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UNITED STATES
DEPARTMENT OF THE INTERIOR
HAROLD L. ICKES, SECRETARY

BUREAU OF MINES
R. R. SAYERS, DIRECTOR

REPORT OF INVESTIGATIONS

REPORT ON THE INVESTIGATION OF THE FIRE AT THE LIQUEFACTION, STORAGE, AND REGASIFICATION PLANT OF THE EAST OHIO GAS CO., CLEVELAND, OHIO, OCTOBER 20, 1944

BY

M. A. ELLIOTT, C. W. SEIBEL, F. W. BROWN,
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CONTENTS

	Page
Introduction	3
Historical background of the natural-gas liquefaction process	3
General description of plant	5
Description of process	7
Description of storage tanks for liquefied natural gas	11
Spherical tanks	11
General	11
Material used in construction of inner tank	11
Connections for gas and liquid	12
Relief valves and rupture disks	12
Ventilation of space between spheres	13
Cylindrical (toro-segmental) tank	13
General	13
Construction of tank	13
Material used in tank	14
Foundation	15
Connections for gas and liquid	15
Ventilation of space between inner and outer tank	16
Relief valves and rupture disks	16
Liquid-level indicators	16
Hydrostatic tests	17
Occurrence and repair of crack in bottom of tank	17
Placing tank in service	18

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	Page
Provision for controlling leakage from tanks..........	18
Conditions at time of fire..............................	19
Description of disaster.................................	23
Observations at scene of fire...........................	26
Damage to plant and adjacent areas................	26
Types of failure observed...........................	28
Distribution of fragments............................	28
Distribution of mineral wool from No. 4 tank.........	29
Intensity of heat from fire..........................	29
Evidence of explosions............	30
Extent of damage by fire.............................	30
Other pertinent observations and information.........	31
Frost spots on storage tanks..	31
Results of laboratory tests.............................	31
Gas analyses...	31
Analyses of steel....................................	32
Discussion of possible causes of disaster...............	33
Failure caused by an event occurring external to No. 4 tank structure......................................	33
Consideration of possibility of failure caused by shock from explosion in space beneath tank..	33
Consideration of possibility of explosive shock from a bursting ammonia cylinder...............	34
Consideration of possibility of No. 4 tank being subjected to an abnormal shock as the result of an operating failure in the liquefaction plant.	35
Consideration of possibility of No. 4 tank being subjected to abnormal shock as the result of a sudden release of pressure....................	36
Consideration of possibility of No. 4 tank being subjected to seismic shocks.....................	37
Mechanisms depending on conditions in the tank structure..	37
Consideration of possibility of crack, strain, or flaw in metal...............................	37
Consideration of possibility of superheating of liquids in No. 4 tank.......................	38
Conclusions...	39
Possible causes of failure...........................	39
Stress analysis..................................	39
Suitability of steel for service................	40
Possibility of flaw in tank or welding..........	40
General conclusions..................................	40
Recommendations...	40
Acknowledgments...	43
Bibliography..	44

INTRODUCTION

At approximately 2:40 p.m. on October 20, 1944, a disastrous fire occurred at the Liquefaction, Storage, and Regasification (LS&R) Plant of the East Ohio Gas Co., Cleveland, Ohio, as the result of failure of an insulated cylindrical tank in which liquefied natural gas was stored at less than 5 p.s.i. pressure and at a temperature of -250°F. Eye witnesses of the initial stages of the failure of the tank reported that streams of liquid or fog issued from its side, and that almost immediately the tank opened and discharged its entire contents of liquefied natural gas over the plant area and adjoining property at a lower elevation. The gas or vapor was ignited almost immediately after failure of the tank. Liquefied gas entered storm sewers, mixed with air, was ignited, and exploded. The explosions damaged the sewer system and the paving of some of the streets. The intense fire in the vicinity of the plant caused great loss of life and property. Final tabulation of fatalities by the coroner's office indicated that 128 had been killed. The East Ohio Gas Co. paid 109 death claims. The difference between claims paid and fatalities estimated by the coroner's office may have been due to difficulties of identification of bodies or to the possibility that some of the fatalities may have been transients or persons having no relatives. Estimates of the number injured ranged from 200 to 400. Property damage was estimated by the company at $6,800,000.

Interest in the disaster was widespread, because this plant was the only one in the world in which large quantities of liquefied natural gas were stored at low temperature and pressure. The plant site has been in the company's possession 50 years or more and is close to residential and industrial areas. This partly accounts for the large loss of life and property, although the greatest loss of life occurred within the plant area.

In accordance with the following provision of the organic act creating the Bureau of Mines (37 Stat., 681), the Bureau investigated the disaster to obtain technical information that might help to prevent other similar occurrences:

> Sec. 3. That the director of said bureau shall prepare and publish, subject to the direction of the Secretary of the Interior, under the appropriations made from time to time by Congress, reports of inquiries and investigations, with appropriate recommendations of the bureau, concerning the nature, causes, and prevention of accidents, * * *.

This report summarizes the results of the investigation.

HISTORICAL BACKGROUND OF THE NATURAL-GAS LIQUEFACTION PROCESS

The Liquefaction, Storage, and Regasification (LS&R) Plant of the East Ohio Gas Co. at Cleveland, Ohio, was the first commercial plant of its kind in the world. In it, natural gas was liquefied and stored during off-peak periods and was regasified during periods of peak demand. Thus, a large quantity of gas could be stored against peak demands more economically than by the usual gas holder.

Large quantities of natural gas had been liquefied by the Bureau of Mines at its helium-production plant prior to the design and construction of the LS&R plant. This development had demonstrated that commercial liquefaction of natural gas was practical; however, in the Bureau's helium plants, liquefied natural gas is not stored but is regasified after removing the helium.

Much of the credit for conceiving and developing the gas liquefaction, storage, and regasification system used by the East Ohio Gas Co. is due H. C. Cooper, former president of Hope Natural Gas Co., now retired but practicing as a consulting engineer. Cooper had considered the possibilities and economics of the liquefaction, storage, and regasification of natural gas as early as 1937 and had carried on preliminary negotiations with Lee Twomey, holder of basic patents on gas liquefaction processes and on storage and transportation systems for liquefied gases.

Under Cooper's general direction, development work on natural gas-liquefaction processes was begun at the Cornwell, W. Va., station of the Hope Natural Gas Co. After examining various gas-liquefaction processes, it was decided to use a cascade system covered, in part, by patents issued to Lee Twomey(1).7/ In the cascade system employed water is used to condense ammonia, liquefied ammonia is used to condense ethylene, and liquefied ethylene is expanded and condenses natural gas at a high pressure. In the pilot plant, refrigeration was produced by ammonia (boiling point, -27°F. at atmospheric pressure), then ethylene (boiling point, -152°F. at atmospheric pressure), and finally by throttling liquefied natural gas from a high to a low pressure.

The pilot plant at Cornwell was capable of liquefying 300 to 400 thousand cubic feet of natural gas per day(2,5). The liquefied gas was stored in a horizontal cylindrical tank 10 feet in diameter and 18 feet long and having a capacity of 14,500 gallons of liquefied gas, which, when evaporated, would yield 1,000,000 cubic feet of gas. The tank was insulated by a 2-foot layer of formed cork. The storage tank was constructed of 2 percent nickel-alloy steel(8), and all pipe lines that were to operate at temperatures below -50°F. were either copper or stainless steel.

The pilot plant was completed in January 1940(2,11) and was put into operation shortly thereafter. Four days were required to cool all of the equipment operating at a low temperature and to obtain the first liquefied gas. In three additional days the tank was approximately 90 percent full. The plant was operated almost continuously for 4 months. During this time, evaporation studies were made and showed that the rate of evaporation of liquefied gas from the tank was 28,000 cubic feet per day.

As a result of the tests, the following conclusions were reached(2,11) as to the performance of the plant and the suitability of metals at low temperature:

7/ Numbers in parentheses refer to references listed at the end of this report.

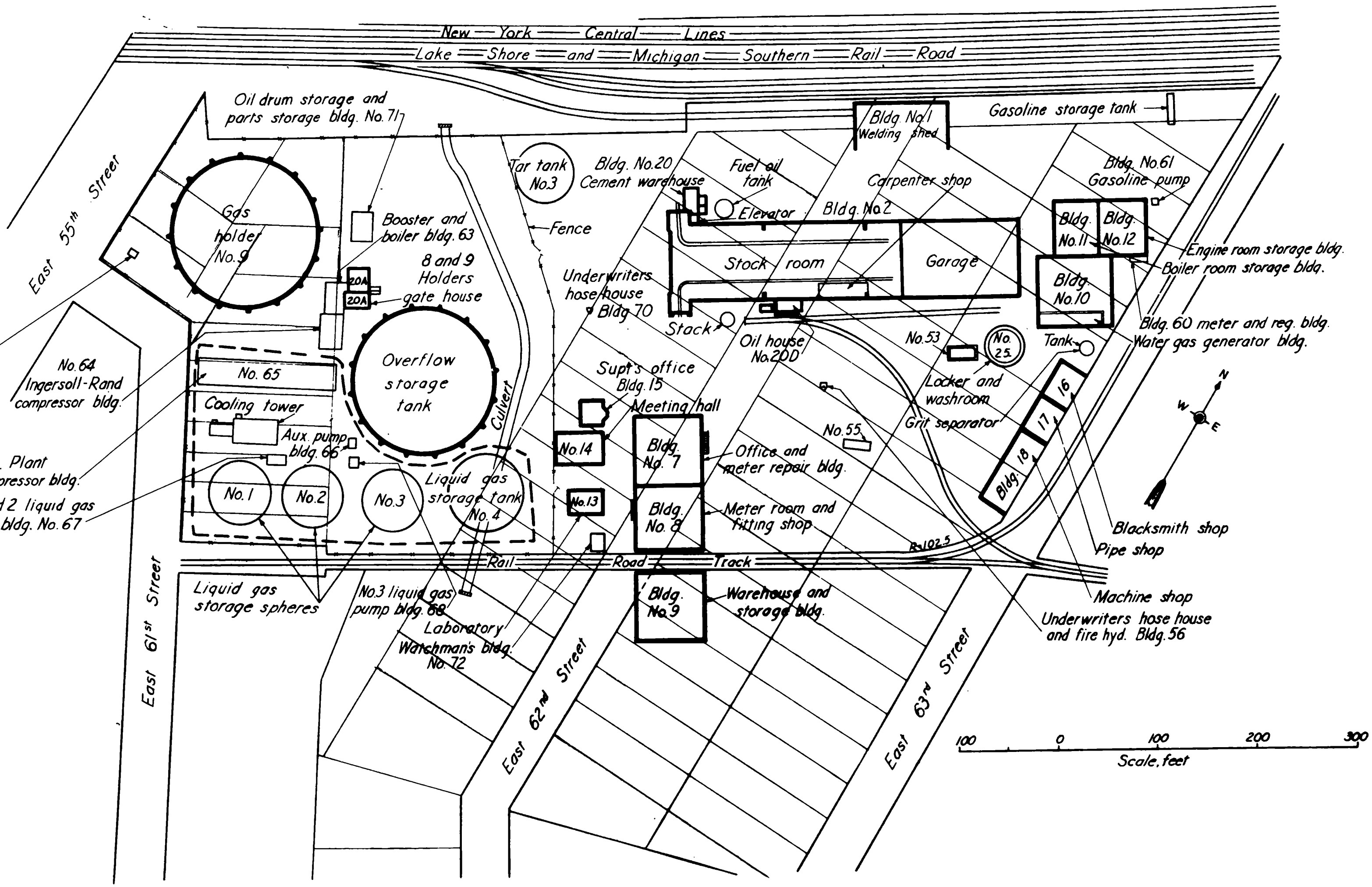


Figure I.—Plan view of No. 2 works, East Ohio Gas Co., Cleveland, Ohio.

3. After going below -50°F., the pipe and tank steel becomes so brittle it is entirely unsafe. The metals which retain a safe Charpy impact test value are, in order of excellence, pure copper, bronze, Monel metal, red brass, stainless steel, and steel plate, with carbon content less than 0.09 percent and nickel over $3\frac{1}{2}$ percent.

4. The best insulator we have found so far is cork, although something better may be discovered later* * *.

5. The evaporating liquid has exactly the same analysis as the raw gas used for feed. However, the evaporation from the stored liquid is entirely methane and eventually, if allowed to stand for long periods, the liquid left will become increasingly high in ethane-plus contents.

Shortly after the pilot plant had been operated successfully, an opportunity was presented to install the process in a full-scale plant when the East Ohio Gas Co. decided to construct a liquefaction, storage, and regasification plant to take care of peak demands in the winter. The need for augmenting the supply of gas during peak-load periods was indicated by the following statement(2):

> The city of Cleveland is supplied with natural gas principally through four 20-inch and 18-inch lines from the Hastings station of the Hope Natural Gas Co., 150 miles distant. During January 1940 the cold wave which hit every gas company in the East made it very difficult to keep the supply ample, and by spring it was felt something would have to be done to augment the supply.

The East Ohio Gas Co. had made plans(2) for an extension of a 12-inch high-pressure line to the city limits that would have cost about $2,500,000. However, as a result of the experimental work at Cornwell, and in view of the cost of a gas-liquefaction plant estimated at $750,000, it was decided to build a liquefaction plant in lieu of the high-pressure line. Erection of the liquefaction plant was started in September 1940 and completed January 1941.

GENERAL DESCRIPTION OF PLANT

The LS&R plant of the East Ohio Gas Co. was erected on the west end of the company's No. 2 works in East Cleveland, Cuyahoga County, Ohio. (See fig. 1.) The principal units of the No. 2 works were within an area approximately 900 by 500 feet, and the LS&R plant occupied an area about 350 by 250 feet. Roughly, the No. 2 works was bounded on the north by the New York Central and Lake Shore & Southern Railroad tracks, on the east by East 63d Street, on the west by East 61st Street, and on the south by a residential area. In addition to the LS&R plant, the No. 2 works included, at the time of the fire, certain shops and buildings associated with the company's natural-gas activities and some buildings and equipment formerly used in manufactured-gas operations. It was stated that the company had occupied this plant site for approximately 50 years.

The decision to locate the LS&R plant at the No. 2 works was made after considering the demands on the distribution system during peak-load periods. Some of the factors to be considered are discussed by Turner(13). According to W. G. Hagan, executive vice president of the East Ohio Gas Co., the greatest benefit to the system was obtained by feeding gas in at the north end of the distribution system and as this condition could be realized by feeding gas from No. 2 works, then, from the viewpoint of improving the operation of the distribution system, that site was the most logical one for the LS&R plant.

The principal units of the plant were a compressor building, cooling tower, heat exchangers, liquefied gas-storage tanks, and regasification equipment. The general location of these units is shown in the area enclosed by dotted lines in figure 1, and the detailed plant layout is shown in figure 2.

The main compressor building (fig. 1, building 65; see also fig. 2) housed a 600-horsepower raw-gas compressor, an 800-horsepower recycle compressor No. 1, a 150-horsepower recycle compressor No. 2, two 600-horsepower ethylene compressors, and one 500-horsepower ammonia compressor. The first three were two-cycle, gas engine-driven compressors built by the Cooper-Bessemer Corporation, Mt. Vernon, Ohio, and the last three units were two-cycle, gas engine-driven compressors manufactured by Clark Brothers, Inc., Olean, N. Y. All were provided with adequate speed and pressure controls(10). The compressor building was adequately protected against lightning.

Equipment for removing carbon dioxide from the gas and for dehydrating the gas was in the open. (See fig. 2.) The heat exchangers in which the gas was cooled were insulated and enclosed by a large boxlike housing, which also was in the open. (See fig. 2.) Other equipment in the open included the ammonia condenser, ethylene condenser, and ethylene-storage tank. The regasification equipment was housed in a small sheet-metal building (fig. 1, building 67).

As initially constructed, the plant contained three spherical storage tanks for liquefied gas. Each had an internal diameter of 57 feet and a working capacity of about 50,000,000 cubic feet of natural gas from stored liquid. Insulated copper tubing with Van Stone joints, bronze flanges, and bolts(12) was used for all lines containing cold liquids or gases at temperatures below -50°F.

After the plant had been in operation for some time, it was decided to provide additional storage capacity to care for peak demands while still supplying the increased base-load demand for war industries. Accordingly, in the spring of 1943(9,12), construction began on a toro-segmental storage tank having a capacity of 90,000,000 cubic feet of natural gas from stored liquid. This container and the spherical containers are described in detail elsewhere in this report.

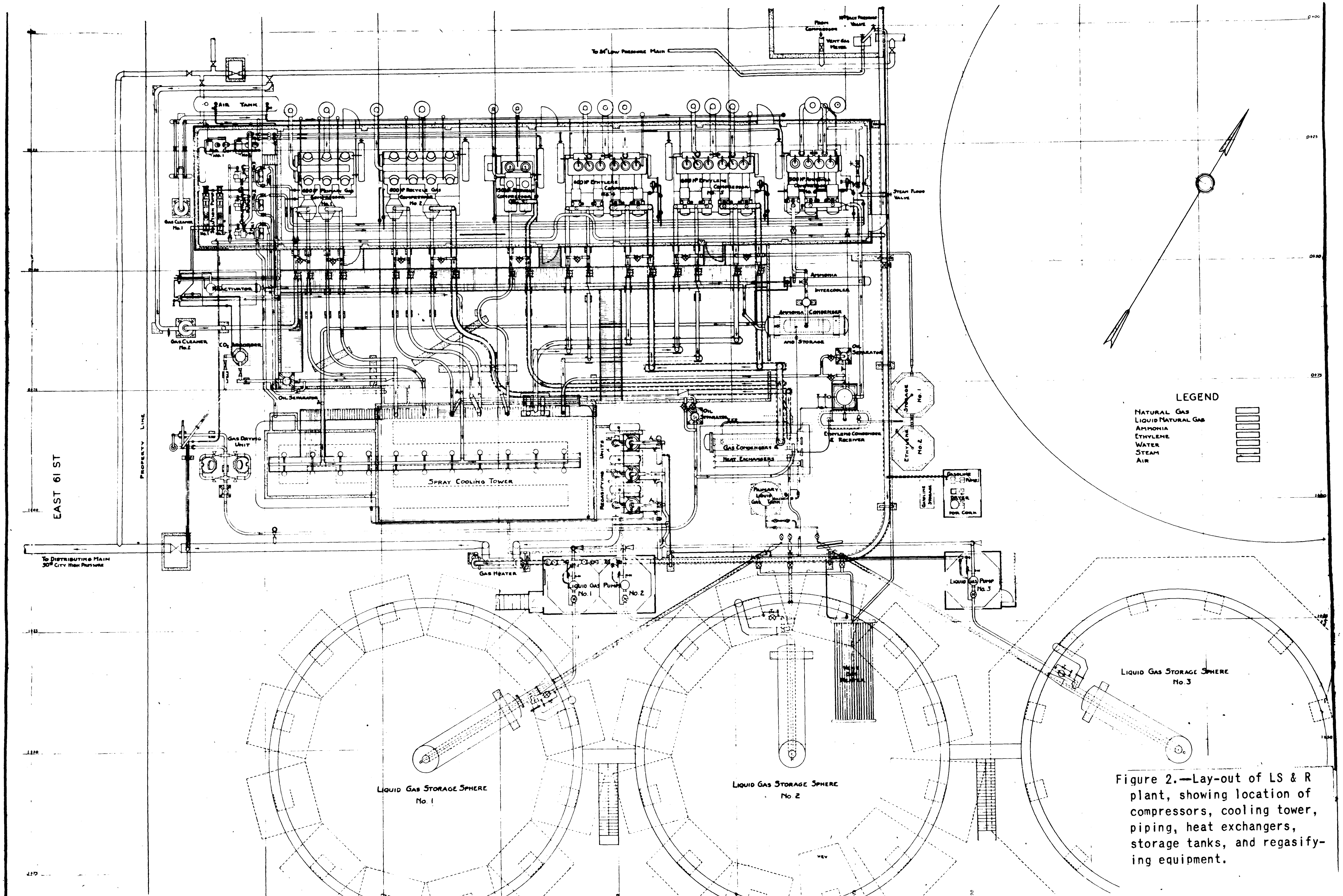


Figure 2.—Lay-out of LS & R plant, showing location of compressors, cooling tower, piping, heat exchangers, storage tanks, and regasifying equipment.

The plant was designed to liquefy 4,000,000 cubic feet of natural gas per day and to regasify 3,000,000 cubic feet of natural gas per hour. (Both gas volumes are at ordinary temperatures and pressures.)

The estimated cost of the original plant has been given as $1,250,000(4), including foundation and buildings, $260,000; three spherical storage tanks, $420,000; and $570,000 for piping, cooling towers, gas scrubbers, and auxiliary equipment.

The plant was built by the Gas Machinery Co. of Cleveland, Ohio(12). Construction was begun in September 1940 and was essentially complete January 29, 1941. (Prior to the construction of the liquefied natural gas plant at the No. 2 works, W. G. Hagan advised that a building permit was obtained from the city of Cleveland.) Liquid was first produced on February 7, 1941(4), and by February 19, 1941, 16,000,000 cubic feet of natural gas had been liquefied and accumulated in the storage containers. It had been estimated that approximately 38 days would be required to fill the three spherical containers with the liquefaction plant operating full time. Various quantities of liquid were regasified between February 19, 1941, and the latter part of March, 1941. At one time (March 17), 50,000,000 cubic feet of liquefied gas was in storage.

DESCRIPTION OF PROCESS

A simplified flow diagram showing the general features of the liquefaction and regasification process used at the LS&R plant of the East Ohio Gas Co. is given in figure 3. In brief, compressed natural gas was liquefied by refrigerated ethylene; the liquid was then cooled by cold natural gas flashed off when the liquefied natural gas was further cooled by expanding from a high pressure to a pressure slightly greater than atmospheric. Refrigerated ethylene was obtained by cooling with liquid ammonia, which was produced by cooling compressed ammonia gas with water. The details of the process, taken from published reports (2,3,4,5,6,10,11,12,13) and from observations at the plant, are given below.

The natural gas liquefied in the LS&R plant of the East Ohio Gas Co. came from West Virginia and was supplied by the Hope Natural Gas Co. Typical analyses of the gas for 1929, 1936, 1942, and 1944 are given in Exhibit "A", which is a copy of a letter to J. F. Robinson, president, East Ohio Gas Co., from R. W. Miller, research director, Hope Natural Gas Co.

Exhibit A

HOPE NATURAL GAS COMPANY

Pittsburgh, Pennsylvania

October 30, 1944.

Mr. J. French Robinson, President,
The East Ohio Gas Company,
1405 East Sixth Street,
Cleveland, Ohio.

Dear Mr. Robinson:

Below, you will find average Podbielniak analysis of West Virginia natural gas sold to your Company at the Ohio River for transmission to Cleveland.

Constituent	1929 %	1936 %	1942 %	1944 %
Methane	83.45	84.00	85.04	85.59
Ethane	11.07	10.15	9.28	8.43
Propane	3.23	3.65	3.37	3.63
Isobutane	.42	.40	.49	.59
Normal Butane	.70	.60	.67	.77
Pentane	.13	.20	.23	.21
Carbon Dioxide	.10	.10	.10	.10
Oxygen	.10	.00	.10	.00
Nitrogen	.80	.90	.72	.68
Total	100.00	100.00	100.00	100.00

If you need additional information, we shall expect to hear from you.

Yours very truly,

R W Miller
Research Director

The natural gas to be liquefied (raw gas) was taken from the East Ohio Gas Co.'s medium-pressure system at 30 p.s.i. gage, and was compressed to 600 p.s.i. gage by a 600-horsepower gas engine-driven, 2-stage compressor (raw-gas compressor known as engine No. 1). The compressed gas was then purified by removing (a) lubricating oil with activated alumina; (b) carbon dioxide by scrubbing with a solution containing 10 percent monoethanolamine, 10 percent diethylene glycol, and 80 percent water, and (c) the last traces of water in a drying unit containing activated alumina.

The purified gas at high pressure (approximately 600 p.s.i. gage) then passed through the tubes of a heat exchanger, into which ethylene at 5 p.s.i. gage and -145°F. was fed on the outside of the tubes. The natural gas was cooled to -132°F. (at 600 p.s.i. gage), under which conditions nearly all of it was liquefied. The mixture of liquid and vapor passed into a surge tank, where the vapor was removed from the system. It was stated that the gas thus removed contained approximately 75 percent methane and 25 percent nitrogen and was used as boiler fuel. The liquefied gas from the surge tank was cooled to -139°F. in passing through two heat exchangers in which flash-gas was the coolant.

The cooled, liquefied, natural gas at high pressure passed through the first expansion valve into the primary-liquid tank maintained at a pressure of 35 p.s.i. gage. In this expansion, approximately half of the liquefied gas was flashed back to the gaseous state. This cold gas was used as the coolant in heat exchangers and was reprocessed after being compressed to 600 p.s.i. gage by an 800-horsepower gas engine-driven compressor (No. 1 recycle compressor, also known as engine No. 2).

The liquefied gas from the primary liquid tank passed through a second expansion valve directly into a header connected to the storage tanks. At this point, the temperature was reduced to -250°F.; and the pressure was approximately 8 p.s.i. gage. About 15 percent of the liquefied gas flashed into gas. This flash gas, which was virtually pure methane, along with the gas evaporated from stored liquid, passed through flash-gas heat exchangers and was compressed to 35 p.s.i. gage by a 150-horsepower gas engine-driven compressor (No. 2 recycle compressor, also known as engine No. 3). The gas from the compressor entered the suction of recycle compressor No. 1 and, after compression to 600 p.s.i. gage, was reprocessed.

The ethylene refrigerant was in a closed system and was compressed from about 3 p.s.i. and 30°F. to 335 p.s.i. gage and 60°F. by two 600-horsepower, gas engine-driven compressors (engines No. 4 and 5). The compressed ethylene gas was then condensed by ammonia in the ethylene condenser. The temperature of the liquid ethylene was reduced to -48°F. by passing through two flash-gas heat exchangers. The liquid ethylene was then expanded to 5 p.s.i. gage, resulting in a temperature of -145°F. Ethylene at this condition entered the natural gas-ethylene exchanger, in which the high-pressure natural gas was liquefied.

