing, tower is the tallest of these and is mounted on a reinforced concrete pedestal with a combination spread footing.

Attendant structures

The structures surrounding various processing units are primarily for the purpose of providing support for auxiliary equipment and access for maintenance, observation and control. In the pipe stills, the attendant structure is independent of the support structure for the process units. It is an open steel structure with shear members for diagonal bracing and has platforms and catwalks at various levels with stairways between. The two catalytic cracking units have 13-story structures with an elevator on one corner and support most of the auxiliary process equipment, except for the fractionator.

In the light ends and alkylation units, the fractionating towers are generally equipped with ladders and platforms attached directly to the towers.

In all units, steel structures within 35 feet of the ground are fire-proofed with a coating of concrete.

Heat exchangers, condensers and horizontal drums

These are generally supported by reinforced concrete cradles or columns with spread footings.

In the #3 alkylation unit, the horizontal sulfuric acid reactors have electric motor driven stirring paddles inserted along their length from above.

In general, the horizontally mounted vessels have a low profile and are mounted close to the ground where there would be a considerable amount of shielding from blast and thermal damage.

Controls

Most processing equipment controls are pneumatically actuated and are "fail safe"; that is, loss of instrument air will operate the valves and equipment in the safest way. Even though all electrical equipment used in processing areas is of explosion-proof construction, there is nevertheless greater hazard in its use than with pneumatic equipment.

The controlhouses, or headquarters buildings, contain most of the temperature and pressure recorders, gauges, flow meters, pilot lamps, switches, alarms, etc., pertaining to the transmitters and transducers mounted at the controlled devices in the process areas.

Several electric motor driven air compressors scattered throughout the refinery provide compressed air for the pneumatic controls. During the shutdown following the power failure in April 1960, it was the loss of this air, as much as anything else, that actually shut down the plant. (For discussion of the shutdown, see section 3.10.)

Storage tanks

Storage tanks, meeting the American Petroleum Institute standards, cover a range of sizes and are of three types: floating roof, cone roof, or spherical. The cylindrical tanks are welded, riveted, or seal-welded (welded over or around the rivets to seal against leaks). The newer tanks are all-welded. The spherical tanks are for storage of light hydrocarbons and LPG under pressures up to 110 psig for the 5,000 barrel tanks and 30 psig for the 30,000 barrel tanks. They are of all-welded construction and mounted on legs. The cone roof tanks have a pressure vacuum vent mounted on the roof which permits pressure equalization inside the tank, and the seam welds joining the roof to the wall are intentionally weak, to provide additional safety against internal pressure buildup. Their roofs have been known to buckle when the vents became plugged. The vapors which occasionally escape could possibly be ignited by thermal radiation emanating from a nuclear explosion. (For discussion of thermal radiation, see section 3.8.)

Gasoline is blended by batch. Blending tanks have electrically-driven mixer blades inserted into the tank at such an angle as to produce a rotational movement of the product. All grades of gasoline must be blended, the formula varying with the requirements in the season and the geographical areas where they will be sold, and this operation requires about 8 hours. The ground area around each tank is saucer shaped and surrounded by a dike (low wall) designed to contain 50% of the tank capacity.

A.1.2 Operation and flow

In this section a few key processes and their units are described in conjunction with flow charts. (See Figures A-1 through A-9). The processes that have been selected are those considered essential to gasoline and fuel production. The units described here are those which were analyzed in detail at the refinery as being representative of their group.

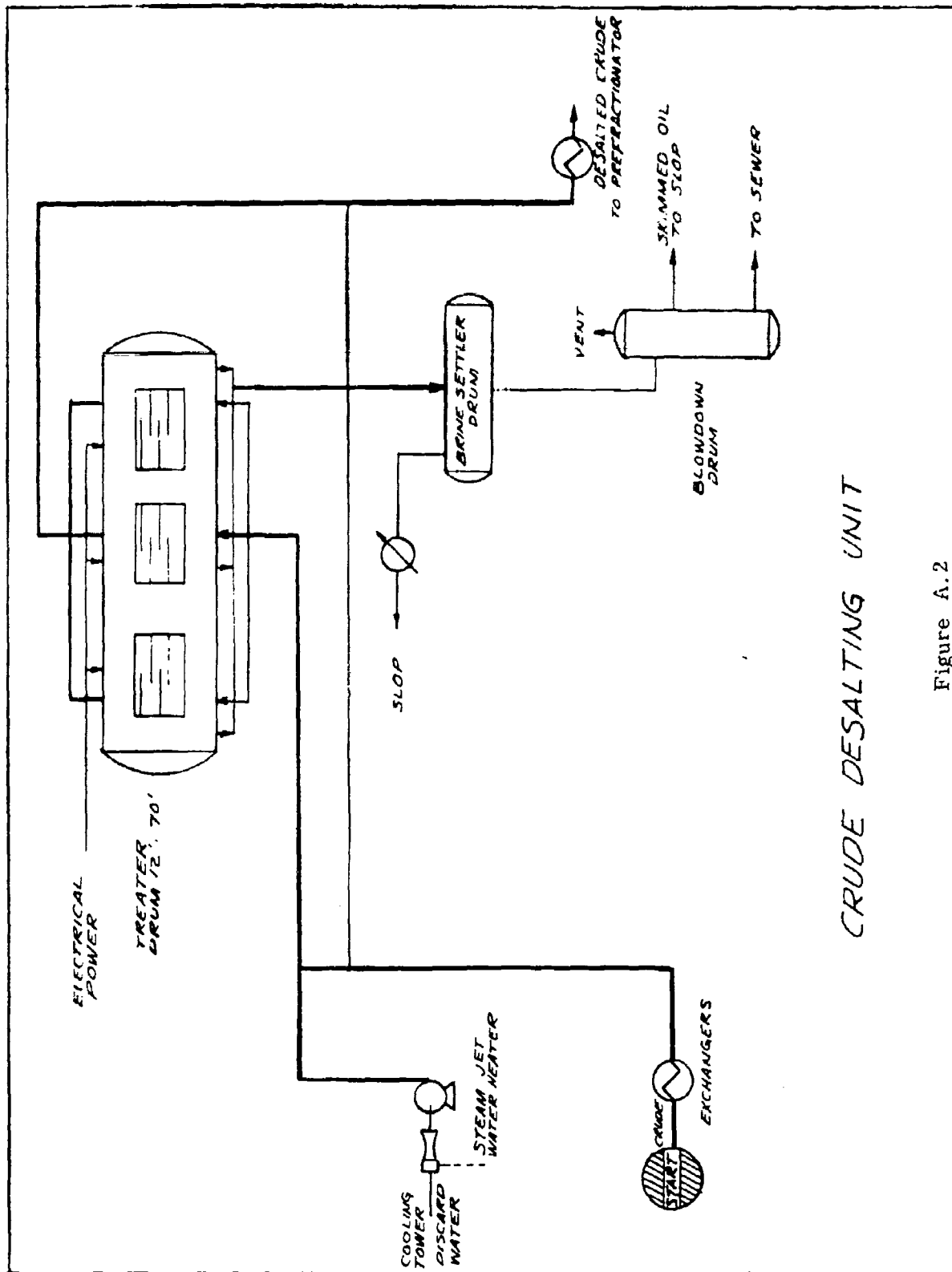
Crude supply

The two tank farms supplying the Baton Rouge refinery are at North Baton Rouge and across the river at Anchorage. The five principal crude producing areas for this refinery are in Mississippi, northern Louisiana, and three in southern Louisiana, of which one is offshore. There are seven river crossing pipelines underneath the river. The grade of crude used at Baton Rouge is classified a "sweet" crude—low in hydrogen sulfide. A "sour" crude is one having greater than 0.05 cu. ft.³ of dissolved H₂S per 100 gallons, and is dangerous because of toxicity. Such a crude is not

The diagram illustrates the complex process of refining crude oil into various petroleum products. The main components and flow are as follows:

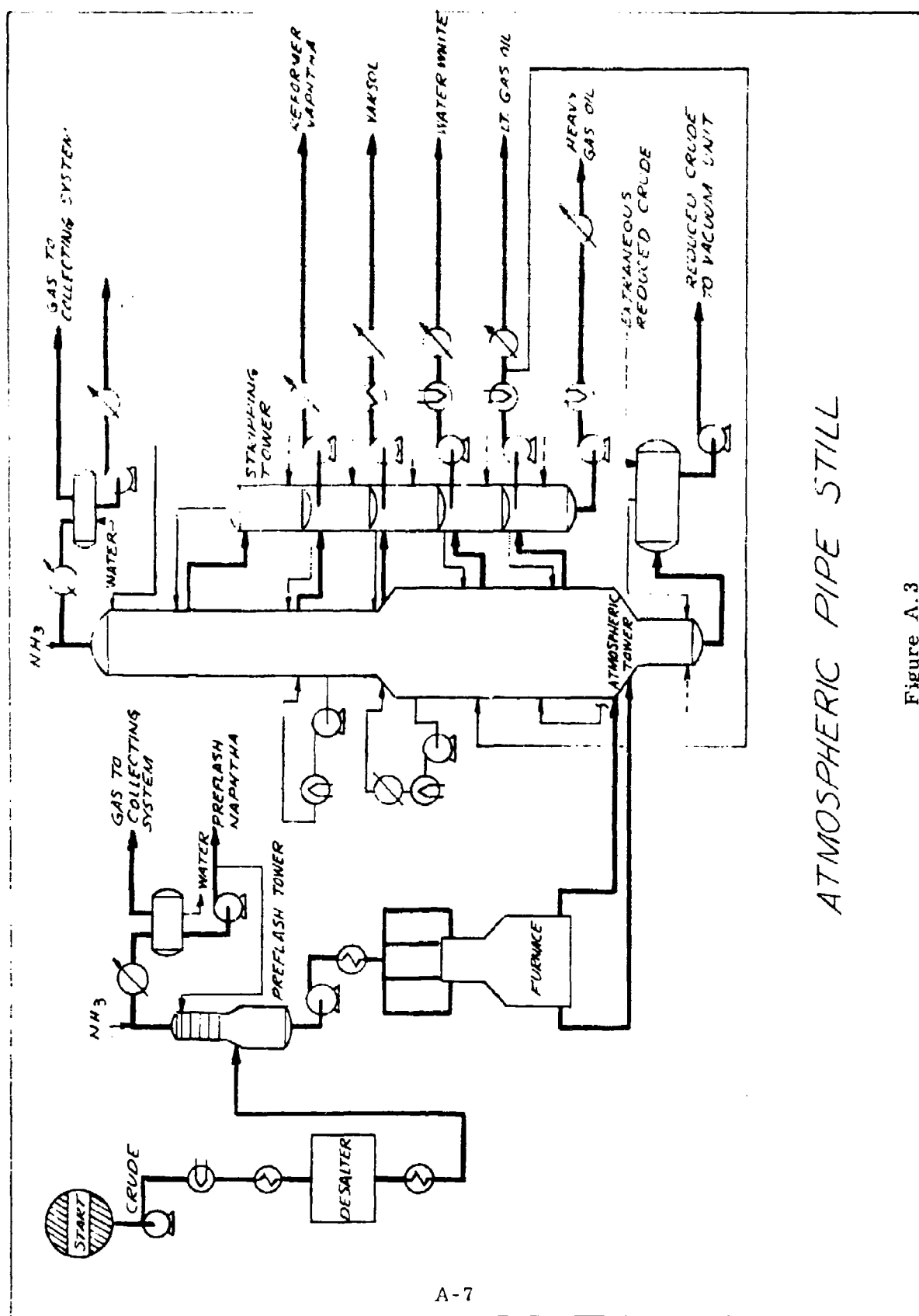
- Crude Oil Input:** Enters the **ATMOSPHERIC FRACTIONATOR**.
- Atmospheric Fractionator Outputs:**
 - Top:** GAS TO ABSORPTION
 - Below Top:** GAS TO SALES, C₃ TO ALKYLATION, NAPHTHA TO GASOLINE
 - Below:** GAS COMPRESSION, D & S FRACTIONATION UNIT, GAS TO FUEL, C₃-C₄ TO FRACTIONATION, NAPHTHA TO GASOLINE
 - Below:** NAPHTHA TO GASOLINE, JET FUEL & SPECIALTY SOLVENTS, POWERFORMER UNIT
 - Below:** KEROSENE, GAS OIL TO HEATING OIL & DIESEL
 - Bottom:** PARAFFIN DISTILLATE
- Gas Processing:**
 - Top:** C₂ TO LPG, C₃ TO LPG, POLYMER TO CHEMICALS, POLYMER TO GASOLINE
 - Below:** GAS, C₃, C₄, NAPHTHA TO GASOLINE, ABSORPTION & FRACTIONATION UNITS
 - Bottom:** PURGEWASH ISOBUTANE, 3-ALKYLATION UNITS, ALKYLATE TO GASOLINE
- Cracking and Refining:**
 - CATALYTIC CRACKING UNIT:** Receives DISTILLATE HEATING OIL, CLARIFIED OIL TO PHENOL TREATING, and DISTILLATE HEATING OIL. Outputs: GAS, DISTILLATE HEATING OIL, CLARIFIED OIL TO PHENOL TREATING.
 - PHENOL TREATING UNIT:** Receives DISTILLATE HEATING OIL. Outputs: DEPHENOLIZED OIL, PHENOL TREATING UNIT.
 - SOLVENT DENATURING UNIT:** Receives DEPHENOLIZED OIL. Outputs: DEWATERED OIL, WAY TO CATALYTIC CRACKING.
 - PROANE & HEX DENATURING:** Receives DEWATERED OIL. Outputs: DEWATERED OIL, WAY TO CATALYTIC CRACKING.
 - HYDROFINING UNIT:** Receives DEWATERED OIL. Outputs: CRITICAL GRADE LUBE OILS, FINISHED LUB OILS.
 - PARAFFIN OILS:** Receives DEWATERED OIL. Outputs: PARAFFIN OILS.
- Asphalt and Residue Processing:**
 - DEASPHALTED OIL:** Receives PARAFFIN DISTILLATE. Outputs: DEASPHALTED OIL.
 - PHENOL TREATING UNIT:** Receives DEASPHALTED OIL. Outputs: DEPHENOLIZED OIL, PHENOL TREATING UNIT.
 - PRECIPITATED ASPHALT:** Receives DEPHENOLIZED OIL. Outputs: PRECIPITATED ASPHALT, DELAYED COKING UNIT.
 - ASPHALT:** Receives PRECIPITATED ASPHALT. Outputs: ASPHALT.

