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A Study of the Subsurface Method of Application
of Foam for the Extinguishment of Fuel Oil Tank
Fires

by

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NAVY DEPARTMENT

Report
on

A Study of the Subsurface Method of
Application of Foam for the Extinguishment
of Fuel Oil Tank Fires

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ABSTRACT

Results are given concerning the analyses by Laboratory methods of this fundamentally new oil fire extinguishment procedure initially developed in Great Britain. Theoretical and small scale findings are substantiated by a full-scale oil tank fire test. Evidence is presented establishing the extinguishment operation as being largely a function of the cooling by the water in the foam rather than a smothering action. Unique among firefighting procedures, the predetermination of necessary equipment and materials is possible in this method. Maximum protection from enemy action and a greater degree of safety to personnel are among the advantages of the system.

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INTRODUCTION AND BACKGROUND OF PROBLEM

1. Authorization. This project was authorized by letter from Chief of Bureau of Yards and Docks to Director of NRL, N27, dated 19 July 1942.

2. Statement of Problem. In the spring of 1942, the Bureau of Yards and Docks became interested in work being done in England on an emergency method of extinguishing oil tank fires, whereby a mechanically produced air foam was injected into the oil-filled product line of the burning tank and the fire extinguished by the foam which rose upward through the oil. Because this method of foam application violated several basic principles of ordinary fire-foam manipulation, considerable adverse criticism was encountered from the American foam system manufacturers and oil fire-fighting authorities. Nevertheless, the Bureau was interested in obtaining some data and first hand experience in the use of this subsurface method of foam application and therefore authorized the Naval Research Laboratory to initiate an investigation and study of this method in preface to a full-scale fire test using a standard Naval fuel oil storage tank. Dependant on the results of this test, the Bureau was also interested in obtaining engineering recommendations leading to the installation of this method in Naval fuel oil storages as an additional protection from fire, both from a point of view of its indicated efficient use of material and manpower and its effectiveness during emergency conditions.

3. Theoretical Considerations and Basis of Method. The three well known basic principles of fire extinguishment are: (1) the elimination of oxygen; (2) the cooling of the material below its ignition temperature; (3) the removal of the combustible material itself. Of these three the one considered most applicable for oil fire extinguishment has been the elimination of oxygen, thus preventing the formation of a combustible mixture with the petroleum vapors. This is most effectively done on a large scale by applying a foam which will float on the oil and be fluid enough to flow over the surface in all directions forming an effective seal between the hot vaporizing oil surface and the air above. When oil burns it liberates great quantities of heat, and, when the oil is a blend of various hydrocarbons with diverse boiling points, such as Navy Special fuel oil, a certain amount of this heat is transferred downward into the oil by a circulation mechanism caused by changes in specific gravity as the lighter fractions are distilled off at the surface. This hot oil is called the "heat wave", and, as its lower boundary is sharply defined, the rate at which this "wave" progresses in Navy Special fuel oil has been determined to be 10 to 15 inches per hour. Graphically, this mechanism of the burning of an open top fuel oil tank is represented on Plate 1 where it will be seen that certain definite relationships will exist between the composition of a fuel oil, its heat wave rate, and the temperatures

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at various levels of the tank at succeeding stages of the fire (Mechanical Engineering, July 1925, Vol. 47, No. 7, page 540).

4. A heat balance calculation, based on the burning rate and heat wave rate, shows that from 96% - 98% of the heat generated from such fires is evolved upward into the surrounding air. Thus it is seen that any foam introduced from above the surface must be very resistant to heat in order to persist and flow from 50 - 100 feet through temperatures of 1300° - 2000°F. Violent up-drafts are present, sweeping an unknown amount of foam up into the flames where it is lost. Additionally, if the foam is applied from any height above the surface it partially submerges and becomes covered with hot oil which breaks it and makes it useless as a smothering blanket. Several devices are used to minimize these factors, but since these methods are fixed to the tank plates they are extremely vulnerable to damage from enemy action or heat buckling, which might render them inoperative. Should this happen, it becomes necessary for personnel to approach the burning tank with portable equipment and force an entry to permit the application of foam. This type of work is without a doubt a hazardous one with the danger of slop-overs always present.

5. The second possible manner of extinguishing an oil tank fire is by cooling the oil to a temperature where no more inflammable vapors are given off, this temperature being designated as the flash point. A very good direction from which to attack a fuel oil fire (as shown by the heat balance calculations) is the underside of the heated oil where, in contrast to the top, temperatures of only 500°F and only 2% - 4% of the heat must be encountered. However, since water is heavier than oil it involves supplying a mechanical means of lifting the water to the hot oil where its cooling capacity will take effect. It is the purpose of this report to show how a stable, mechanically generated foam introduced into the product line will act to achieve this end.

6. The large majority of present foam installations are of the chemical foam type in which the foam is made by a soda-acid reaction in a closed system. In recent years a new process for foam generation has been developed using a generator which mechanically aspirates free air into a solution of water and a foam agent to form a fire-fighting foam. Equipment for operating the air foam system is simpler, and greater volumes of foam are produced per weight of materials used. (Compare: One pound of chemical powder = 7.5 gallons of foam. One pound of foam fluid mechanically used = 25 - 50 gallons of foam.) The mechanical foams vary greatly in character and in volume, according to the type of stabilizer used, a hydrolized protein or similar product giving a heavy, low volume foam and the synthetic "soanless soap" product a light, large volume foam. No general agreement has yet been reached on which type is superior, the British favoring the former, and the U. S. being of divided opinion, manufacturing both.

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7. In this mechanical foam process, the entrainment of air in the water and foam-compound solution produces a foam mixture containing from 10% to 20% water which will readily rise through fuel oils. When oil above 212°F is reached, the water will be boiled off with a resultant cooling of surrounding oil; and it is obvious that oil contamination and heat resistance of foam will not play a major role in the process but instead the volume of water lifted becomes the significant factor. Large volumes of cold water coming in contact with hot oil are disastrous because of the sudden steam formation beneath the viscous oil surface, but if the water addition is done slowly, giving the steam time to dissipate, this danger is minimized to a point where the expansion is only a few inches.

8. In determining the time and amount of water necessary for the extinguishment of any given fuel oil tank fire, a few simple calculations give the amount of water needed to cool oil from 500°F to a temperature below its flash point of 175°F. This is found to be .09 gallon per square foot of surface area per inch of heat wave depth. However, since the addition rate of water is quite low it is necessary that the amount of heat being simultaneously generated by the fire also be taken into consideration. This value, calculated from the rate of heat wave propagation, (10 inches per hour) shows that an additional .02 gallon water per minute per square foot of surface area is required to offset the burning fire. Thus the time of extinguishment of a tank may be found if the heat wave depth, or burning time, and rate of water addition are known. The experiments necessary to determine the rate of water addition to the hot oil for any tank will be covered later in this report.

9. Estimates made from the presently accepted value for minimum rate of surface foam application for successfully extinguishing an oil fire, i.e., 0.75 gallon per minute per square foot tank area, led to the belief that an expected two-thirds loss in foam volume in the new method would necessitate a prohibitive amount of equipment and water when the tank diameters approached 150 feet. Causes for these losses were indefinite and variously estimated to be from the compression due to head of oil, mechanical breakdown passing through the oil, and effect of the volatile hydrocarbons on the bubble film. Also, assuming that a small amount of foam did reach the surface, it would be covered with oil, the more viscous the oil, the worse the contamination, and in a more ideal condition to burn, there being a plentiful supply of air well dispersed throughout the oil emulsion. Thus, the intense burning of this mixture would more than offset any extinguishing properties the foam might possess. These were the factors that caused subsurface application to be judged inefficient and non-workable.