When the liquefaction plant was shut down, the ethylene was stored under pressure in two all-welded vertical cylindrical tanks

The ammonia refrigerant was also in a closed system and was compressed from about $3\frac{1}{2}$ p.s.i. gage and 30°F. to 114 p.s.i. gage and 70°F. by a 500-horsepower gas engine-driven compressor (engine No. 6). Ammonia gas was liquefied in a water-cooled condenser. The liquid ammonia was then cooled to 19°F. in passing through two flash-gas heat exchangers. Liquid ammonia was expanded through a valve to 4 p.s.i. and a temperature of -20°F. Ammonia at this condition entered the ethylene condenser, where ethylene at 335 p.s.i. gage was liquefied, as mentioned above.

The liquefied natural gas was stored in four insulated, specially constructed storage tanks, three of which were spherical and one cylindrical (toro-segmental). These tanks are described in considerable detail in a subsequent section of this report.

The cold liquid at a temperature of -250°F. in the tanks was continually receiving some heat from the atmosphere around the outside shell of the tank. Accordingly, some liquid was always being vaporized. Tests on one of the spherical containers, after being filled for three weeks, showed evaporation of 105 to 115 thousand cubic feet of gas per day. When the liquefaction plant was not operating, this gas from stored evaporating liquid (vent gas) was warmed by a vent gas heater and discharged through a back-pressure regulator into the low-pressure distribution system.

The equipment for regasifying the stored liquid has been described in considerable detail by Clark and Miller(2) and Turner(13). Stored liquid at storage pressure flowed to a manifold to which was connected three pumping units. These pumps raised the pressure of the liquid to about 30 p.s.i. gage and discharged into the tubes of one or more of three 2-stage heat exchangers. High-pressure steam at 150 p.s.i. gage was supplied outside the tubes of the exchangers. The gas vaporized from the liquid discharged into a 20-inch steel main that was a part of the medium-pressure (30 p.s.i. gage) distribution system.

Each regasifier unit, consisting of pump and exchanger, could deliver 1,000,000 cubic feet of gas per hour, making the total output 3,000,000 cubic feet per hour. At the maximum gasification rate, the steam requirements were met by taking the full output of two boilers rated, respectively, 300 BHP and 600 BHP but delivering 2,200 BHP (245 percent of rating). These boilers were oil-fired during peak-load periods but were equipped for either gas or oil firing.

The operation of the LS&R plant was followed by the use of indicating and recording pressure gages, flowmeters, thermometers, and level indicators. Typical charts during normal operation could not be obtained, as these charts were destroyed by the fire. However, the daily log sheet and copies of some of the gas-pressure and flow records on the day of the fire were obtained and are presented and discussed in a subsequent section of the report.

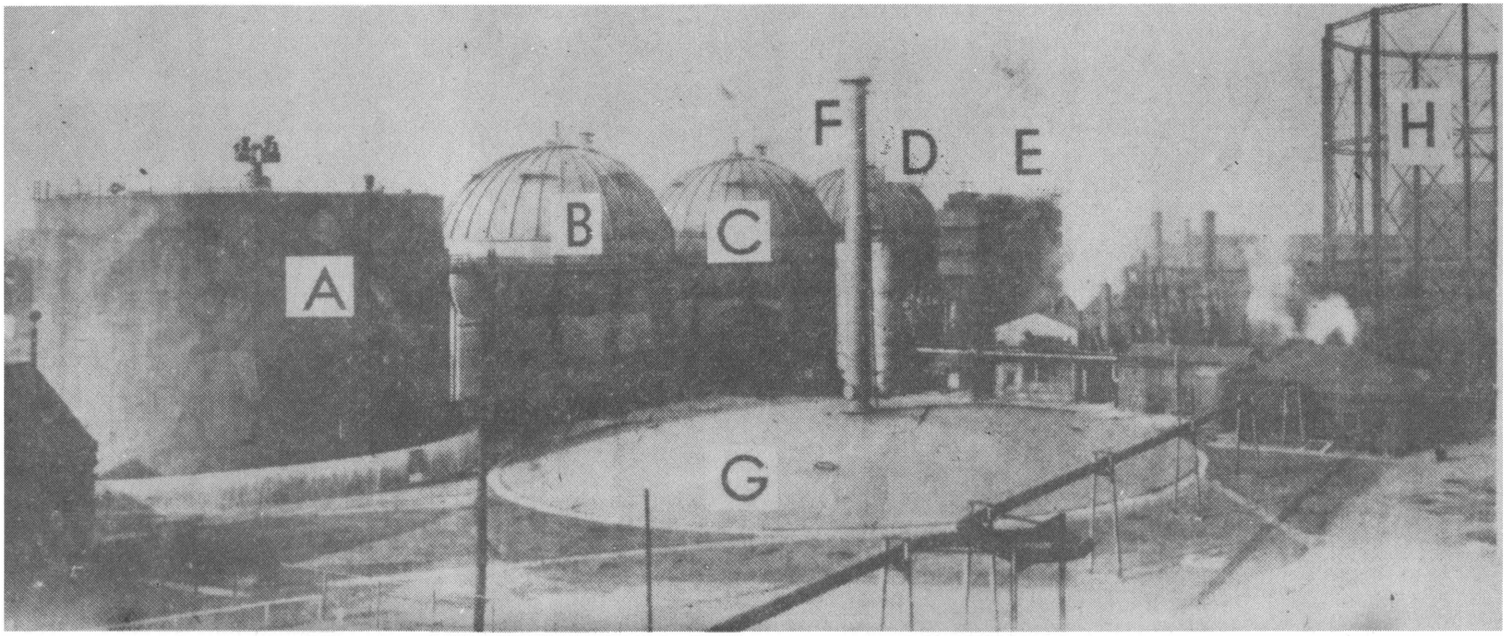


Figure 4.—General view of storage tanks, (A, B, C, and D) and overflow gas-storage tank (G), LS & R plant, East Ohio Gas Co.

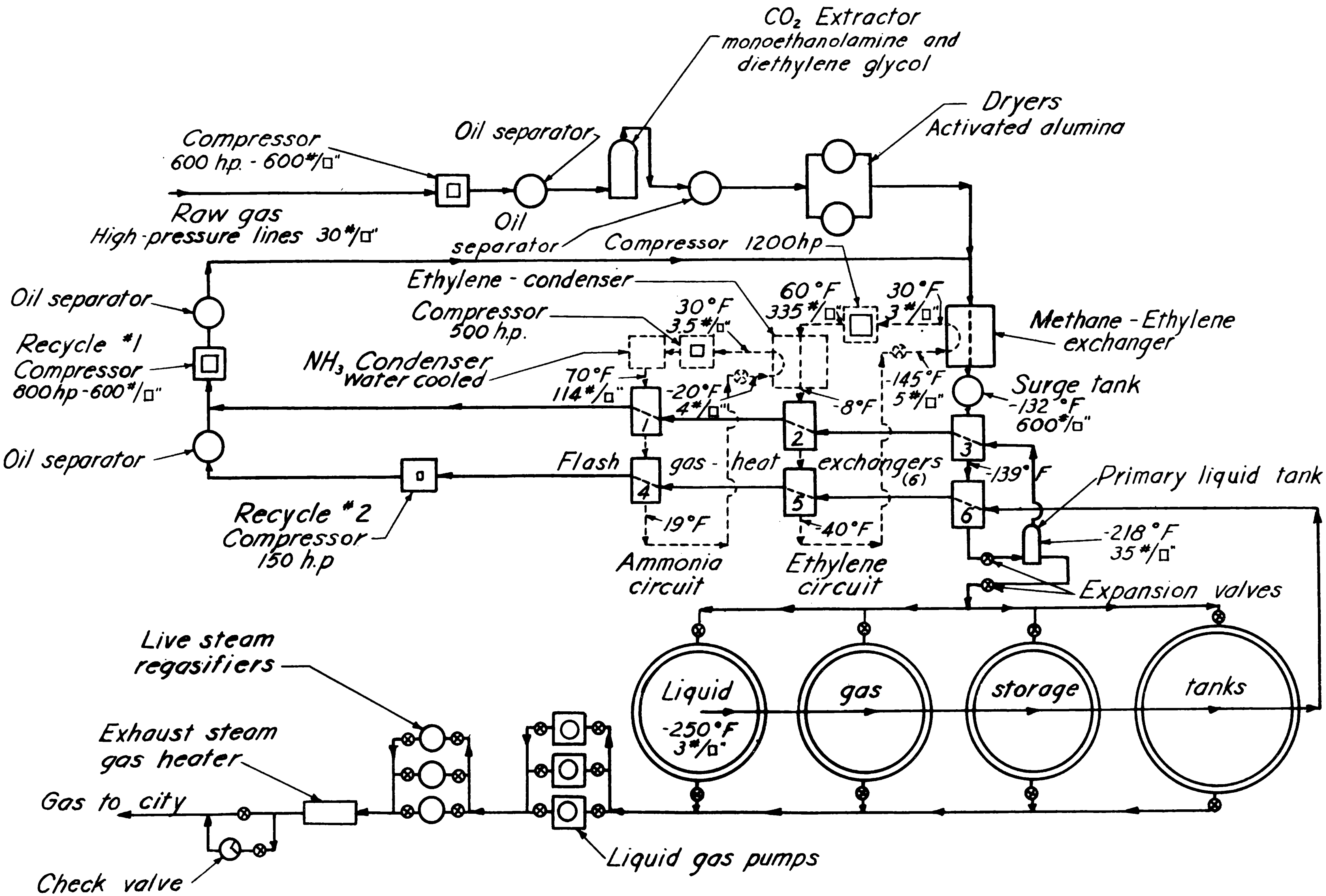
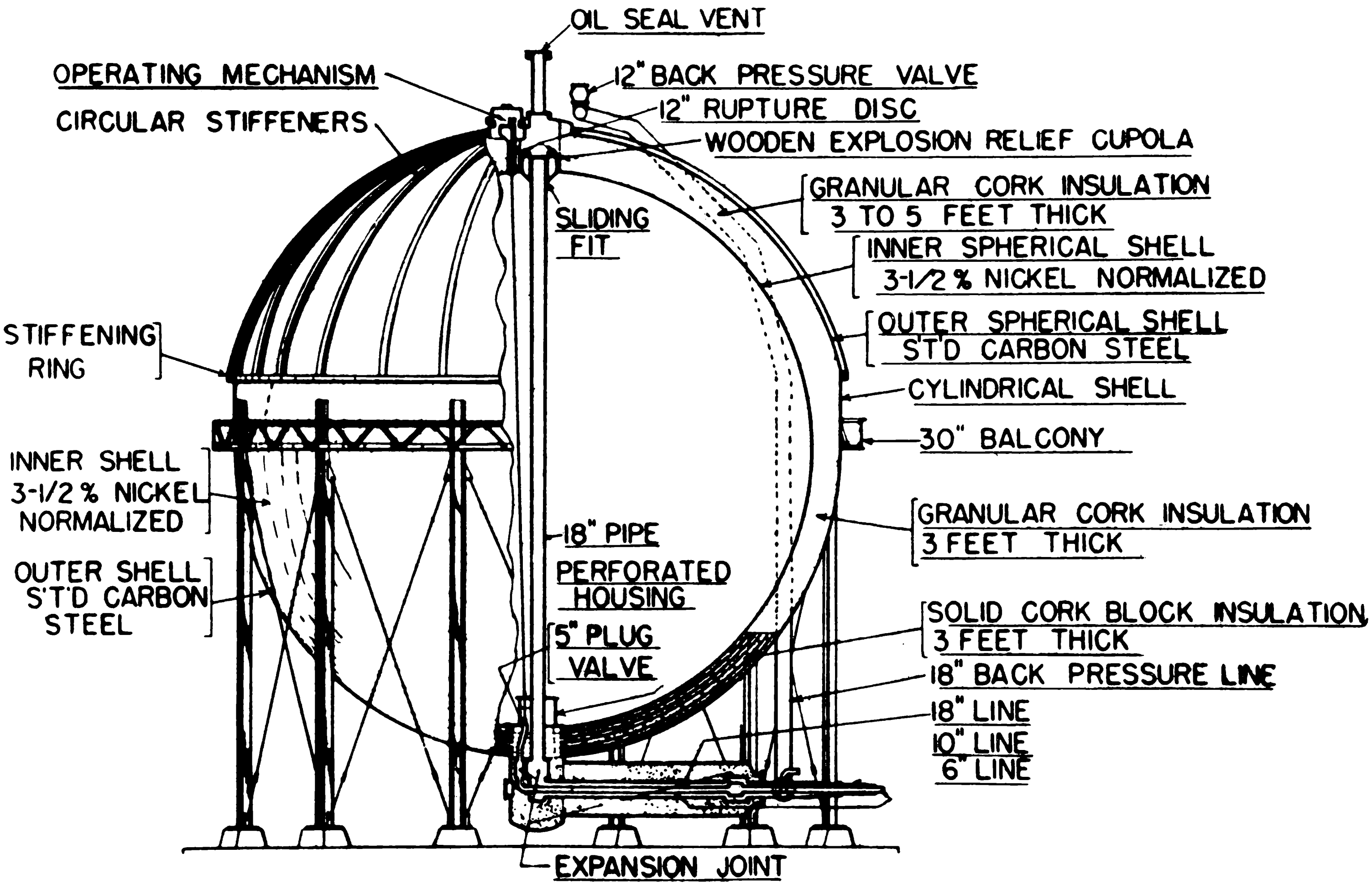


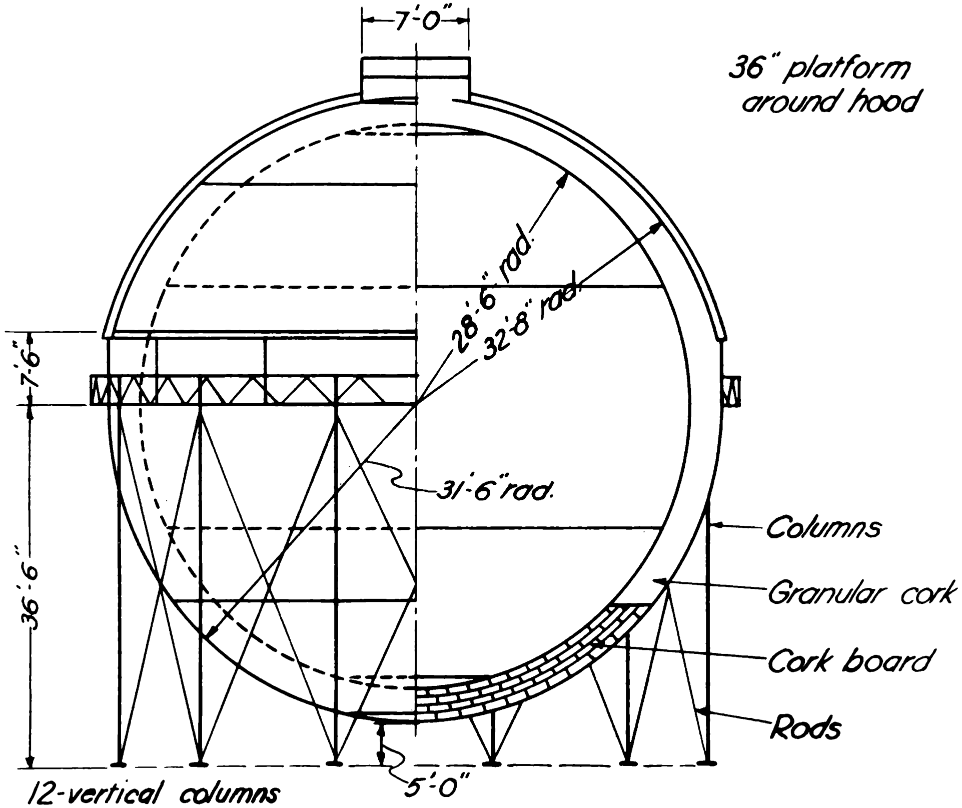
Figure 3.—Flow diagram of LS & R plant, East Ohio Gas Co.



DRAWING NO 1

LIQUID GAS HOLDER

Figure 5.—Diagrammatic sketch showing general features of spherical storage tank.



All seams inside and outside tanks to be butt welded

Plates for inside sphere to be 3½% nickel normalized

Remainder of steel to be std. carbon

Diameter of inside sphere 57'-0"

Basis of design

Maximum vapor pressure 10*/□"

Weight of liquid methane 26*/cu. ft.

Test hydrostatic to 125% of working stress in plates

Maximum working unit stress in plates = 13,750*/□"

Net capacity 55,840,000 cu. ft gas, 89,300 cu ft. liquid

Vapor space 8.58% of net liquid volume

55,840,000 cu. ft. container for liquid methane

Figure 6.—Details of design and construction of spherical storage tank.

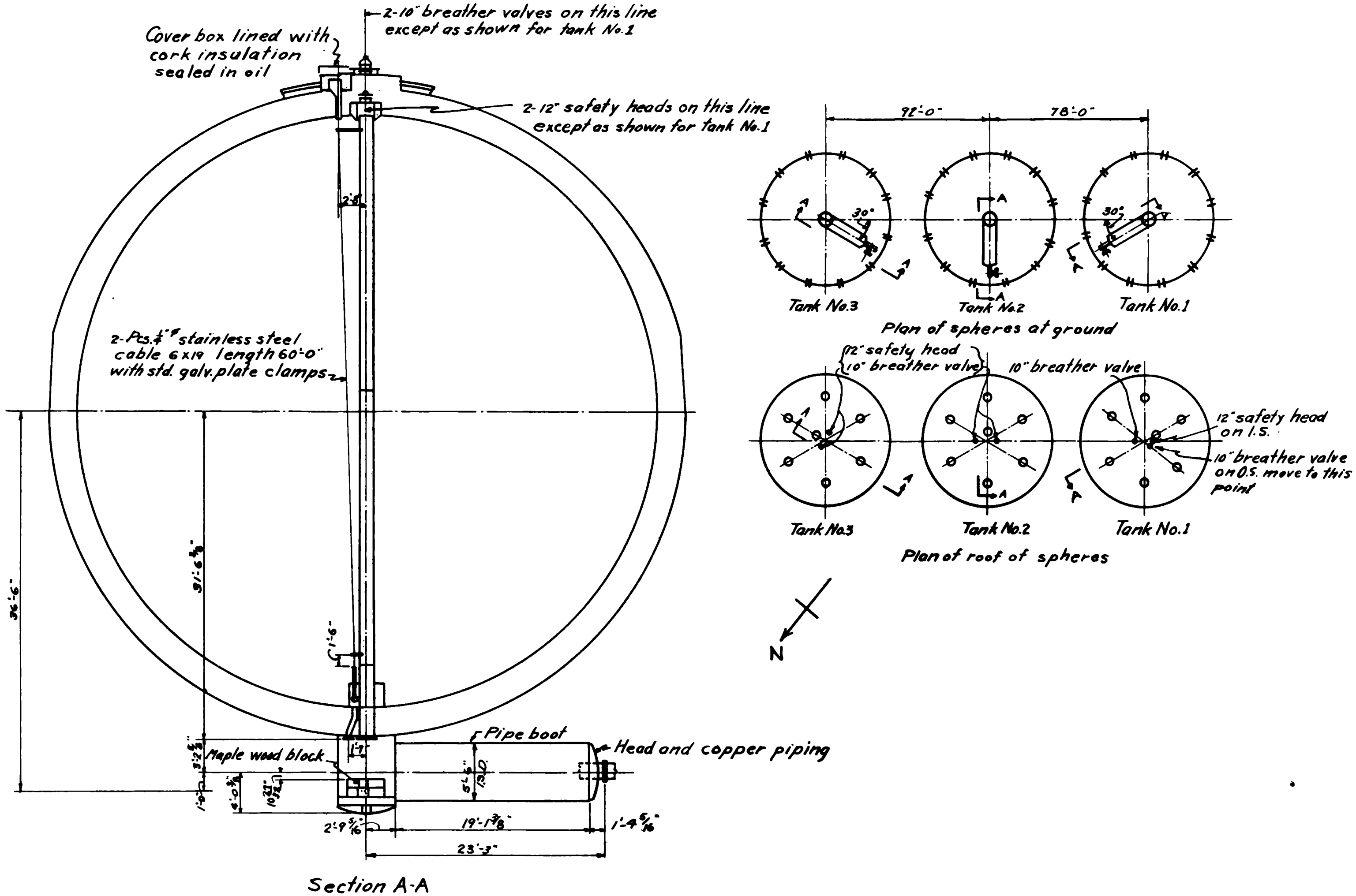


Figure 7.—Erection diagram for liquefied-gas-storage tanks 1, 2, and 3. (Partial reproduction of drawing E-8, Pittsburgh-Des Moines Steel Co., Pittsburgh, Pa.)

All equipment at the LS&R plant was adequately protected by relief valves and check valves.

DESCRIPTION OF STORAGE TANKS FOR LIQUEFIED NATURAL GAS

Liquefied natural gas was stored in four insulated tanks at the LS&R plant of the East Ohio Gas Co. Three of these tanks (Nos. 1, 2, and 3) were spherical and one (No. 4) was cylindrical (toro-segmental). (See fig. 4.) These tanks were designed, fabricated, and erected by the Pittsburgh-Des Moines Steel Co., Pittsburgh, Pa. Their total working storage capacity was about 400,000 cubic feet of liquefied natural gas, which, when gasified, would yield about 240,000,000 cubic feet of gas at normal temperature and pressure. Each of the spherical tanks had a working capacity of 50,000,000 cubic feet of natural gas (83,300 cubic feet of liquefied gas), and the cylindrical tank had a working capacity of 90,000,000 cubic feet of natural gas (150,000 cubic feet of liquefied gas). The details of the design and construction of each type of tank are summarized below.

Spherical Tanks

General

The three spherical storage tanks for liquefied gas were erected at the time the gas-liquefaction and regasification plant was built. The general features of their design have been given in the technical press (7,9). The more important features are shown in figures 5, 6, and 7 and are discussed below.

Each spherical storage tank consisted essentially of two concentric spheres separated by 3 feet of cork-board insulation. The inner shell had a diameter of 57 feet and was a specially welded structure made from a low-carbon, 3½ percent, nickel-alloy steel. The inner sphere was supported by cork-board insulation, which in turn was supported by the lower part of the bottom half of the outer shell (see figs. 5 and 6). The entire structure was supported by 12 columns, the flanges of which were attached to the outer shell by fillet welds, as shown in figure 5. The supporting columns and the outer shell were of ordinary open-hearth steel welded with mild-steel, coated electrodes. Granular cork was used as insulation in the upper part of the space between the spheres. In this region, no load was carried by the cork, and therefore the granular material was satisfactory.

Material Used in Construction of Inner Tank

The importance of the physical characteristics of materials subjected to low temperatures had been recognized and was studied during developmental work on the liquefaction process, and it was concluded(2) that the order of excellence of metals that retain a safe Charpy impact test at temperatures below -50°F. is pure copper, bronze, Monel metal, red brass, stainless steel, and steel plate having a carbon content less than 0.09 percent and a nickel content greater than 3½ percent. The foregoing work on the properties of metals at low temperatures was referred to by the designer of the tank(9), who stated that considerable research and development work had been done to determine the best material for use in sections of the tank subjected to low temperatures. It was further stated(9) that a nickel-alloy steel of the following composition was "satisfactory and less costly than other materials considered."

	Percent
Carbon...........	0.08 to 0.12
Manganese........	.30 to .60
Sulfur....	.045 maximum
Phosphorus.......	.04 maximum
Silicon.........	.10 to .20
Nickel..........	3.25 to 3.75

Steel of this composition was used for the inner spheres. It was de-oxidized, and, after rolling, the plates were normalized at 1,550°F. After this treatment, the grain size ranged from 6 to 7 McQuaid, and the Brinnell hardness from 149 to 152(9).

Development work on the welding of the spherical tanks was done by the Pittsburgh-Des Moines Steel Co.(9) and indicated that electrodes containing 25 percent chromium and 20 percent nickel would be satisfactory with moderate preheating of the plates (212°F). Weld specimens in all thicknesses and positions were tested(9) at -260°F. and showed Charpy impact values greater than 15 ft.-lb. either in the weld metal or heat-affected zones.

Connections for Gas and Liquid

The liquefied gas entered and left the inner sphere through a 5-inch plug valve in the bottom of the sphere (see fig. 7). This valve could be operated from the top of the outer sphere by a cable and linkage.

Gas from vaporized liquid left the inner sphere through an 18-inch vent pipe, which extended from the top to the bottom of the inner sphere (see figs. 5 and 7). The gas vent pipe was designed to carry off the maximum quantity of evaporated liquid that might be obtained under any anticipated normal condition. The pipes for liquid and gas were connected at the bottom of the outer sphere to copper expansion joints. This was the only connection between the inner sphere and exterior piping. Pipes for either gas or liquid were copper and were contained in an insulated boot outside the bottom of the tank (see figs. 5 and 7). The pipes leaving the boot were insulated and were connected to the liquefaction and regasification plant as shown in figure 2. All pipe lines at temperatures of -50°F. and lower were copper, with Van Stone joints, bronze flanges, and bolts.