40



CRUDE DESALTING UNIT

Figure A.2



ATMOSPHERIC PIPE STILL

Figure A.3

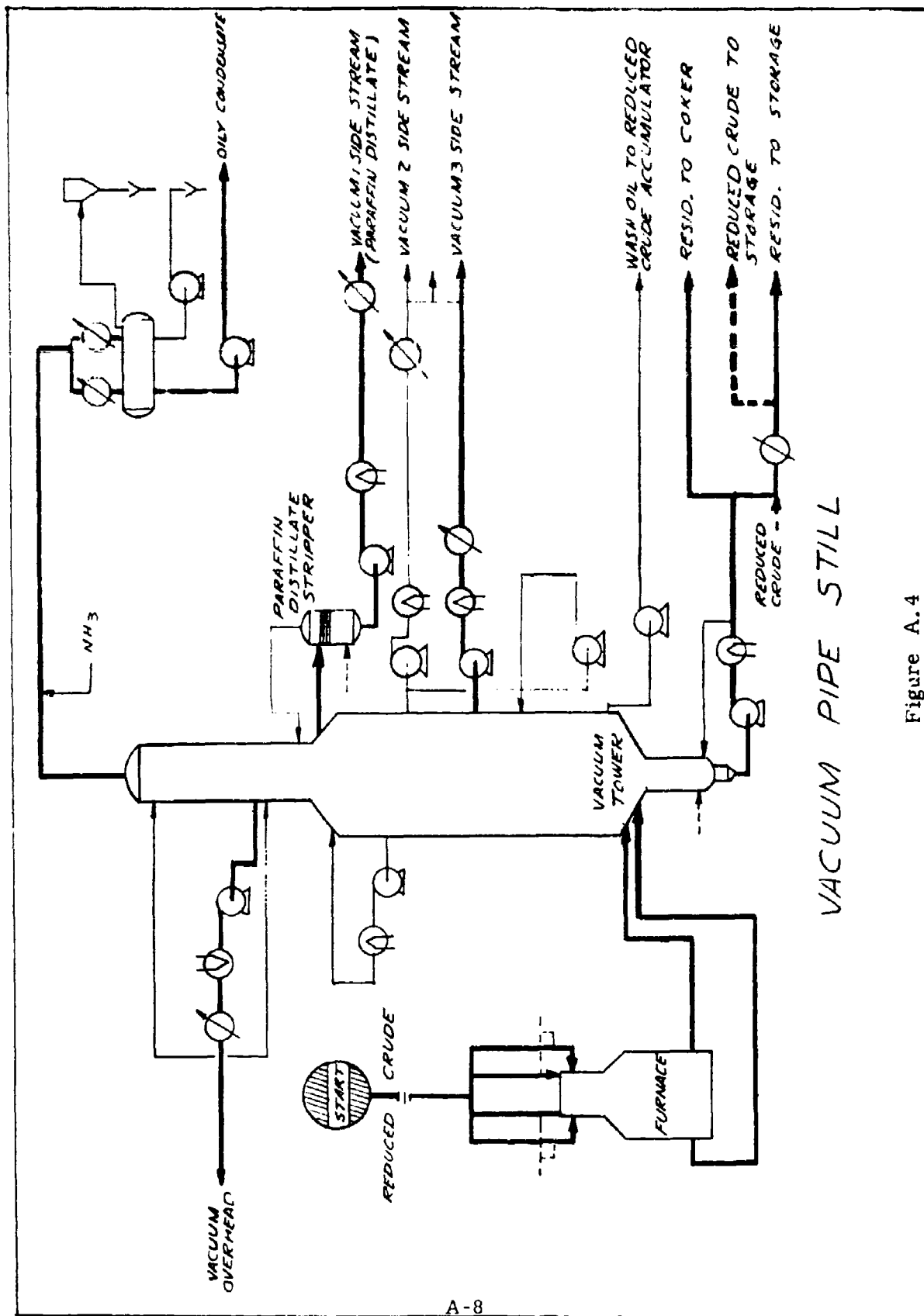


Figure A.4

excessively corrosive unless H₂S content exceeds 0.5 cu. ft. per 100 gallons. Sweetening, or treating, processes are used for sulfur and H₂S removal.

Capacity

Refining capacity, as of January 1, 1965, was 362,000 barrels/calendar day, or 375,000 barrels/stream day, the largest in the United States. This is further broken down as follows (10):

Charge capacity — (Barrels/stream day)

Vacuum distillation	141,600
Thermal operations	40,000 (gas-oil cracking)
	22,500 (delayed coking)
Catalytic cracking	175,400 (fresh feed)
	11,700 (recycle)
Catalytic reforming	38,000 (powerforming)
Hydrogen treating: Solvent feed	3,800 (Esso Hydrofining)
Lube oil feed	11,000 (Esso Hydrofining)
Wax feed	800 (Esso Hydrofining)

Production capacity — (Barrels/stream day)

Alkylation	23,800 (H ₂ SO ₄)
Polymerization	7,800 (catalytic)
Lubes	12,000
Coke (tons)	1,125
Asphalt	12,300

Distillation

Pipe stills No. 7, 8, and 9, are large modern units, with crude capacities from 70-95,000 barrels per day. There is an atmospheric distillation section and a vacuum distillation section, each with its own gas-fired furnace. The crude passes through an electrostatic, 20,000 volt desalter, where the salt is removed at a rate of approximately 50 lbs per 1000 barrels, then through the preflash tower at 35 psig and 325°F. Next it passes through the atmospheric furnace and into the atmospheric fractionating tower where the pressure is 7-8 psig. Four or five side streams are typical; this tower has five, which are: 1) heavy naphtha, which goes to catalytic reforming charge, 2) water white, 3) a solvent cut (or kerosine), 4 and 5) light and heavy gas oil which go into diesel blending or catalytic cracking. The overhead, or light naphtha and light ends, go to the debutanizing and splitter units for debutanizing, depropanizing and deethanizing. The side streams pass through the steam strippers, and the reduced crude is passed into the vacuum furnace and distilled again in the vacuum tower, at 750°-800°F under about 29 inches of mercury vacuum, pulled by surface condensers and steam jet ejectors. The vacuum fractionating tower has three distillate vacuum gas oil streams which go to catalytic cracker charge and a vacuum residuum to coker charge. There are thus no products of the atmospheric fractionator that are used, as is, for motor gasoline.

The controls on the pipe stills are almost completely pneumatic. The drives are both electric and steam, but No. 8 pipe still has only steam drives and could thus be operated without electric power, whereas the others could not.

The fractionating towers are mounted on reinforced concrete foundation frames 35 feet high, as described elsewhere. The service, or attendant, structures, are steel and are not attached to the towers. The furnaces are mounted on steel columns, surrounded by steel structures.

Catalytic cracking

The first fluid catalytic cracker was built and operated at the Baton Rouge refinery. Now shut down and being dismantled, it was built in 1941, and designated No. 1 Catalytic Cracker. There are at present two others, built in 1943 and 1944, both on stream, one of them continuously for nearly four years, a possible record.

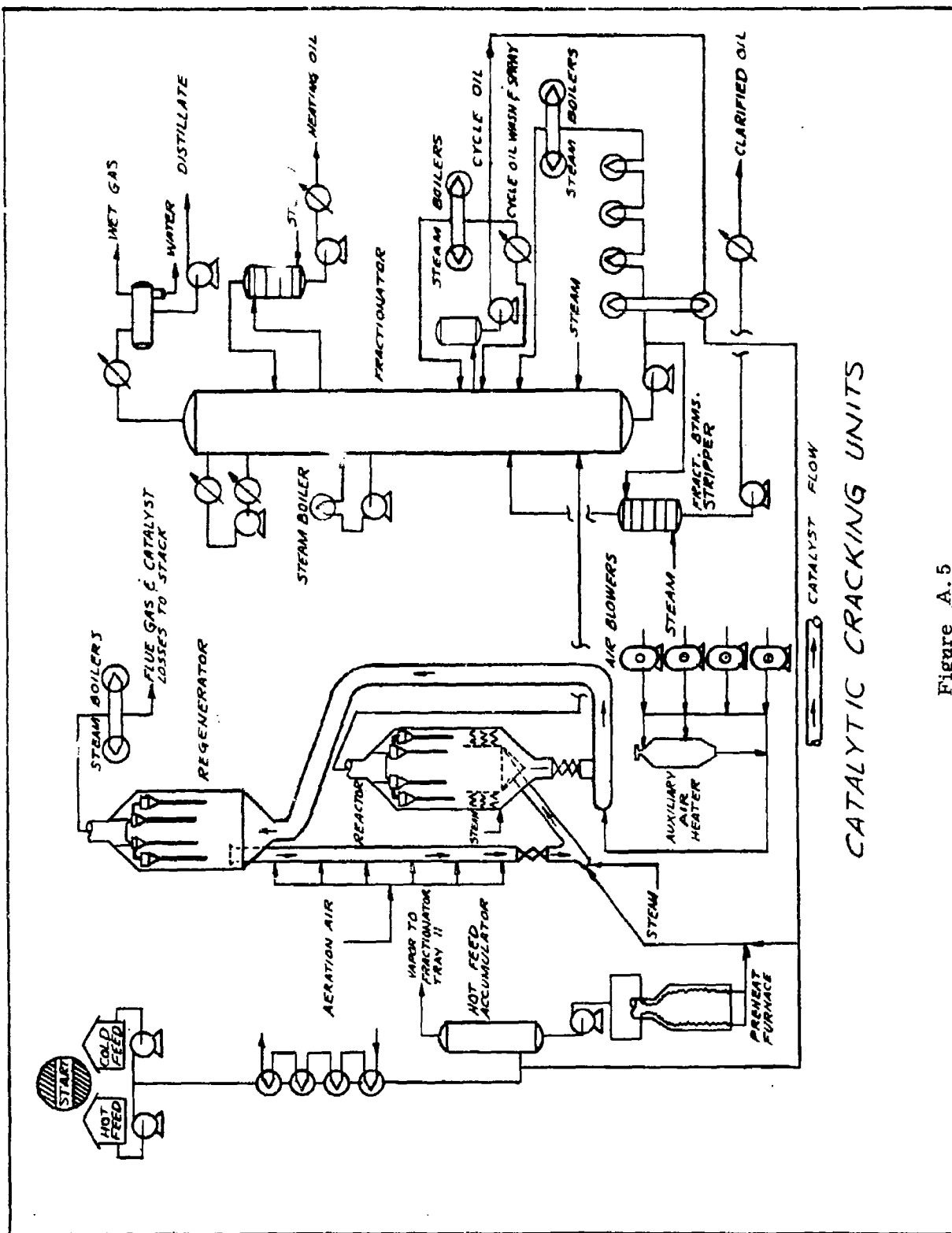
The support structures provide access to the equipment and support for the reactor and regenerator vessels and associated valves, piping, blowers, motors, etc. The regenerator is located high in the structure, its base at about 150 feet above ground level, and presents one of the more obviously vulnerable pieces of equipment. The reactor vessel is below it, near the center of the structure.

The two crackers are basically identical except with respect to their fractionating towers. Originally the fractionators were on the south side of the structure, but recently No. 3 catalytic cracker was furnished with a new fractionator, and this was placed just east of the structure on its own foundation. The original fractionator on No. 3 catalytic cracker is still in place but disconnected.

The support structures for these units, having been built under war-time emergency conditions and shortages, are a bit cumbersome and redundant. The units themselves, being early examples, have been modified repeatedly and have a somewhat more cluttered appearance than recent vintage cat crackers.

The so-called "fluid" catalyst supplied by Davison Chemical Division of Grace Chemical Corporation is actually a fine alumina-silica powder which, when inserted into a high-velocity high-temperature stream of vaporized oil, steam, or air, behaves like a fluid. If flow should stop, as in emergency shutdown, the catalyst "slumps" and behaves like a solid, plugging lines.

The catalyst circulates at a rate of 50-60 tons/minute, and about 2 or 3 tons per day are lost through the regenerator stack. Periodically, spent catalyst is drawn off, and new catalyst is added. There are two principle flow paths in the cracking process: that of the oil and that of the catalyst. They join just before entering the reactor, pass together into the reactor, then the catalyst drops from the reactor through the stripper and is airblown into the regenerator where the coke is burned off while the cracked hydrocarbons are fed into the fractionator.



The oil feed for the catalytic crackers is the light and heavy gas oil streams from the atmospheric and vacuum pipe stills. The cracking process is essentially a means of breaking up these heavier hydrocarbon molecules coming out of the pipe stills so that they can in large part also be used ultimately as stocks for motor gasoline, along with the lighter fractions from the pipe stills.