10. Reports from Great Britain have indicated that one of the first results of a bombing attack on oil tanks is damage to the fixed foam systems on the tank sides. As quite often the

conditions inside the berm prevent approach with portable equipment, the product line, usually underground, provides a good emergency entrance which only a direct hit could disrupt. The British Pyrene Company has developed the first forcing type branchpipe which enables the generation of foam against heads of oil up to 60 feet, and they have applied these successfully to several tank test fires. However, since their data available in this country was incomplete and did not supply enough values for proper computations, certain preliminary work was necessary in order to study how foam was effected by generation against backpressures and transmission through oil. Foam volume and the oil and water percentage of the foam were the factors of most interest.

11. Equipment and Methods of Mechanical Subsurface Foam Generation. The mechanical type foam system consists of the inductor which proportions the correct amount of foam compound into the water supply, and the "branchpipe" or "playpipe" which aspirates free air into the water-foam compound solution making a homogeneous foam.

12. For laboratory study and the full-scale fire test the British No. 10 branchpipe was used. (See Plate 2) This unit is rated as using 120 gpm water at 100 psi pressure and 4 gpm foam compound to produce 960 gpm foam. It is 69 inches overall in length, 4 inches in diameter, and weighs 32 pounds. When it is desired to operate the branchpipe against a backpressure, a liner must be inserted into the standard No. 10 model. The liner constricts the air entrance at the point where the four nozzle streams converge, the high water velocity preventing the backward escape of foam. Thus a method is provided for generating and introducing foam into tanks against pressure exerted by head of oil. This liner, because of its construction, reduces the normal foam output by about 20%. Varying the water pressure at the nozzle has very little effect on the maximum exit pressure that can be developed. Instead, the critical balance is in the relationship between the cross sectional area of the water stream and the area of the air entrance. A standard 4-inch pipe thread on the exit end of the branchpipe facilitates connections into any piping system.

13. Two other larger branchpipes are manufactured, the No. 20 and No. 30, which have a rated capacity of two and three times, respectively, that of the No. 10 unit. These large size units are for use in large installations where it is desired to simplify the operation by replacing No. 10's.

14. Three types of inductors, all based on the Venturi principle, are available in the British equipment for proportioning and introducing the concentrated foam compound into the water stream supplying the branchpipe. The first is the portable type in which the Venturi tube is contained in the water head of the branchpipe and the foam fluid is fed through a rubber hose from

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a knapsack. As the amount of compound that can be conveniently carried is small, this unit is necessarily limited to short periods of operation or to branchpipes smaller than the No. 10. It has no use in a fixed installation. The second type is the in-line inductor in which a large Venturi (and attached supply tank) is connected directly into the hose line. This is a simple arrangement but has the disadvantage of requiring a large pressure drop and therefore, means much higher water pressures at the booster pump.

15. The third type is the multiple jet inductor, a simple and efficient device, but one which does not operate satisfactorily under all conditions. It utilizes the always existent pressure difference between the suction and discharge sides of the water pump as the necessary energy source for introducing sufficient foam compound to operate from one to four No. 10 branchpipes. (See Plate 3) Water is supplied to a set of four Venturi tubes by means of a one-inch hose tapped into the pump discharge line which is supplying the branchpipes with water at 100 - 120 psi pressure. As water passes through the Venturi's the compound is inducted from the 32-gallon supply tank below, and the resulting mixture is fed into the suction line of the pumper by a second hose line, becoming diluted and thoroughly mixed in passing through the pump. Each Venturi is individually controlled by a cock, which, when wide open, will properly supply one No. 10 branchpipe. This affords a manual control for different operating conditions such as using four No. 10's or one No. 10 and one No. 20, etc. The amount of water by-passed around the pump in this operation is 8 - 10 gallons per minute for each Venturi or about 2% of the pump capacity (500 gpm). Two serious limitations are imposed by using this piece of apparatus as designed. First, when four No. 10 branchpipes are in operation simultaneously, foam compound is withdrawn at a rate of 20 - 24 gpm; thus, the supply tank will hold only enough for a minute's operation. Moreover, at the Penniman test it was found impossible in any manner to drain the 20-gallon shipping drums into the supply tank in less than 3 or 4 minutes time exclusive of the time required to handle the unwieldy 300-pound drums. Therefore, in this test it was found necessary to use a 1200-gallon auxiliary tank filled in advance as a reservoir and then feed the inductor tanks by a 3-inch line as needed. Secondly, the design of this unit requires a 100 psi difference in pressures which does not permit operation from a hydrant where the pressures may exceed 15 psi. Because of the relatively small pressure changes over normal range conditions of drafting water, the proportioning is sufficiently accurate, but when 10 - 15 psi positive pressure occurs in the pump suction line the pressure drop is not large enough for proper compound addition. For this reason in the Penniman test hydrant water at 70 psi was fed into a 500-gallon sunken tank from which the pump took suction.

16. The British foam fluid compound used in the Laboratory tests and the full-scale fire test is a dark colored liquid said

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to be the result of the hydrolysis of hoof and horn meal, containing additives in the form of oxidizable iron salts and suitable preservatives. In storage, certain reactions continue to take place which result in a thick viscous deposit on the bottom of the container.

17. The foam generated by the use of this compound is of the low-expansion-ratio, high-water-content type. In practice the British equipment is designed to use 4 gpm of this foam fluid with 120 gpm water at 120 psi to produce 1000 gpm foam, measured by the customary open tank volume testing method. This foam is a thick, full-bodied, homogeneous, air emulsion which stiffens upon exposure to air, leaving a foam layer on oil which will exist for an indefinite period of time, the only change being the drainage of liquid from the skin of the bubble and interstices between them.

18. Since the operation of branchpipes in general requires greater water pressure than is supplied by the usual hydrant, a booster pump is necessary to provide sufficient water at a minimum pressure of 100 psi to operate the branchpipes. Four No. 10 British branchpipes may be satisfactorily operated from a static water supply by one mobile gasoline powered pump with a rated capacity of 500 gpm against a head of 120 psi with a vertical lift of 12 feet. Standard Yards and Docks, Chrysler trailer pumps were used in this entire study and proved to be very satisfactory.

19. The preliminary experimentation concerned with this problem obviated the use of large-scale equipment as a result of the extreme expense and operating difficulties connected with large-scale operations. As a consequence of this, an American type small, foam playpipe with an operating capacity of 1/7 that of the British No. 10 branchpipe was used for a considerable number of tests. In order to enable this unit to overcome backpressures in the laboratory small-scale experiments, a liner similar to that used in the British unit was devised. (See Plate 4) Without the liner this unit delivered 240 gpm of foam using the British foam compound but this volume was reduced to 100 gpm when the liner was in place. The playpipe, with the normal water intake of 19.5 gpm, consumed 0.75 gpm of British foam compound.

METHODS OF LABORATORY TESTING

20. Study of Foam Volume Yield Under Backpressures. One of the important factors in any type of foam system is, of course, the volume of foam produced per unit generator with a given solution. This, in fact, has apparently been the criterion of development of the foam manufacturers; i.e., the greater the volume of foam obtained from a definite volume and weight of the material, the more highly developed the system. Consequently, one of the pieces of test equipment set up was a 2000-gallon calibrated wooden tank which was arranged to enable the branchpipes to

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17. The foam generated by the use of this compound is of the low-expansion-ratio, high-water-content type. In practice the British equipment is designed to use 1 gpm of this foam fluid with 120 gpm water at 120 psi to produce 1000 gpm foam, measured by the customary open tank volume testing method. This foam is a thick, full-bodied, homogeneous, air emulsion which stiffens upon exposure to air, leaving a foam layer on oil which will exist for an indefinite period of time, the only change being the drainage of liquid from the skin of the bubble and interstices between them.

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introduce the foam tangentially downward in order to prevent any abrupt change of velocity or direction. (See Plate 5) This also served to measure other characteristics of foam generators such as water consumption and compound consumption. The values obtained on these runs using standard methods agreed favorably with those claimed by the manufacturers.

21. In order to estimate the maximum head against which the subsurface foam generators or branchpipes would satisfactorily operate, a device was constructed by connecting a short nipple and valve to the exit end of the foam generator. An ordinary pressure gauge tapped into the nipple indicated the pressures developed when the end valve was throttled. This made a compact piece of apparatus which could be easily manipulated throughout any conditions of backpressure with the resulting foam delivered into the calibrated volume test tank.