Relief Valves and Rupture Disks

Each tank was provided with two 12-inch, weight-loaded, Foster safety valves connected to a line extending from the gas vent pipe at the boot to the top of the sphere. Operation of these valves was checked once each

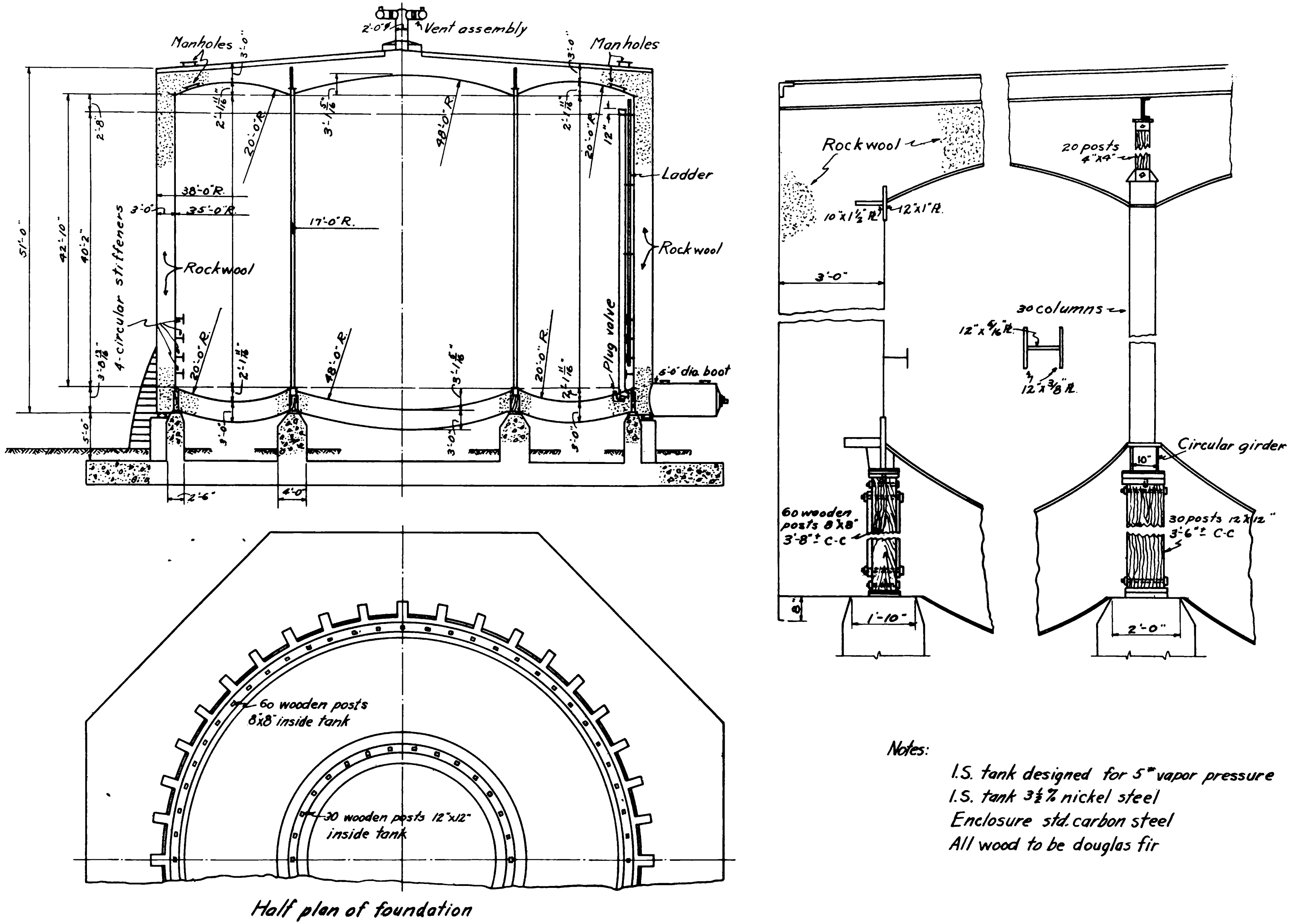


Figure 8.—Liquefied-gas-storage tank No. 4. (Partial reproduction of drawing 8063a, Pittsburgh-Des Moines Steel Co., Pittsburgh, Pa.

shift, according to George Binder, superintendent of the plant. The tank was also provided with two 12-inch rupture disks designed to rupture at 5 p.s.i. when at a low temperature. (See figs. 5 and 7.) According to Binder, one head blew at 10 p.s.i. when one of the tanks was tested with air at ordinary temperatures.

Ventilation of Space Between Spheres

The space between the spheres was vapor-tight, and the atmosphere in this space was replenished continuously by circulating dry, low-pressure natural gas therein, discharging it into the ambient atmosphere through relief or breather valves at the top of the tank. According to G. W. Horsley, general superintendent of the East Ohio Gas Co., approximately 15,000 cubic feet of natural gas per day was used for replenishing the atmosphere between the shells of the three spherical and one cylindrical tanks. According to R. W. Miller, it was originally planned to use nitrogen for the purpose, but the cost was excessive.

Cylindrical (Toro-Segmental) Tank

General

The cylindrical or, more precisely, the toro-segmental tank was finished in the spring of 1943 and put into service in the fall of 1943(1), approximately 2½ years after the three spherical tanks had been put into service. The general features of the tank are shown in figure 8. According to the designer (J. O. Jackson, chief engineer, Pittsburgh-Des Moines Steel Co.) the cylindrical tank has many structural advantages when the storage capacity for liquefied gas is equivalent to 100,000,000 cubic feet or more of gas at ordinary pressures and temperatures. Jackson stated that the unit bending stresses set up in the sphere along its greatest horizontal diameter become excessive as the size of the sphere increases beyond a liquid capacity yielding 100,000,000 cubic feet of gas. The reason for this may be traced to the method of supporting the sphere at the bottom. Jackson also pointed out that emptying and filling the spherical tank would cause repeated flexure in the region of maximum bending stress and might result in a fatigue failure in larger tanks. In further discussing spherical and cylindrical tanks, Jackson indicated that the difference in cost between the two type of tank was not the factor that influenced his recommendation of the cylindrical tank to the East Ohio Gas Co. He stated that the stress analysis for the cylindrical tank could be made with greater certainty.

Construction of Tank

The cylindrical storage tank consisted of an inner cylindrical container (inner tank shell) approximately 42 feet high and having a diameter of 70 feet, and an outer cylindrical shell (insulation jacket) 51 feet high and having a diameter of 76 feet (fig. 8). The top and bottom of the inner tank shell had essentially the shape of a dished circular head within a dished annulus (fig. 8). The diameter of the so-called dished circular head was approximately 34 feet, and the width of the so-called dished annulus was 18 feet. The outer edge of the bottom dished head and the inner edge of the bottom annulus were welded to a circular girder bent to a 17-foot radius (fig. 8). This circular girder formed the base for thirty 12- by 12-inch columns. These interior columns supported the top of the inner tank shell and carried the weight of the insulation above this top and also the weight of the roof of the insulation jacket. The columns extended from the bottom to the top of the inner tank and were welded at the top to a circular girder corresponding to the circular girder in the bottom of the inner tank. The dished annulus and the dished head forming the top were welded to this circular girder, as described above for the bottom of the inner tank shell.

The walls of the inner tank shell were approximately 3 feet from the insulation jacket, and the intervening space was filled with rock-wool insulation. The inner tank shell was supported on two circular footings. One of these was approximately 70 feet in diameter, and the other was approximately 34 feet in diameter (fig. 9). The weight of the inner tank shell and its contents was transmitted to the footings through wooden columns. There were 30 of these wooden columns or posts, 12 by 12 inches (fig. 8), which transmitted the load from the inner circular girder, and 60 posts 8 by 8 inches (fig. 8), which transmitted the load from a belt ring at the outside edge of the bottom of the inner tank shell to the reinforced-concrete footings.

The wooden posts used were made from selected Douglas fir and were milled square on each end. This type of wood was selected by the Pittsburgh-Des Moines Steel Co. after extensive tests of woods exposed to liquid nitrogen for periods of two weeks. The steel end plates of the wooden posts were designed to provide sufficient radial rocker action to permit the center of the top of the posts to be erected on a radius 3/4 inch greater than that of the center of the base of the posts. This provision was necessary to take care of the contraction of the inner tank shell when cooled to -260°F. At that temperature, all posts would be exactly vertical if they had been erected as described above. The outer posts (fig. 8) were braced diagonally with 2- by 4-inch bracing to provide circumferential stability.

<u>Material Used in Tank</u>

Jackson stated that the steel used in the cylindrical tank and the spherical tanks had the same chemical composition, and that a joint efficiency of 80 percent was used in the design. The maximum fiber stress in the inner tank shell was stated to be 12,496 p.s.i., which gives a safety factor of about 5 based upon the strength at normal temperatures.

In discussing the metal used in constructing the tank, Jackson stated that the nickel-alloy steel used was to all intents and purposes brittle at -260°F., despite a satisfactory Charpy impact value. He indicated that when a sheet of nickel-alloy steel was at a low temperature, a sledge might be driven through it. In his opinion, this should not obviate the use of this material for construction purposes, and he cited as examples the large number of brittle materials used in construction.

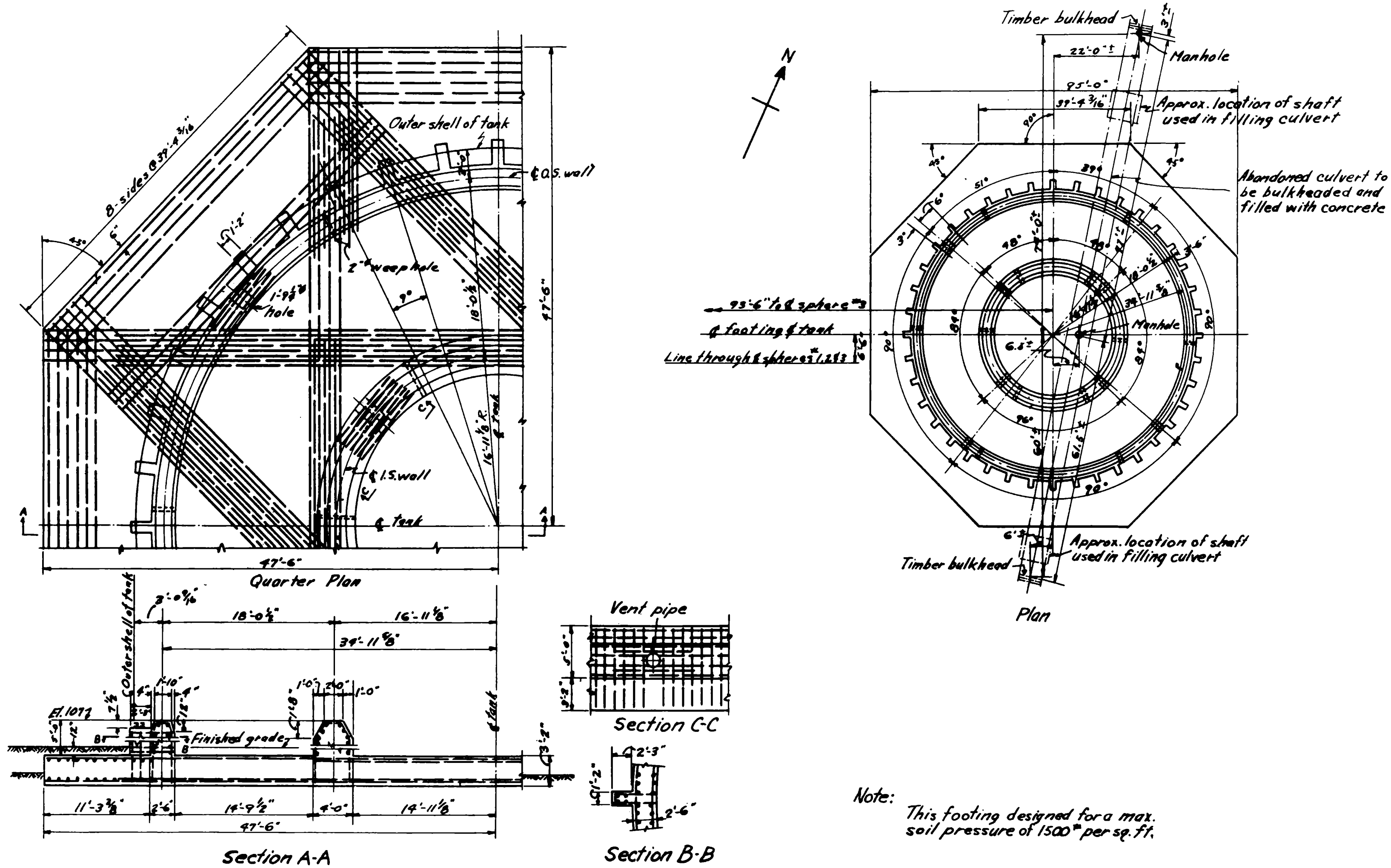


Figure 9.—Reinforced-concrete foundation for liquefied-gas-storage tank No. 4. (Partial reproduction of drawing 1-S, file 4503, Wilbur Watson and associates, Cleveland, Ohio.)

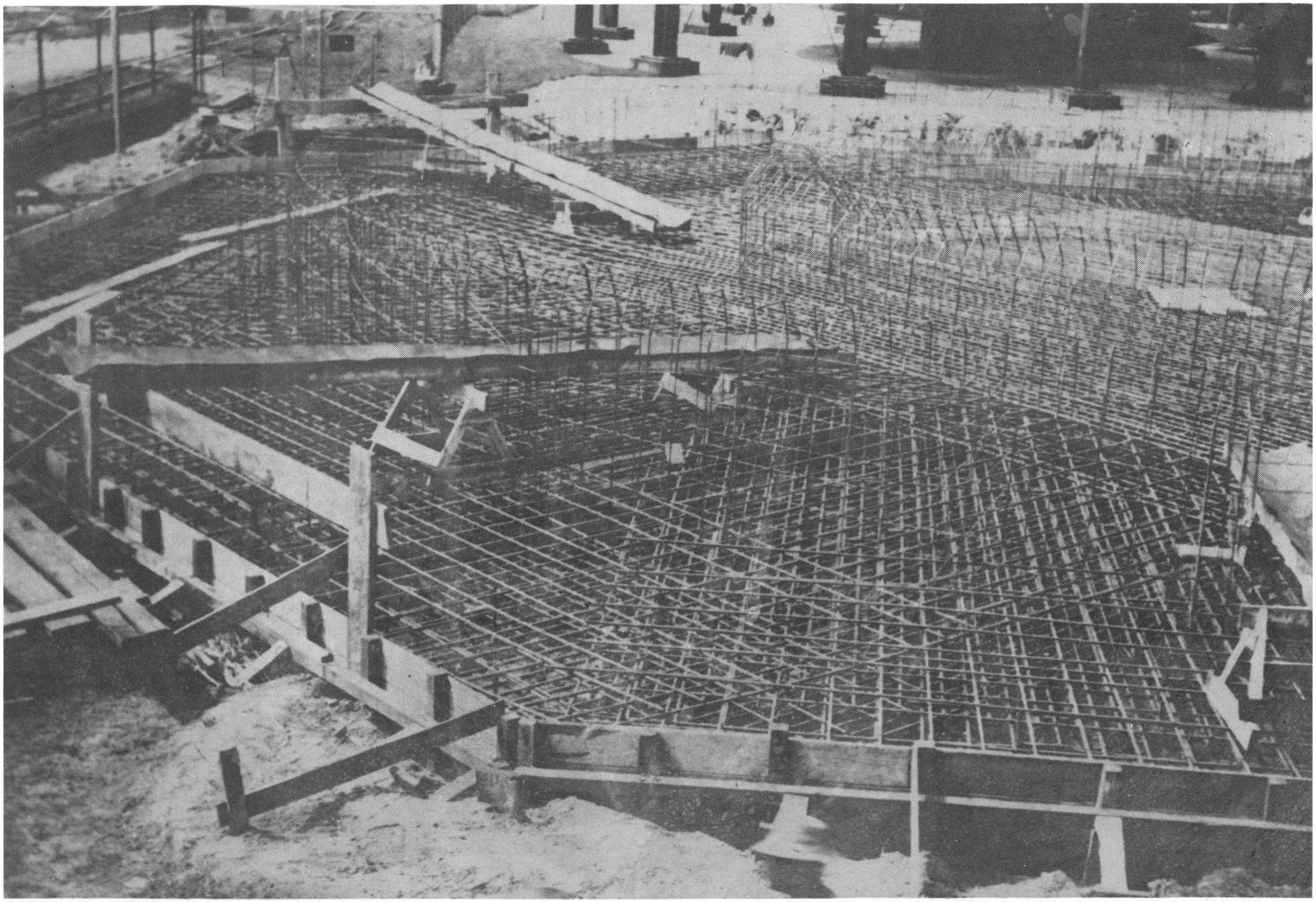


Figure 10.—Reinforcing and form for foundation pad for toro-segmental tank.

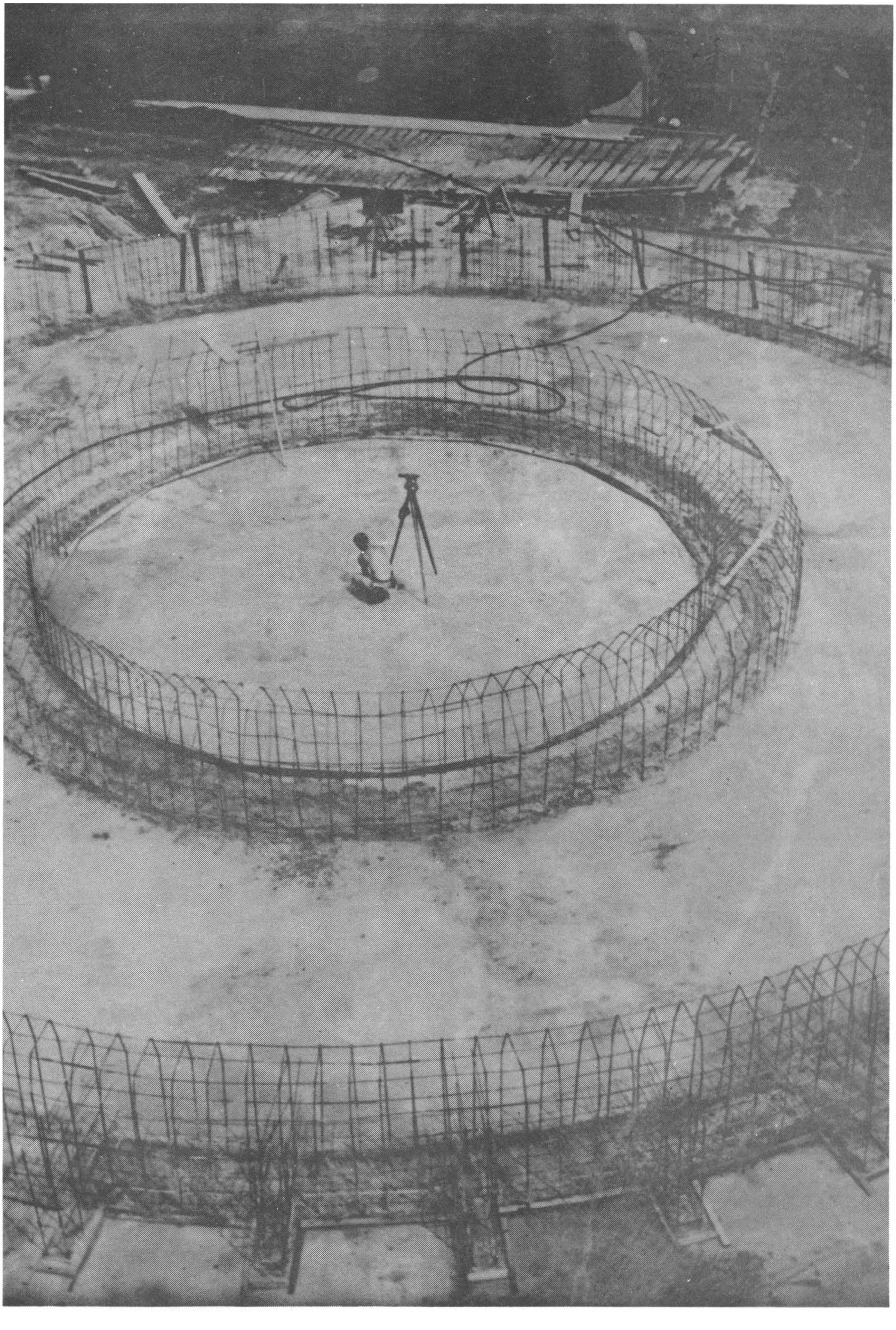


Figure 11.—Reinforcing for ring-shaped footings for toro-segmental tank.

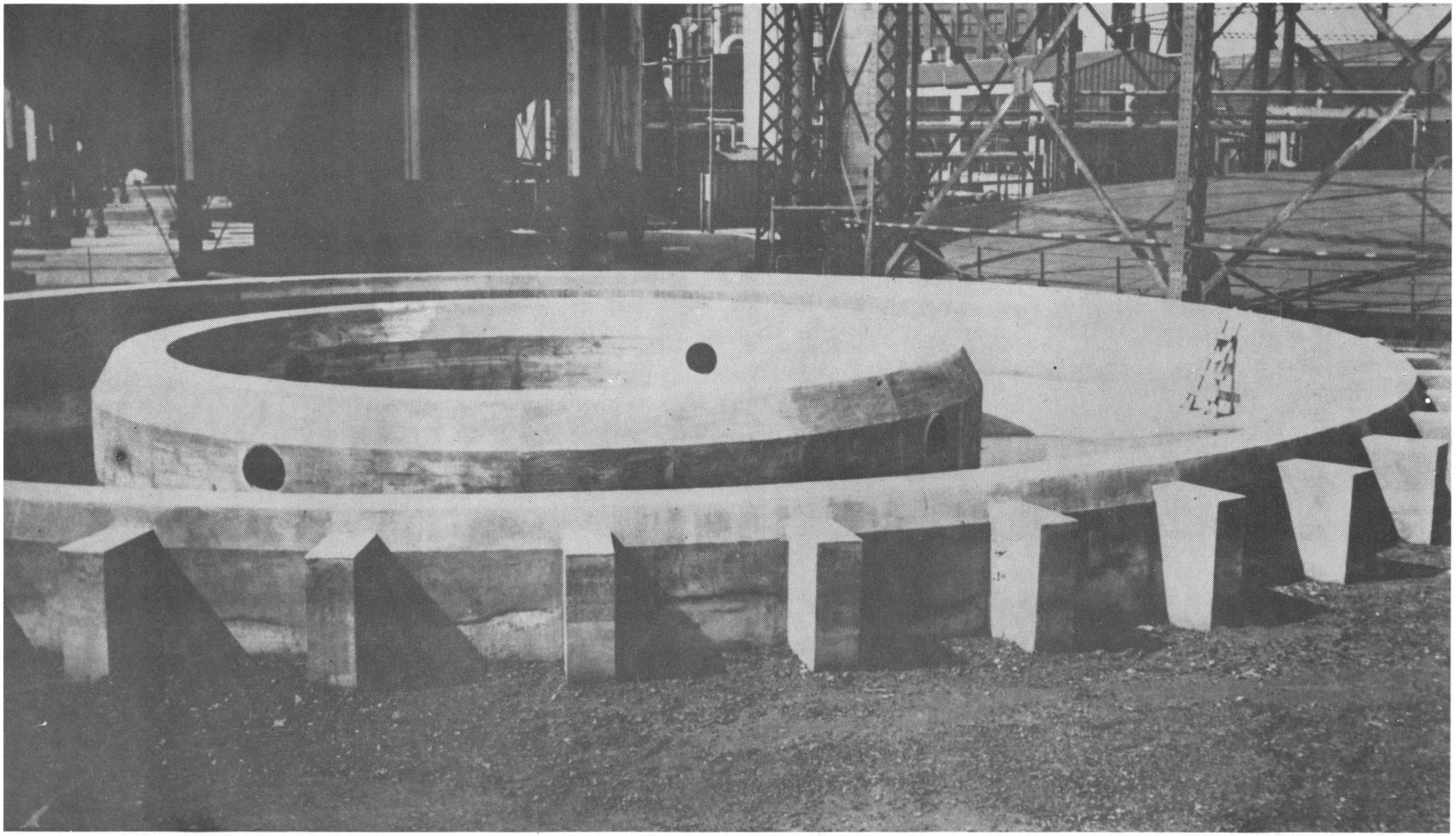


Figure 12.—Completed foundation for toro-segmental tank, showing ring-shaped footings with pilaster on outside of outer footing.

Foundation

The details of the foundation as constructed are given below:

The foundation for the cylindrical tank was studied intensively because of poor ground conditions at the site selected for the cylindrical tank. This site had at one time been used as a dump for spent oxide from dry purification boxes. The ground, therefore, probably contained considerable spent oxide mixed with wood shavings. Consequently, a bearing pressure o only 1,400 pounds per square foot was used in designing the foundation.

The foundation for the cylindrical tank was designed by Ralph Harding of Wilbur Watson Associates, Inc. After he had arrived at a preliminary design, it was discussed with the Pittsburgh-Des Moines Steel Co. The design used is shown in figure 9 and resulted from these discussions. The foundation consisted of a reinforced-concrete pad approximately 3 feet, 2 inches thick. Construction phases of the foundation are shown in figures 10, 11, and 12. The two ring-shaped footings mentioned above for supporting the wooden column posts of the cylindrical tank rested on this thick, reinforced-concrete pad (fig. 12). Directly through the middle of the area in which the tank was situated was an abandoned culvert approximately 6 feet in diameter (figs. 1 and 9). W. G. Hagan stated that this culvert was filled with concrete, as indicated in figure 9, before the foundation was built. Because of the questionable nature of the ground upon which the cylindrical tank was placed, Wilbur Watson Associates carefully measured the elevation of the foundation after the tank had been hydrostatically tested and also during the first several months of its use when liquefied gas was stored in it. According to Hagan, no significant settling had taken place. He reported also that after the fire, Ralph Harding, the engineer of Wilber Watson Associates, again rechecked the level of the foundation, and, as nearly as he could tell, there still had been no change in the elevation from that measured in October 1943, when the tank was first put into service.

As shown in figures 9 and 12, ventilating ducts were provided in the inner and outer footings (ducts in outer footings are not visible in the photograph but are shown in fig. 9). These ducts were provided so that air could circulate beneath the tank and maintain the temperature of the outer wall of the bottom insulation jacket at or near ambient temperature.