Operating pressures in the catalytic crackers are relatively low—30 psig in the reactor, 10 psig in the regenerator, 40 psig in the standpipe feeding the reactor, and 12-15 psig in the fractionator. Temperatures, however, are relatively high, being 250° - 700°F in the fractionator, 900°F in the reactor, and 1160°F in the regenerator where the coke is burned off the catalyst.

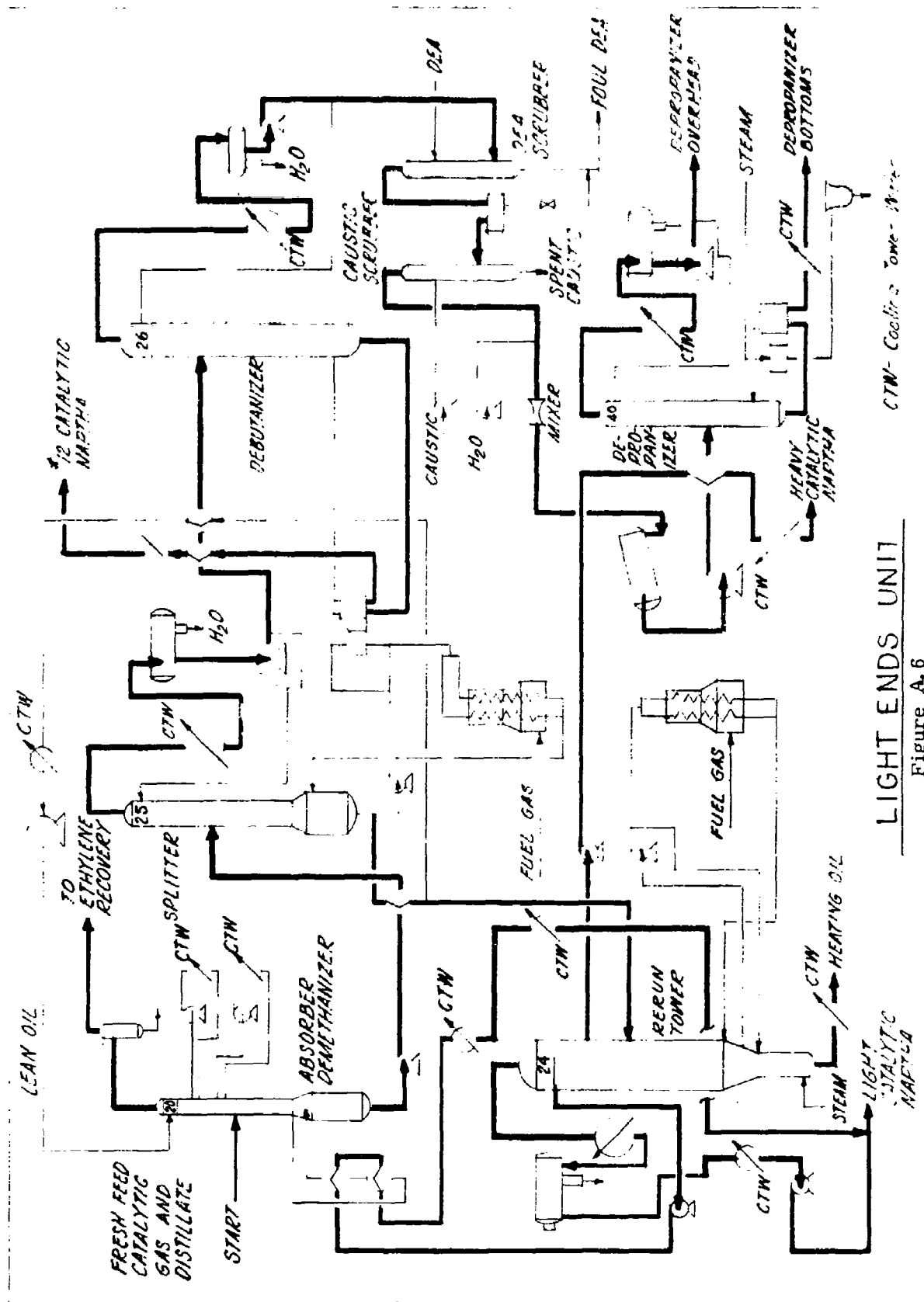
The lighter fractions coming out of the catalytic cracker fractionating towers go to the light ends units where they are further fractionated to produce motor gasoline, and aviation gasoline. The higher pressures in the light ends recovery units (25-300 psig) require that the light hydrocarbons be first compressed from the 12-15 psig of the catalytic cracking fractionator. This is done by a group of two-stage compressors (known as GLA's) run by natural gas engines and located near the catalytic crackers.

Light ends

Light ends, consisting of material ranging from methane to motor gasoline, produced at the pipe stills, catalytic crackers, powerformers, cokers, and natural gas field plants are processed in several light ends units to produce a variety of end products — mostly motor gasolines and liquid petroleum gases.

A typical light ends unit consists of an absorber tower, splitter, debutanizer, depropanizer and rerun tower; also pumps, heat exchangers, and sulfur scrubbers. The primary product streams are the overhead gas from the absorber which is further processed in a high pressure-low temperature unit for ethylene recovery, the depropanizer overhead stream which is fed to a polymerization unit to produce polymer gasoline, the depropanizer bottoms which is alkylation unit feedstock, and various motor gasoline fractions. A majority of the vessels in the light ends area operate at pressures greater than 50 psig, with some operating as high as 300 psig. The vessels, therefore, have strong walls making them less susceptible to collapse from blast. However, any leaks which might develop from blast damage would be more serious here than in other parts of the refinery.

These units were constructed in the middle 1950s and have a relatively uncluttered appearance. The towers are free standing on their foundations and are unencumbered with attendant structures. Each tower has ladders, platforms and piping attached to it with brackets, rather than by a separate structure.



LIGHT ENDS UNIT

CTW- Cochrane Town - 10000

Alkylation

The alkylation process is the most practical method of producing high octane alkylate, or iso-octane, the standard used to measure antiknock value. It is also a valuable process in the production of compounds used in gasoline inhibitors, lubrication oil additives and synthetic detergents. The chemical reaction is the uniting of a saturated, branched-chain hydrocarbon (isobutane) with an olefin hydrocarbon (propylene, butylene or amylene) to obtain a product rich in isomeric octanes (iso-octane). The use of a catalyst, either sulfuric acid, as at Baton Rouge, or hydrofluoric acid, allows the reaction to take place at a low temperature. Refrigeration brings down the temperature in the reactors to about 40°F. There are two electric-motor-driven refrigeration compressors and a steam-driven one. The reactors in the No. 3 alkylation unit are of the stirred reactor type: there are four horizontal drums, or reactors, each with several electric-motor-driven stirring paddles inserted into them from above. The reactor product passes through settling drums, is neutralized by caustic, and then into fractionation, where unreacted isobutane is separated in the deisobutanizer, and butane and propane are separated in the debutanizer and depropanizer towers, respectively. The fractionating towers in the alkylation units are similar in design and appearance to those in the light ends recovery units, except for the deisobutanizer, which with its 205 feet of height is much taller.

Product distribution

The dock and the Plantation Pipeline Company pumping station facilities are located on the river bank at the western side of the plot. The piers are in three sections, one for barges, two for tankers, and in total are about 1800 feet long. They are steel pile frame structures supporting a pier surface of concrete.

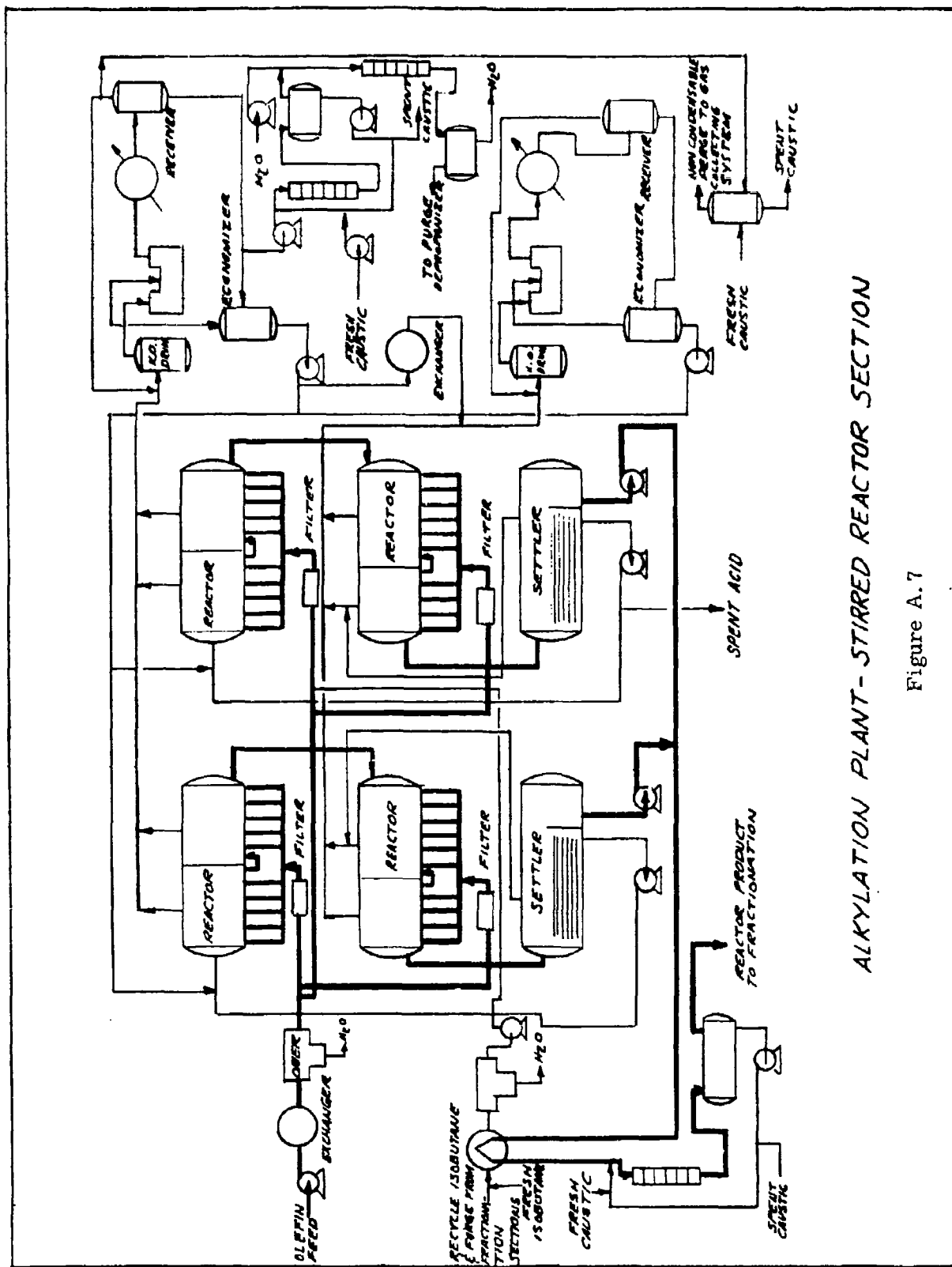
The products are transported by tanker (34%), by pipeline (34%), by barge (29%), and by truck (3%).

Tankers are loaded from the piers by hoses connected to pipe fittings on the tanker (in the case of Esso tankers) and pipeline terminals on the pier. Mating pipe flanges are not necessary, because in some cases tankers are loaded through an open hatch to avoid contamination. Several derricks on the piers are used for manipulating the heavy hoses.

A.1.3 Utilities

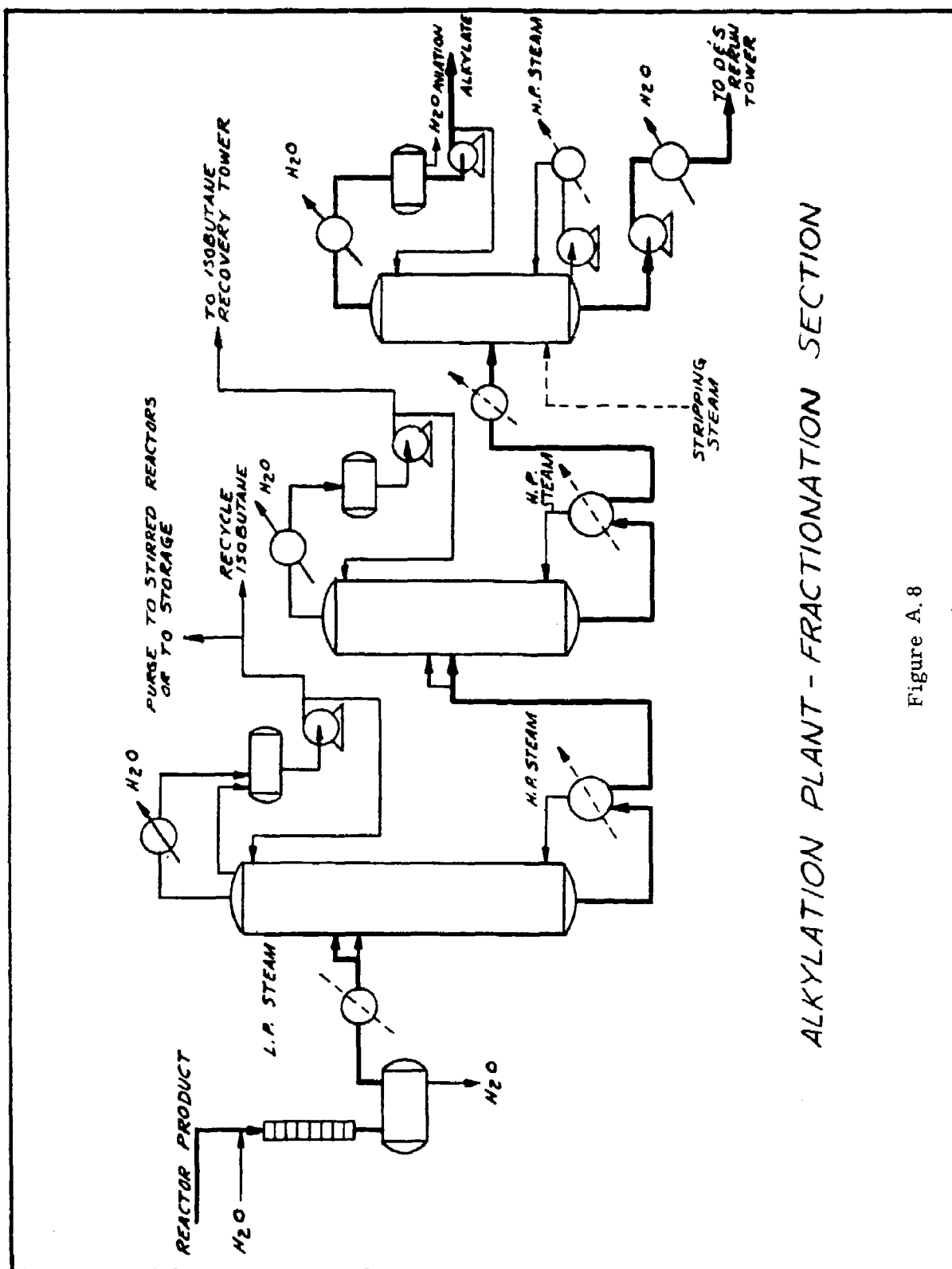
The importance of utilities has been demonstrated by the situation that developed in 1960 as a result of a power failure at Gulf States Utilities (see 3.10). Included in utilities are the supply of water, steam, electric power, and natural gas.