22. In this study of the volume relationships of the British No. 10 branchpipe with increased backpressures, various conflicting data was collected using the open-tank volume testing method. This gave rise to a question of whether actual foam volumes similar to those to be obtained in a closed system were being measured or whether the foam was picking up additional air in flight thus generating more foam in its passage from the exit end of the branchpipe to the volume tank.

23. In order to check this factor a simple method was evolved whereby the foam volume leaving the branchpipe was calculated from the percentage of water plus compound contained in the foam at this point. This was done by collecting one liter samples of the foam in a graduate held directly in the foam stream and then allowing this volume to drain to a constant liquid volume (requiring 8 to 12 hrs.). A very interesting set of curves was produced by these tests. (See Plate 6)

24. Several pertinent generalizations become evident from this data. The theoretical foam volume represents a maximum stable volume production which should be possible if no drop in velocity occurred upon increase of imposed backpressure, since the water and fluid input are constant. The tank measured volumes show an abrupt drop on increase of backpressure but still not as rapid a volume decrease as shown by water content analysis, the latter curve having an entirely different slope. The obvious explanation for this difference is that at low imposed backpressures an excess volume of air has been aspirated by the branchpipe to produce as large a volume of foam as the solution is capable of generating, but when the backpressure is increased an insufficient amount of air is induced and the foam has a tendency to absorb air during its turbulent flow into the volume testing tank, resulting in an abnormal measured volume.

25. Thus, it is evident that in the testing of foam generators by this method of imposing backpressures, the use of the

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one liter sampling method gives a more accurate picture of the conditions which occur in a closed system. This is especially true when other types of foaming agents are used which show an almost infinite capacity for generating foam.

26. Retrogressing now to one of the objectives of the imposed pressure test, namely, the volume loss of foam upon increase of backpressure on the generator, the measured volume curve shows a 50% loss of volume at a backpressure equivalent to 32 feet of oil, and the water content volume curve shows an even more discouraging loss amounting to 66% of the original capacity of the No. 10 generator. This loss, due to generation, before any oil is contacted, was entirely unanticipated before this experimental work was started.

27. It was about this time that concurrent fire tests showed that water played a major role in the extinguishment of oil fires and attempts were made to determine what correlation occurred in the curves so far developed with those obtained when the foam is generated under a depth of oil at various imposed pressures.

28. Study of Effect of Oil on Foam Volume. An API 100-barrel bolted steel tank containing Navy Special fuel oil, 6 feet in depth, and fitted with bottom connections for an American playpipe and a No. 10 branchpipe, was used in determining effects of the oil on the foam. (See Plate 7) The American playpipe with liner provided an approximate scale model of the full-scale test but did not prove to be of much value. On the other hand, the No. 10 was much oversized for the tank but did bring out some valuable and interesting data. (See Plate 8)

29. It will be seen that as the backpressure increases and the volume of foam decreases, the water percentage in the foam increases proportionately, the total water remaining constant. Although there was a considerable initial loss of water in travel through the oil, the volume reaching the surface remained fairly constant over a range of backpressures with the water percentage in the foam seeming to reach a constant maximum of 38%. Thus, the large foam generation loss was partially offset and was even somewhat aided by the fact that the foam breakdown in passing through oil becomes less when the foam is higher in water content (See Plate 9) Moisture in the foam was determined by scooping 100 cc samples of foam from the surface and distilling them in an ASTM moisture-in-oil apparatus using a Dean and Stark trap, Barret type. It is very necessary that these samples be taken immediately to avoid any losses incurred by the water draining back into the oil. Oil contaminating the foam was determined by taking similar samples and adding water to dissolve the foam, then centrifuging to separate the oil. Only a few oil determinations were made, these averaging about 30% oil content.

30. An additional advantageous condition observed in these

tests was the manner of foam distribution in the 100-barrel oil tank. Here, instead of rising vertically to the surface immediately over the inlet, the injected foam spread fanlike through the oil and distributed generally over the tank oil surface. No attempt was made to measure the pattern quantitatively but the effect was appreciable even in the concrete fire pit where the ratio of area to depth was 8 to 1. An even better spreading would occur in most cases in full-scale storage tanks where ratios of 1 to 1 were possible. This regular distribution of the water helps prevent any localized violent reaction occurring when hot oil is contacted, an especially important factor in a full tank where slopping-over might easily occur.

31. A box arrangement designed so that the inflow of air of the American playpipe could be measured with an anemometer was also used in the studying of the output of foam. No definite relationships were drawn from these tests run both on American and British foam fluids at different backpressures with and without liner, but it appeared in most instances that the foam output was considerably higher than the air input. This strengthened the opinion that much of the foam generation ordinarily occurs in flight especially with the American type compound used and, further, that a volume test method was unsatisfactory for measuring foam outputs.

32. Small-Scale Fire Tests. Lack of space and proximity of buildings necessitated that all fire testing at the Laboratory be conducted on a very small scale. The first fires were in an open-top 50-gallon drum which had thermocouple wells placed vertically six inches apart. No foam was applied to the first fire, which was used to determine the heat wave rate of propagation and the "boil-over" characteristics of Navy Special fuel oil. A foot of oil on a foot of water gave a very excellent boil-over after 1-1/2 hours of burning. A heat indicating paint consisting of a cuprous mercuric iodide pigment produced a wide range of colors for the various temperature levels in this experiment.

33. After several test fires in this container in which slop-overs occurred, it was concluded that the rate of addition of subsurface-applied foam and the subsequent agitation was too great for the area involved and that a larger area must be used.

34. Therefore, a concrete pit 8 feet by 9 feet by 3 feet was fitted with a two-inch foam vertical inlet which ended in an elbow one inch above the bottom, parallel to it and directed toward the tank center. The American forcing-branchpipe was connected to this foam inlet at the edge of the pit. (See Plate 10) An oil depth of about 2 feet was obtained in this tank using 800 gallons of Navy Special fuel oil, thus leaving an 11-inch outage and about a 20-inch oil depth over the mouth of the submerged foam inlet pipe.

35. The first fire was allowed to burn 6 minutes to establish a one-inch hot oil layer before foam was applied by the sub-surface method. This fire was completely extinguished in 1 minute and 45 seconds leaving a steaming froth 6 to 8 inches deep above the original oil level. Within an hour this froth had disappeared leaving a layer of stiff foam 1 inch thick which remained on the surface for several days. (See Plate 11) At the time of this fire, the average water content of the oil had been increased from 0.05% to about 3.0% because of rains and several trial foam applications.

36. The second fire test was conducted four days later on the same oil using this time a four-inch hot oil layer obtained by burning for 23 minutes. Progress of the heat wave and temperature distribution was closely followed by thermocouples placed at levels 2 inches above the surface, at the surface, 2 inches below the surface and 4 inches below the surface. Each thermocouple was directly exposed in order to eliminate lag from the use of a metal well and each junction was located in the oil at a point 4 inches distant from the inside surface of the tank wall. Typical heat distribution in this fire as in the others approximated the following: 1500°F in the combustion zone, 500°F in the hot oil layer and 80°F in the remainder of the oil below the hot layer. The heat wave progression rate varied from 8.5 to 10 inches per hour in these tests. Immediately after foam injection started, the temperatures in the hot oil layer began to decrease uniformly, indicating a rapid circulation throughout the hot oil layer. Flames and smoke obscured the oil surface, but after about 45 seconds of foam application the burning level became visible and was noted to be about 6 inches above its original level and still rising. The flames had decreased considerably in intensity and copious clouds of steam were rising. After 1 minute and 10 seconds foam injection the burning level reached the top of the experimental tank and a mass of burning oil and foam slowly ran over onto the ground. Plate 12 shows the froth and steam during extinguishment resulting from action of water on the hot oil.