Connections for Gas and Liquid

The arrangements for adding liquid to the cylindrical tank and for venting gas from the tank were essentially the same as used for the spherical tanks. One difference lay in the size of the gas vent pipe, which was only 10 inches in diameter in the cylindrical tank, as compared to 18 inches in the spherical tanks. Another difference was that the liquid inlet and outlet connections and the gas vent pipe were placed near the side of the tank instead of at the center. As with the spherical tanks, the gas line and liquid line were in an insulated boot at the bottom of the tank (fig. 8), and both of these lines were rigidly connected to the inner tank shell only at the bottom. An expansion joint was provided just outside this connection. Another difference between the lines for gas and liquid in No. 4 tank and those in the spherical tanks was that the lines to No. 4 tank that were to be at -50° F. or lower were of nickel-alloy steel, whereas all of the lines to the spherical tanks operating at -50° F. or lower were copper.

Ventilation of Space Between Inner and Outer Tank

The arrangements for keeping the space between the two tanks dry and filled with an atmosphere of natural gas were the same as in the spherical tanks. The space between the two shells was protected by a relief valve set at ½ inch of water. A large oil-sealed cover was provided, also.

Relief Valves and Rupture Disks

A 24-inch vent pipe extended from the center of the roof of the inner tank shell up through the roof of the insulation jacket and then branched in two directions. On each end of the resulting tee were placed two complete sets of relief valves. Each set consisted of one 12-inch pressure relief valve and one 12-inch safety disk. One 6-inch vacuum relief valve also was provided. The relief valves were arranged so that both sets would normally be in service and so that either set could be blocked off for servicing or repair. A linkage was provided, so that both sets could not be blocked at the same time.

The two 12-inch pressure-relief valves were set at 5 p.s.i., and the two 12-inch aluminum safety disks were set to rupture at 6 p.s.i. The pressure required to rupture these aluminum safety disks was determined at the temperature of liquid nitrogen. The calculated venting capacity of one 12-inch safety head at 6 p.s.i. pressure was slightly greater than 2,000,000 cubic feet per hour. The calculated venting capacity of one 12-inch pressure-relief valve at 6 p.s.i. was 860,000 cubic feet per hour. The calculated evaporating rate of the liquid within the tank, with an outside mean temperature of 120°F., was 6,680 cubic feet per hour, and the calculated evaporating rate at 1,000°F. was only 22,316 cubic feet per hour. The maximum calculated venting capacity of the two 12-inch valves and the two 12-inch safety heads was 5,426,000 cubic feet of gas per hour. The calculated values were taken from the design calculations of the Pittsburgh-Des Moines Steel Co.

Liquid-Level Indicators

The cylindrical tank was provided with a float-operated liquid-level indicator with a tell-tale on top of the tank and a recorder situated some distance from the tank. Each spherical tank was provided with indicating pressure gages connected to a line going to the bottom of the sphere and arranged so that nitrogen could be fed into the gage line to prevent liquid from entering(13). Each tank was provided with a tube bundle consisting of copper tubes of different lengths extending, in the case of the cylindrical tank, to the eighth points of tank capacity. The liquid level was approximated by observing the character of the discharge from adjacent tubes.

Hydrostatic Tests

After the cylindrical tank was constructed, it was filled with water to approximately one-half its maximum possible depth (the density of the liquefied gas, 26 pounds per cubic foot, is about half that of water), and, in addition, air under a pressure of 5 p.s.i. gage filled the space above the water. Jackson stated that they were afraid to fill the tank with water because of the uncertain nature of the soil under the foundation. He indicated that test holes had been drilled in the area prior to the construction of the foundation, and it was determined that the soil could not support more than 1,400 pounds per square foot.

Occurrence and Repair of Crack in Bottom of Tank

After the tank had been tested as described above, an effort was made to cool it and fill it with liquefied gas. According to Jackson, only three control thermocouples were installed - one at the top near the vent, one at the outside ring near the liquid inlet, and one at another location (precise location of the third thermocouple was not determined by Bureau of Mines investigators). As soon as the cold liquid filled the dished annulus (fig. 8), liquid spilled over the circular girder into the dished bottom, and a crack developed in one of the plates in the north quadrant of the bottom of the inner tank shell about 90° from the boot. This crack was entirely in one plate and is shown on drawing 8021A of the Pittsburgh-Des Moines Steel Co. A copy of this drawing is in the files of the Bureau, along with a complete set of design data furnished by the Pittsburgh-Des Moines Steel Co.

The crack occurred in June 1943 and was repaired in July 1943. In making the repair, a section of the plate was cut out by drilling and chipping instead of by burning. This was done to prevent any change in the physical properties of the steel in the vicinity of the section removed. The section removed was shaped somewhat like an elm leaf, with the dimension from point to point about 26 inches and the dimension across the leaf about 16 inches. A sheet of material of the same composition as that initially used in the inner tank was cut in the shop. One edge of it was welded in place, and the other edge was precision-welded by cooling the insert with dry ice. Cooling was controlled by observing strain gages placed between the insert and the bottom plate of the tank. Shrinkage of the insert necessary to compensate for the expansion in the weld was computed and controlled, so that when the repaired plate was at a uniform temperature, it would contain no residual stresses.

While the tank was being repaired, provisions were made for uniformly cooling it when it was again put into service. This was accomplished by installing four rings of 3/4-inch copper tubing having small holes approximately 1/16 inch in diameter punched in the copper tubes at 1-foot intervals spirally around the axis of the pipe. Two of these rings were 70 feet in diameter and two were 34 feet in diameter. One of the larger rings was placed inside the inner tank shell at the top and the other at the midsection. One of the smaller rings was placed inside the interior columns at the top and the other at the midsection. The tubes were manifolded outside the jacket and connected to the liquid line outside the boot. All copper tubing outside the tank was insulated.

Placing Tank in Service

After repairs and cooling coils were installed, the cylindrical tank was again tested hydrostatically, as described previously, and then was cooled under the supervision of the Pittsburgh-Des Moines Steel Co. Cooling was controlled by observing the temperature at 28 points on the shell of the inner tank. Thermocouples were attached at each of these points through a micarta tube and were fastened to the shell by freezing a drop of water placed on the end of the thermocouple. The rate of cooling was controlled by controlling the boiling point of the liquids supplied to the cooling coils. This boiling point was controlled by controlling the composition of the liquid in the liquefaction plant. Additional control was obtained by blanking off appropriate cooling coils.

Provision for Controlling Leakage from Tanks

Some time after the leak developed in No. 4 cylindrical tank when it was first cooled, the East Ohio Gas Co. erected concrete dams and cement skirts around the spherical tanks and a dam around the cylindrical tank with a covering annulus (apron wall) that extended from the top of the dam to within a few inches of the outside of the insulation jacket. The details of these are given in figures 13 and 14.

According to representatives of the East Ohio Gas Co., these dams were installed to confine liquid from a small leak that might develop in one of the storage tanks. The dams on the three spherical tanks were approximately 58 feet inside diameter and had a wall thickness of about 1 foot and a height of 57 inches. Above these dams a skirt extended to within 13 feet of the girder around the middle of the outer sphere. These cement skirts were approximately 2½ inches thick, with a center of metal lathing.

The outer edge of the dam around the cylindrical tank was about 8½ feet from the wall at the edge of the tank. The wall of the dam was 8 inches thick, and the dam was 7 feet high. An annular cover extended from the top of this dam to a point 6 inches from the insulation jacket where it was 4 feet, 4 inches above ground level. (Fig. 13.)

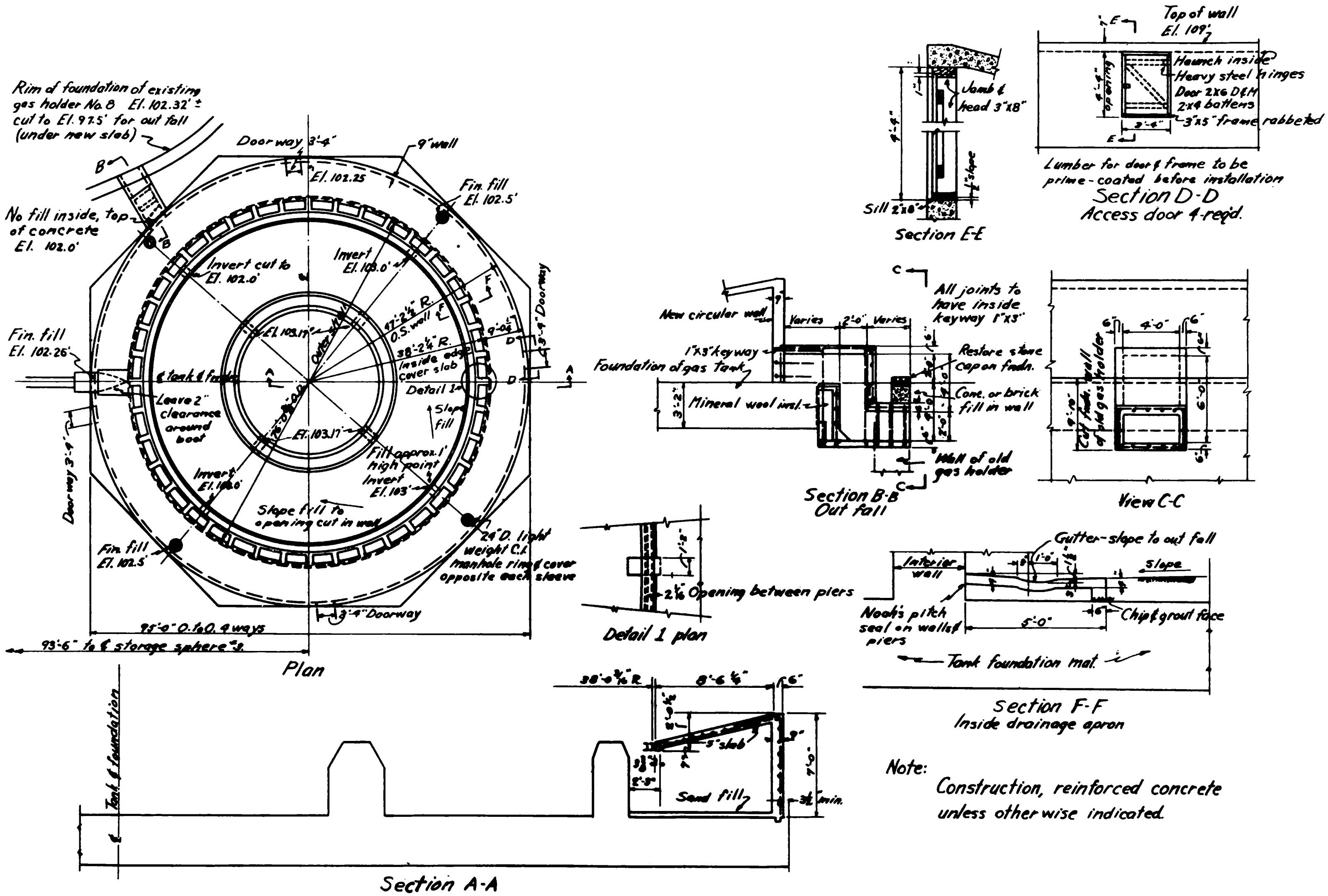


Figure 13.—Apron, wall, and drain for liquefied-gas-storage tank No. 4. (Partial reproduction of drawing 2-5, file 4503, Wilbur Watson and associates, Cleveland, Ohio.

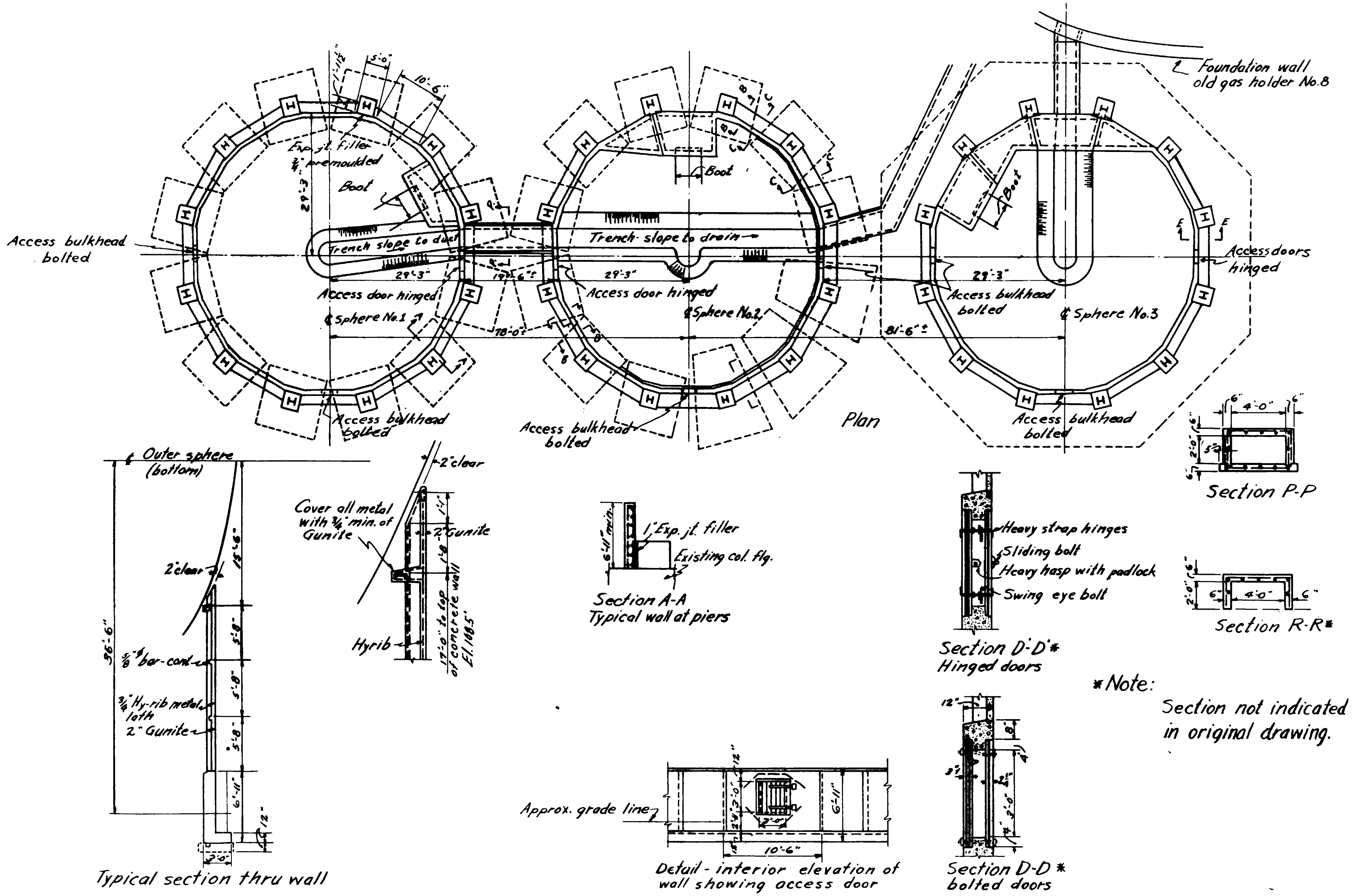


Figure 14.—Retaining walls and ducts for liquefied-gas-storage tanks 1, 2, and 3. (Partial reproduction of drawing 3-5, file 4503, Wilbur Watson and associates, Cleveland, Ohio.

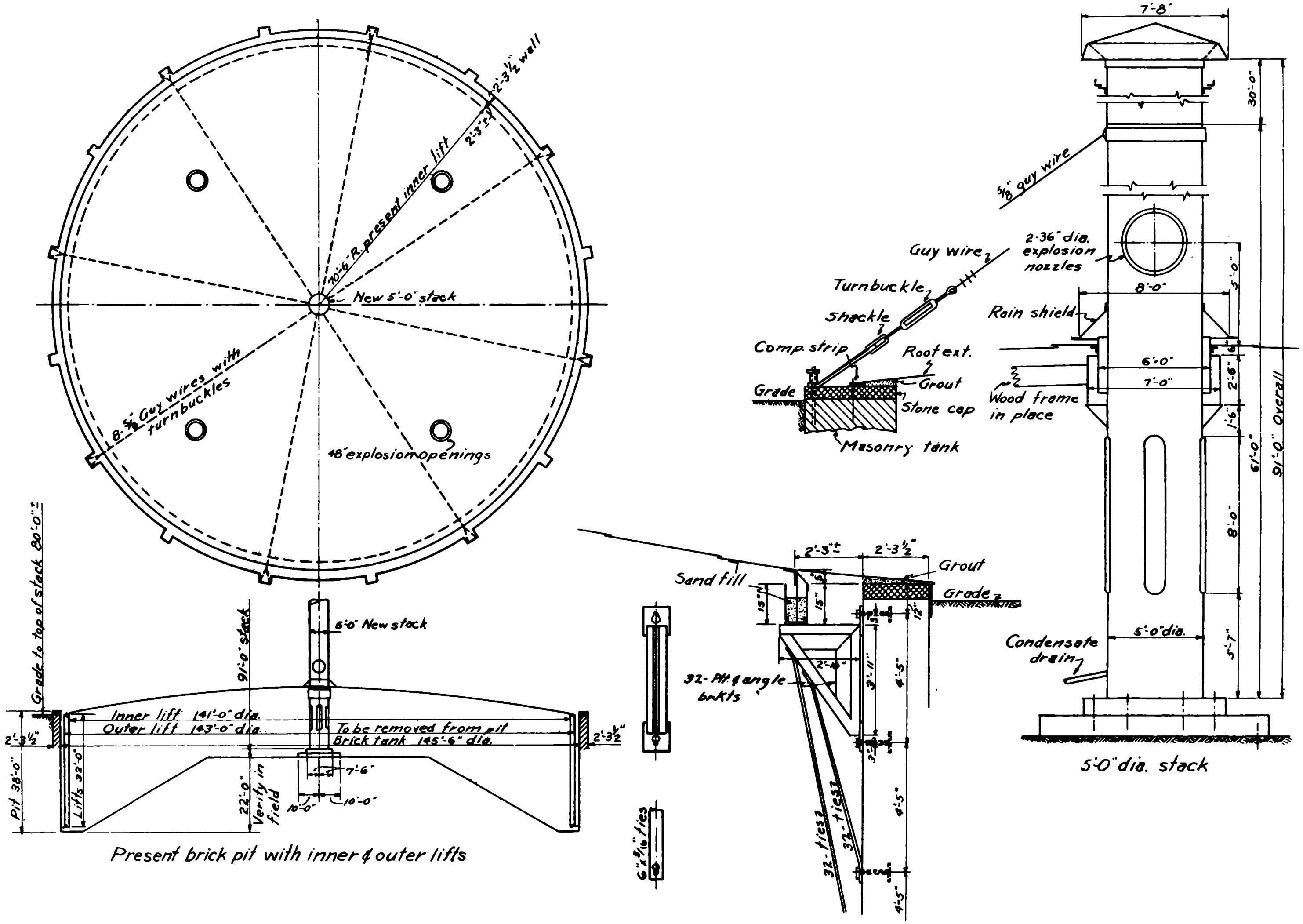


Figure 15.—Overflow-gas-storage tank. (Partial reprocuction of drawing furnished by East Ohio Gas Co., Cleveland. Ohio.)

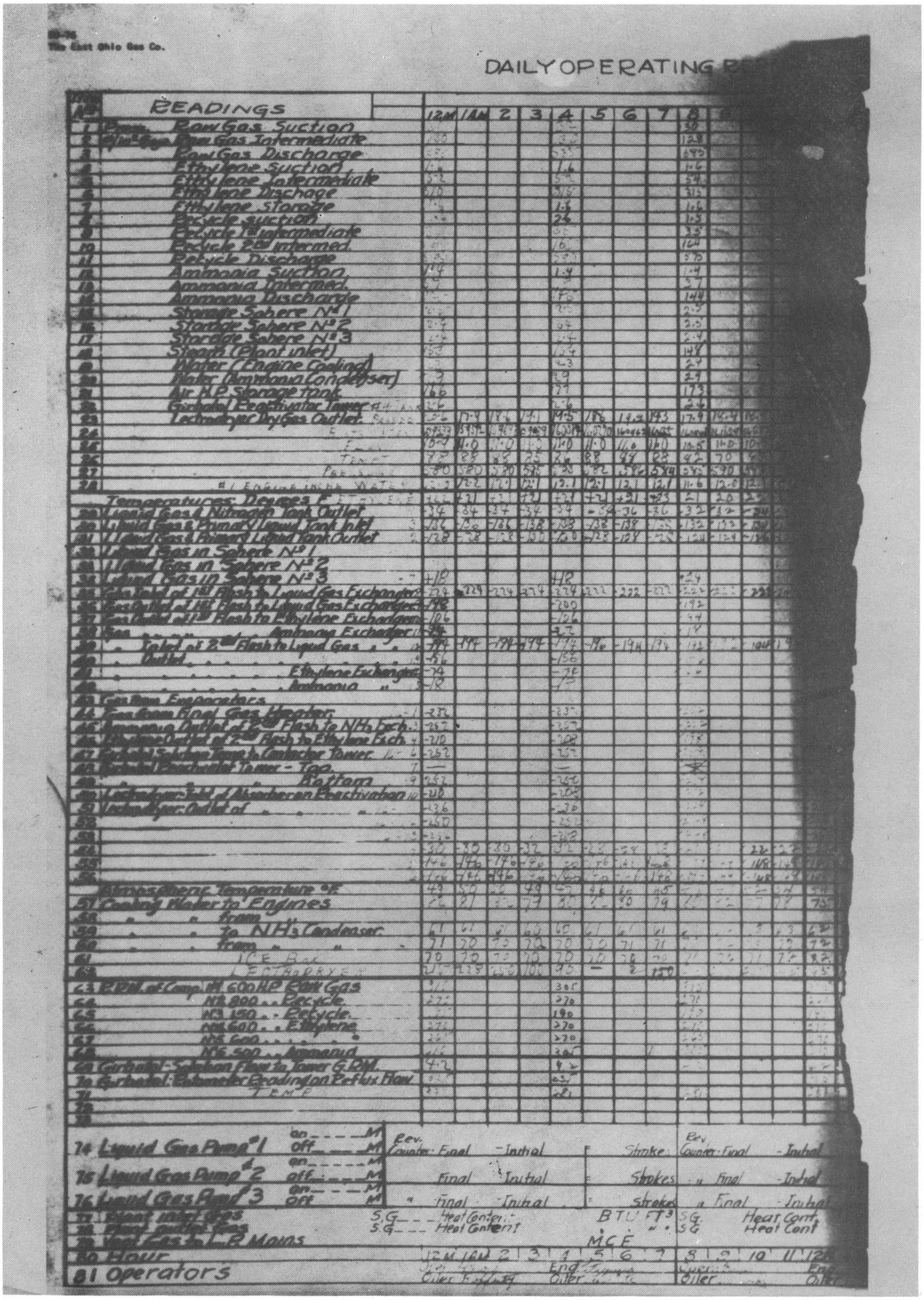


Figure 16.—Photostat of daily operating log for Oct. 20, 1944.

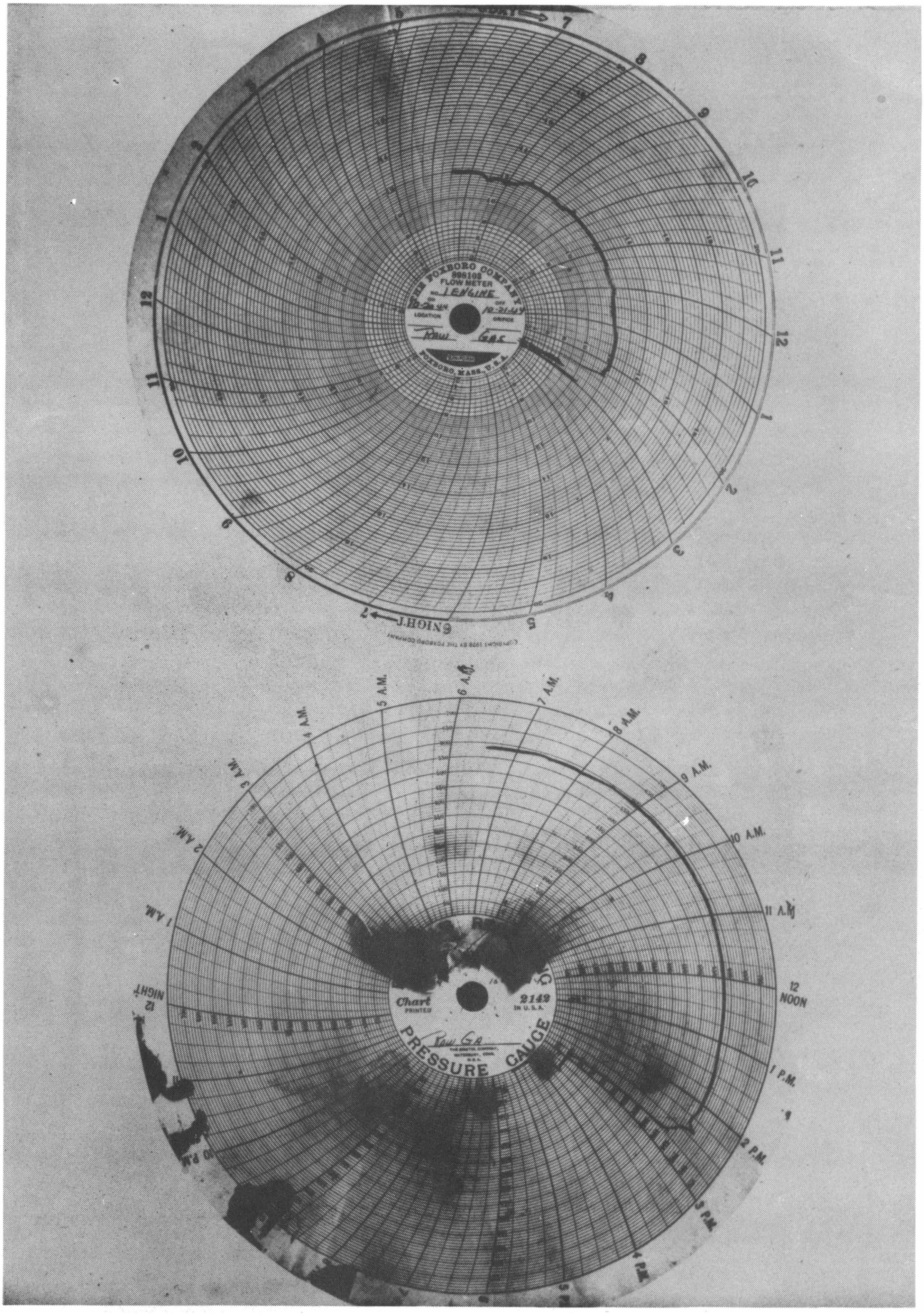


Figure 17.—Photostat of charts showing raw-gas flow (top chart) and raw-gas pressure at outlet of compressor (bottom chart) on Oct. 20, 1944.