Water is supplied from several wells located throughout the plant. Electric-motor-driven pumping units are installed above ground at each well. The water supply is plentiful, clean and pure, with the greatest volume used for cooling water in heat exchangers and condensers.



ALKYLATION PLANT - STIRRED REACTOR SECTION

Figure A.7



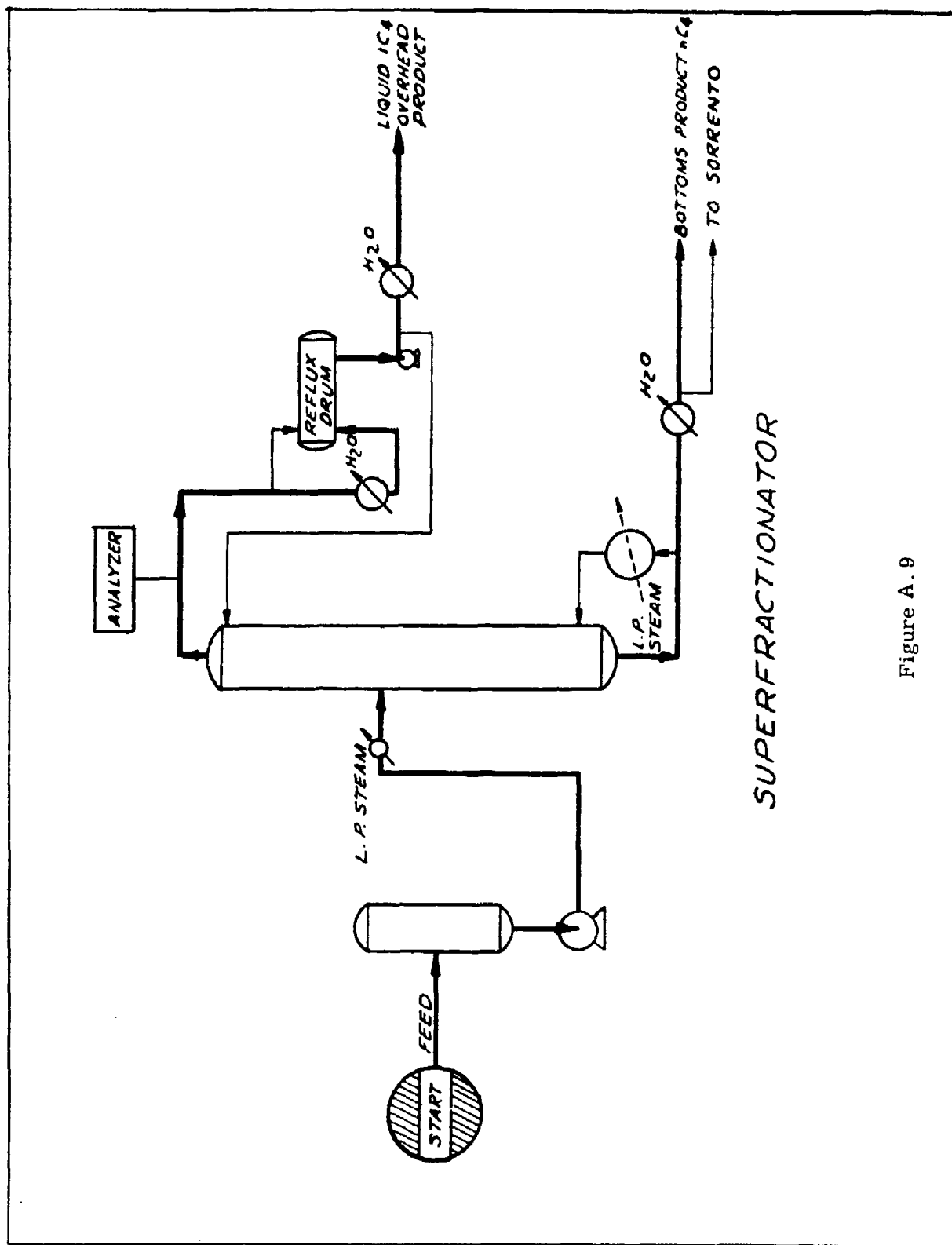


Figure A. 9

River water is used to a limited extent but could be used more extensively in an emergency, although in most cases of loss of well water due to power failure, the river water would also be unavailable because its pumps are also electric motor driven. River water must be treated for removal of any oil it has picked up before being returned to the river.

All steam is supplied by the adjacent Gulf States Utilities Plant. Humble Oil and Refining Company contracts for the use of 150 psi exhaust steam from the electric utility company and finds this more economical than maintaining and supplying steam from their own facilities. All steam line piping is carried on steel supports throughout the plant.

Electric power is primarily supplied by the utilities plant under a contract basis. Since the power failure in 1960, (see section 3.10) additional precautions have been taken by Gulf States to insure that power is available from several sources, through interconnecting links in the national network of power line facilities. The likelihood of a power failure is now very remote indeed. The natural gas used for heating requirements throughout the plant is piped into the area. Produced refinery gases are also mixed with this and used in the furnaces for heating the oils in process. It is generally believed that the sources of supply are adequate for all emergencies. The overhead distribution lines around the plant are relatively vulnerable, but these would probably not fail at a greater rate, as a result of a nuclear blast, than the equipment which they feed.

A.2 Whiting Refinery: Introduction

The Whiting refinery (207,000 b/cd), located on the southern shore of Lake Michigan, is analyzed because in 1955 it suffered a major process unit explosion, and a petroleum liquids fire which lasted 8 days (see 3.8.2). Started in 1889, the refinery has been almost completely renovated and retains very little of the older equipment, mostly in lubes and heavy oils departments.

A.2.1 General

The processing facilities consist of crude distillation, fluid catalytic cracking, ultraforming, H_2SO_4 alkylation, vapor recovery units, delayed coking, heavy oils distillation, propane and methyl-ethyl-ketone (MEK) dewaxing, phenol extraction, treating, and in-line blending. Other facilities are the tank farms, crude pumping station and manifold, two power stations, two pumping stations for lake water, a central air compressor plant, a maintenance building, and the engineering, research and administrative buildings.

Layout

Since the fire in 1955, the tank fields have been moved farther away from processing units, which are now grouped in the northern part of the refinery near the lake front. Tank fields are to the south and southwest, and engineering and administration buildings are on the west. The water pumping stations are in the north near the lake shore, and the two power stations are near the center of the processing area.

A.2.2 Operation and flow

In this section, processes are described which contribute to the production of motor fuels and lubes. In order to avoid repetition, there are no descriptions duplicating those of Baton Rouge.

Crude supply

The Whiting refinery is set up to handle both sour and sweet crudes, received entirely by pipeline from Texas and Oklahoma. No. 12 pipe still handles a sweet crude and considerable modification would be required to convert to sour. No. 10 and 11 pipe stills are designed for sour and can therefore handle either. The sour crude is high in sulfur and hydrogen sulfide. A considerable amount of sulfur is produced at the refinery, as a byproduct.

Distribution of crude throughout the refinery is handled at the centrally located crude station and manifold. The pump controls are in a small one-story brick building from which the flow of crude to all processing units is controlled. Loss of this vital system would mean shutdown of process units. Although the building housing the controls is fairly vulnerable, the pumps and pipelines themselves are not, and crude supplies could therefore probably be restored to the processing units on an emergency basis by manual control if the building and automatic controls in it were destroyed.

Capacity

Refinery capacity, as of January 1, 1965, was 207,000 b/cd or 215,000 b/sd (10). The breakdown by process is as follows:

Charge capacity—(Barrels/stream day)

Vacuum distillation	113,000
Coking operations	30,000
Catalytic cracking	111,000 (fluid) (fresh)
	12,000 (recycle)
Catalytic reforming	43,000 (Ultraforming)
Hydrogen treating	54,000 (naphtha Ultrafining)

Production capacity —(Barrels/stream day)

Alkylation	15,000 (H_2SO_4 stirred)
Lubes	7,400
Coke	1,470 tons (delayed)
Asphalt	15,500

Crude distillation

The No. 12 pipe still is a large, modern unit with a crude capacity of 140,000 b/d. The unit is automatically monitored and, to a moderate extent, controlled by a digital computer located in the controlhouse next to the unit. The unit can be operated without the computer but not without the controls, because manual control is not safe.

Catalytic cracking

The two fluid catalytic crackers were built in the late 1940s and are similar to the units at Baton Rouge, although slightly newer. The regenerator, reactor and fractionator are mounted on their own independent reinforced concrete foundations, and surrounded by a steel structure of platforms and stairways with two elevators. The regenerator is mounted at a lower position in the complex than at Baton Rouge and for this reason would probably be less susceptible to overturning from blast. The two catalytic crackers, FCC 500 and 600 are similar, except that FCC 500 has been equipped with a carbon monoxide boiler, producing 350,000 lbs/hr. of 400 psi steam with waste heat from the regenerator. Most of this steam is used on the unit itself, with any excess being fed into the 400 lb. steam supply system of the refinery. This cannot be considered as an emergency steam supply in the event the power stations were down because the catalytic crackers would also be down as a result of electric power failure.

Light ends

There are two vapor recovery units (VRU 100 and 200) located opposite the two catalytic crackers. These units have absorbing, stripping and depropanizing towers and can each take their feed from either or both of the cat crackers. Blast vulnerability would probably be the same as for the light ends recovery units at Baton Rouge.

A third vapor recovery unit (VRU 300) receives feed from crude distillation units or other process units and is equipped with absorber, stripper, depropanizing and debutanizing towers. It is therefore a more complete light ends recovery plant than VRU 100 and VRU 200.

Alkylation

The sulphuric acid alkylation unit is a relatively new unit (1961) with three stirred reactors. The deisobutanizing tower is 150 ft. high x 20 ft. diameter, located next to the reactors and the controlhouse. The reactor vessels are mounted on fireproofed cradle-type foundations and have two sections: the reactor section and the settling section. Next to the deisobutanizing tower there is a deisobutanizer reflux drum, mounted on a fireproofed cradle, a debutanizer tower and a depropanizer tower, both smaller than the deisobutanizer. The deisobutane reflux drum, fairly vulnerable to blast, is mounted on two 21-foot-high "T" piers and contains highly volatile isobutane under pressure. Fire would be a very likely result from rupture of any of the connecting lines, although the drum itself would not be a difficult item to replace.

Lubricants

The lubes plant, producing lube oils, greases, and wax, contains the heavy oils pipe still, the MEK and propane dewaxing plants, and the phenol extraction plant. Feed for the pipe still is gas oil from #12 pipe still vacuum fractionator, or it could be from #11 pipe still if this were on sweet crude. Any feed which the lubes plant cannot use goes to the catalytic cracking units.

Of the three processes—fractionation, phenol extraction, and dewaxing—only the phenol extraction could be skipped under emergency conditions, as its predominant purpose is to provide viscosity control independent of temperature such as is found in the so-called multiviscosity lube oils. The pipe still is essential for production of the different viscosities or grades of oils—SAE 10W, 20 or 30— and the dewaxing process is required to remove wax from the lube oils which would otherwise be deposited on the inside surfaces of engines at temperatures below 100°F.

The MEK dewaxing process employs methyl-ethyl-ketone as the solvent. The wax is precipitated out as a solid in refrigerated drums and then removed in cylindrical, rotating, filters.

The pipe still for heavy oils is probably neither more nor less vulnerable to blast than other pipe stills or units with fractionating towers such as light ends recovery units. The dewaxing plant, however, would be invulnerable unless the walls of the building came in onto the filters—then nearly total destruction would result.

Blending

The blending of motor fuels at the Whiting refinery is accomplished by an in-line blending system, automatically controlled by computer. This eliminates the need for blending tanks as employed at Baton Rouge and other refineries. The formula is programmed into one of three computer-controlled blending units. Valve or flow controls are pneumatic or electro-pneumatic.