37. In a few hours another fire was run on the same oil but because of the volume loss from the previous test the oil depth above the inlet had been reduced to 5 inches so that the bottom of the 4-inch heat wave was only 1 inch distant, and, immediately on foam injection, a violent boiling took place which caused a severe slopover.

38. Several conjectures resulted from the behavior of these fires; first, that the violence and turbulence in the hot oil upon the addition of foam depend largely on the rate and turbulence of the foam application; second, that the volume expansion of the hot oil varies with the depth of the hot oil layer, this ratio being an increase of 1 to 8; and third, that basically, the cooling effect of the water is largely responsible for the extinguishing property of the foam.

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39. In the next fire an attempt was made to observe the smothering effect when foam was applied in the standard surface method. All factors remained the same as in the previous test except that the 2-inch foam inlet elbow was placed about 1/2 inch above the oil surface instead of 12 inches below it. When a 4-inch hot oil layer had been formed by firing the oil, foam was introduced and the temperatures closely observed. In 30 seconds an over-all blanket of foam had formed and no flames were visible. However, the heat wave temperature had only dropped to 100°F and in a few seconds the entire area reflashd into flame. An additional application of foam for 30 seconds was required to extinguish the flames, by which time the hot oil layer had been reduced in temperature to 200°F thus effecting complete extinguishment. It was interesting to note that when foam was being added, the temperatures at the bottom of the 4-inch hot layer as well as at the center followed within a few degrees those temperature changes occurring at the surface, a result identical to that obtained in the subsurface application experiments. The hot oil expansion amounted to a total of about 8 inches or about one-half the expansion rate per inch of heat wave shown by subsurface application. Thus, cooling seemed to play just as important a part in the action of surface extinguishment in this test as in the subsurface application of foam, and high water content of foam becomes much more important than such properties as large volume and high heat resistance, previously thought to be most desirable.

40. Putting the fire extinguishing strictly on a cooling basis, of course, leads to theoretical estimates of how long foam must be applied to supply enough water for the necessary cooling. Samples of foam were taken from the pit after foam injection through the oil with no fire and analyzed for water content to give a fairly accurate estimate of the water volume actually reaching the oil surface. The average water content was analyzed to be 23.0% which, with a foam volume of 47.5 gpm, meant that 60.0% of the water input to the playpipe was effective in reaching the surface and enough water to extinguish a fire with a 2-inch heat wave, i.e., 7 gallons, could be provided in 34 seconds of operation. Such a value assumes a perfect distribution of water and other ideal conditions. Therefore, to allow for such imperfections, an arbitrary factor was used, increasing the time of foam injection from 34 to 60 seconds.

41. To test out this theory of the addition of the correct amount of water (by means of foam) to lower a fuel oil to below its flash point, a burning test was made in the fire pit. After burning 10 minutes to give a hot oil layer of 2 inches, the injection of foam began and was continued for a period of one minute then halted, although the fire still burned vigorously. The flames soon began to abate, however, and in 3-1/2 minutes, without any further addition of foam, complete extinguishment was accomplished. The froth of 12 inches depth formed by the expansion of hot oil quickly disintegrated, leaving a clean oil

surface with no indication of residual foam and thus eliminating any possibility of a foam blanket being present to affect a smothering.

42. In these tests oil burning in the cracks and fissures of the concrete fire pit where foam and water could not reach it always added considerably to the time required for complete extinction of a fire.

43. Samples of oil taken at various times from the fire pit showed that the oil increased greatly in viscosity as the lower boiling fractions were consumed by fire. The viscosity of unused oil was 41.70 seconds (Saybolt-Fural) compared to 95.57 seconds for oil which had been burned a total of 1 hour and 19 minutes. The pour point increased from approximately 15°F to approximately 30°F on this sample. No results in the fire testing seemed to be affected by these changes and since the effect will be lessened in the burning of oil in large tanks and the changes in constitution of the oil are independent of the foam system used, they are unimportant except where a limited source of oil for test fires necessitates repeated firing of the same oil volume.

FULL-SCALE TESTS OF SYSTEM,

44. Preliminary Tests in Oil-Filled Tank. Concurrent with the studies of this method of extinguishment at the Laboratory a bolted steel tank was being erected at the Naval Fuel Depot, Penniman, Virginia, according to our specifications for an adequate standard-sized oil tank which could be used for foam tests and a fire test of this application of foam. It was placed in such a location that it could be filled and emptied at will during the tests by the regular oil transfer equipment at the station, yet the firing of its contents would not endanger surrounding installations. (See Plate 13) The tank itself is an *ADVANCE* base 10,000-bbl bolted steel tank remodeled by welding two 8-foot rings on top to give a maximum oil depth of 40 feet. In order to compensate for this added stress a concentric shell two rings high was placed around the tank and filled with water.

45. Foam stations were provided at points 150, 300 and 600 feet distant from the tank, each with connections to attach four branchpipes through swing check valves into the 12-inch product line. It was planned that a large number of tests would be made before the fire which would yield important data for correlation with the Laboratory small-scale tests. Unfortunately, this could not be done at this time because of operational difficulties and also because of possibly excessive contamination of the oil with water before the fire test.

46. Two of the several foam injection tests on the tank were quite successful, yielding data of considerable importance. In order to present the values obtained and to compare them with

those obtained in the Laboratory, the following tabulation has been compiled. Conditions in Test No. 4 were exactly the same as during the fire and these values closely represent what was occurring during the extinguishing period.

Animan Test #1

Oil Depth.....	12 ft.	Ratio:	Imposed Pressure
Injection Station....	150 ft.	Full-Scale Test	Lab. Test (data
No. of Branchpipes		Small-Scale Test	taken from curves
Used.....	4 No. 10's		plate 8)
Branchpipe Back-			Oil Depth - 5 ft.
pressure.....	5 psi		Imposed Backpressure -
			5 psi

Oil Depth.....	1 in.	----	----
(1/2 tank area)			
Sampling Time.....	75 sec.	----	----
Total Surface Foam.....	750 gal.	----	----
Surface Foam,			
gpm, per No. 10.....	150	.394	381
Surface Foam			
gpm/sq.ft.....	0.252	----	----
Total gpm Water Input			
at Product Line.....	560	----	140
Total gpm Water at			
surface (by analysis)....	126	----	35
gpm Water per No. 10			
at Surface.....	31.5	.371	85
gpm Water at Surface			
per square foot.....	0.053	----	----
Average Analyzed % Water			
at Surface Layers.....	21	.933	22.5
Initial Average % Water			
in Foam.....	20.5	----	20.5

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Penniman Test #4

Tank Oil Depth.....	32 ft.	Ratio:	Imposed Pressure
Injection Station..	600 ft.	Full-Scale Test	Lab. Test (data
No. of Branchpipes		Small-Scale Test	taken from curves
Used.....	4 No.10's		plate 3)
Branchpipe Back-			Oil Depth - 5 ft.
pressure.....	15 psi		Imposed Backpressure -
			15 psi
Foam Depth.....	2 in.	----	----
umping Time.....	7 min.	----	----
Total Surface Foam.....	3000 gal.	----	----
Surface Foam,			
gpm, per No. 10.....	107	.398	269
Surface Foam,			
gm/sq.ft.....	0.130	----	----
Total gpm Water Input			
at Product Line.....	560	----	140
Total gpm Water at			
Surface (by analysis).	150	----	93.5
gpm Water per No. 10			
at Surface.....	37.5	.401	93.5
gpm Water at Surface			
per Square Foot.....	0.063	----	----
Average Analyzed % Water			
at Surface Layers.....	35	1.03	34.0
Initial Average %			
Water in Foam.....	37.5	----	37.5

47. It may be seen by a perusal of the above tabulated data that a very nearly constant relationship existed between the full-scale tests and the small-scale laboratory tests. This was one of the most important results of the Penniman testing program as it proved that an easily constructed and controlled laboratory arrangement could be utilized for reproducing conditions found in large tank farm installations. With the exception of the percentage water at the surface, which was exactly reproduced, the values found in the large-scale work bore a relationship of 0.4 to those determined in the small-scale laboratory tests.