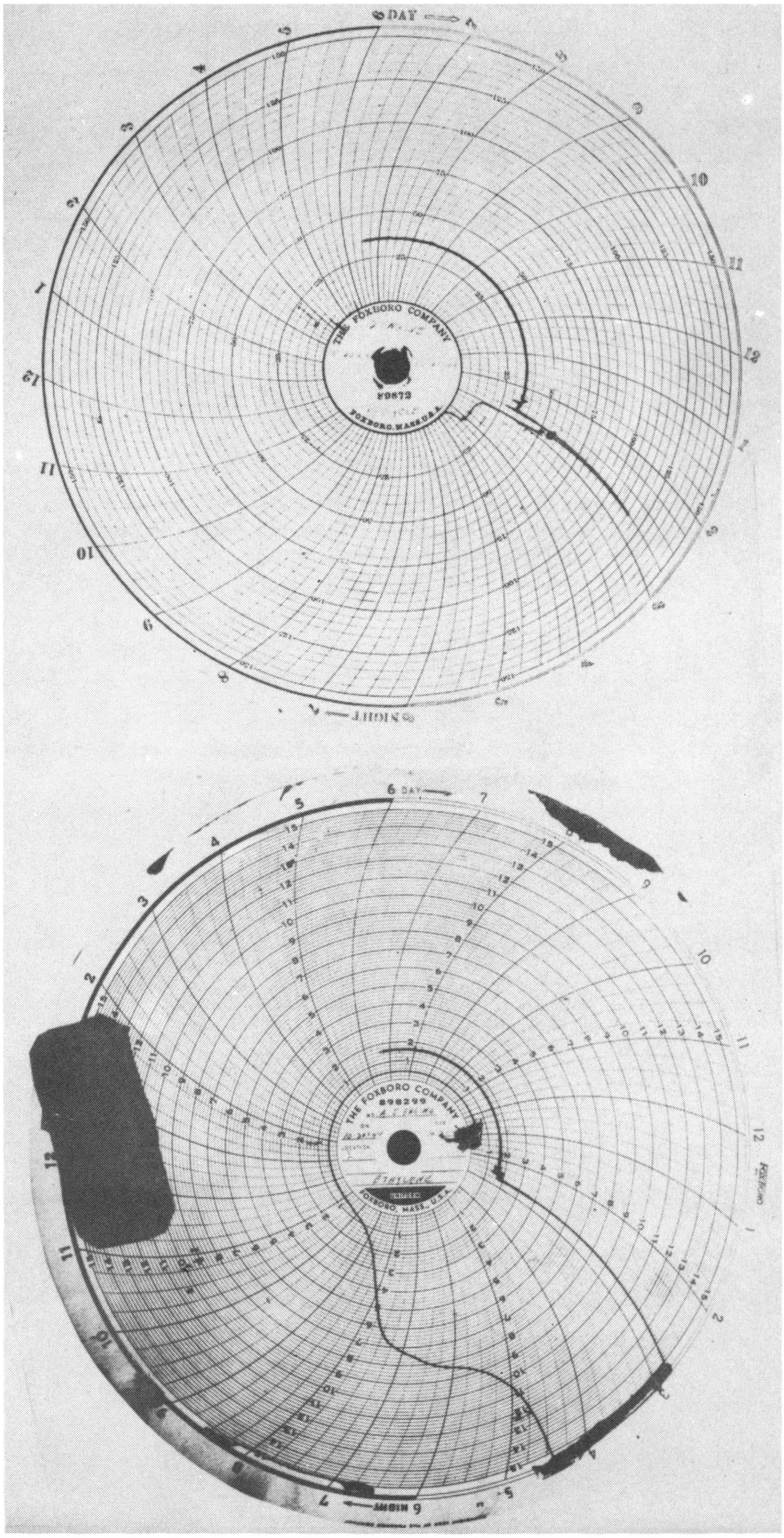


Figure 18.—Photostat of charts showing discharge pressure of recycle gas compressor 2 (top chart) and suction pressure of ethylene compressor (bottom chart) for October 20, 1944.

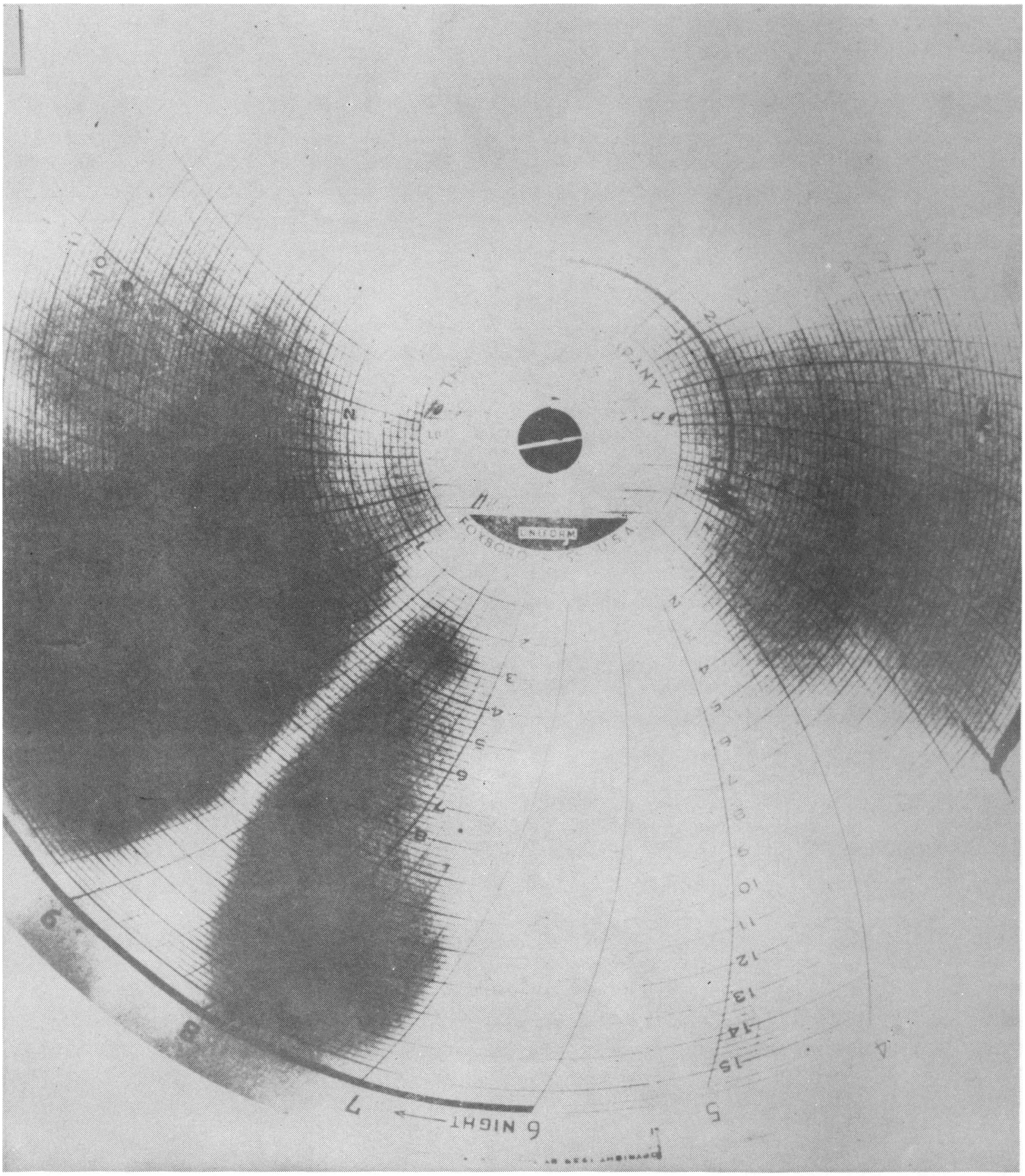


Figure 19.—Photostat of chart showing suction pressure of ammonia compressor on October 20, 1944.

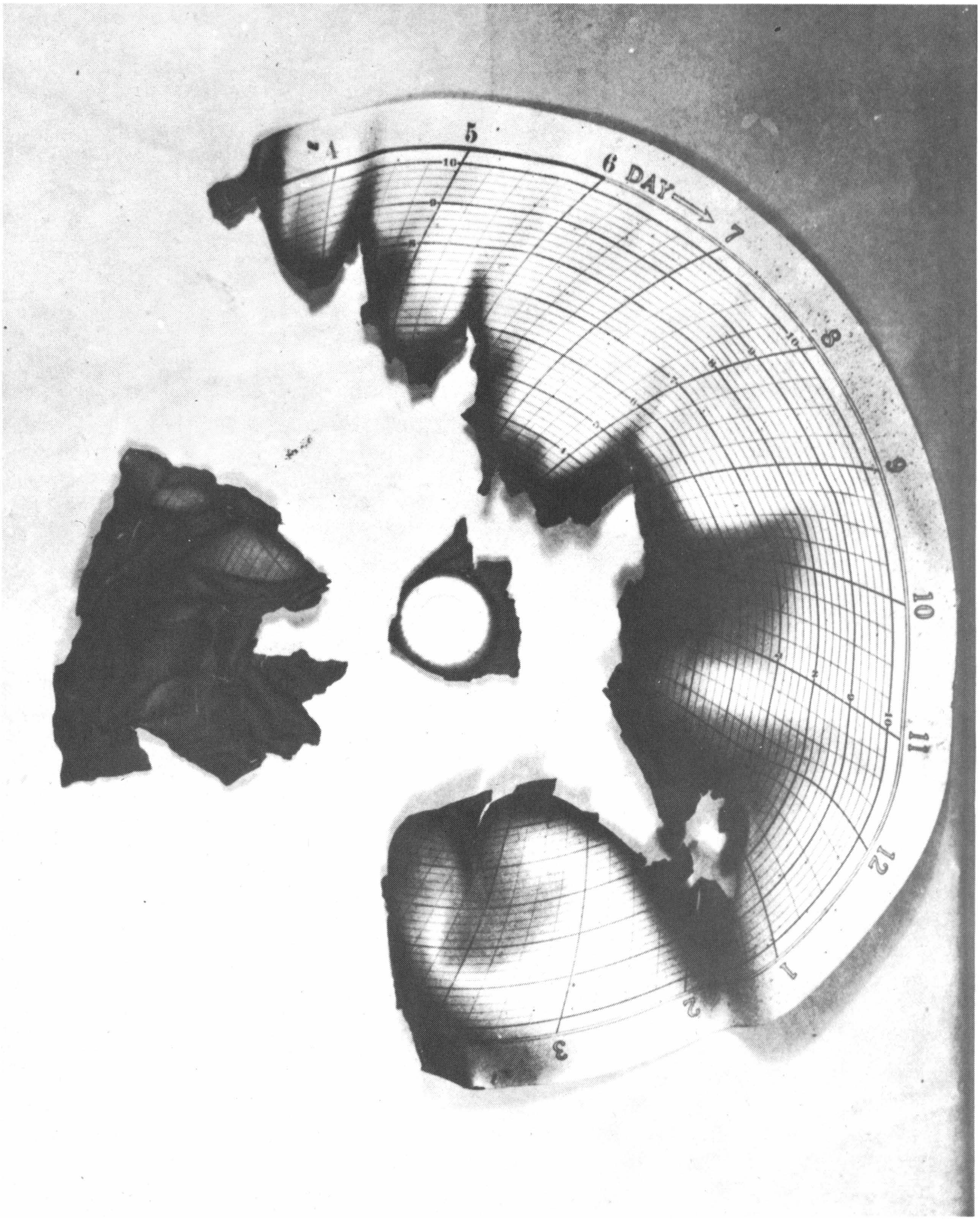


Figure 20.—Photostat of remains of chart on the suction of recycle gas compressor 2 on October 20, 1944.

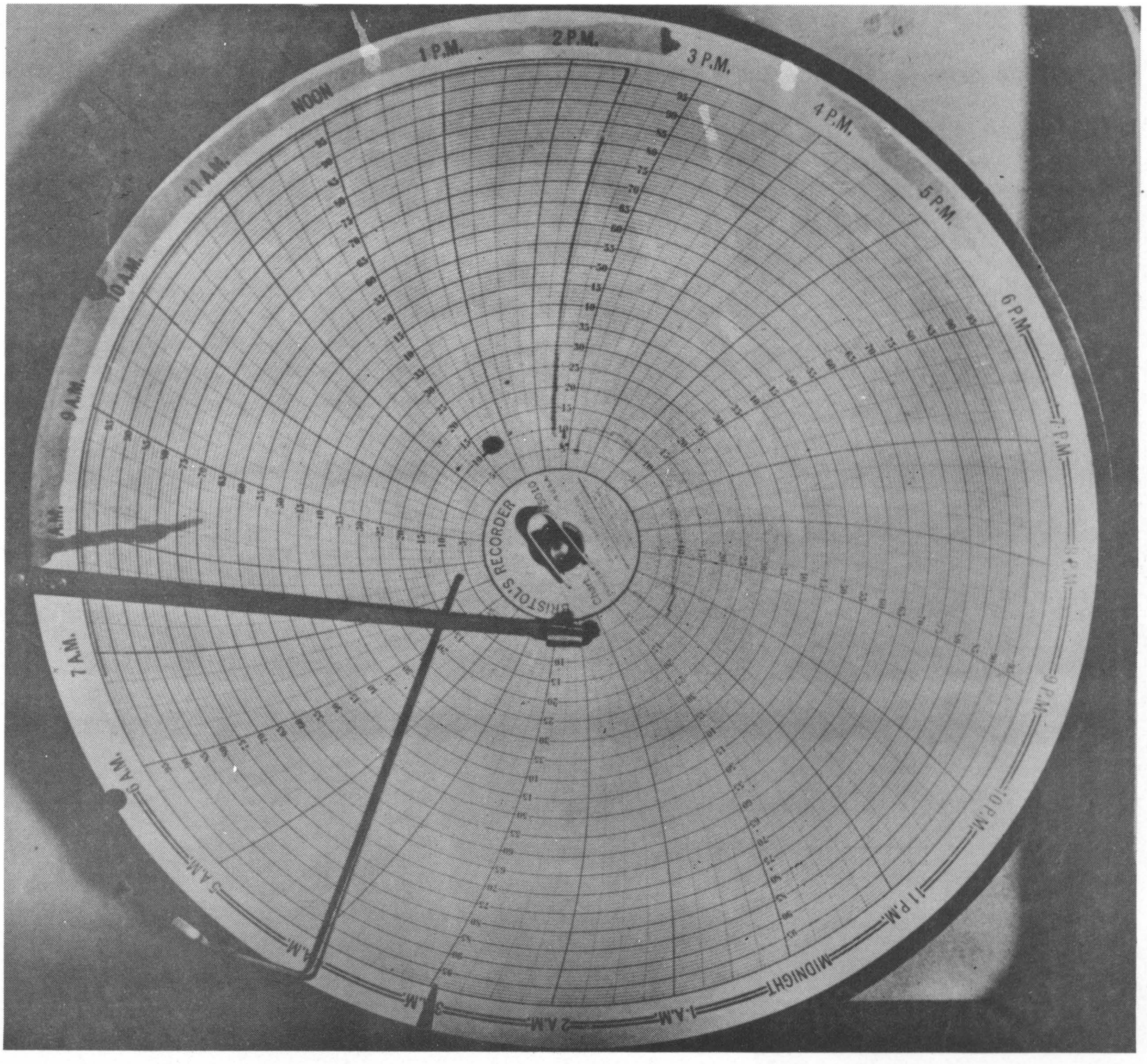


Figure 21.—Photostat of chart showing liquid level in tank 4 on October 20, 1944.

In addition to the dams and skirts around the tanks, the company took a gas-storage holder out of service and grouted the crown section into the old holder pit. (Fig. 4.) At the top of the crown, a stack approximately 40 feet high was erected. This tank was designated as an overflow storage tank and was approximately 150 feet in diameter and 35 feet deep. The bottom was dome-shape, with the top of the dome about 15 feet below the top of the pit. The details of this installation are shown in figure 15.

The overflow storage tank was connected to the dams under the liquefied gas-storage tanks by rectangular ducts. The dams from No. 1 and No. 2 tanks were connected, and a duct approximately 2 by 4 feet was provided to empty any liquefied gas leakage from these tanks into the overflow storage tank. (Fig. 14.) Each of the other two tanks was connected directly to the overflow storage tank by a 2 by 4 foot duct. (Fig. 13 and 14.)

According to representatives of the gas company, this system for controlling leaking liquid was intended to take care of small leaks of liquefied gas such as might develop if a line broke.

When Jackson learned of the company's plan, he expressed the opinion that the construction of protecting wings around the various tanks would confine the air in the space beneath the tanks and would interfere with ventilation of the space beneath the tanks. In his opinion, ventilation of the underside of the tanks was advisable, because the tanks had been designed on the assumption that the outer walls of the insulation jacket would be maintained at ambient temperature. The skirts of the spherical tank and the annular cover or apron wall of the cylindrical tank interfered with natural ventilation and therefore with the transfer of heat from the atmosphere to the tank.

CONDITIONS AT TIME OF FIRE

According to information furnished by C. P. Binder, plant superintendent, and testimony at public hearings, all liquid-storage tanks were full at the time of the fire. The practice was to fill all tanks nearly to capacity, then to complete the filling later. The final filling was referred to as "topping off". Tanks 2, 3, and 4 had been filled prior to October 20, and the topping off of No. 4 tank had been completed at 6:30 p.m. on October 19. On the day of the fire, No. 1 tank was being "topped off", and No. 4 tank was off the line. It was stated that the topping off of No. 1 had been completed, and the liquefaction plant was being shut down at the time of the fire.

Certain details on the operation of the liquefaction plant just prior to the disaster and when the fire started may be obtained from undestroyed charts on recording gages in the compressor house and at other locations and from the portion of the daily log not damaged by fire. Photostats of these records are shown in figures 16, 17, 18, 19, 20, and 21.

From the operating log (fig. 16) and from published information(6), design conditions and actual operating conditions of the raw-gas compresser, recycle compressor No. 1, and recycle compressor No. 2 can be compared. Such a comparison is shown in table 1.

The daily operating log also furnished data on the pressures on each of the four storage tanks on the day of the fire. These data are summarized in table 2.

TABLE 1. - Comparison of design conditions of compressors with actual operating data for October 20, 1944

		Design condition		Average operating condition, from operating log for period 12m-10a.m.
	Cooper-Bessemer 600-hp. raw-gas compressor 1/ Capacity 4 million cu. ft./day			
1st stage	Suction pressure	45 p.s.i. abs.	30.8 p.s.i. gage.	30-32 p.s.i. gage.
Do.	Discharge	168	153.8	128-130
2d stage	Suction	165	150.8	
Do.	Discharge	615	600.8	585
Speed	R.p.m.	326		305-315
	Cooper-Bessemer 800-hp. recycle compressor No. 1 1/			
1st stage	Suction	54 p.s.i. abs.	39.8 p.s.i. gage.	35 p.s.i. gage.
Do.	Discharge	183	168.8	164-165
2d stage	Suction	180	165.8	
Do.	Discharge	615	600.8	575-585
Speed	R.p.m.	300		260-270
	Cooper-Bessemer 150-hp. flash gas and vent gas compressor (recycle compressor No. 2) 1/			
1st stage	Suction	16 p.s.i. abs.	1.8 p.s.i. gage.	1.5 p.s.i. gage, 8 a.m.
	Discharge	54	39.8	35
	R.p.m.	300		185-195

1/ Provided with automatic speed control.

TABLE 2. - Pressures[1] on storage tanks from operating log for October 20, 1944

Tank	Time of day		
	12 m.	4 a.m.	8 a.m.
1 (spherical)............	2.5	2.5	2.5
2 (spherical)............	2.4	2.4	2.5
3 (spherical)............	2.4	2.4	2.4
4 (cylindrical)............	2.6	2.6	2.6

1/ All pressures are p.s.i. gage.

The charts and tables 1 and 2 indicate that the plant was operating normally until approximately 2:15 to 2:20 p.m., when the operators started to shut down the plant. J. Roy Feightner, assistant engineer at the LS&R plant, stated in a public hearing that the shut-down was proceeding normally prior to the fire. According to him and also to Binder and Herold (one of the operators of the 12 to 8 shift on October 20, 1944), the fluctuating suction pressure of the ammonia compressor (fig. 19) and the peak noticeable in the raw gas-discharge pressure from the compressor (fig. 17) are typical of the shut-down operation.

Further evidence that the plant was being shut down when the fire occurred was presented by H. Schroder, who is in charge of all records in the main office of the company. He presented flowmeter charts for October 20, 1944, showing the flow of fuel gas to the compressor engines and the flow of gas being liquefied. Both charts showed a sharp drop at 2:25 p.m., indicating a shut-down. The fuel-gas chart indicated that the compressor engines were idling at the time of the fire.

From testimony at public hearings and from discussions with employees of the LS&R plant, information was obtained on the general procedure for shutting down the plant. The first step was to start pumping the ammonia into storage. This was done by shutting off the discharge valve from the ammonia receiver. The entire system would then begin to warm. Shortly after starting to pump ammonia into storage, the valve between the storage tank for ethylene and the suction of the ethylene compressors was closed, and ethylene gas bled from the discharge of the compressors into the storage tanks. As the system warmed, it became necessary to unload the raw-gas compressor to keep the pressure in the high-pressure natural-gas line to the liquefaction plant at 600 p.s.i. gage or less. Eventually, the raw-gas compressor was shut down. At some convenient time during the shut-down operation, the vent gas from the storage tanks was diverted into the low-pressure distribution system, and the No. 2 recycle compressor shut down. When the ammonia was pumped to storage, the ammonia compressors were shut down; and, similarly, when all ethylene had been pumped into storage, the ethylene compressors were shut down. When the system had warmed to the desired temperature, No. 1 recycle compressor was shut off, and the shut down was then completed.

According to Feightner, preparation for shut-down started at about 2 p.m., and shortly thereafter pumping of ammonia into storage commenced. The shut-down operation was proceeding normally, and at the time of the disaster Feightner was discussing it with Conrad Daiber, chief engineer, and Dale

Keller, oiler at the LS&R plant, while standing near the north-center door of the compressor building. (Fig. 1.) This time was fixed at about 2:40 p.m., the time at which the electric clock on the control board in the compressor house stopped. This time was also corroborated by eyewitnesses and by the charts from recording pressure gages (figs. 4, 5, and 6), which indicated an abnormal condition occurring at 2:40 to 2:45 p.m. The time at which the liquid level dropped suddenly in No. 4 tank was 2:25 p.m., according to the recording gage (fig. 21). It is believed that this gage was either slow, or the chart was not timed properly when it was put on. Such a conclusion seems justified, because it is inconceivable that the outer shell could have withstood the effect of the cold liquid and retained it for 15 minutes.

Feightner stated that at the time of the disaster approximately 95 percent of the ammonia in the system had been pumped into storage, and that approximately 50 percent of the ethylene had been pumped into storage. This latter operation had been started 15 or 20 minutes before the disaster. According to Feightner, No. 2 recycle compressor (No. 3 engine) had been shut down 10 to 15 minutes before the disaster. He was not sure whether the valve admitting vent gas to the low-pressure distribution system had been opened. However, he stated that the time at which this valve was opened was not critical, as the pressure in the storage tanks built up only very slowly, even when no vent gas left the tanks.

According to Feightner, No. 1 recycle gas compressor (No. 2 engine), one ethylene compressor (No. 5 engine), and the ammonia compressor (No. 6 engine) were operating at the time of the fire. He was not certain that the raw-gas compressor (No. 1 engine) was shut down, but he did state that it was either shut down or completely unloaded and idling. In either case, pumping of raw gas to the liquefaction plant had ceased.

Inspection of the charts reproduced in figures 17, 18, and 19 shows a rapid increase in the pressure in the suction line to No. 2 recycle compressor (No. 3 engine) at 2:45 p.m., the ethylene compressors (Nos. 4 and 5 engines), and the ammonia compressor (No. 6 engine). According to Feightner, this rapid increase in pressure was caused by a sudden shut-down of the compressors. In all three instances, refrigerated liquids were being vaporized in three separate systems, each connected to the respective suction lines of these compressors. A sudden shut-down of a compressor would therefore cause pressure in the suction line to increase. Feightner stated that, even during normal plant operation, if a compressor shut down because of some difficulty, the pressure in the suction line would increase and relief valves would function.