The blend components are drawn from pipelines or storage tanks into a common pipeline, where the actual mixing takes place, then into product pipelines or other storage tanks. The accuracy and rapidity of this system, together with the reduced storage capacity required, are its principal advantages.

The blending plant is located in the south tank field, next to a rail siding where the tetraethyl lead tanks are parked. The controlhouse is typical of others at the refinery and houses the computer and controls.

As in the case of the crude pumping station, loss of this controlhouse would shut off the flow of refined products to markets while some other means of blending was being devised. This would not be a serious problem however, because some batch blending tanks are available, and all blending could be done by batch if required.

Controls

Processing unit controls are electric, electro-pneumatic or pneumatic, with the last predominating, but the trend is toward electronic miniaturized components. Automatic process control used on the large No. 12 pipe still, No. 3 Ultraformer and the in-line blending unit has been working out very satisfactorily.

Controlhouse roofs will collapse at low blast overpressures from 1.0 - 1.5 psi, which would not cause serious damage to rugged processing equipment. In this low range of blast damage, then, the damage would be primarily confined to instruments and controls located in the controlhouse. The repair or replacement of flow, temperature and pressure controls would be essential for startup of the unit. Further discussion of controlhouse vulnerability will be found in section 3.7.2.1.

In general, instruments have much less lead time in procurement than other items of process equipment, and there is a fairly good chance of interchangeability. Recorders are the most easily interchanged, and probably the major repair effort would be devoted to replacement of wiring and air lines; and calibration and system readjustment. Following attack, return to computerized control would probably be delayed long after startup.

Instrument air is obtained from plant air which is dehydrated at the process units. Emergency air compressors, steam driven, are located at each unit, and work through the same dehydrating system.

A.2.3 Utilities

Steam and electricity

The Whiting refinery generates its own steam and electricity in two power stations, located next to each other and tied in so that they are essentially operated as one. There is no tie-in with public power, but this could be arranged under emergency conditions by providing circuit breakers and transformers.

The No. 1 power station, built in 1928, has seven boilers, each with a capacity of 160,000 lbs/hr. of 400 psi steam. This operates four 5000 KW turbogenerators which exhaust into the 100 psi steam system.

The No. 3 power station, built in 1947, has five suspended boilers, each with a capacity of 335,000 lbs/hr. of 1500 psi steam. This drives four 10,000 KW turbogenerators which exhaust into the 400 psi steam system. The suspended boilers are supported at the top from the main building frame. The boilers in both stations are either oil or gas fired, depending on the availability of fuels.

There are also three 1000 KW turbogenerators in the old power station operating on 100 psi steam.

There are waste heat recovery boilers on No. 12 pipe still and No. 3 Ultraformer with a combined capacity of 130,000 lbs/hr., and one in operation on Fluid Catalytic Cracking Unit FCU 500, with 350,000 lbs/hr. of 400 psi steam. These waste heat recovery units primarily supply steam to their respective process units.

With the refinery completely dependent on these two power stations, a high degree of flexibility is required and has been provided. The system is schematically diagrammed in Figure A.10.

Outdoor substations at each refining unit are served by a system of two underground feeders each, which take different routes from the power station to the substation. Here the voltage is stepped down from 13,600 V. to 2,300 and 4,000 V.

A quick shutdown of the power stations would create problems for the boilers and turbogenerators. The boiler tubes must be cooled slowly, otherwise a too-rapid cooling rate will split the tubes at the bends from uneven thermal contraction, requiring replacement of tubes in order to resume operation. Using water, 1-1/2 days are normally required to cool the turbogenerators properly. For a more thorough discussion of shutdown of an electrical facility, refer to our Electric report.

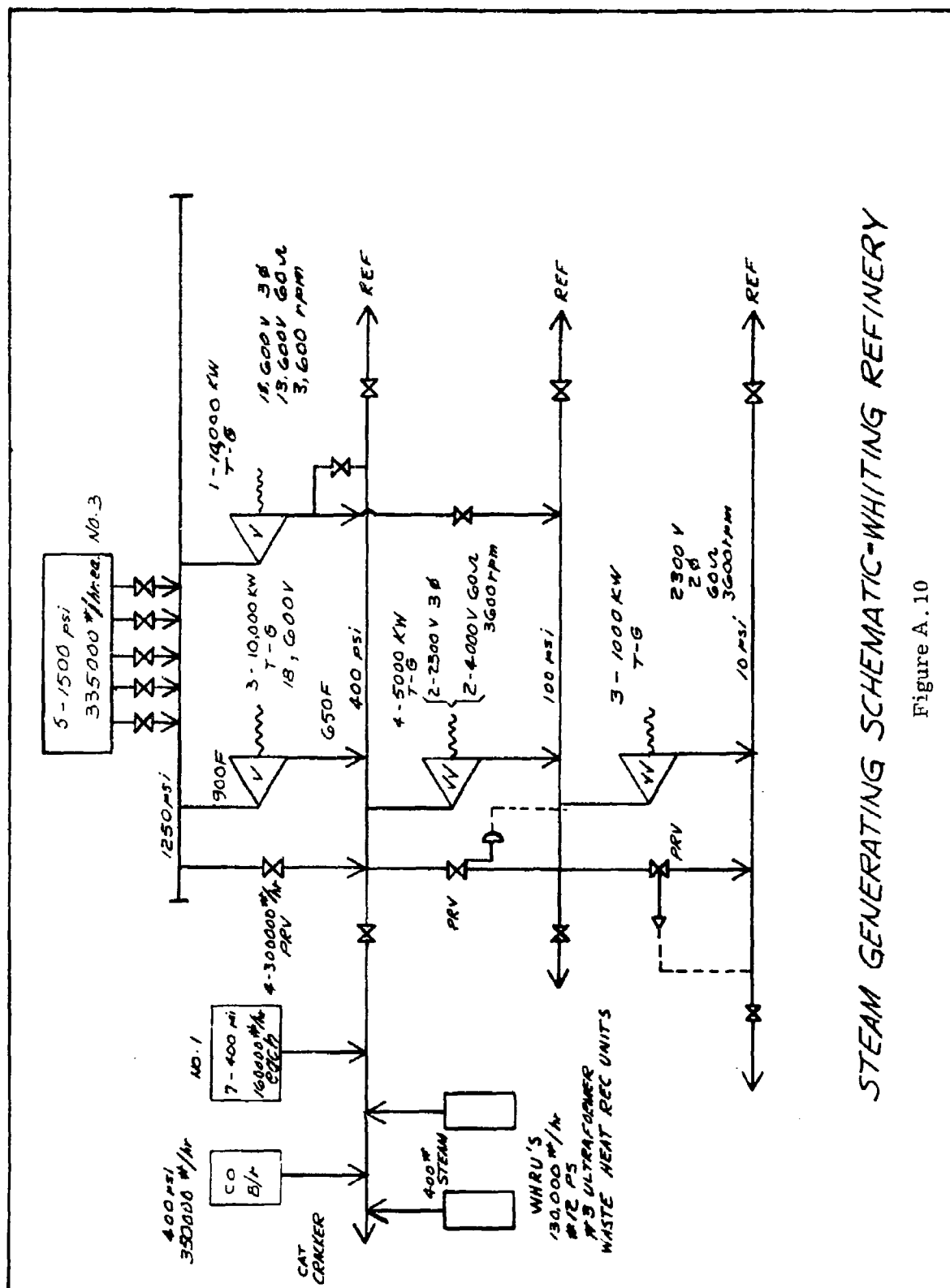
For restarting the powerhouse after shutdown, portable diesel units would have to be brought in to provide a source of power for starting the first boiler. After that, each boiler could be started up in turn.

Compressed air

Air is compressed for the refinery at the central air compressor plant, where a group of piston type, two-stage compressors, driven by synchronous motors, maintain the compressed air at 90-100 psi. Instrument air is taken from this system and dehydrated at the process units, each of which is also equipped with standby steam driven air compressors for emergency use.

Water

Lake water is pumped from two pumping stations, located side by side on the lakefront, for the refinery and for the City of Whiting. The No. 1 pump station has five centrifugal pumps, the No. 2 has four, driven by 2,300 V. synchronous motors with standby 100 psi steam turbine drives on the same shaft coupled by mechanical clutches. The switchover to steam is completely



STEAM GENERATING SCHEMATIC-WHITING REFINERY

Figure A. 10

automatic. In a test of the automatic system, no noticeable pressure drop occurred during the switchover.

Cooling towers

Cooling tower water at Whiting is supplied to all process units from two centrally located groups of cooling towers, between the catalytic cracking units and the No. 12 pipe still. The vapor recovery units, Ultraformers, and No. 2 alkylation unit are not far away. This arrangement contrasts with that at Humble's Baton Rouge refinery, where each process unit has its own cooling tower. Although no doubt justifiable in terms of operating requirements at Whiting, this tower centralization could lead to problems in greater vulnerability and postattack repair.

A.3 Pascagoula Refinery: Introduction

The Pascagoula refinery, built in 1963, is one of the newest in the United States and exemplifies the modern refinery. It is located near the source of crude oil. Construction was completed in just over two years from start of design to the first units' going on stream, probably a record for construction of a major refinery. Labor requirements were 13,900 man-months of on-plot labor, and 14,800 man-months off-plot.

Of the main processing units, the Fluor Corporation designed and built the hydrocracker, the crude unit, hydrogen plant, and catalytic reforming plant. Bechtel Corporation built the fluid catalytic cracking plant, and Chicago Bridge & Iron Company built the tank farm. The alkylation unit was designed and constructed by Standard Oil Company.

Drawings of all equipment, structures and foundations at the refinery are stored in three places: 1) originals at the refinery, on the first floor of the administration building (where they could easily be damaged in a flood), 2) one set of prints at the company headquarters in San Francisco, 3) one set of prints at the contracting engineer's office, primarily Fluor, in Los Angeles, or Bechtel, in San Francisco.

A.3.1 Operation and flow

The principal refinery process units are a 100,000 B/D two-stage crude unit, a 42,200 B/D FCC unit, a 17 MMcf hydrogen plant, a 16,805 B/D hydrodenitrogenation plant, a 17,600 B/D two-stage isocracker, a 28,800 B/D cat reformer with a 15,750 B/D pretreat section, a 5,500 B/D H_2SO_4 alkylation plant, light ends recovery plants, and an acid, caustic treating plant. There are no lube or petrochemical operations. The refinery produces its own steam in three Wickes water tube boilers, each rated at 175,000 lb/hr. of 600 psig steam.

This refinery reflects the latest trends in design and technology. There are, however, few radical departures, with the exception of the isocracker, which reflects a current trend toward this particular process. The isocracker is a fixed bed catalytic cracking process which has as its principal advantage unusual flexibility of operation. It is possible to operate it for maximum yield of gasoline, or for maximum yield of heating oils or jet fuel, without changing the feedstock. Thus, variations in market demand from summer to winter are easily accommodated, and the value of this flexibility under conditions of postattack recovery is apparent. Also, unlike many other new plants, the Pascagoula refinery has considerable flexibility in its overall rate of throughput. In this respect, the hydrogen plant and the isocracker are the least flexible units, but the overall refinery crude refining rate can be varied from 50,000 B/D to 131,000 B/D. Individual processing units can be shut down without shutting down the entire refinery because storage between units is available.

The refinery employs 350-400 people, of which 1/3 are operators, 1/3 are for maintenance, and 1/3 are office, laboratory, and engineering personnel, and the operating force per shift is 30-35 people.

The refinery uses a sweet crude, low in sulfur content, brought in by a 20" pipeline from the Louisiana delta, 148 miles away, 104 miles of which is laid under water on the floor of the Gulf of Mexico. The pipeline is operated by Cal-Ky Pipeline Company, a Kyso affiliate, and has a capacity of 140,000 B/D. It is designed to be heavier than water when full of crude. Crude storage capacity at the refinery is 1.5 million barrels, approximately a 15-day supply.

Thirty per cent of refined products are transported by pipeline 115 miles to Collins, Mississippi, where they join the Plantation Pipeline Company system for distribution to Kyso's five-state marketing area. The remaining seventy per cent of products are shipped to local markets via tank car and tank truck, and by tanker to more distant markets. The marine terminal on the Gulf of Mexico can handle tankers up to 32,000 dead weight tons in its channel, which is 38 feet deep at low tide.

Located on the Gulf of Mexico, the plant layout reflects the logic and functionalism of a refinery which is built entirely from one master plan rather than built up piecemeal over the years. The processing units and the administration building are grouped together in the southern part of the plot, nearest the Gulf. The tank farms are located in the northern part of the plot and are separated from the processing areas by a roadway. Two-thirds of the tanks are the floating roof variety, and the remainder have cone roofs. All were constructed by Chicago Bridge & Iron Company. Propane tanks and butane storage spheres are located along the northern boundary of the plot to minimize the fire danger. Gasoline, crude, and other volatile liquids are generally stored in floating roof tanks. They are located in groups of about 10 in depressed areas between elevated roadways. The tanks are not individually diked, and the depression is large enough to contain the contents of only one full tank, in the event of spillage. In the event of blast, tank leakage would probably not be limited to one tank in each depression, and spillage into butane and propane storage areas, or processing areas, with subsequent ignition would be a probability.

Firefighting equipment consists of one mechanical foam truck and portable foam extinguishers and foam towers. Hydrants are not numerous, and there are no foam chambers on tanks.

Ground water level is only 6 to 9 feet below road level. The softness of the soil had dictated friction piles and foundations for the process units, but the tankage has been built on the soft soil with berms

of sand. Future settling of 2 to 4 feet is allowed for in the design by providing a slope in the tank bottoms of 1 inch in 3 feet downward from the center. As the tank settles (and some 50% of this has already occurred) it is expected that the tank bottoms will gradually flatten out.