48. Several other basic principles are to be noted from this data: (1) The percentage of water retained in the foam does

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not vary with the length of passage of the foam through oil. That is, foam which had 37.5% water as it left the branchpipe still possessed 34% water whether it traveled through 5 feet of oil in the laboratory small-scale test or through 600 feet of oil at Penniman. (2) The water bearing property of the foam was greater when the foam was generated against 15 psi backpressure; thus, more water was brought to the surface per minute in Penniman Test No. 4 even though the length of oil passage increased from 162 feet to 632 feet. (3) When foam was injected against a fixed backpressure, the loss in water volume (and foam volume) reached a maximum at a point between 5 feet and 162 feet of travel through oil and remained constant through a travel of 632 feet. (4) The pressure loss due to friction in forcing the foam through the product line amounted to about 3 psi/1000 feet.

49. In arriving at these values or any values which denote a water content of the foam or oil layers after foam application without fire, it must be remembered that there is a continual drainage of water from the foam downward into the oil or into the new foam which has come to the surface beneath the old foam. Consequently, the sampling procedure must be conducted in such a manner that it is the new foam arriving at the oil surface that is obtained. Additional work must be done on this question at the Laboratory but there appears at this time to be a fixed relationship between the rate of water drainage and the type of foam compound used.

50. During these tests without fire, it was thought desirable to increase foam production by use of the No. 20 branchpipe. This piece of equipment did not prove satisfactory because in use the foam backflow was excessive to a point where it piled up, blocking the air inlet and thus preventing proper operation. Changes in design will be necessary to make this unit operate successfully.

51. Full-Scale Fire Test. Final preparations for the test fire in the tank were made when it was seen by the tests of foam injection through oil that adequate amounts of water were reaching the surface of the oil. The only change in the arrangements for the conduct for the extinguishment of the fire was one necessitated by the fact that the inductor tanks were found to have insufficient capacity when more than one branchpipe was operated from each tank. The multi-jet inductor tanks were connected one to each pump and each tank then fed two No. 10 forcing branchpipes installed on the product line 600 feet from the tank, as will be seen by an inspection of Plates 14, 15, 16 and 17. The detailed installation of this unit is typified by the photograph on plate 16.

5. It was planned that the oil in the tank would be allowed to burn for 15 minutes to generate about a two-inch heat wave for an efficient test of the method. However, the overall ignition of the oil surface was slow, partly due to old foam

remaining from the previous day's tests, and it was seen that about five minutes were necessary for ignition to be complete over the entire surface. To compensate for this, it was decided to defer foam application for an additional five minutes; but when it could be seen that the tank was bulging badly at the fire line and the plates buckling, thus imperiling the entire test, it was decided to revert to the original plan of adding foam 15 minutes after ignition.

53. The actual progress of the fire and its extinguishment can best be followed by the examination of the Kodachrome 16 mm silent film titled, "Extinguishment of a Fuel Oil Tank Fire by the New Method of Subsurface Foam Application", which was prepared in cooperation with personnel of the Photographic Science Laboratory, Naval Air Station, Anacostia, D. C.

54. For the purposes of this report the following log of the events directly connected with the fire is given:

10:40 Six hundred thousand gallons Navy Special fuel oil giving a 32-foot depth in tank with an 8-foot outage touched off with two gallons gasoline from side opposite product line entry. Wind about 3 mph NE.

(See Plate 18, Photograph A)

10:42 Fire spreading over complete area of tank rapidly.

(See Plate 18, Photograph B)

10:45 Fire now coming from complete surface of tank. Flames about thirty feet high.

(See Plate 18, Photograph C)

10:47 Flames generating on edges of tank then circling to center and combustion occurring with maximum height of about sixty feet above tank top. Black smoke voluminous, ascending about one hundred and fifty feet and trailing to SW.

10:50 Top ring of tank beginning to buckle out of shape and plates within one foot of flames swelled outwards noticeably. No visible rupture however.

(See Plate 18, Photograph D)

- 10:55 (Total burning time - 15 min.)
Foam injection began with NRL
equipment. Red smoke signal set
off to photographers and air camera
for start of recording.
(See Plate 19, Photograph A)
- 10:59 (Foam injection - 1 min.)* Flames
increasing somewhat in intensity.
Black smoke slightly diminished.
Branchpipe backpressure - 15 lbs.
- 10:59.5 (Foam injection - 1.5 min.)
Intensity of flames and smoke
decreasing.
- 11:00 (Foam injection - 5 min.) Sudden
flare-up of fire and smoke about
equal to original intensity.
- 11:00.5 (Foam injection - 5.5 min.) Fire
being diminished. Flame and smoke
appeared to part in center and
slight steam column visible.
- 11:01 (Foam injection - 6 min.) Fire
quite visibly diminished. Approx-
imately only one-half of area covered
with flame and smoke. Other part of
area evolving steam clouds.
- 11:01.5 (Foam injection - 6.5 min.) Fire
practically out, some black smoke
in windward side of tank top. No
increase in oil level shown by
heat-indicating paint.
(See Plate 19, Photograph B)
- 11:02 (Foam injection - 7 min.) Tank top
area evolving steam over entire sur-
face. No flame visible, slight wisps
of black smoke evolved at various
points on side of tank.
(See Plate 19, Photograph C)
- 11:02.5 (Foam injection - 7.5 min.) Fire
completely extinguished. Steam and
vapors evolving from entire surface.

* This includes a three-minute measured time
lag for foam traversal of 600 feet product
line before reaching tank.

- 11:03 (Foam injection - 8 min.) Steam and vapor volume decreasing rapidly. Tank cooling.
(See Plate 19, Photograph D)
- 11:05 (Foam injection - 10 min.) NRL equipment and foam generators stopped. Approximately 200 gallons British Foam Fluid consumed over ten-minute period of subsurface foam injection.
- 12:05 (One hour after cease of foam injection.) Personnel inspected and photographed foam layer on surface of oil in tank. Two inches of clean foam remained on entire oil surface. This layer when disturbed with a paddle showed its solidity, breaking up only in chunks and the surface thus exposed was closed up by foam within seconds of time.
(See Plate 20, Photographs A & B)
-

55. A very interesting group of pictures was taken from the air during the fire test by photographic personnel from the Photographic Laboratory, Naval Air Station, Norfolk, Va. These show excellent air photography and are best viewed in sequence. (See Plates 21 through 28)

56. Inspection of the inside of the tank one hour after the fire showed that expansion of the hot oil had undoubtedly taken place when subsurface foam had contacted it during the fire. (See Plate 20) However, this "wet oil mark" was irregular in height, it being highest on the side at which ignition was initiated (opposite the product line entry). The variation in height was from a minimum of 4 inches to a maximum of 8 inches. This phenomenon pointed to an existence of a heat-wave of irregular depth, it being greater on the oil surface initially ignited where the burning time was greater by about five minutes.

57. Because of the difference in rates of foam addition between the Laboratory fire tests and the large-scale test it does not appear that the value of 6 to 8 inches expansion per inch of heat wave may be applied to this test. Unfortunately, the heat-indicating paint stripe could not be observed from the 600-foot station and no thermocouples were attached to the tank so that conclusive data as to the depth of hot-oil encountered by the subsurface foam is missing.

58. The tank appeared to be in good condition following the fire. (See Plate 29) An interesting observation was the manner

in which the leeward half of the inside of the tank was badly scaled with oxide while the windward half was covered with a heavy carbon layer.

59. Comparison with British Fire Tests. Based on the latest available information, the U. K. Petroleum Board report dated May 1942, the British have conducted three full-scale tests comparable to the test at Penniman. Generally speaking, amounts of material used and the times for extinction were less than the NRL values. Although their fires were more severe because of longer burning, other factors such as distance of foam injection from tank, tank diameter, and oil depth were not as exacting.