At approximately 1:50 p.m., Feightner had looked beneath No. 4 tank inside the outer footing but had observed nothing unusual. This casual inspection was made incidental to obtaining a piece of flexible steam hose from the heater used for heating the air circulated beneath No. 4 tank. Furthermore, according to company officials, nothing unusual had been observed in recent inspections of the tanks. Binder stated that it was customary to inspect the storage tanks periodically for evidence of leaks

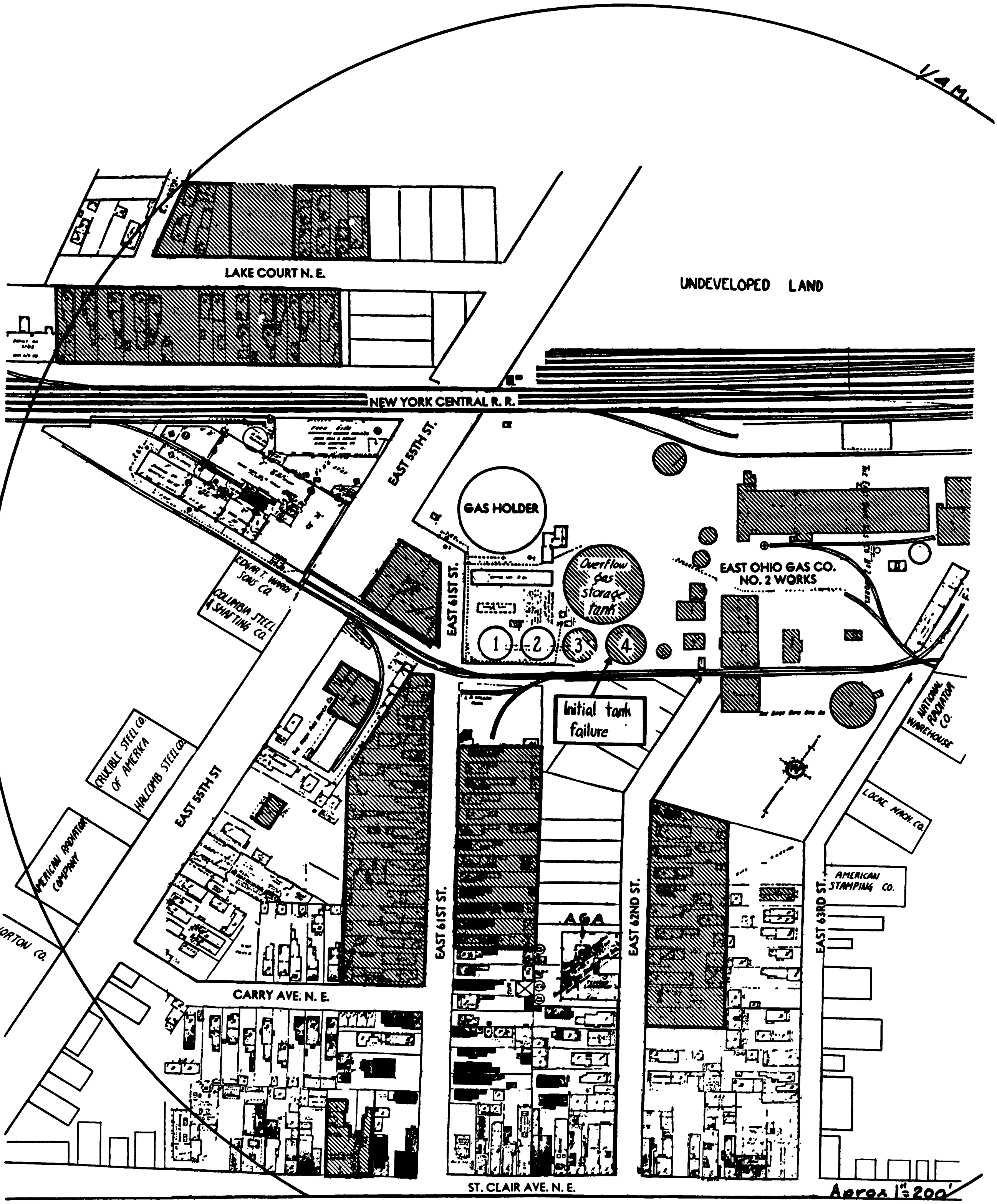


Figure 22.—Damage by fire in LS & R plant, East Ohio Gas Co., and surrounding area. Cross-hatched sections show areas of partial or total destruction.

and to determine the condition of the various safety relief valves. He stated that the weight-loaded relief valves were inspected at least once a shift and had been inspected on the morning of the disaster. The bottom of the cylindrical tank had been inspected less than 3 days before the fire, and nothing unusual had been noted.

Feightner stated, also, that all of the liquid-level indicators on the tanks were operating properly. The level in No. 1 spherical tank 1 was 13 feet below the top just prior to shutting down the plant. The level in No. 4 tank was 1 foot below the top of the vent pipe. According to information furnished by J. O. Jackson, of the Pittsburgh-Des Moines Steel Co., the capacity line for the spherical tank was about 18 feet below the top, and the capacity line for No. 4 tank was 1½ feet below the top of the overflow. The difference in elevation between the rated capacity lines in the spheres and in No. 4 tank was 0.07 foot, the capacity line in the spheres being at the higher elevation. At the time of the fire, the liquid level in No. 1 tank was about 5 feet above the rated capacity line and about 4½ feet above the liquid level in No. 4 tank. The latter level was half a foot above the rated capacity line.

The United States Weather Bureau in Cleveland furnished the following information bout the weather on October 20, 1944: Clear, with high clouds. There was no electrical display throughout the day. The following detailed data were obtained:

Time (E.S.T.)	Wind		Overcast, ft.	Dry bulb temp., °F	Dew point, °F
	Velocity	Direction			
1:30 p.m.	12 m.p.h.	NNE	8,000	51	37
2:30 p.m.	10 m.p.h.	NE	6,500	51	38
3:30 p.m.	14 m.p.h.	NNE	6,000	51	39

The visibility was 3 to 4 miles as a result, primarily, of smoke. The barometer was 29.98 inches of mercury reduced to sea level (29.13 inches of mercury at the airport). The elevation of the airport is 805 feet, and the average elevation of the lake is 570 feet.

DESCRIPTION OF DISASTER

At approximately 2:40 p.m. on October 20, 1944, No. 4 cylindrical (toro-segmental) liquefied gas-storage tank at the LS&R plant of the East Ohio Gas Co. failed. The first stages of disintegration of the tank were witnessed by at least four employees of the American Gas Association Laboratory, which is about 600 feet south of No. 4 tank (fig. 22). These individuals testified, at a public hearing on October 27, 1944, that they saw vapor or liquid issuing from the tank prior to its complete collapse. In addition, Feightner stated that he and Daiber and Keller saw a cloud of white vapor, 10 or 12 feet above the ground, coming across the top of the overflow gas-storage tank from the direction of No. 4 tank (fig. 1).

Several of the employees of the American Gas Association stated that streams of liquid or vapor issued from No. 4 tank at a point approximately one-half or one-third of the distance from the ground to the top of the tank. These streams seemed to come from one or both sides of the middle of the south-southeast face of the tank. One observer at the AGA laboratory stated that his attention was drawn to the LS&R plant by a slight earth tremor and by hearing a low rumble. He then looked in the direction of the plant and saw white vapor issuing from the No. 4 tank, and it seemed to him that the tank was bursting, but he was not positive; nor was he certain he saw flame. Three other employees of the American Gas Association did not state how they happened to be looking in the direction of the LS&R plant at the time of the disaster, but all of these employees stated that they saw clouds of vapor first and fire subsequently. One of the AGA employees stated that he saw a dull red glow and felt a slight concussion a few instants after he saw the first large streams of vapor issuing from the tank. No direct evidence of the events immediately following the initial failure of No. 4 tank is available, as almost everyone close to the LS&R plant was killed. Those who did manage to escape were able to give only meager details as to the early stages of the disaster.

The two survivors who had been closest to No. 4 tank when it failed were Feightner and Dale Keller of the LS&R plant. Feightner testified at the public hearing, but Keller was so badly injured that he was unable to testify at any of the public hearings held up to December 8, 1944. Feightner was standing near the center door on the north side of the compressor building talking to Keller and Daiber. They heard a rumble like distant thunder and stepped out of the door and looked east toward No. 4 tank, from which direction the noise apparently had come. They had seen the vapor rolling across the overflow storage tank and immediately suspected a large leak of liquid in the vicinity. Feightner said that shortly thereafter they realized the white vapor was aflame. He ran in a westerly direction and finally submerged himself in the water of the gas-holder pit of No. 9 holder (see fig. 1). Dale Keller, the oiler, also escaped by submerging himself in the water of the holder pit, although he had left the building after Feightner and was severely burned.

From statements of employees of the AGA laboratory, of employees of the LS&R plant, from personal observations, newspaper accounts, and statements of officials of the East Ohio Gas Co., and of the engineer who designed No. 4 tank, it seems certain that the disaster resulted from the failure of No. 4 storage tank from causes not apparent to eye-witnesses of the disaster. When No. 4 tank failed, 1,100,000 gallons of liquefied natural gas at a temperature of $-250^{\circ}F$ was released. The liquid started to evaporate immediately, giving off quantities of natural gas along with clouds of white vapor consisting of particles of unvaporized liquid and possible particles of ice that were frozen from water vapor in the surrounding air. The liquid from No. 4 tank spread over a considerable area, but apparently most of it must have gone to the east and southeast, and that portion going to the east engulfed the laboratory, office, and meter shops. No. 4 tank was considerably higher than the area in the vicinity of the American Gas Association laboratories. Accordingly, the liquid from No. 4 tank ran down toward East 62d

Street (fig. 22), where some of it entered the storm sewers. The gas from this liquid mixed with the air in storm-sewer system and formed an explosive mixture, which subsequently ignited. The effects of the resultant explosions were apparent several blocks from the LS&R plant. Clouds of white vapor were observed billowing up East 62d Street shortly after the tank failed. Before all of the employees of the AGA laboratories (600 feet from the tank) had left the building, the gas from the evaporating liquid ignited.

There were innumerable sources of ignition within 200 feet of No. 4 tank. These included open flames in the laboratory and meter repair shops and ordinary electric wiring, lights, and switches. It is not necessary or important to seek the actual source of ignition.

The dwellings on East 62d Street across from the AGA laboratory (fig. 22) were ignited by the burning gas, or possibly the gas was ignited in one of these buildings. The north-northeast wind drifted the burning gas over the buildings on East 61st Street, and they caught fire. Reports indicate that gas leaked into the basements of some of the buildings on East 61st and East 62d Streets and formed an explosive mixture, which ignited and razed the walls of the buildings.

Approximately 20 minutes after the failure of No. 4 tank, it appears that No. 3 spherical storage tank failed and discharged its contents of liquefied gas, amounting to approximately half the quantity stored in No. 4 tank. In all probability, No. 3 tank failed as a result of the failure of overheated columns that supported the sphere, although some of these columns may have been weakened by the impact of sections of No. 4 tank that were being carried along by the surge of liquid. The time at which No. 3 tank failed is fixed by the appearance of a large quantity of flame and by a muffled sound that indicated the ignition of a large volume of gas.

Observations at the scene of the disaster indicated that the contents of No. 3 tank probably were discharged also in an easterly direction. Accumulations of mineral wool, which had been used to insulate No. 4 tank, were spread over a considerable area as the result of the failure of No. 4 tank. When No. 3 tank failed, the mineral wool left by the liquid of No. 4 tank probably again floated on the liquid and was distributed further throughout the plant area. Mineral wool was piled to a depth of about 14 inches against the footings of the columns outside of the compressor building.

The flames from the burning gas extended a considerable distance above the ground, and the radiant heat from these flames was intense. Many persons who fled the vicinity of the plant were burned or blistered on the back of the head and neck, and the backs of coats and wraps of some were ignited. It seems probable that the buildings on Lake Court NE (fig. 22) and the New York Central Railroad bridge were ignited by radiant heat from the flames, as there was no evidence that any quantity of burning liquid came into this area. According to newspaper reports, an engineer who was on St. Clair Avenue, approximately 1,000 feet from the fire, estimated that the flames were at least 2,800 feet high.

On Saturday, October 21, the main body of the fire was under control, but vent gas from No. 1 and No. 2 storage spheres, which had withstood the heat of the fire, was burning at a break in the vent-gas line. This break resulted from a separation at a Dresser coupling on the line to the vent-gas heater. Gas escaping from the hole and from the crack in the vent-gas line (shown in fig. 47) was burning. There was also a fire in a line (probably a vent-gas line) near the collapsed No. 3 storage tank. In addition, the coal pile south of No. 2 storage tank was still burning.

On Sunday morning, October 22, employees of the gas company and J. O. Jackson, the tank designer, who had been notified by the gas company of the fire, arrived at the scene and began to put the plant into reasonably safe condition. Jackson observed that smoke was issuing around the vent at the top of No. 2 spherical tank. He climbed to the top of this sphere and found that the smoke was coming from burning cork insulation. Jackson and McCartney, an employee of the Gas Co., closed the foot valves of Nos. 1 and 2 storage tanks and arranged with the fire department to get as much liquid carbon dioxide as could be obtained for smothering the fire in the cork insulation. Later, solid carbon dioxide was put into the space between the two shells of No. 2 tank, and eventually fire in the insulation was brought under control.

Rehabilitation work was begun on Sunday, and gas-company employees purged some of the equipment and repiped gas from the vents of the spheres to a point about 350 feet from No. 2 tank. Emergency steam lines were run into the plant from locomotives on the tracks of the New York Central Railroad. This steam was used to vaporize the liquefied gas stored in Nos. 1 and 2 storage tanks. When these tanks were empty, several weeks later, they were purged with inert gas.

OBSERVATIONS AT SCENE OF FIRE

Damage to Plant and Adjacent Areas

The fire that started in the vicinity of the plant of the East Ohio Gas Co. spread rapidly to adjacent buildings in the plant and to many frame structures within a quarter-mile radius of No. 4 tank (cylindrical tank). The extent of the damage by fire may be seen from figure 22. A general idea of the damage to the plant may be obtained from figures 23 to 29, inclusive.

Figures 23 and 24 are aerial photographs taken on the afternoon of October 21. The photograph shown in figure 23 was taken looking toward the north, and the one shown in figure 24 was taken looking toward the west. Figure 23 is a general view of most of the area affected. Burned dwellings are shown in the foreground, and the damaged LS&R plant is shown in the background. Figure 24 is a close-up of the damaged LS&R plant and the office, meter-repair shop, fitting department, and laboratory at the No. 2 works adjoining the LS&R plant. Figure 24 shows Nos. 1 and 2 spherical tanks still standing, No. 3 spherical tank collapsed in place (center), and

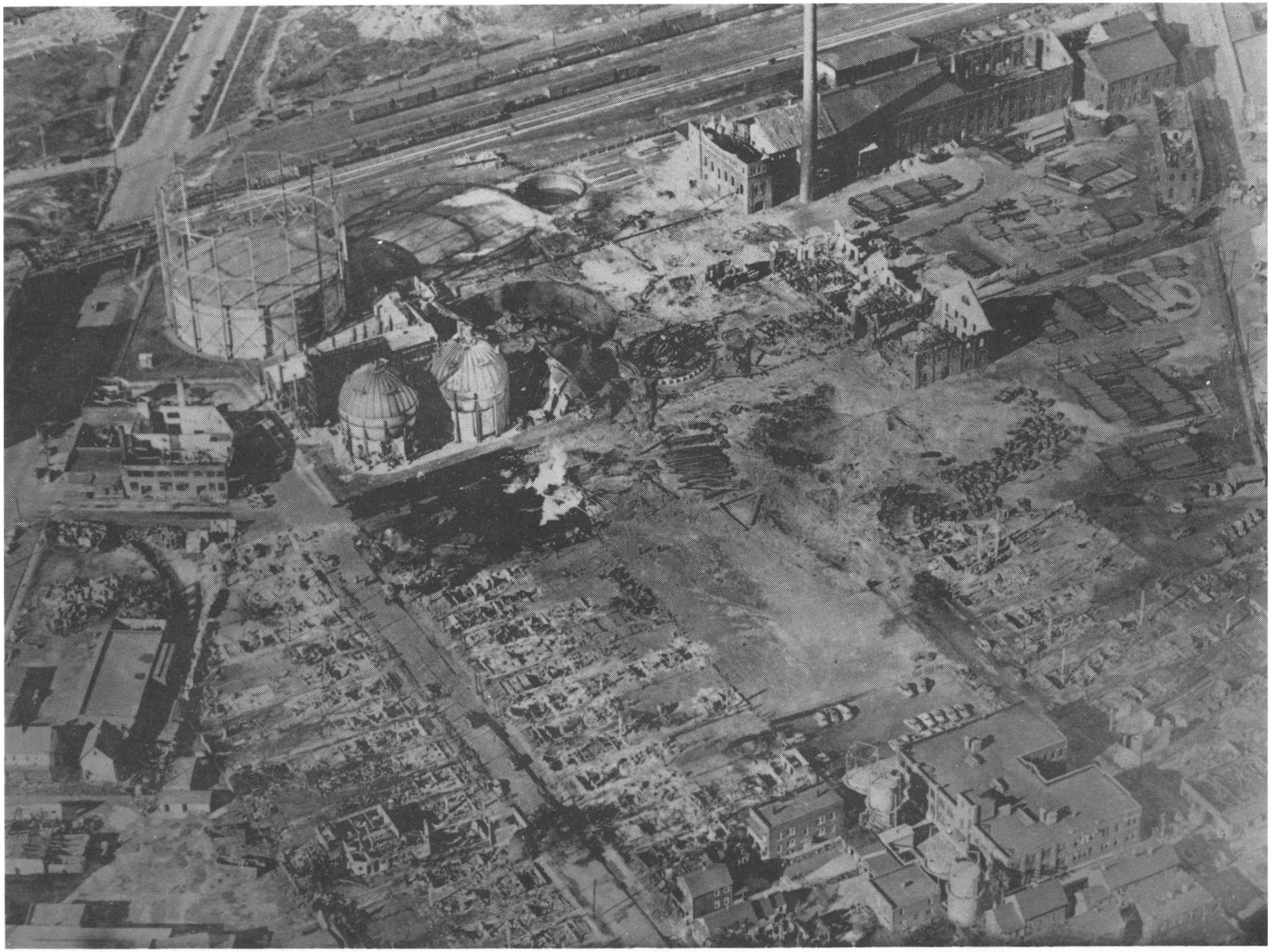


Figure 23.—Aerial view of LS & R plant and No. 2 works, East Ohio Gas Co., and adjoining property damaged by fire October 20, 1944, looking north.

Figure 24.—Aerial view of damaged LS & R plant, East Ohio Gas Co., and a portion of No. 2 works and adjoining property damaged by fire on October 20, 1944, looking southwest.

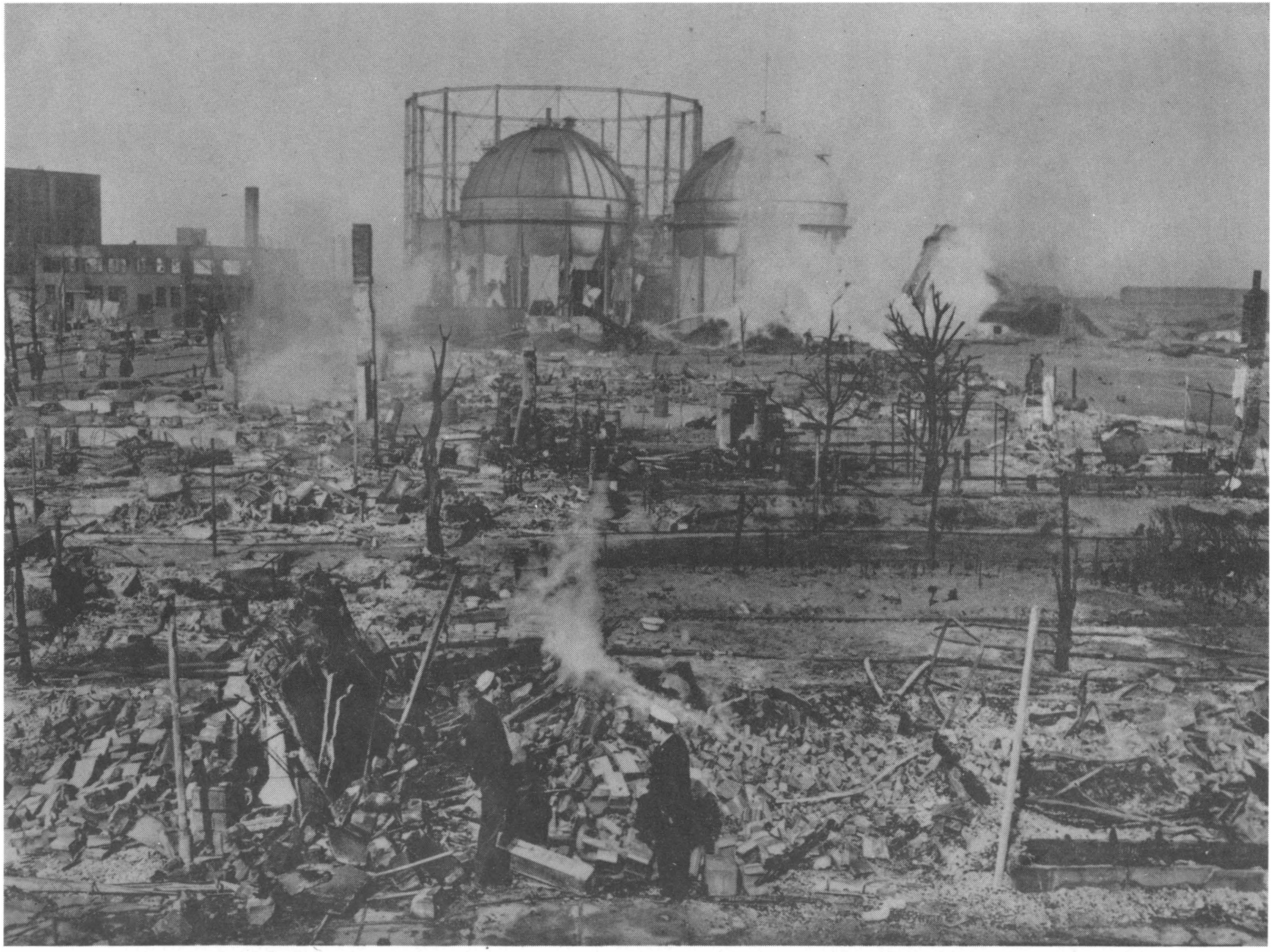


Figure 25.—Damage in the vicinity of the LS & R plant, East Ohio Gas Co., looking toward the northwest and showing remains of dwellings on the east side of East 61st Street.

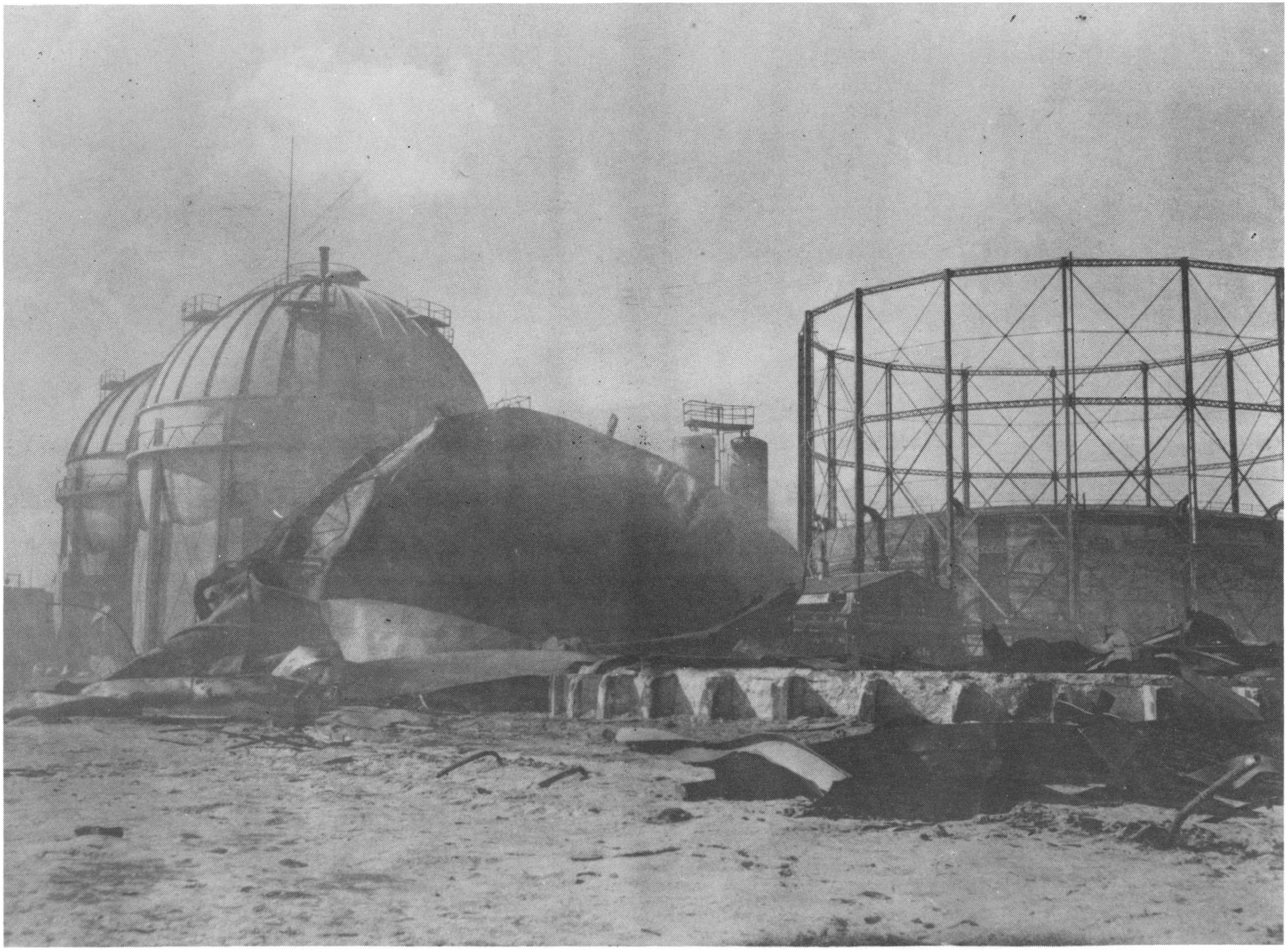


Figure 26.—Damage to LS & R plant, East Ohio Gas Co., looking west, showing foundation of tank 4 in the foreground and collapsed spherical tank 3.

Figure 27.—Damage to No. 2 works, East Ohio Gas Co., adjacent to LS & R plant (boiler house in background and remains of meter-repair shop and offices in foreground).