The Pascagoula refinery uses in-line blending, and the system is perhaps the most highly automated in the industry. It is similar to the in-line blending system at the company's Richmond, California refinery, but has several additional features which principally provide greater flexibility. Three automatic blenders are used. A 16-component 5700 bbl/hr gasoline blender makes motor and aviation gasolines. An 8-component, 4,000 barrel/hr midbarrel unit blends diesel oils, kerosines, and kerosine and gasoline-type jet fuels. The residual fuel blender is a 3-component, 3500 barrel/hr unit. Loss of the in-line blending system would be very serious, but some batch blending of the products in storage tanks could be done.

The control center for the in-line blending system also acts as a control center for all of the refinery systems except processing units. These are: automatic tank gauging, flow recording and tank switching on incoming crude oil through the Cal-Ky pipeline, remote operation of the pumping station for products going out via pipeline, automatic control of products going out to the wharf, automatic monitoring of the tank-truck loading-rack Keystop system, remote control of treating facilities for slop oil, and remote control of feed stocks for the various process units. The controlhouse is also designed to be used as a communication and fire alarm center for emergencies.

TEL and TML are brought in by rail or tank truck and stored in outdoor weigh tanks.

A.3.2 Utilities

Gas is brought in by pipeline from offshore, but the refinery can operate without it by using refinery gas. In fact, this was done when the refinery was first started up before the gas line was operating.

All cooling water is processed in one centrally-located crossflow cooling tower, the largest in the United States, erected as a package by Marley, 325 feet long, 91 feet wide, and 72 feet high. It is rated for 1220 million Btu/hr at a 74,000 gpm water circulation rate and has 9 cells, each with an 8-foot diameter 125 hp fan. Loss of this cooling tower would certainly mean plant shutdown. It is relatively vulnerable to blast because of its large drag area and the fact that the internal baffles over which the water falls are not part of the main supporting structure, and therefore, are probably not very securely anchored. If these internal baffles were blown out, but the cooling fans were still able to operate, it might still be possible to cool some water in the tower, although certainly not as efficiently or in the quantity for which it was designed.

The extensive use of air-cooled heat exchangers at process units, although not handling the bulk of the cooling load, still represents a large portion and as such is a significant innovation. These are mounted over, or straddling, pipeways on relatively lightweight structural steel frames. The liquid to be cooled is piped through a series of finned tubes and fans draw the cooling air through them. The entire assembly, mounted fairly high up in the unit, is enclosed in rectangular sheet metal boxes, and presents a high drag profile which would cause failure at relatively low overpressures.

Electric power is supplied from outside the refinery by Mississippi Power Company, backed up by the Southern Electric System. A 50-minute power outage was experienced recently at the refinery, requiring emergency measures to cut feeds and furnace flames at process units. Most instrumentation is air-operated, and steam was not lost, being generated in the refinery's own boiler plant, so that losses from the power outage were relatively minor. Loss of the steam plant would shut down the refinery. Because of its fluid catalyst the FCC unit is the most difficult to shut down in an emergency, and it is equipped with enough steam turbine drives to operate without electric power. The other process units are equipped with only enough steam drives to assure an orderly shutdown, which normally takes 12-18 hours.

Fresh water is supplied to the refinery from the Pascagoula River by the Jackson County Industrial Water System. The refinery uses about 7 million gallons of fresh water daily, but the water system has been designed to accomodate future expansion in the industrial area, so that it can ultimately supply 25 million gallons per day.

The steam plant, built by Combustion Engineering of New York, has three Wickes water-tube boilers, with sheet metal covers and an air space between this cover and the firebricks, each capable of producing 175,000 lb/hr of 600 psig steam. The 1800 gpm water treating plant, the fuel oil treating plant, and the air compressor plant are located adjacent to the steam plant. Controls are primarily pneumatic, as in the refinery overall, thus assuring continued operation of the steam plant and the air plant with its steam drives, in the event of electric power failure.

A.3.3 Emergency repairs and procedures

As previously mentioned, a 50-minute power failure has already occurred, but loss was minor because steam and air supply were not affected and all units are equipped with sufficient steam drives to assure orderly shutdown.

There is a unique system for relieving key personnel of the anxiety of the welfare of their families if they are required to remain at the plant during a disaster, such as a hurricane or flood. This is the so-called "buddy" system, where a key man on one shift is paired with a non-key man on a different shift, whose responsibility it is to look after the key man's family, as well as his own, in an emergency, while the key man is on duty.

Manual control of all processing units, except the isocracker, is possible, if there are sufficient numbers of additional personnel. It is not desirable, however, because it is hazardous and quality of product would suffer. A situation could develop where manual operation of a unit would be attempted, because controlhouses and their instruments are relatively vulnerable at low overpressures. After a blast of one or two psi, therefore, it might be feasible to operate a pipe still manually while the controlhouse is being repaired.

It would be possible to operate the refinery with a crew from outside, or from elsewhere in the company, provided there was a nucleus of about 20% of operating personnel familiar with this refinery and they could be put on an overtime schedule. Since the isocracker is the only such unit in the company, there would be greater difficulty in trying to operate it with a crew unaccustomed to its operation.

In the way of shortcuts for emergency operation, a cat cracker fractionator can be run as a primitive form of crude still, and if the demand for jet fuel is suddenly increased the crude still can be operated to produce JP-4 directly and in maximum quantity.

Damaged storage tanks, provided they do not leak, can be used for diesel fuel, crude, or kerosine. Some emergency covering would have to be provided, however, to prevent escape of hazardous vapors. Anything that floats on the surface would serve, such as wooden boards, plywood, plastic sheets, honeycomb panels, if they are not dissolved by the liquid hydrocarbons. There is considerable danger, however, of ignition of vapors by lightning if the tank is left uncovered.

Facilities within the company, but at different locations, can be combined easily by moving feed stocks and partly processed products from one refinery to another by tanker, truck or rail. A little of this is done now, and much more could be done in an emergency. Outside the company, the main problem would be one of communication, to find out where a particular feed stock is needed, or is available, as the case may be.

The design of the Pascagoula refinery is quite foolproof; this is an asset because, in case of trouble, there is no readily available local supply of skilled technical people for repair and troubleshooting.

There are several aspects that seem indicative of future trends. There is increased use of automation, and the in-line blending system is the most highly automated in the industry. Larger units of equipment are used, making possible savings in operating personnel, since it takes the same number of people to run a large unit as a small unit. Vapor recovery units—absorbing towers, depropanizers, debutanizers, etc.—are combined with the cat cracker, cat reformer and hydrocracker units, and run from the same controlhouses, instead of being set up as a separate plant.

There is also sharing of controlhouses: the crude still and the treating plant share one controlhouse, the FCC and alkylation units share a second, and the isocracker, hydrogen plant, and cat reformer share a third. The steam plant has its own controlhouse. This sharing of controlhouses, although not too widespread for large refineries, is common among small ones.

The two-stage compressor handles the entire load for recovery of light ends from cat cracker output, where in older plants several are required. Also, there is only one air blower on the cat cracker.

Pneumatically operated instrument lines use primarily flexible plastic tubing instead of metal tubing.

There is a ready supply of steel plate and fabricating facilities at the Pascagoula shipyard, six miles away. Employing about 5,000 people, this yard has extensive machining and fabricating facilities for heavy vessels which could be used in an emergency for repair of the Pascagoula refinery, if so allocated, and could also possibly provide extra labor.

Bearings and standard machine components are available locally and probably would not be a large problem. Piping is also available at a local piping warehouse.

Spare turbine rotors are kept in stock, either at Pascagoula or somewhere else within the company, because of the long lead times involved in replacement. There are very few other spare parts stocked at the refinery.

The company headquarters in San Francisco keeps an accurate inventory of spare and idle equipment in the company, and orders for new components are always screened against this inventory. In the postattack environment, it would be helpful to have such an inventory for the entire industry, because problems of communications in locating spares and idle equipment outside one's own company would be quite a problem.

H_2SO_4 for the alkylation unit is brought in by barge from DuPont, near Houston. The spent acid is normally returned to the manufacturer for reclaiming, and this reclaiming might become a problem.

The fixed bed catalyst for the isocracker is the most critical in supply among the catalysts because it is available only from Universal Oil Products Corporation and Standard Oil Company. Normally one complete charge is kept in storage somewhere in the company, but not at Pascagoula, because the catalyst is replaced infrequently and can be scheduled in advance. Once exposed to air this catalyst is spoiled, and like other catalysts, it must be regenerated by the manufacturer, UOP or Standard Oil Company. Fluid catalyst is not stockpiled either, but it is available from a number of sources. Hydrogen plant catalyst is available from Filtrol, Girdler, or other companies, and there are at least six sources for cat reformer catalysts.

Routine maintenance and instrument installation and repair is handled by refinery maintenance personnel, but construction, welding, and pipefitting is done by contractors, so that the permanent refinery work force can be kept at a minimum. Pipefitters and welders are the most critical labor skills, almost always in tight supply.

Construction equipment at the refinery is sufficient for a turn around of only one unit at a time. There is one 25-ton crane used for pulling exchanger bundles, one 50-ton truck crane, one 15-ton hydraulic crane, one 10-ton hydraulic crane, and some small contractor's cranes, of which the biggest is 25 ton.

The refinery has a well-equipped repair shop, with an overhead 15-ton traveling crane, which is capable of a wide range of repair work, and is limited only by its capacity in handling the large pressure vessels and towers. The contractors do the same kind of work as the refinery maintenance force but have greater capacity.

There is quite a lot of repair work that can be done on a unit after startup, but it would have to be done without using an open flame. This probably rules out welding. In the case of the two-stage crude unit, the atmospheric section could be repaired first and put into operation before starting repair on the vacuum section.

A.4 DuPont's Chambers Works (TEL Plant)

A.4.1 Plant and equipment

There are four buildings in which the batch process is used. Three of these are TEL plants, one a TML plant. The four buildings are basically identical, being five-story steel framed, with reinforced concrete floors and brick walls.

In the batch process, the lead sodium alloy hoppers are brought to the fifth floor in an elevator and unloaded through a pipe connection into one of the 16 autoclaves which are located on the fourth floor. Each autoclave has a still directly below it so that the top of the still is on the third floor and the bottom of the still is on the second floor. When the reaction has been completed, the charge is dropped from the autoclave into the still, where the TEL "oil" is stripped by steam distillation.

There is also an alloying building, and a three-story continuous process building for TEL production. These are of a similar type construction to the four batch plant buildings.

The blending building is also a steel-framed building with brick walls and no intermediate flooring, because the TEL tanks extend to the full height of the building.

The melthouse is a steel-framed building with corrugated metal siding, located next to the TEL continuous plant with a molten lead pipe-line in between.

Other buildings in the TEL-TML group are the sludge pit, with steel frame and corrugated metal siding, adjoined by the lead recovery building, with steel frame and concrete block. Also there is a shop, a shipping and receiving building, and a sodium unloading building with steel frame and glazed block walls, where two sodium tank cars at a time can be thawed by circulating hot oil in the jackets, and unloaded.

There are also two ethyl chloride fractionating columns, or towers, pedestal-mounted on footings with piles. One of these, 135 feet high, serves the continuous TEL plant, and is located directly to the north of it. The other one, 85 feet high, serves the four batch plants and is located about 1000 feet to the north.

The TEL storage tanks are welded steel tanks with cone roofs, conforming to API standard 650. Of the 16 tanks, one is 50 feet in diameter, and the others are 30 or 35 feet in diameter. They are individually mounted on reinforced concrete foundation frames and individually diked in a depression capable of containing the contents of the full tank plus 10%. They are laid out in a line with reinforced concrete firewalls between the tanks.

From a fire protection standpoint this is a very good arrangement. In blast, however, the failure of the concrete walls could create debris and secondary missiles capable of doing extensive damage to the tanks.

A. 4.2 Utilities

Steam and electricity are supplied by the Atlantic City Electric Company power station, located on the opposite side of the Salem canal from the Chambers Works. There are five boilers serving the Chambers Works: two, coal or oil fired, producing 400,000 lb/hr of steam, and three, oil fired, producing 165,000 lb/hr. The plant uses 10,000 lb/hr of process steam.

The same power station supplies 38,000 KW of electric power at 11,000 volts. It is stepped down at 13 substations, scattered throughout the plant, to 2300 volts, 550 volts, and 110 volts. Most motors and their starters run on 550 volts, rather than the more common 440 to 220, and this would be a problem in replacement of damaged equipment.

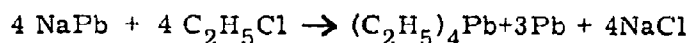
Water pumps are also located at the power station. The peak cooling water load in summer is 35,000 gpm, pumped from the Delaware River.

Portable air compressors are scattered throughout the plant and would not be a problem under emergency operations.

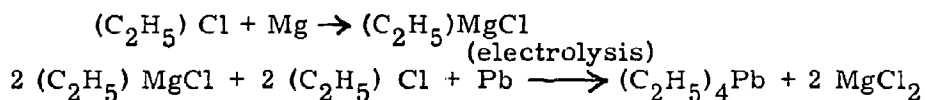
A.5 ADDITIVES PLANTS DESCRIPTIONS

A.5.1 TEL manufacture

There are three processes commonly in use, using two different reactions. The first reaction is the ethylation of sodium lead alloy, as follows:



Two processes are associated with this reaction. These are: 1) the batch process,²³ by which the first TEL was manufactured and which still accounts for the bulk of production, and in which ethyl chloride is reacted with lead sodium alloy in autoclaves, followed by steam distillation; 2) the continuous process, employing the same reaction between ethyl chloride and lead sodium alloy, but on a continuous throughput basis. A different reaction is used in the Nalco electrolytic process, in which magnesium chips are reacted with ethyl chloride to produce magnesium ethyl chloride, followed by a continuous electrolysis with ether solvent, in which lead pellets are the anode and the vessel's steel walls are the cathode. The tetraethyl lead forms at the anode and magnesium chloride forms at the cathode.²⁴ In chemical terms, the reactions are:



These three processes are the only ones in commercial use at this time.