60. In their first reported fire test a "light grade" fuel oil was used in a steel tank 40 feet in diameter and 26 feet high, the oil being 24 feet deep. After burning 15 minutes the fire was attacked with one No. 10 branchpipe which was connected directly into the bottom of the tank. This fire was completely extinguished in 5 minutes of operation consuming about 30 gallons of compound. Their next test most closely approximated the NRL full-scale test. A fuel oil similar to Navy Special (Pool Fuel) 24 feet deep in the above mentioned tank was allowed to burn freely for 38 minutes at which time foam was introduced through 75 feet of 6-inch pipe by one No. 10 branchpipe. As the temperature was below freezing, difficulties arose from the freezing and choking of the inductor jets which necessitated a shut-down after 6 minutes of operation. A second No. 10 branchpipe was then connected into the system and when foam generation was ready to be resumed, the fire had been burning 61 minutes. Within 5 minutes of operation the fire was reduced to an occasional flickering around the edges where the high wind prevented the foam from closing, and for this reason foam was added for another 5 minutes to insure complete extinction. Total estimate of foam compound used for the successful application was equal to 92 U. S. gallons. A second test was run on the same oil a few days later in which the oil was allowed to burn freely for 60 minutes before foam was injected. After 1-1/2 minutes of application a slop-over occurred, necessitating a 20-minute shut down to extinguish the ground fire. On resuming the foam injection a second slop-over occurred, causing a 5-minute delay, but with the third attempted application of the foam the fire was extinguished in 1-1/2 minutes. This entire operation, including work on the ground fires, required only 36 U. S. gallons of compound. These times of injection seem remarkably short when compared to the Penniman test in which four No. 10's were operated 7 minutes on a fire 15 minutes old. One important factor influencing this was, no doubt, the volume and length of the Penniman product line through which the foam was forced, where, although the 600-foot length of 12-inch line was probably not filled to its 3500-gallon capacity, 3 minutes, or about 50% of the total time of extinguishment, was required for foam to reach the oil surface. All Penniman apparatus was of the same type as used by the British except for necessary thread adaptations. However, the method used by them for replenishing

the compound supply in the inductor tank is not known.

61. A viewpoint expressed in the British report is that the water in the oil causes slop-overs when foam is applied by this method. Before their second test on the Pool Fuel, several days had elapsed, during which time rains had caused an increase in the water content of the oil, raising it to 0.9%, and they believed this responsible for the slop-overs which occurred during the foam addition. In all our Laboratory fire tests no variations in expansion of the hot oil were observed, even though the water content varied from 0.05% in tests with new oil to 5% in tests where the oil had been previously fired. A surface sample of oil taken just before the fire at the Penniman test ran 0.3% water content. The slop-overs which occurred in the British tests would seem to have been caused by factors not evident in their report. It is important to state the conditions under which the sampling is done as the water varies greatly with the depth and time of standing. It has been found that when an excess amount of water has been added at the surface, this variation amounts to an increase of about 0.5% water per foot of depth starting from the surface.

62. Their analyses for oil content of samples of foam taken after it had passed through the oil varied considerably from NRL values. In a British test where foam was forced through 402 feet of 6-inch line into a tank containing "vaporizing oil" 28 feet deep, foam samples were taken which analyzed approximately 11% water and 2% oil. (No specifications were given for this "vaporizing oil" but it must be an oil lighter than Navy Special. In the NRL tests the foam after passing through 6 feet of Navy Special contained about 20% water and 30% oil immediately after injection stopped. These values, as stated previously, are undergoing constant change because of rapid drainage; therefore, the conditions of sampling should be noted when it is desired to compare investigations.

SUMMATION AND CONCLUSIONS

63. The descriptive data in the foregoing pages represents a detailed scientific investigation of a new procedure of fighting oil tank fires. This method lends itself to a factual analysis and an exact treatment which, to our knowledge, has not been possible with most of the existing oil fire extinguishment methods and materials in use today.

64. Fundamentally, this new extinguishment procedure is based on the use of the large heat-absorbing property of water in its transformation from the liquid to the vapor state. This water is applied at the point in the burning system where the system is most vulnerable to any heat-dissipating mechanism. Heretofore, because of the greater specific gravity of water compared to that of petroleum hydrocarbons, this attack has only been carried out from a direction which, as a simple calculation

will show, involves the opposition of 96 to 98% of the total heat evolved by the fire. In this new method a buoyant agent in the form of air-containing foam is added to the water and released at a point that allows it to impinge on the lowest, and thus coolest, point in the fire system. Additionally, in petroleum hydrocarbon fires in which oils with diverse boiling points are encountered, when this function of the water in the foam has been utilized and the total heat of the system has been decreased, the buoyant foam then reacts in the commonly regarded manner of a sealing agent, preventing the escape and consequent reignition of any combustible vapors.

65. A calculation of the heat evolved in the burning of a fuel oil such as Navy Special shows that 9000 BTU per minute of burning are evolved per square foot of burning surface. As this burning process goes on, a layer of hot oil, at 500°F by our measurements, is produced directly under the surface. In order to reduce the temperature of this hot oil to 175°F (or below its flashpoint) a total of 310 BTU per inch of hot oil per square foot of surface must be dissipated. Simply, then, the water requirements per square foot will necessitate the addition of 0.02 gallons of water per minute to absorb the constant evolution of 9000 BTU's from the fire alone, plus the amount of water required to cool the hot oil or 0.09 gallons per inch per square foot. Thus the addition of water by means of foam to the extent of 0.11 gallons water per minute per square foot would extinguish a fire with a hot oil depth of one inch in one minute's time. In actual practice a safety factor of about 2 is desirable.

66. It follows then that with rates of water addition by means of the foam being a constant because of capacity limitations of apparatus the time of extinguishment varies with the hot oil depth generated by the fire previous to foam addition.

67. Because of these considerations of water content exposed to a fire and volumes of foam per unit area and time, some important conclusions may be experimentally proven for any given tank system as to the degree of its protection by laboratory investigations on a small scale and analysis of its performance.

68. The present picture of the efficiency of this method in terms of water supplied to the tank and water brought to the surface useful for heat dissipation is not too bright a one. Our tests show that only 22 to 27% of the water added to the tank in the form of foam arrives at the surface after 162 feet of oil passage. The reader is cautioned against regarding the foam loss (which is in the order of 90%) as the critical factor judging this system.

69. Analyzing the causes for this 73 to 78% water loss it becomes evident that the major loss occurs in the passage of the foam through some distance below 162 feet of oil since the loss does not proportionately increase when it travels through 632 feet

of oil. Furthermore, the water loss due to backpressure increase is negligible since the total volume per unit generator is the same even when the pressure was increased threefold in the Penniman tests.

70. The question of slop-over tendency of this method has been studied at the Laboratory using constant rates of water addition which resulted in expansion ratios of 6 to 8 inches per inch of hot oil, but it is thought that this ratio will vary slightly with rates of foam addition. However, it is well to remember that any contact of water in a foam with hot oil, if it is to accomplish a useful purpose, will result in a similar expansion whether it is applied from the top or the bottom.

71. Perhaps one of the most unexpected results of the large-scale testing of this method was the distribution pattern of the foam rising to the surface of the oil in the tank. Despite the low calculated inlet velocity of the foam of 1.3 feet per second entering the tank, its distribution was uniform over the surface of the oil in both 12 foot and 32 foot depths when viewed from the top of the tank. This remarkable distribution obviates the occurrence of any local actions during a fire which might result in a loss of efficiency.

72. It has been suggested that it would be useful for purposes of this report to tabulate the relative materials and equipment necessary to extinguish a fire in a 55-foot diameter tank filled with Navy Special fuel oil using the standard chemical foam applied by one overhead foam chamber in one instance and a projected installation for subsurface-applied foam in the other.

73. The following listing is merely for rough comparison purposes since this Laboratory is not in a position to be able to recommend chemical foam installations for tank fire protection.