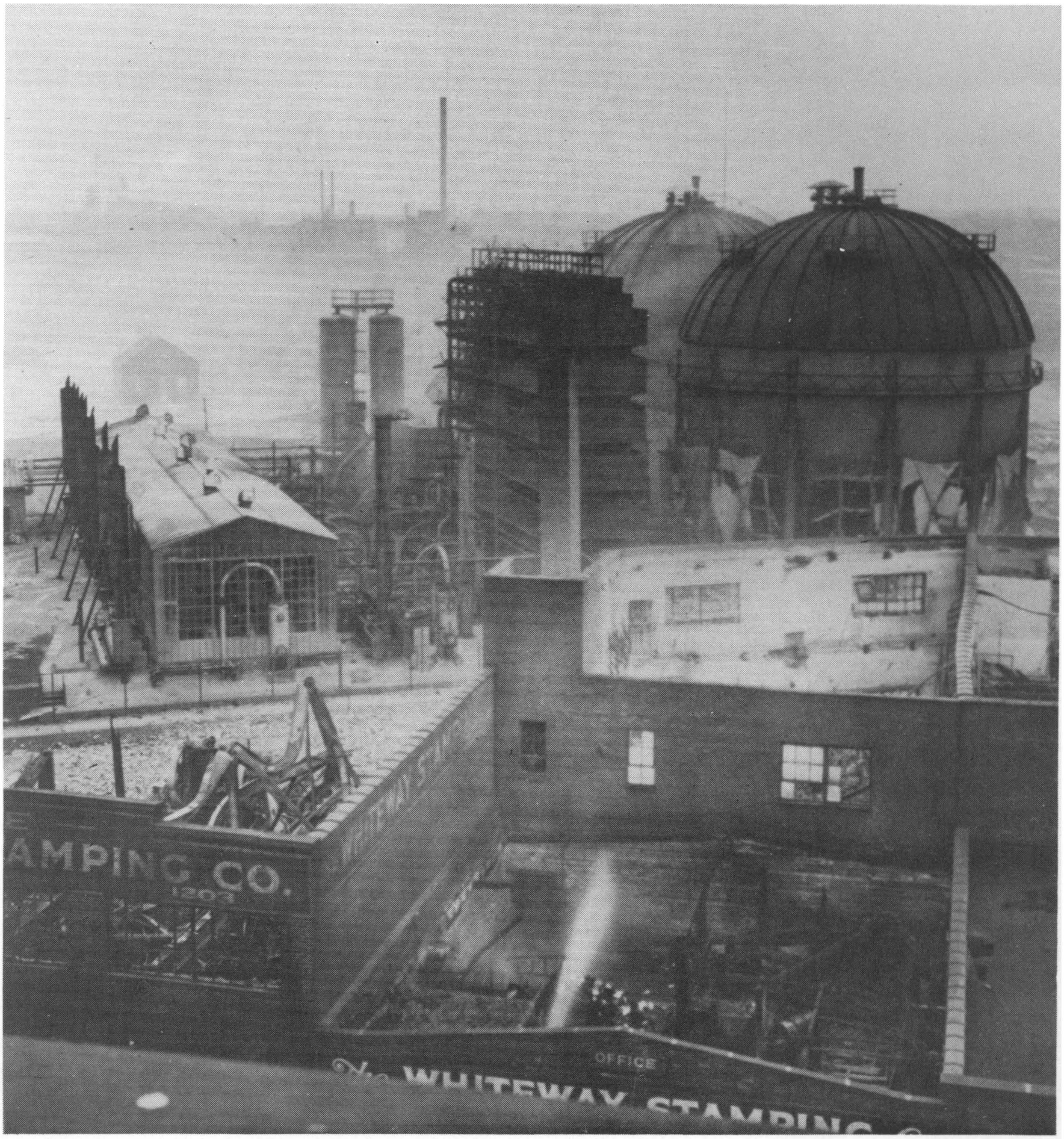


Figure 28.—General view of damage to LS & R plant, East Ohio Gas Co., looking east, showing spherical tanks 1 and 2 standing at the right and cooling tower with burned grids in the center and compressor building with broken window panes at left. Damaged building of the Whiteway Stamping Co., in foreground.

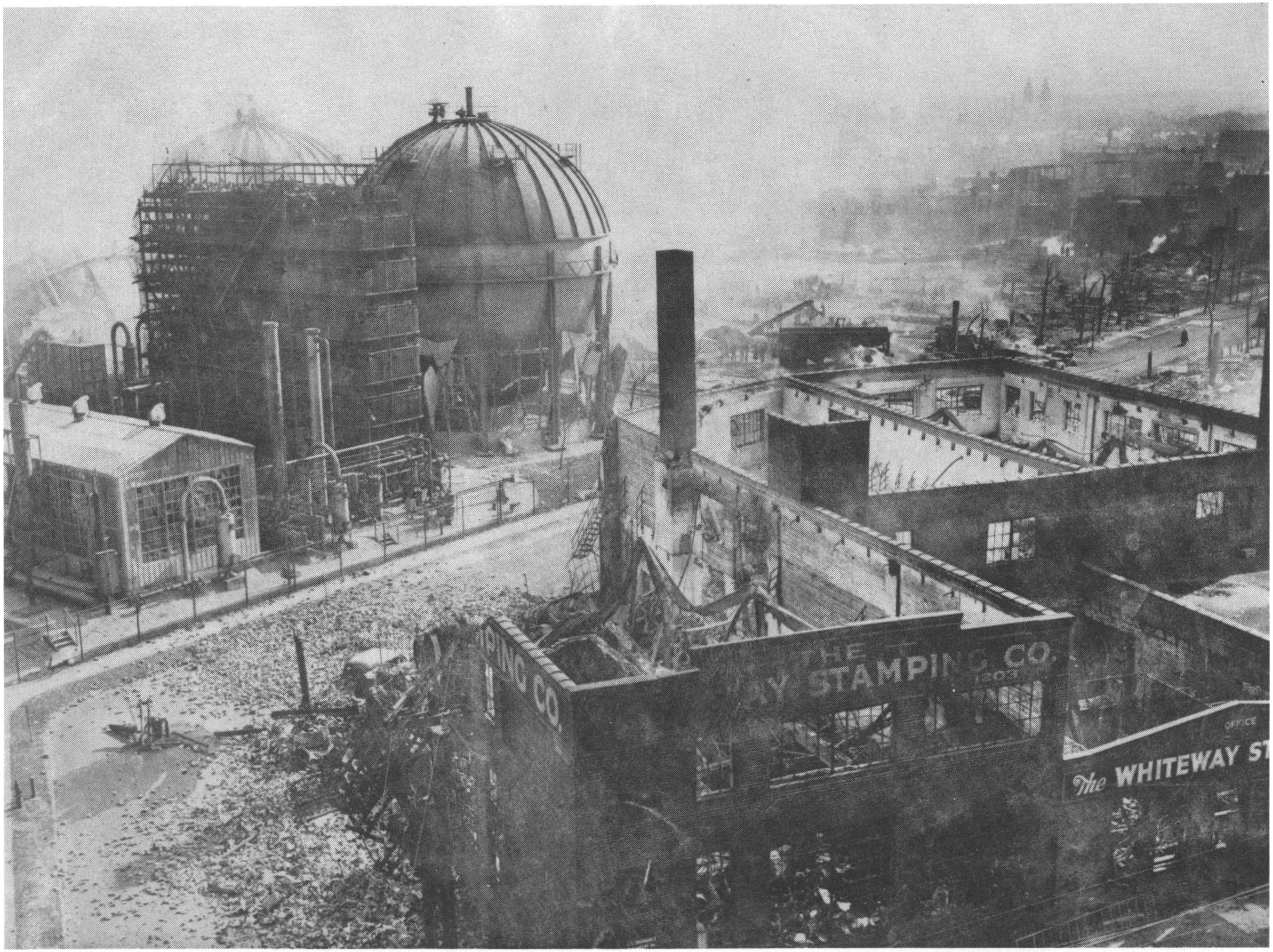


Figure 29.—View of damage in the vicinity of the LS & R plant, East Ohio Gas Co., looking east, and showing damage to the Whiteway Stamping Co. in the foreground, remains of dwellings on the east side of East 61st Street (right background), and spherical tanks 1 and 2, cooling tower, and compressor building of the LS & R plant (left background).

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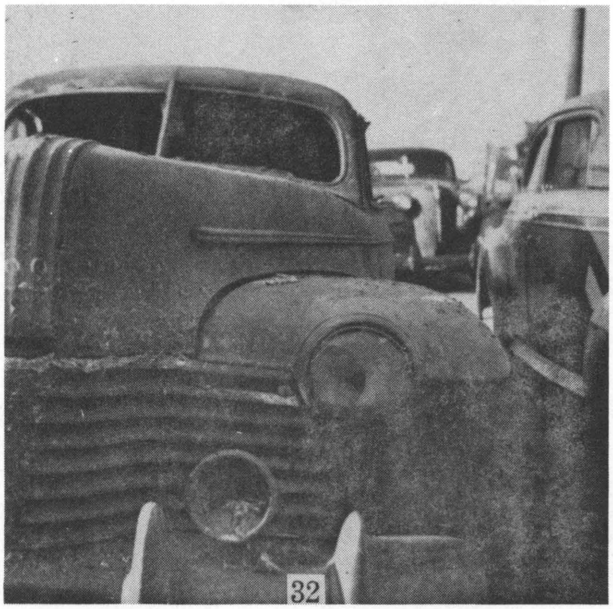

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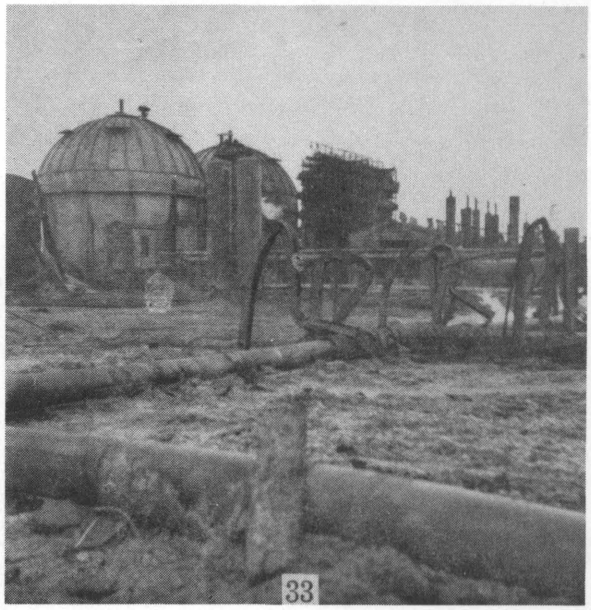

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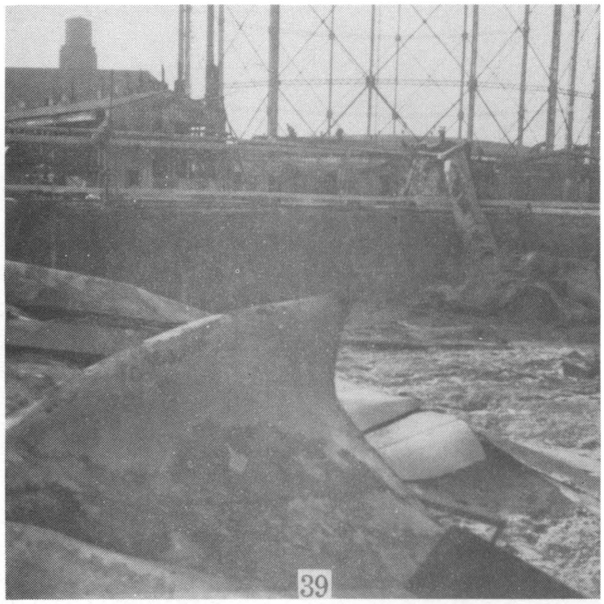
Figure 30.—Damage to east side of gas holder caused by heat from the fire.

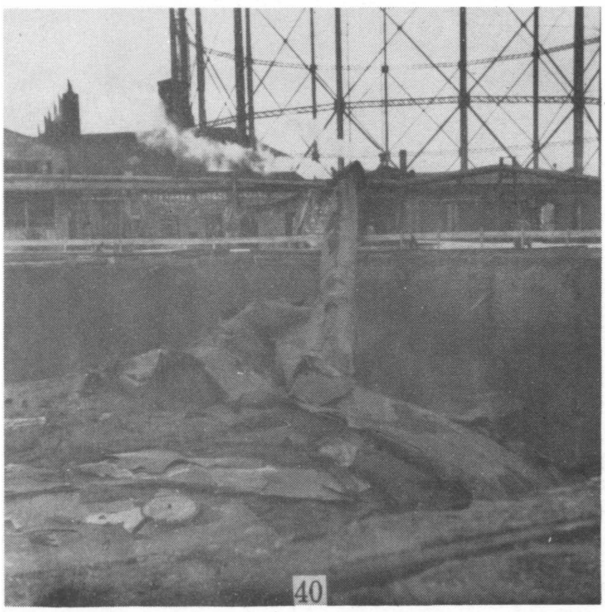
Figure 31.—Effect of radiant heat from the flames at a point approximately 1/4 mile away from tank 4

Figure 32.—Damage to an automobile parked on the west side of East 62d Street near the American Gas Association laboratory.

Figure 33.—Failure of steel-column supports for the steam line in the East Ohio Gas Co. plant.

Figure 34.—Sewer at East 62d and St. Clair Streets in the process of being repaired.
Figure 35.—Sewer at East 62d and St. Clair Streets.
Figure 36.—East 62d Street, looking north.
Figure 37.—East 62d Street, looking south.





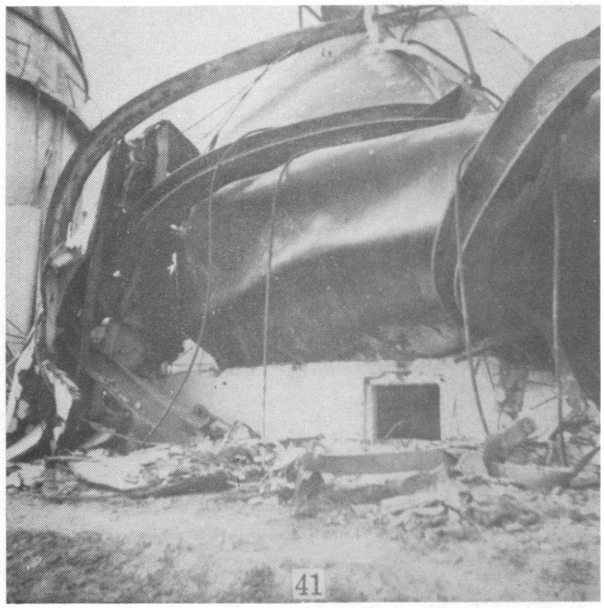


Figure 38.—Ducts leading to the dams of the three spherical tanks.
Figure 39.—Damage to top of overflow gas-storage tank.
Figure 40.—Damage to top of overflow gas-storage tank.
Figure 41.—Columns of spherical tank 3 bent by heat from the fire.

Figure 42.—Portions of the circular girder to which the interior columns were attached.

Figure 43.—Interior columns of tank 4, showing typical embrittlement fractures and deposit of rock-wool insulation.

Figure 44.—Plates in outer ring-shaped footing of tank 4 showing typical embrittlement fractures.

Figure 45.—Plates in outer ring-shaped footing of tank 4 showing typical embrittlement fractures.

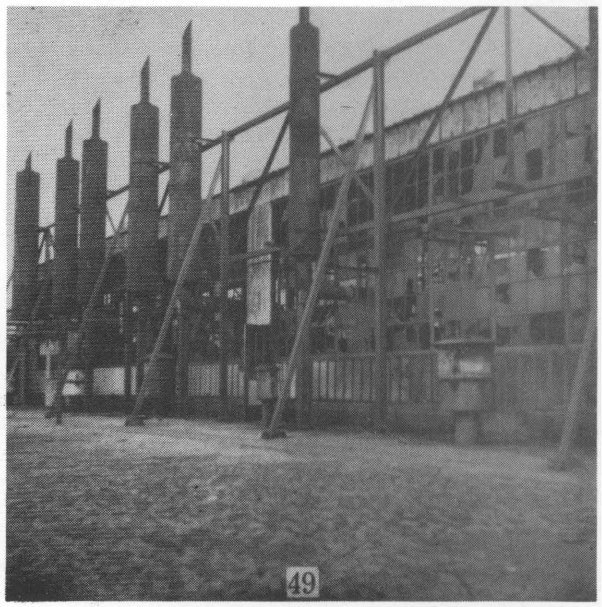


Figure 46.—Failure at a weld.
Figure 47.—Failure in the vent-gas pipe line.
Figure 48.—Typical embrittlement fractures shown by fragments of tank 4.
Figure 49.—Damage to the compressor building.

the remains of structural members of No. 4 cylindrical tank. The damaged overflow gas-storage tank (old holder pit) may be seen to the right of Nos. 3 and No. 4 storage tanks. The stack and part of the cover of the overflow gas-storage tank may be seen in the upper right (northwest) quadrant of the pit. The compressor building may be seen directly west of the holder pit. The cooling tower is south of the compressor building (to the right in fig. 24). The two cylindrical storage tanks for ethylene may be seen adjacent to the upper left (southwest) quadrant of the holder pit.

Figures 23 and 24 show the distribution of the mineral-wool insulation from No. 4 tank. This is indicated by the light areas on the ground. Mineral wool extended beyond the automobiles shown at the lower left in figure 24. The relative positions of these automobiles is of interest because the photograph shows that they have been displaced from their original positions. This furnishes an indication of the magnitude of the force in the surge of liquid that was released when No. 4 and No. 3 tanks failed.

Figure 25 shows the two remaining spherical tanks, and at the upper right is shown what remained of No. 3 spherical tank. No. 4 tank was just to the right of No. 3 in figure 25, but the figure shows only some of the flattened plates at the site of No. 4 tank. The foreground of this figure shows the area where dwellings once stood on the east side of 61st Street (fig. 22).

The remains of the outer footing for No. 4 tank and portions of the steel from No. 4 tank are shown in figure 26. This photograph also shows clearly how the columns supporting No. 3 tank were bent by the heat of the fire.

Most of the buildings that were within the plant area and less than 300 feet from No. 4 tank were completely destroyed. Some of the walls of these buildings were left standing, as shown in figure 27. These buildings included the superintendent's office, conference hall, laboratory, office and meter-repair building, meter room and fitting shop, and warehouse storage building. (Also see fig. 1.)

Damage to the liquefaction plant was caused principally by fire. The compressor building was damaged, but the compressors can be salvaged. Insulation on piping and equipment was burned, and the wood grids on the cooling tower were burned. This may be seen in figure 28, which shows the compressor building, the cooling tower, and, between these, the two storage containers for ethylene. Another view of broken window panes and burned paint on the compressor building is shown in figure 49.

The top of the overflow gas-storage tank (crown of top lift of old holder) was collapsed, and, as nearly as could be observed, most of the pieces remained in the old holder pit. This may be seen from figures 38, 39, and 40. Figure 38 also shows, at the right center, the ducts leading to the dams of the three spherical tanks.

Types of Failure Observed

Extensive examination of the wreckage disclosed only isolated instances of metal fragments that might have come from a pressure break in a container or pipe. The few such failures that were observed undoubtedly resulted from the bursting of cylinders containing either ammonia or ethylene. In a few instances, markings on fragments could be identified definitely as markings found on cylinders. None of the metal fragments were found at distances greater than approximately 300 feet from No. 4 tank.

A detailed examination of the fragments from No. 4 tank disclosed that the fractures were characteristic of failure due to low-temperature embrittlement. This may be seen by examination of figures 42, 43, 44, 45, and 48, all of which show metal pieces from No. 4 tank. The plates show typical embrittlement fractures. Figures 44 and 45 show the plates remaining within the outer ring-shaped footing. Figure 43 shows the interior columns of the tank (see fig. 8). This photograph also shows rock-wool insulation deposited on these columns. Figure 42 shows portions of the circular girder to which the interior columns were attached. When this photograph was taken, it was not possible to determine whether the girders were the top or bottom girders, as the drawings of the tank were not available to Bureau's investigators at that time.

In addition to embrittlement failures, there was ample evidence of failures that had occurred at a weld, although the location of the welds in the tank or shell could not be determined at that time. Whether or not the heat of the fire contributed to these failures could not be determined. Such failure is shown by figure 46.

The bending of the columns of No. 3 spherical tank as a result of the heat from the fire in No. 4 tank is clearly shown in figure 41, which also shows a portion of the dam wall around No. 3 tank.

Two other types of failures were observed in the vent-gas pipe line. These are shown in figure 47. A failure at the bend indicated by the two cracks was apparently due to flexure, probably as the result of expansion. Failure shown in the middle of the photograph was probably caused by fire that burned through the wall of the pipe.

Distribution of Fragments

A detailed fragment map was made under the supervision of the Mayor's investigating committee. Observations made by representatives of the Bureau disclosed nothing of significance in the distribution of the fragments except that no fragments were found at a great distance from the tank. This, along with the type of failure and size of fragments observed, indicates that the tank probably disintegrated rather than exploded.

Four large sections of the bottom ring of the tank were found between 200 and 300 feet from the tank. These fragments weighed between 1 and 2 tons. The approximate distance that these large fragments were projected furnishes information on the force exerted by the surge of liquid when the tank failed. The sudden release of hydrostatic pressure would furnish sufficient impulse to project even these large fragments to the position observed, and it is not necessary to presuppose an explosion to account for their position.

After the disaster, the outer shell (Insulation jacket) of No. 4 tank was approximately in one continuous sheet and extended from north to south. The outside of the shell was uppermost, and the top was toward the east. The damaged shell extended from the middle of the bottom of the holder pit (see fig. 1) up the side of the pit (see fig. 38) between Nos. 3 and 4 and across the railroad tracks (see figs. 1 and 24).

The position of this shell is interesting, as it fixed the location of the initial break-through of the stored liquid in the region of the east or southeast face. It may also indicate that the major portion of the liquid was released in the direction of the first break-through.

Distribution of Mineral Wool from No. 4 Tank

As mentioned, a considerable portion of the plant area was covered by mineral-wool insulation from No. 4 tank. In places, this insulation was 2 feet deep. It was found under automobiles parked on East 62d Street, 500 feet from No. 4 tank. It was deposited on the columns at the east end, north side of the compressor building to a depth of 14 inches. When placed in the tank, this insulation weighed about one million pounds. Its presence in the plant area interfered with finding all of the metal parts in the tank, because many of them were covered by it. The gas company arranged for the removal of the mineral wool to facilitate the location of fragments.

Intensity of Heat from Fire

Some idea of the intensity of the heat from the fire may be obtained from figures 30, 31, 32, and 33. Figure 30 shows the east side of the gas holder that faced the fire. The paint is blistered on the top left as well as one side of the guide girder. The other side of the holder was not exposed to the radiant heat of the fire, and the paint on it was not burned. Figure 32 shows the front of an automobile that was parked on the west side of East 62d Street near the American Gas Association laboratory, facing away from and 600 feet south of the East Ohio Gas Co. plant. The glass lenses on the fog lights and headlights were melted, as was the glass in the windshield. The interior of the car was burned, and the paint was burned. It is probable that this car was exposed to gas burning from the surface of evaporating liquid, as mineral wool was found under the car.

Figure 33 shows the failure of steel-column supports for the steam line in the East Ohio Gas Co. plant. These supports were approximately 300 feet from No. 4 tank, and yet they were heated by burning gas until they were bent by the weight of the steam line.

The effect of radiant heat from the flames at a point approximately $\frac{1}{4}$ mile away from No. 4 tank may be seen in figure 31, which shows the blistering of paint on a door on the south side of St. Clair Avenue. This door was recessed, and the top of it, which was shielded from the direct heat of the flames, was not blistered.

Evidence of Explosions

As stated previously, liquefied gas probably flowed into the storm sewers on East 62d Street and possibly at other points. Eventually, mixtures in the explosive range resulted and were ignited. The explosion in the sewer cracked the street three blocks distant from the gas plant. Figures 34 and 35 show the sewer at East 62d and St. Clair Streets in the process of being repaired. Figure 36 is a view of East 62d Street looking north, and figure 37 is a view looking south. On this street, manhole-cover supports were damaged and loosened in the streets as far distant as five blocks from the plant.

Evidence of explosions within the plant area was very meager. Apparently, a low-order explosion occurred beneath spherical tank No. 1. The skirt of this tank was blown out. (See figs. 25, 28 and 29.) This explosion was not violent, but it cracked the skirt and blew some of the pieces as far away as 20 feet. Apparently, an explosive mixture, probably near the upper or lower limit, was ignited either in the duct or in the space beneath the tank. The skirts on No. 2 tank also indicated that they had been subjected to a low-order explosion, but they were not blown from the tank. (See figs. 25, 28, and 29.) It is probable that the explosion that damaged the skirt of No. 1 tank occurred after No. 4 tank had failed, but there is no direct evidence of this.

A cylinder of ammonia exploded near the southeast corner of the compressor building. The ammonia in this cylinder was used for make-up, and the cylinder was connected to the ammonia receiver. The explosion displaced the ammonia receiver, blew down supports for lines to the ammonia condenser, and damaged the southeast corner of the compressor building. It was evident from the relative positions of the supports blown down and of fragments from No. 4 tank that the ammonia cylinder had exploded subsequent to the failure of No. 4 tank. This was also indicated by the testimony of Feightner. Undoubtedly, the cylinder containing liquid ammonia exploded after being heated by burning gas.

Extent of Damage by Fire

Figure 22 shows the extent of the damage by fire. The cross-hatched sections show areas of partial or total destruction. The circle shown on figure 15 represents a distance of $\frac{1}{4}$ mile from No. 4 tank. Extensive damage by fire was confined within the circle shown, although minor damage to buildings (blistered paint) was observed at distances slightly greater than $\frac{1}{4}$ mile from No. 4 tank.