The DuPont continuous process is about ten years old, and is commercially feasible only in large quantity throughput. The Nalco process has been in commercial use only about one and one-half years, and accounts for 5 per cent of the U.S. production.

TML is essentially interchangeable with TEL. It is made by the batch process only, using methyl chloride instead of ethyl chloride. The process is basically the same as the TEL batch process, with a few differences. These are primarily that in TML production higher autoclave pressures are used and a dry graphite lubricant is mixed with the reactants to prevent paddle binding in the autoclave.

With a moderate amount of equipment modification, a TML batch plant could be converted to a TEL batch plant. The reverse is not true, however, because of the greater pressure needed for TML.

The six basic steps in TEL manufacture are, 1) mixing the lead-sodium alloy, then chilling and flaking it in a nitrogen atmosphere, 2) ethylation in a steam-jacketed, agitated autoclave, in which the lead sodium alloy is reacted with ethyl chloride, 3) steam distillation, which separates the TEL from the sludge, 4) ethyl chloride recovery, 5) recovery of lead from the sludge, and 6) blending per customer's specifications.

In the alloy making, the pig lead is melted in a furnace and pumped to the alloy pots to make a lead sodium alloy containing 10 or 11% sodium. The alloy is then chilled and made into flakes in a flaking machine. The flakes are loaded into two-ton hoppers, still in a nitrogen atmosphere, and taken by lift truck and elevator to the top floor of the ethylation building.

In the batch process, the charges of alloy are loaded into the autoclaves from above. The reaction requires 1 1/2 to 2 hours, and then the charge is dropped out through the bottom of the autoclave into a still on the floor below, where the TEL "oil" is stripped from the sludge. The sludge is then pumped to the sludge pit, where it is dried for lead recovery in a furnace. The ethyl chloride recovery is accomplished at the autoclave, where the overhead, or lightest fraction, is drawn off and sent to the fractionating column for ethyl chloride purification. After distillation, the TEL is washed, blended and sent to storage.

In the continuous process, the alloy is prepared the same way, but the rest of the process is quite different. The reaction takes only five or ten minutes at a higher temperature and pressure than in the batch process. For this reason the continuous plant can be shut down in twenty minutes, while the batch plants require 2 and 3/4 hours to shut down because the batches in process must be allowed to continue through the autoclave and still. In the continuous process, there are normally about sixty shutdowns per month, mostly to clean out and check the equipment. After cleanout and before startup, the system is pressure tested with ammonia gas, but both cleanup and pressure test could be omitted in an emergency. In general it requires more maintenance and engineering than the batch process plant, and the volume of production is less flexible.

A.5.2 Principal materials

The principal materials are lead, sodium, ethyl chloride, and in the case of TML, methyl chloride. Lead is obtained by rail or water, 40% from domestic sources, 60% from foreign sources, chiefly Mexico. Sodium is brought in by rail in jacketed tank cars, and is then thawed and pumped out. Melting point is 97.5°C. Ethyl chloride is either purchased and brought in by pipeline. Methyl chloride is 100% purchased.

Other materials used, all in small quantities, are the catalysts and inert gases. The catalysts include aluminum chloride, and acetone. Substitutes are available. The nitrogen, used as an inert gas, is normally supplied by pipeline but in an emergency tank trailers are used. In TML manufacture, the dry powdered graphite lubricant is of an imported, specially fine, very dry grade. This could be obtained from domestic sources, but more per charge would be required because of the difference in quality. TEL is extremely toxic, whether ingested, inhaled, or in contact with the skin. An elaborate ventilation system is used in all buildings where it is handled, so that the air is changed approximately every five minutes. Shafts, shaft seals and joints on vessels that might produce leaks are hooded and vented to the exhaust system. Personnel who work in the buildings are given regular checks to monitor any buildup of lead in the system. Because the hazard is recognized and is being dealt with effectively, an excellent safety record has been established.

A.5.3 Emergency operation

Under emergency operating conditions, there are several things that could be done to simplify operations. Since the continuous plant is more highly automated than the batch plants, and less flexible, it would be logical to repair the batch plants first if both are damaged. The batch plants can be run without instruments, using extra manpower if available, but the continuous plant cannot be run manually because of the increased hazard. Expansion of the batch plants can be done easily by adding more autoclaves, but expansion of a continuous plant is difficult, if not impossible. For this reason, new plants are generally designed for batch operation.

If the ethyl chloride fractionating columns are damaged, but ethyl chloride is in ample supply, the ethyl chloride recovery system would be eliminated and ethyl chloride vented from the autoclaves to the outdoors.

APPENDIX B

GLOSSARY
and
LIST OF SYMBOLS

APPENDIX B

GLOSSARY

air agitation: a supplementary method of fighting fires in petroleum products or crude oil storage tanks whereby air is pumped into the tank in order to mix and cool the hot surface layer or reduce the intensity of the fire by creating an excessive proportion of air.

alkylation (unit): the process unit in which the alkylation process is used for the production of alkylate used in high octane gasoline. The reaction is the union of an olefin and isobutane, a branched chain paraffin, to form a more highly branched paraffinic hydrocarbon.

amylene: a petroleum hydrocarbon of the olefin series, formula C_5H_{10} , used in the alkylation process, known also as pentene.

API: American Petroleum Institute.

asphalt: black to dark brown solid or semisolid cementitious material which gradually liquefies when heated and in which the predominating constituents are bitumens.

attendant structure: steel structures, stairways and platforms adjacent to or surrounding vertical vessels and fractionating columns in petroleum process units, to provide access for maintenance or observation, and support for auxiliary pieces of equipment such as pumps, piping, and heat exchangers.

b/cd barrels per calendar day, the total capacity of a petroleum process unit over a period of time divided by the number of days in that period, including shutdown time.

b/d: barrels per day. One barrel equals 42 U.S. standard gallons

blending: the mixing together of various streams from different processes to provide a final product with the necessary characteristics to meet specific market specifications. Almost all gasolines marketed are blended, either by the batch process or by in-line blending.

blow(ing): in petroleum tank fires, the sudden explosion or eruption of the tanks contents.

blow out: the uncontrolled and sudden eruption of an oil well under pressure; a potential hazard in drilling when unexpected high pressure areas may be penetrated by the drill bit.

boiling range: in distillation, the range between the temperature at which boiling commences, called the initial boiling point (I. B. P.), and the temperature at which the last portion of liquid evaporates, called the final boiling point (F. B. P.).

boil over: in crude oil tank fires, a violent eruption of the tank's contents caused by sudden flashing to steam of a layer of water in the tank bottom on contact with a "heat wave" from the burning oil.

b/sd: barrels per stream day, the capacity of a petroleum process unit while the unit is operating.

bunker "C" fuel oil: a heavy residual fuel oil, specified as ASTM No. 6 fuel, with a maximum viscosity of 300 sec. Furol at 122°F.

butane: a petroleum hydrocarbon of the paraffin series, formula C_4H_{10} . It can be either normal butane, which has a straight chain and is often blended with gasoline, or isobutane, which is a branched chain and is alkylated. Either kind of butane is sometimes blended into LPG.

butyl: the organic radical having the formula $CH_3(CH_2)_3-$. Used in synthetic rubber manufacture.

butylene: a petroleum hydrocarbon of the olefin series, formula C_4H_8 , used primarily in the alkylation process, also called butene.

catalyst: a substance which affects, provokes, or accelerates chemical reactions without itself being altered.

catalytic reforming: the rearranging of hydrocarbon molecules in a gasoline-boiling-range feed-stock to produce other hydrocarbons having a higher antiknock quality.

closed loop: in automatic control systems, a term used to describe a system having feedback of output to input where it is compared to a reference for automatic adjustment of controlled parameters such as flow rates, pressures, etc.

coking (furnace): in a crude oil furnace, the formation of coke on the inside surfaces of hot furnace tubes when oil flow is cut off, or with time.

coking (unit): the process unit used for the production of coke, a solid refinery or commercial fuel, produced by the delayed coking process, fluid coking process or a batch coking process.

cone roof: on a liquid storage tank, the cover which is permanently welded to the tank walls and is in the shape of a cone; convex surface facing outward.

cracking: a process in which the complex hydrocarbons comprising petroleum oils are broken up by heat and usually pressure into lighter hydrocarbons of simpler molecular formulas. Catalytic cracking, which has generally replaced thermal cracking, does not utilize pressures as high as did the older thermal cracking process.

crude (oil): unrefined petroleum as it comes from the well, or at any stage prior to distillation.

cyclones: in the fluid catalytic cracking process, centrifugal dust separators which are built into the top portions of both reactor and regenerator to separate the fine particles of catalyst from gas and vapor streams in order to avoid loss of catalyst in the form of fine dust.

end point: in a laboratory distillation test, the maximum temperature required to vaporize the last liquid portion of the sample is recorded as the end point (E. P.).

ethylene: a petroleum hydrocarbon of the olefin series, formula C_2H_4 , a gas at room conditions. Although often burned with hydrogen, methane, and ethane as refinery fuel, it is sometimes produced for use in manufacturing petrochemicals.

fail safe: a term used to describe a device which operates automatically in such a manner as to provide maximum safety in the event of a failure or malfunction of a system. In the petroleum industry it refers to the operation of a control device, on failure, to reduce temperature and/or pressure.

FCU, FCCU: abbreviations for fluid catalytic cracking unit.

flare stacks: in a petroleum refinery, tall chimneys with a pilot light at the top for burning excess gases and vapors which cannot otherwise be disposed of.

flare (to): in a petroleum refinery, to burn excess quantities of gases and vapors in tall chimneys, called flare stacks.

floating roof: on a liquid storage tank, the cover which floats on the surface of the stored liquid by means of pontoons, or air spaces, in the roof. Used to reduce loss by evaporation.

foam: an even suspension of carbon dioxide in a liquid, in which the small gas cells are separated from each other by thin liquid films. Extinguishes fire by forming an air excluding blanket.

fractionator: a vertical steel cylinder divided horizontally into a number of sections by means of plates or trays, for the separation of the constituents of a mixture through differences in boiling point.

heat exchanger: an apparatus used to transfer heat from one fluid to another.

hydrogen treating: a hydrosulfurization process using a catalyst of cobalt molybdenum on alumina.

hydroreforming, or hydroforming: a process in which naphthas are passed over a catalyst at elevated temperatures and moderate pressures, in the presence of hydrogen, to form high-octane motor fuel.

inhibitors: an agent or additive that slows or interferes with a chemical action. Inhibitors are added to gasoline to retard the formation of gum in storage.

in-line (blending systems): gasoline blending by simultaneously pumping all the components into a common discharge pipe or "header" at rates of flow corresponding to the required portions of the components in the blend.

instrument air: a supply of compressed air used to operate control instruments. It is usually maintained at lower pressure and is cleaner and drier than the regular plant compressed air.

isobutane: a petroleum hydrocarbon of the branched chain paraffin series, formula C_4H_{10} , used primarily in the alkylation process.

lead susceptibility: ability of gasolines to respond to the addition of TEL, or other organometallic lead antiknock compounds, as reflected in the anti-knock quality per increment of lead.

light ends: either a single hydrocarbon or a hydrocarbon mixture having a Reid vapor pressure of 18 psia or more. Examples are methane, ethane, propane, butane, and pentane.⁶⁹

LPG: liquid petroleum gas—hydrocarbon gases, either extracted from natural gas and gasolines or a refinery product, which liquefy under pressure. Principally propane and butane, used for domestic and industrial heating.

lubes: a fluid lubricant used to reduce friction between bearing surfaces. Petroleum lubricating oils may be produced either from distillates or residues.

manifold: a piping arrangement which allows one stream of liquid or gas to be divided into two or more streams, or which allows several streams to be collected into one.

MEK: methylethyl ketone, a solvent used in dewaxing of lubricating oils.

middle distillate: a middle range boiling point petroleum product obtained between kerosine and lubricating oil fractions in the refining process. Includes light fuel oils and diesel fuel.

missile: an object broken off or picked up by the blast and hurled at high speed. Capable of causing considerable damage on striking equipment or buildings.

MON: motor octane number, a method of testing the knock characteristic of gasoline established in 1948 and designated by ASTM as F-2 or D357. Conducted at 900 rpm, it represents high speed performance on the highway.

Navy Special: a residual fuel oil, less viscous and with stricter specifications than bunker "C" fuel oil.

olefin: a series of petroleum hydrocarbons, with type formulae C_nH_{2n} , composed of unsaturated hydrocarbons, with names ending in .ene, such as ethylene, propylene and butylene.

on stream: a term used to indicate that a process unit or piece of equipment is operating.

overhead: in a fractionating column, the stream being drawn off from the top of the column. The lightest of the products of fractionation.

petrochemicals: chemicals manufactured from petroleum hydrocarbons such as olefins.

phenol: the chemical name for carbolic acid, used in the solvent treatment of lubricating oil, for removal of undesirable aromatics.

pipe still: a continuous-flow crude oil distillation unit. Most modern stills have two stages: atmospheric and vacuum.

polymerization (unit): the process unit in which the polymerization process is used for production of high octane gasoline from the lighter, cracked olefin gases. The reaction combines a number of small unsaturated molecules to form a single large molecule, known as a polymer.

powerformer unit: the process unit in which the powerforming process is used for production of high octane gasoline. It is a proprietary process of Esso Research & Engineering Company and is a fixed bed cyclic process employing a platinum catalyst.

propane: a gaseous petroleum hydrocarbon of the paraffin series, formula C_3H_8 , used primarily as LPG.

propylene: a gaseous petroleum hydrocarbon of the olefin series, formula C_3H_6 , used in the alkylation process.