	<u>Chemical Foam Installation</u>	<u>Subsurface Foam Installation</u>
Foam Generating Apparatus	1 Fixed Foam Chamber, 1 Hopper	4 No. 10 Branchpipes, 1 Fluid Inductor
Water Volume & Pressure	200 gpm Water at 100 psi	560 gpm Water at 120 psi
Intake of Foam Material	200 lbs/min Powder	16 gpm Fluid (128 lbs.)
Storage Excess of Material	8000 to 15000 lbs	1000 gal. Fluid (8000 lbs)(960 gal. Fluid/2 hrs preburn time)
Foam Material Needed to Extinguish Fire	2000 to 4000 lbs	Dependent on Burning Time
Manpower Necessary for Operation	5 Men	2 Men

74. It becomes apparent by the above rough comparison that, using quite liberal estimates of the amounts of standby material necessary in the subsurface method, no great savings in weights can be expected by its installation. However, it must also be remembered that this method is extremely reliable and certain in its action, requiring no fixed apparatus or heat-damageable fittings for its dissemination, thus decreasing the possibility of requiring excessive amounts of material in reserve.

75. It is to be emphasized in considering estimates of materials and equipment needed for tank fire protection, as dealt with in the foregoing paragraphs, that such estimates are made using the apparatus and foam fluid which were imported for our tests. It is much to be hoped that continued research by the Laboratory will evolve newer and more efficient systems for this purpose.

76. However, it is believed that protection will be installed using this apparatus for the present. Consequently, using the data we have at hand, provided by the large-scale fire test and the Laboratory results, a rather interesting nomograph has been prepared, by the use of which a number of factors may be instantly calculated if the tank diameter and time of burning be known. (See Plate 30)

77. Again it is to be noted that the above correlation of information is an estimating guide, using what facts have been collected, for the purpose of arriving at some recommendations of the amount of material and equipment necessary for the protection of different sized tanks filled with Navy Special fuel oil.

RECOMMENDATIONS FOR THE FUTURE PROGRESS OF THIS INVESTIGATION

78. Perhaps the most important line of development of this process of tank fire protection is the study of foam-forming agents which will be capable of increased water retention and stability in contact with petroleum hydrocarbons. Evidence has been gathered in our research that the maximum water volume which the British-manufactured foaming agent is capable of retaining, even on contact with only 5 feet of oil, is only about 66% of the original water volume. This is not stable under greater lengths of passage through oil, and it should be possible to decrease by a great amount the 30% loss in water volume which occurs in traveling through 162 feet of fuel oil.

79. The stability under storage of this foaming agent must also be improved. In its present form some undesirable reactions occur in storage which result in the formation of insoluble matter in the container in which it is kept. It is not known at the present time whether this is harmful to the desired qualities of the foam fluid.

The question of susceptibility of the foam fluid to a

change in constitution upon exposure to freezing conditions is also a matter for important study.

80. The procurability of a suitable foam-forming agent for this system of protection will of course influence the entire picture of its usefulness, but it is not too optimistic a viewpoint to assume that no difficulty will be encountered in obtaining the necessary materials in this country. In fact, it is not impossible that when further testing gets underway, it will be found that one of the presently manufactured foam agents in use for surface application of foam in this country is completely satisfactory for this method.

81. Another very fruitful course of investigation is concerned with the question of the usefulness of this method for the protection of a low boiling-range hydrocarbon, such as Diesel oil. It has been said that this subsurface application is of little use in the protection of liquids of comparatively high vapor pressure. The efficiency of this method may also be found reduced in cases of cold weather storage of high viscosity oils such as Bunker "C" where the resistance to flow of the buoyant foam is too great to allow it to rise rapidly to the surface.

82. In connection with the apparatus and equipment necessary for the induction of the foam fluid into the water stream and its subsequent injection against pressure differences, the Laboratory has under design and construction a much improved form of injection apparatus. It is hoped that this will be more efficient in its generation of foam and pumping it through the oil.

83. The improvement of the method of introducing and metering the foam-fluid into the water stream is another difficult problem which must have immediate attention. Obviously the type of fluid induction used in the British system which required a 120 psi pressure difference between pump suction and pressure discharge is of little use where pump suction is taken from hydrants varying from 40 to 70 psi. To perfect this method of induction so that it becomes positive and foolproof will require a well designed unit which can only be produced by maximum thought and effort.

84. Undoubtedly, a great number of future developments of this system of tank fire protection will suggest themselves in the mind of the reader of this report. Many alluring combinations of mobile and fixed equipment are possible, which will give, we think, a much more complete and satisfactory protection to above-ground oil tanks at a lower financial cost than is possible by present-day chemical installations. However, these details are beyond the scope of the present study, but it is hoped they will be dealt with in the due course of the investigation.

ACKNOWLEDGEMENTS

The Laboratory wishes to acknowledge at this point the foresight and determination of Captain F. C. Bedell, USN, formerly of the Radio, Marine Corps and Storage Division, Bureau of Yards and Docks, who initially was responsible for the subjection of this broadly contested system of fire protection to scientific scrutiny and its ultimate proof in practice.

A correspondingly large measure of credit is due to his successor in office, Lieutenant Commander E. E. Saunders, USNR, and Mr. M. A. Spamer, whose constant cooperation and effective assistance in many of the details of the large-scale program of testing made possible its successful completion.

Many separate Naval and industrial organizations have been connected with the conduct of this research since its inception and it is desired that the appreciation of the Laboratory be conveyed to personnel from the following groups for their efficient cooperation:

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Pyrene Manufacturing Co., Newark, N. J.

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APPENDIX I

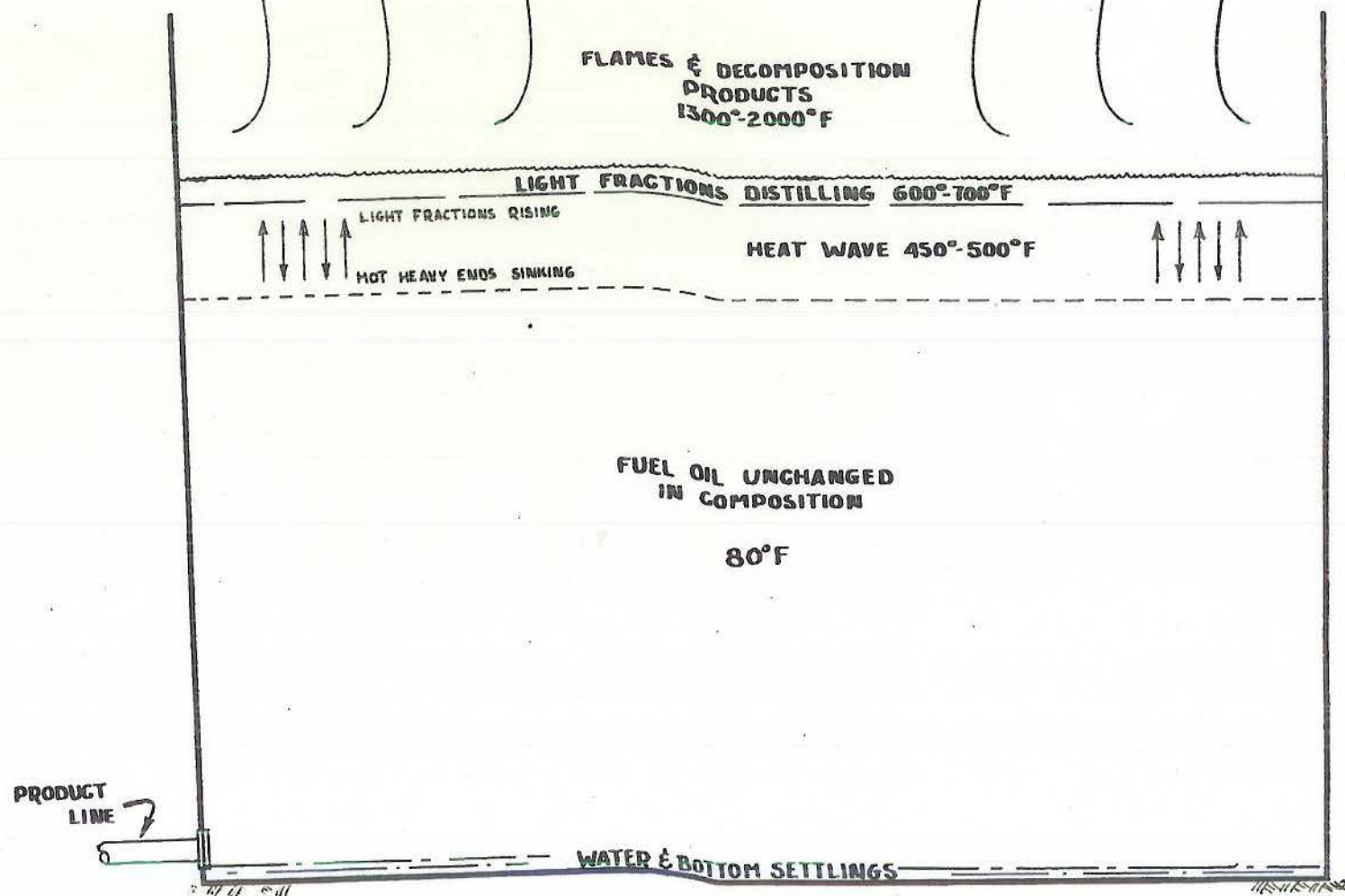
Test	Limit	Limit	Limit	Method No.	
	Special	Grade I	Grade II	F.S.P.	A.S.T.M.
Flash point, closed cup, degrees F., minimum	150	150	150	110.22	D93-40
Fire point, degrees F., minimum	220	220	---	110.33	D92-33
Viscosity, SSF, at 122°F., maximum	25	65	300	30.43	D88-38
Water, percent, maximum	0.12	0.12	---	---	---
Water, by distillation, percent, maximum	0.5	0.5	1.0	300.13	D95-40
API gravity, numerical, minimum	10.0	10.0	---	40.1	D287-39
Cloud point, degrees F., maximum	15	50	---	20.15	D97-39
Carbon residue, percent, maximum	15.0	15.0	---	500.13	D189-39
Sediment by extraction, after refluxing, percent, maximum	0.12	0.12	---	300.2	---
S. and W. by centrifuge after refluxing, percent, maximum	0.5	0.5	---	300.32	D96-40
Sediment by extraction, percent, maximum	---	---	0.25	300.2	---