Other Pertinent Observations and Information

Frost Spots on Storage Tanks

Testimony by Feightner and information obtained in an interview with J. O. Jackson indicated that frost spots appeared on the bottom of No. 4 tank several months before the tank failed. According to Jackson, these spots occurred as a result of the restriction of ventilation on the bottom of the tank by the dam and wing wall. In Jackson's opinion, the spots appeared when the dew point of the ambient atmosphere was such that moisture condensed on the bottom of the tank. Jackson advised the company to ventilate the space beneath No. 4 tank continuously with heated air, and, according to him, the spots disappeared when this was done. Feightner stated that ventilation was not continuous and that the spots reappeared when the ventilation was cut off. He also reported that frost spots were observed on the top of one of the spherical tanks some time ago.

According to testimony of Robert Bending, operator, and of Winfred Hendrikson, gas engine operator at the LS&R plant, frost spots had appeared on the outer shell of No. 4 tank near the top. Bending stated that those on the outside of the tank had appeared toward the top of the outer shell on the southeast side of the tank. Hendrikson stated that the frost spots near the top of the outer shell of No. 4 tank had appeared as a result of the settling of the rock-wool insulation. When more insulation was added, the frost spots disappeared. According to Hendrikson, between 2 and 2½ railroad carloads of rock wool were added in the summer of 1944 to fill the space left by settling of the insulation. Hendrikson stated that before adding rock wool, the top of the insulation was 8 feet below the top of the outer shell. It was also stated that frost spots that had appeared near the top of some of the spherical tanks were removed by adding granular cork insulation to fill the space created by settling of insulation.

RESULTS OF LABORATORY TESTS

Gas Analyses

Dr. Seibel collected a sample of the regasified liquid from No. 1 tank on October 31. This sample was obtained by displacing air from an 8-ounce bottle having a screw cap. It was recognized that the sample might be contaminated with air, but this was not considered important, as it was collected primarily to obtain information on the concentration of unsaturated hydrocarbons.

A portion of the sample of regasified liquid was analyzed in the Bone & Wheeler apparatus, and the following results were obtained:

	Percent by volume
Carbon dioxide....................	0.07
"Unsaturates" (decrease in volume after contact with fuming sulfuric acid).............	.07
Oxygen.............................	.44

The concentration of unsaturated hydrocarbons is not significant, as the value obtained is considered within the experimental error of the method used.

The sample remaining after the foregoing analysis had been made was analyzed in a Bureau of Mines Orsat, and the following results were obtained:

	Percent by volume
Carbon dioxide..........	0.0
Oxygen..........	.4
Methane..............	70.9
Ethane..........	27.2
Nitrogen..........	1.5
	100.0

According to information furnished by the gas company (see exhibit A), the raw gas contains approximately 85 percent methane and 14 percent ethane and higher hydrocarbons (determined by Podbielniak analysis). Comparison of these values with the results obtained in the Orsat analysis indicates that the liquefied gas in No. 1 tank was enriched in the higher-boiling hydrocarbons as a result of the distillation of the lower-boiling fractions, which were not recondensed and returned to the storage tank.

Analyses of Steel

A small piece of the inner shell of No. 4 tank was brought to Pittsburgh by Dr. Seibel for analysis after obtaining permission from Dr. Gerber, the County coroner. Portions of this sample were analyzed under the supervision of Dr. R. C. Buehl, Metallurgy of Steel Section. The results are given below, along with the specifications for a steel that was considered satisfactory by the Pittsburgh-Des Moines Steel Co. for use at -250°F.(9).

	Sample of inner shell (No. 4 tank) percent by weight	Specification range of constituents given by Pittsburgh-Des Moines Steel Co., percent by weight
Carbon...............	0.12	0.08 to 0.12
Manganese............	.40	.30 to .60
Sulfur...............	.019	.045 maximum
Phosphorus...........	.025	.04 maximum
Silicon..............	.14	.10 to .20
Nickel...............	3.45	3.25 to 3.75

The results of the analysis indicate that the sample analyzed conformed to the specifications.

The Metallurgical Division of the Bureau of Mines analyzed samples of steel taken from fragments of No. 4 tank for the Technical Committee appointed by the Mayor of Cleveland. The results of these tests furnished no information of assistance in determining the cause of the failure of No. 4 tank. The chemical analyses showed no significant deviations from specifications.

DISCUSSION OF POSSIBLE CAUSES OF DISASTER

In the fire at the LS&R plant of the East Ohio Gas Co., as in many other disasters, the information and evidence obtained up to the time of writing this report was not sufficient to establish definitely the primary cause. Certain facts were established in the investigation, and these suggest certain possible mechanisms by which No. 4 tank might have failed. These mechanisms will be discussed, and the evidence supporting and contradicting them will be presented subsequently.

It was definitely established that No. 4 tank failed and spilled its contents of liquefied natural gas, which subsequently was ignited by one of the many sources of ignition that were close to the tank. It was also established by eyewitnesses that liquefied natural gas issued from No. 4 tank prior to the inflammation of the vapor or gas. From the foregoing, it is apparent that the ignition of the contents of No. 4 tank was a secondary effect; and as there were many sources of ignition near the tank, it is not necessary to establish definitely where the ignition occurred. It is important, however, to seek the sequence of events leading to the failure of No. 4 tank.

Consideration of possible causes of the failure of No. 4 tank indicates that these fall into two general classes: (1) Failure caused by some event or events occurring external to No. 4 tank, and (2) failure caused by some event occurring within the tank structure itself. The more likely possibilities under each of these mechanisms are discussed in detail below.

<u>Failure Caused By An Event Occurring External To No. 4 Tank Structure</u>

<u>Consideration of Possibility of Failure Caused by Shock From Explosion in Space Beneath Tank</u>

There was evidence that a gas-air mixture had exploded or inflamed beneath No. 1 and No. 2 spherical tanks. From the appearance of the damage, it seemed that the explosion under the No. 1 tank exerted greater force than the one under the No. 2 tank, although neither explosion was violent, and the damage and other evidence indicates that the mixtures might have been near the upper or lower limit. As the space beneath these tanks was more or less confined by the dam wall and skirts around the bottom of the tank, it was possible for this explosion to be communicated through the ducts to the overflow gas-storage tank and thence through a duct to the space beneath No. 4 tank. Furthermore, it is possible of course, that the explosion could have originated in the space beneath No. 4 tank or in the overflow gas-storage tank and could have propagated to the space beneath any of the tanks.

There is no evidence that an explosion of any violence whatsoever occurred in the overflow gas-storage tank. The top of this tank had fallen into the pit, and the stack was displaced only slightly from its original position. If an explosion of any magnitude had occurred in the overflow gas-storage tank, many pieces from the top of the tank would have been found some distance from the tank. It seems likely that the few pieces of the top of this tank that were found some distances from the tank probably were transported by the surge of liquid from No. 4 tank or from No. 3 tank when it failed.

If an explosion had occurred in the space beneath No. 4 tank, it would have been necessary, first, to account for the formation of an explosive mixture and, second, to account for the presence of an ignition source within the overflow storage pit or in any space communicating with the overflow storage pit. Even if it is granted that an explosive mixture may have been present, it is very difficult to account for a source of ignition in any one of these places. One possible source of ignition was the batteries in the portable potentiometer being used by Bridenstine, an employee whose body was found between Nos. 3 and 4 tanks. However, the location of Bridenstine's body clearly indicated that he was not beneath No. 4 tank when the failure occurred.

Furthermore, an explosion involving the quantities of gas-air mixture that might have been present in the overflow gas-storage tank or in the space beneath any of the tanks probably would have been observed by eye witnesses.

From the foregoing, it appears unlikely that an explosion of any magnitude preceded the failure of No. 4 tank. It seems more probable that the explosion that occurred beneath No. 1 and No. 2 tanks followed the failure of No. 4 tank. It seems likely that the top of the overflow gas-storage tank was collapsed by liquid spilled from No. 4 tank or by part of No. 4 tank falling on it. After this occurred, an explosive mixture could have been formed in the space beneath No. 1 and No. 2 tanks by the entrance of gas from liquid outside the dams and apron walls or by the entrance of gas diffusing from the pit of the overflow gas-storage tank through the duct communicating with the space beneath No. 1 and No. 2 tanks. In the latter case, the mixture in No. 2 tank would have been richer than that in No. 1 and, if sufficiently rich, the explosion would have been less violent in the space beneath No. 2 tank. The remains of charred bills from the coal yard adjacent to the LS&R plant were found beneath No. 2 tank. It is possible that one of these burning bills may have ignited the mixture beneath No. 2. However, flame pervaded the area in the vicinity of No. 1 and No. 2 tanks and therefore there were many other possible sources of ignition subsequent to the failure of No. 4 tank.

<u>Consideration of Possibility of Explosive Shock from a Bursting Ammonia Cylinder</u>

The investigation disclosed that a cylinder containing ammonia had exploded near the southeast corner of the compressor building adjacent to the ammonia receiver. This tank was connected to the receiver for make up.

Examination of the debris indicated that parts of the supports for lines to the ammonia condenser and receiver were deposited on top of fragments of No. 4 tank and also on top of the insulation from No. 4 tank. This would seem to indicate that the cylinder containing ammonia burst subsequent to the failure of No. 4 tank and as the result of heat from the burning gas coming from the liquid spilled from No. 4 tank.

Consideration of Possibility of No. 4 Tank Being Subjected to an Abnormal Shock as the Result of an Operating Failure in the Liquefaction Plant

The possibility that No. 4 tank may have been subjected to an abnormal shock as the result of an operating failure in the liquefaction plant is suggested by the rapid increase in pressure shown on several of the charts taken from the compressor house subsequent to the disaster. This possibility was given detailed consideration and was investigated thoroughly. The investigation disclosed that all variations on the charts taken from the compressor house could be explained on the assumption that the failure of No. 4 tank had occurred prior to the appearance of these abnormalities on the charts, and that the increases in pressure probably occurred as the result of damage to equipment by the fire.

The fire following the failure of No. 4 tank was very intense around the compressor house, as testified by Feightner and others. This could have caused a shut-down of the compressors either by burning the insulation on wires and causing failure of the ignition system or by decreasing the concentration of oxygen in the intake to the engine. If these compressors had been shut down by the fire, the increase in pressure in the suction of No. 2 engine, in the suction of the ethylene compressor, and in the suction of the ammonia compressor would have followed. From Feightner's testimony, it is evident that similar rapid rise of pressure in the suction of a compressor had been observed previously when a compressor had shut down as a result of some minor abnormality in the operation of the plant.

Even if one assumes that an abnormality in the operation of the plant may have caused the build-up of pressure observed, it is very difficult to suggest a mechanism whereby a severe shock would have been placed on No. 4 tank. From the record of the liquid level in No. 4 tank it seems reasonably well established that the valve in the liquid line of No. 4 tank was closed. Therefore, any shock from an operating failure in the liquefaction plant would have been transmitted to No. 4 tank through the vent gas line. As the gas itself offers considerable cushioning, and as the relief valves on the tank seem to be more than adequate to care for sudden surges, it is difficult to see how any major shock could have been transmitted to No. 4 tank as a result of any operating failure that might have caused the increases in pressure shown on the various charts.

The possibility of building up pressure in No. 4 tank as a result of failure to open the valve permitting vent gas from the tank to go through a pressure regulator into the low-pressure distribution system was also considered. It does not seem likely however, that this could have been responsible for a rapid build-up in pressure in No. 4 tank, as Roy Feightner stated to one of the Bureau's investigators that at times it had been necessary to isolate the four tanks completely to prevent vent gas from leaving the system. This was done when it was necessary to make certain repairs or alterations, and was always done under constant supervision. According to Feightner, in an interval of 15 minutes the pressure in the vent gas line would increase only 0.2 or 0.3 pound per square inch gage, even though no vent gas left the system. Feightner also stated that the exact time of opening the valve to permit vent gas to flow into the low-pressure system was not critical in relation to the various events in the shut-down procedure of the liquefaction plant.

If there had been any great increase in pressure in the vent gas line, it would have been indicated by the chart on the suction of No. 2 recycle gas compressor (No. 3 engine). Although a considerable portion of this chart was burned, nevertheless enough of it remained to establish the fact that at 2:15 p.m. the pressure could not have been greater than 7 pounds per square inch gage; at 2:30 p.m. it could not have been greater than 6 pounds per square inch gage; at 2:45, 5½ pounds per square inch gage; and at 3 p.m., 5 pounds. (See fig. 20.)

The possibility that No. 4 tank might have been subjected to an excessive internal pressure as a result of the entrance of high-pressure gas through the line carrying liquefied gas also was considered. This does not seem to be a likely possibility, because it was testified that No. 4 tank was not being filled at the time of its failure, and the valve in the liquid line was closed. If No. 4 tank had been subjected to an abnormal internal pressure, an increase in pressure would have occurred in the vent gas line and would have been recorded by the pressure gage on the suction of No. 2 recycle gas compressor. As stated, the chart on this gage was partly burned, but the remaining record shows that the pressure in the line could not have been greater than approximately 6.5 pounds per square-inch gage at the time No. 4 tank failed. (See fig. 20.) Furthermore, if No. 4 tank had been subjected to abnormal internal pressure, it would seem that the pressure-relief diaphragms would have burst. Inspection of these diaphragms indicated that they had not burst, but probably had been burned by the fire.

Consideration of Possibility of No. 4 Tank Being Subjected to Abnormal Shock as the Result of a Sudden Release of Pressure

The possibility that No. 4 tank may have been subjected to an abnormal shock as the result of a broken vent-gas line was suggested, as the line to the vent-gas heater was broken and burning when the Bureau's investigators first arrived at the scene. There was no evidence to indicate that the vent-gas line broke before No. 4 tank failed. If this had occurred, it would appear that witnesses at the AGA Testing Laboratories would have seen a cloud of liquefied gas and chilled water vapor from the air issuing between No. 2 and No. 3 tanks. This was the location of the break in the vent-gas line. The volume of gas that would have issued from a broken vent-gas line would have been considerable and would certainly have been noticed readily.

The remains of the chart from the suction of No. 3 engine, which was connected to the vent-gas system shows that the pressure in this system could not have been greater than 7 pounds per square inch gage. This would seem to indicate that the line could not have failed at a Dresser coupling as a result of excessive pressure in the system. As the vent-gas line was supported on the steps leading to No. 2 and No. 3 tanks and as these failed as a result of the failure of No. 3 tank or probably as the result of the fire itself, it is evident the vent line would have broken apart when these supports collapsed.

From the foregoing, it does not seem very likely that a break in the vent-gas line could have preceded the failure of No. 4 tank unless this break had occurred at some point north of the tank, where it would not have been observed by the witnesses of the AGA laboratory.

Consideration of Possibility of No. 4 Tank Being Subjected to Seismic Shocks

Witnesses testified that seismic vibrations existed at the LS&R plant of the East Ohio Gas Co. Vibrations of considerable magnitude were reported in the boiler room as the result of the passage of trains on the New York Central Railroad. Vibrations from a drop hammer situated in a manufacturing plant near the LS&R plant also were reported. It is well known that minor shocks can cause failure of brittle materials when these are stressed. It is also readily seen from the design of No. 4 tank that any ground shock would be transmitted directly to the inner and outer circular girders on the bottom of the tank. In this tank there was probably less cushioning of a ground shock than in the spherical tanks, because the circular girders were carried on wooden posts with steel end plates, which rested directly upon the concrete foundation. In contrast, the spherical tanks rested on a cork block 3 feet thick, which probably would very effectively damp-out any ground shocks. Thus, it appears likely that No. 4 tank would have been more vulnerable to seismic shocks than the spherical tanks.

It cannot, of course, be definitely proven from the information available that seismic vibration or shocks were a factor in the failure of No. 4 tank, but certainly this possibility should be given consideration in future designs.

Mechanisms Depending on Conditions in the Tank Structure

Consideration of Possibility of a Crack, Strain, or Flaw in Metal

The presence of frost spots on No. 4 tank, along with the fact that the bottom of the tank cracked when the tank was first put into service, suggest the possibility that a strain or flaw within the tank structure might have caused the failure.

It is recognized that great care and diligence were used in repairing the break that occurred in No. 4 tank. However, it is possible that a minute crack may have passed unnoticed and that the region in the vicinity of the crack might have been weakened gradually until eventually the normal stress on the area was great enought to cause failure.

Frost spots on the bottom of the tank might have indicated a leak in the inner tank, but this does not seem likely, as liquids (higher-boiling hydrocarbons) were never found in inspections of the drain at the center of the bottom of the insulation jacket. Furthermore, these frost spots were not localized but were generally over the bottom of the tank. It seems that the explanation of the tank designer to account for these frost spots is the correct one. J. O. Jackson stated that in his opinion frost spots occurred on the bottom of the tank when the ventilation beneath the tank was restricted as a result of the installation of the dam and apron wall. This interferred with circulation beneath the tank and also with the transfer of heat from the air to the tank. Under such conditions, the dead-air space acted as an insulator, and temperature equilibrium was re-established with a change in the temperature gradient to the outside atmosphere. At the new temperature gradient, the outer shell of the tank was at times at a temperature below that of the dewpoint of the air in the space beneath the tank.

Other facts tend to discount the theory that a leak developed in the tank shell. Among these was the fact that liquid was never drawn from a connection at the bottom of the insulation jacket of the tank, nor was there any detectable increase in the pressure in the space between the inner tank and outer shell of No. 4 tank.

It was stated that the insulation had settled in No. 4 tank and that frost spots had occured in a region extending approximately 4 feet down from the top of the tank. Under such conditions, it is conceivable that the plates at the top of the tank might have been at a temperature slightly higher than that of the plates at the bottom of the tank when the rate of heat flow to the top of the tank was increased as a result of the loss of insulation from the top section. If inequalities in temperature had existed in the shell of the tank, it is conceivable that these might have set up strains that would have made the structure more likely to fail when subjected to minor shocks. This possibility is mentioned for completeness, but it is believed that temperature differences in the shell, even under the conditions outlined, would not have been great enough to set up significant strains.

Consideration of Possibility of Superheating of Liquids in No. 4 Tank

It is reported in the literature(14) that under some circumstances unstirred masses of liquid methane may be dangerous because of the tendency of the liquid to superheat in the absence of suspended solid particles. If this had occurred and gas had been evolved at a very high rate, an abnormal shock would have been placed on the tank structure and possibly would have caused failure. Although such a mechanism is conceivable, it is believed that its occurrence was unlikely under conditions existing in No. 4 tank of the LS&R plant. Evidence that this probably did not occur is furnished by figure 21, which shows the liquid level in No. 4 tank. This was a float-type gage, and if any disturbance in the liquid level had occurred, it seems likely that the gage would have indicated it.

CONCLUSIONS

Possible Causes of Failure

On the basis of information developed up to the time of writing this report, it is not possible to reach any definite conclusion regarding the cause of the disaster. However, certain negative conclusions are indicated:

1. No evidence was found to indicate an operating or personnel failure in the shut-down of the liquefaction plant, which was in progress at the time No. 4 tank failed.

2. In the opinion of the Bureau's investigators, there was no evidence of a gas-air explosion preceding the failure of No. 4 tank.

3. There is no evidence to indicate the performance of any other operation within the LS&R plant at the time of the disaster except those normally connected with the operation of the plant itself.

4. There is no evidence of sabotage.

The foregoing negative conclusions, along with the fact that the foundation of No. 4 tank was essentially intact and in its original position, seem to indicate that the cause of the failure of No. 4 tank might be found within the tank superstructure. The possible fundamental causes of failure of No. 4 tank fall into the following categories:

1. Improper design.

2. Use of steel with properties unsuited to conditions of use.

3. Flaw in tank or in welding.

Each of these possibilities is discussed below.

Stress Analysis

The designers of No. 4 tank made available to representatives of the Bureau of Mines complete details of the stress analysis of No. 4 tank. The calculations were studied, and no reason was found to believe that the failure of No. 4 tank was due to improper analysis or determination of primary stresses. There is every evidence that the tank was built after considerable thought and study had been given to the many factors that must be taken into account in designing equipment for service at low temperatures.

Suitability of Steel for Service

Published reports on the development work preceding the design and construction of the LS&R plant indicated that considerable work had been done to determine a satisfactory material for use in constructing the storage tank. The material selected was a low-carbon steel containing 3½ percent nickel. Of all the materials tested, this one had the lowest impact strength by the Charpy test; nevertheless, it was considered satisfactory.

It appears that the steel used in the three spherical tanks was suitable but may not have been suitable for the cylindrical tank. This point is raised because possible seismic shocks would have been cushioned to a greater extent by the cork insulation in the spherical tanks than by the wood columns in No. 4 tank. In tank 4, shock loads would have been concentrated at the columns and would have been transmitted directly to the circular girder, whereas shock loads transmitted to the spherical tank would have been distributed over the bottom of the tank.

These considerations, along with the fact that most industries handling large quantities of liquid oxygen or air use stainless steel or suitable nonferrous metal tanks suggest the possibility that the steel used in No. 4 tank may not have been suited to the particular design of this tank, or to tanks that might be subjected to seismic shocks in similar applications.

Discussion of Possibility of Flaw in Tank or Welding

The existence of a flaw in the tank or in the welding can only be suggested as a possibility. Evidence available at the time this report was written indicates that the region of the repair made in the bottom of the tank was not involved in the failure of the tank.

General Conclusion

Regardless of the cause of the disaster at the LS&R plant of the East Ohio Gas Co., the application of the system for liquefying and storing large quantities of natural gas is not invalidated, provided proper precautions are observed. It is believed that the recommendations contained in a subsequent section of this report may be helpful in determining the proper precautions.

RECOMMENDATIONS

As the result of the Bureau's investigation of the fire at the LS&R plant of the East Ohio Gas Co. on October 20, 1944, the following recommendations are made:

1. Plants in which large quantities of inflammable gases are liquefied and stored should be isolated, and activities not directly related to the operation of the liquefaction and storage plant should be

prohibited within the plant area. The distance between the boundary of such plant and the nearest inhabited building should be greater than half a mile.

2. Storage containers for liquefied gases should be isolated from other parts of the plant and should be provided with dikes large enough to confine the entire contents of the tank in the event of a failure. The construction of dikes and the distances between tanks should conform with the "Suggeated Flammable-Liquids Ordnance" given in the National Fire Codes of the National Fire Protection Association.

The foregoing recommendations go farther than the requirements set forth in the National Fire Protection Association.(15) One section of this code is entitled "Regulations for the design, installation, and construction of containers and pertinent equipment for the storage and handling of liquefied petroleum gas." The regulation governing dikes and embankments is as follows:

> Because of the pronounced volatility of liquefied petroleum gases, dikes are not normally effective, hence their general requirement is not justified as in the case of gasoline or similar flammable liquids. When, however, in the opinion of the inspection department having jurisdiction, owing to the slope of the ground or other local conditions, above-ground containers are liable, in case of rupture or overflow, to endanger adjacent property, each container shall be surrounded by a dike of such capacity as may be considered necessary to meet the needs of the situation under consideration by the aforesaid inspection department, but in no case more8/ than the capacity of the container in question.

In spite of the great volatility of liquefied petroleum gases or of liquefied natural gas, it would seem that the provision of dikes for storage containers is desirable, because considerable time is required for the liquefied gas to evaporate, and therefore anything that can be done to confine the liquid within a definite area would undoubtedly minimize the damage that would be done by a resultant fire. This statement is supported by unmistakable evidence of the flow of large quantities of liquid topped by burning vapor at considerable distances from the tank.

3. Additional studies on the properties of metals at low temperatures should be made, and industry should be encouraged to publish existing data on the subject.

4. The construction of a storage tank for liquids at low temperatures similar in design to No. 4 storage tank using low-carbon, $3\frac{1}{2}$ percent, nickel steel, should not be undertaken unless the cause of the failure of No. 4 tank is definitely established and unless it can be proved beyond doubt that the properties of the steel were suitable for the particular design in question.

8/ Probably a misprint, and should be "less" instead of "more."

5. All pipe lines carrying cold liquid or cold gas should be furnished with suitable bolted flanged joints. Expansion loops capable of taking care of pipe movement due to changes in temperature should be provided.

6. Storage tanks for liquefied gases should be provided with independent inlet and outlet lines for the liquefied gas. The inlet line should discharge at a point near the maximum liquid level in the tank.

7. Extreme precaution should be taken to prevent spilled liquefied gas from entering storm sewers or other underground conduits.

8. The appearance of frost spots on the outer shell of storage containers for liquefied natural gas should be regarded with suspicion, and the tank should be drained and thoroughly inspected, unless the reason for the appearance of the frost spot can be definitely established.

9. Efforts should be made to prevent wide variations of temperature in the inner shell of storage containers when they are filled for the first time with liquefied gas.

10. Although closely coupled equipment is desirable in low-temperature refrigeration processes, nevertheless some dispersion is indicated when such hazardous material as highly inflammable gases in the liquid state is handled.

11. In future designs of storage containers for liquefied natural gas, provision should be made for remote closing of the foot valve from a point at ground level.

12. Positive and fool-proof liquid-level indicators should be provided for each storage container. These indicators should be equipped with automatic high- and low-level alarms.

13. When possible, the tops of the vent gas lines of all storage tanks for liquefied gas connected to the same manifold should be at the same level, so that accidental leakage of liquid from one tank to another would never result in the overflowing of liquid into the vent gas system. When this is not possible, extreme precautions should be taken to prevent leakage of liquid from one storage container to another in which the level of the liquid is lower. Containers for storage of liquefied gases should not contain liquid in excess of their rated capacity. The liquid level in any tank connected to a common liquid manifold should always be at least 1 foot below the top of the lowest overflow in the group of tanks.

14. All outer portions of storage containers for liquefied natural gas should be readily accessible to inspection and should be in the open to permit proper ventilation.

15. The gas purged through the annular space of storage containers for liquefied natural gas should be metered both into and out of these containers.

16. All sources of electrical ignition should be eliminated in and around gas-liquefaction plants. This hazard should be safeguarded to the extent considered necessary in modern explosive plants. Precautionary measures in such plants include protection against lightning, elimination of static charge on machinery, equipment, and persons, and the use of explosion-proof electrical equipment and wiring throughout hazardous areas.

17. Means should be provided for rapid egress of personnel from the plant area in case of emergency. Escape drills should be held frequently, and damage-control drills should be held after types of damage that might possibly be repaired with safety have been established.

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