Reid vapor pressure: a method for measuring the vapor pressure of volatile fuels, or the tendency to evaporate and form vapor. The Reid vapor pressure determination is carried out on gasolines at 100°F in a special apparatus.

residual(s): the highest boiling point fractions in distillation. Residuals may be blended into residual fuel oil, or asphalts, or processed on a coking unit.

Richter scale: a method of determining the intensity of earthquakes. The Richter values of earthquake magnitude constitute a measurement of the energy released by the disturbance and are rated on a logarithmic scale.

RON: research octane number, a method of testing the knock characteristic of gasoline established in 1948 and designated by ASTM as F-1 or D908. Conducted at 600 rpm, it represents low speed performance during city driving.

shut in: to plug or shut off a completed oil well so that it can be left with contents undisturbed for future crude oil production.

slop over: in crude oil tank fires, a sudden eruption of the contents of the tank which sometimes occurs when foam is applied.

slop tank: a tank used in a refinery to collect off test stocks or wet stocks for reprocessing.

smoke point: in the smoke point test for assessing the burning characteristics of kerosine and jet fuels, the maximum flame height in millimeters at which the fuel will burn without smoking when tested in a special wick-fed lamp.

sour crude: crude oil containing 0.05 cubic feet or more of dissolved hydrogen sulfide per 100 gallons. Such oils are dangerously toxic. High sulfur oils do not necessarily contain hydrogen sulfide, and consequently not all are classified as sour.

sweet crude: crude oil containing less than 0.05 cubic feet of dissolved hydrogen sulfide per 100 gallons.

TEL: abbreviation for tetraethyl lead, $\text{Pb}(\text{CH}_3)_4$, an additive used to improve the antiknock characteristics of gasoline.

thermal cracking: a refining process which decomposes, rearranges, or combines hydrocarbon molecules by the application of heat, without the aid of a catalyst.

TML: an organic compound of lead, $\text{Pb}(\text{CH}_3)_4$, which when added in small amounts, increases the antiknock quality of gasoline.

transite: a cement-asbestos compound, that can be formed into a corrugated building material.

treating: a process applied to petroleum and its refined products to remove undesirable impurities.

tsunami: a giant sea wave produced by water displacement due to a nuclear weapon, an earthquake, or a marine volcanic eruption.

turnaround: time necessary to clean and make repairs on refinery equipment after a normal run; the elapsed time between shutting a unit down and putting the unit on stream again.

Ultraformer: the process unit in which the ultraforming process is used for production of high octane gasoline. A proprietary process of the Standard Oil Company (Indiana), Ultraforming is a regenerative, fixed-bed catalytic process especially designed to produce stocks with clear octane ratings up to 102 to 104 without use of auxiliary processes.

VRU: abbreviation for vapor recovery unit.

vacuum distillation: distillation under reduced pressure; the boiling temperature is thereby reduced sufficiently to prevent decomposition or cracking of the material being distilled.

Technical refining terms defined in the foregoing glossary are derived from Glossary of Terms Used in Petroleum Refining, Second Edition (1962), American Petroleum Institute.

LIST OF SYMBOLS

A_d	Equivalent area subject to drag forces
A_s	Area of tension reinforcement
A_s'	Area of compressive reinforcement
a	1. Depth of compression area in reinforced concrete section 2. Acceleration
B	1. Width of building, perpendicular to blast wave travel 2. Peak value of dynamic load
b	Width of section
b_w	Width of loaded area
C_d	Drag coefficient
C_r	Ratio of maximum resistance, R , to peak load, B
C_t	Ratio of load duration, t , to natural period, T_n
C_{ur}	Velocity of sound behind Shock Front
d	Depth from compression face of concrete beam or slab to centroid of tensile reinforcement
d'	Distance between tension and compression reinforcement
E	Modulus of elasticity
f	Force
f'_c	Ultimate static compressive concrete strength
f'_{dc}	Ultimate dynamic compressive concrete strength
f_{dy}	Dynamic tensile yield stress in steel
f_y	Static yield stress in steel
g	Acceleration of gravity
H	Building height

h_g	Height of centroid or center of gravity
I	Moment of inertia
I_a	Average of I_g and I_t
I_g	Moment of inertia of gross concrete section
I_t	Moment of inertia of transformed reinforced concrete section after cracking
KT	Kiloton, equivalent of 1000 tons of TNT
k	Kip (1000 lbs.)
k_E	Effective spring stiffness, ratio of force to deflection
K_{lm}	Load-mass factor (dimensionless) used in natural period formula to transform multiple-degree-of-freedom system into an equivalent single-degree-of-freedom system
ksi	Kips per square inch
L	1. Length of building, parallel to blast wave travel 2. Span length
M_p	Plastic resisting moment under bending only
MT	Megaton, equivalent to 1,000,000 tons of TNT
m	Mass
N	Quantity; Number
n	Ratio of modulus of elasticity of steel to that of concrete
p	1. Ratio of tensile steel reinforcement to the concrete area above it; A_s/bd 2. Pressure on a surface
p'	Ratio of compressive steel reinforcement to the concrete area bd ; A_s'/bd
p_r	Reflected pressure at angle of incidence of 90 degrees
P_{ro}	Peak reflected overpressure
p_s	Incident overpressure, at any instant of time
P_{so}	Peak incident overpressure

$p_{r-\alpha}$	Reflected pressure at angle of incidence
psi	Pounds per square inch
q	Drag (dynamic) pressure Reinforcement index $(p-p') f_y/f'_c$
q_0	Peak drag pressure
R	Structural resistance of a member or structure, generally the maximum static load which can be carried at dynamic yield stresses
r	Rocntgen
S	Clearing distance
T_n	Effective natural period of vibration
t	Duration of load
t_d	Duration of an equivalent triangular drag load with zero rise time
t_m	Time at which maximum deflection is reached
t_s	Duration of an equivalent triangular overpressure load with zero rise time
t_y	Time at which yielding begins
t_l	Duration of an equivalent triangular reflected pressure load with zero rise time
t_+	Duration of positive phase
U	Shock front velocity
W	Total weight
w	Uniformly distributed load per unit length
x_e	Deflection at effective yield point; elastic deflection
x_m	Maximum permissible deflection
Z	Plastic modulus of section
α	Angle of incidence between blast wave and reflecting surface
μ	Ductility ratio; x_m/x_e

APPENDIX C
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APPENDIX D

EFFECT OF VARIATIONS IN OVERPRESSURE
DURATION ON STRUCTURAL VULNERABILITY

The following graph is designed to give a visual concept of the relationship of peak dynamic load and incident overpressure duration. It covers kiloton range weapons as well as those in the megaton range. It can be used to demonstrate that horizontal surfaces, such as controlhouse roofs, are rather insensitive to incident overpressure duration for any changes in weapon yield within the high kiloton and megaton range.

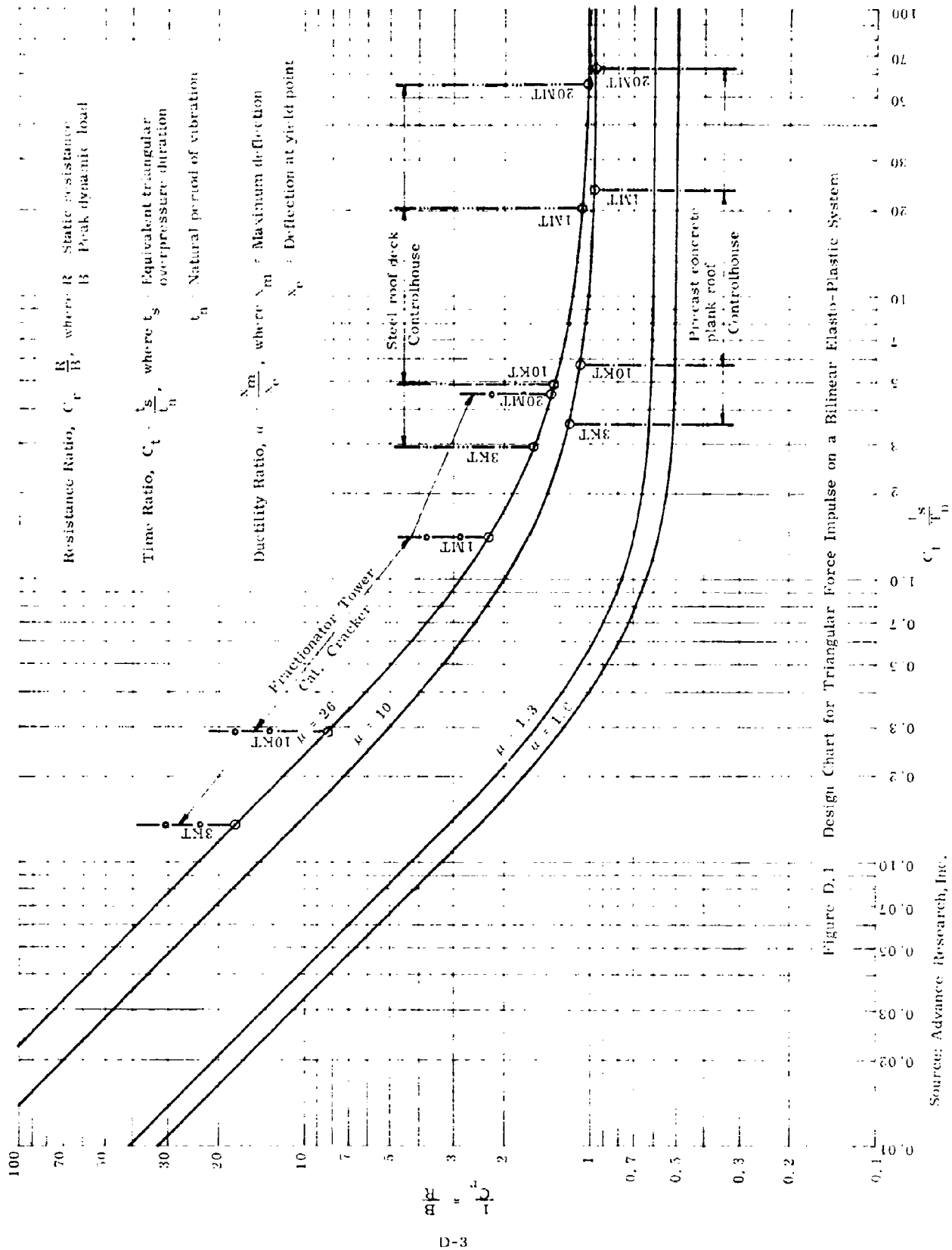
For a given structure or structural element with a known resistance, (R) , natural period (T_n) , and ductility (μ) , the graph shows the relationship of the peak dynamic load, B , and the incident overpressure duration, t_g , taking into account the important physical parameters. Prime examples, cited in chapter 5, are the controlhouse roofs, which will fail at 1.5 psi—the overpressure generated by a 1-MT weapon at a 10-mile distance. For this reason, 1-MT weapons are used as basis for the weapon-by-weapon industrial damage analysis at the beginning of chapter 3. Points corresponding to collapse of both types of roofs have been plotted on the graph. Regardless of the duration of incident overpressure associated with kiloton or megaton range weapons, the peak dynamic load to cause this collapse changes so little that it can be considered as constant. For parameters such as C_t and μ , see table 3.11 in chapter 3. Parameters in table 3.11 are based on a 20-MT weapon, whereas additional calculations were made for collapse following blast from a 1-MT weapon.

Another example of the use of the graph is afforded by the cat cracker as tabulated in table 3.11 (3c). In this case, the peak dynamic load is relatively constant over the megaton range but rises quite rapidly as C_t decreases and passes into the kiloton range.

The curves shown were prepared from those in references 73, 74, and 75, by plotting the data in different dimensions. Assumptions used in deriving the curves include the use of a bilinear resistance function

for failure of elements, with μ representing the ratio between the displacement at fracture and the displacement at the elastic limit, and the use of an equivalent triangular representation of the load. The formula plotted is:

$$\frac{1}{C_r} = \frac{B}{R} = \frac{\sqrt{2\mu - 1}}{\pi C_t} + \frac{1 - \frac{1}{2\mu}}{1 + \frac{0.7}{C_t}}$$



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13. ABSTRACT The American petroleum industry is analyzed in terms of vulnerability to megaton-range weapon attack and of postattack repair, with particular emphasis on refineries, based on three operating refineries which were visited and studied in detail. An appropriate methodology for damage analysis is developed. Results include the first application of CPM charts to the repair analysis, the generation of a generalized model for damage analysis, and the development of a preliminary repair model. Significant findings: Two critical refinery elements are especially vulnerable to blast, controlhouse roofs at 1.5 psi, and cooling towers at 3.5 psi. Repair times are lengthy, with a minimum of 188 eight-hour calendar days for the controlhouse and up to 277 days if a crude still collapses (at 7.0 psi). Shutdown is essential to avoid destruction of processing units by fire due to moderate blast overpressures, and rapid shutdown can be accomplished in less than 15 minutes with less damage than that which would result from a moderate blast striking an operating refinery. Controlhouses are the weak links of the refineries, and the refineries are the weak links of the petroleum industry. Because of geographical concentration, one properly-placed weapon can seriously damage 10 per cent of U. S. refining capacity; three weapons, 25 per cent; and nine weapons, 51 per cent.		

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