APPENDIX I

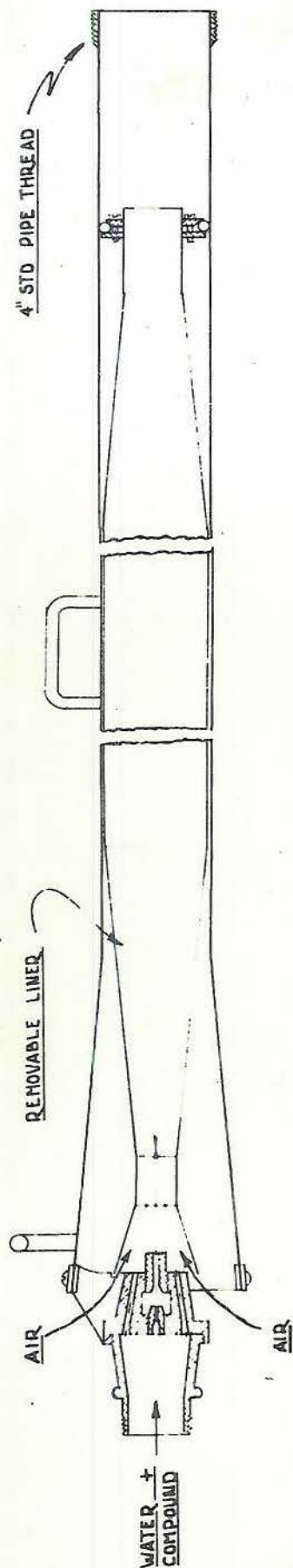
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DECLASSIFIED

PLATE 1



MECHANISM OF HEAT WAVE PROPAGATION
IN FUEL OIL TANK FIRES



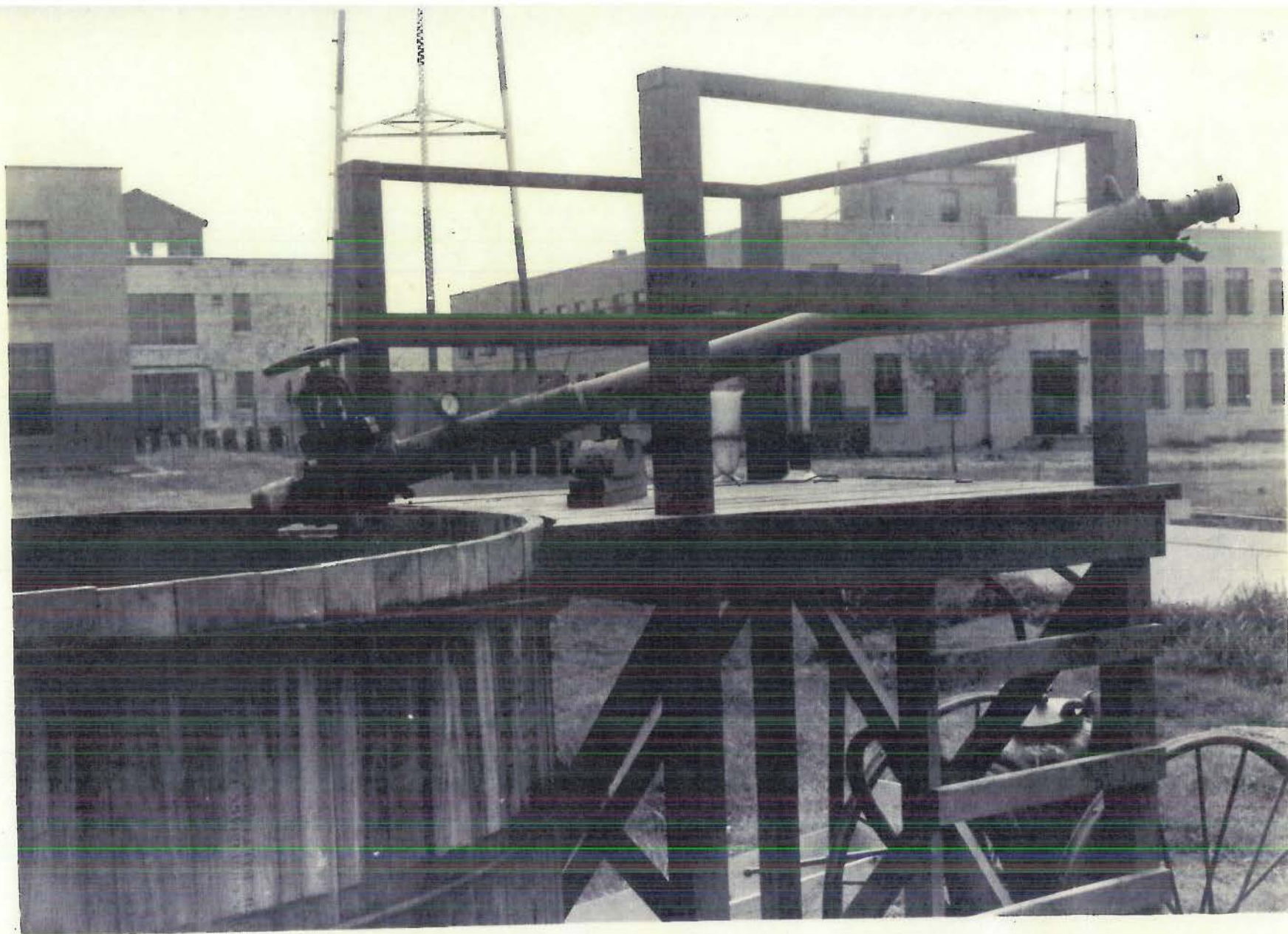
N° 10 FORCING TYPE BRANCHPIPE

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PLATE 2

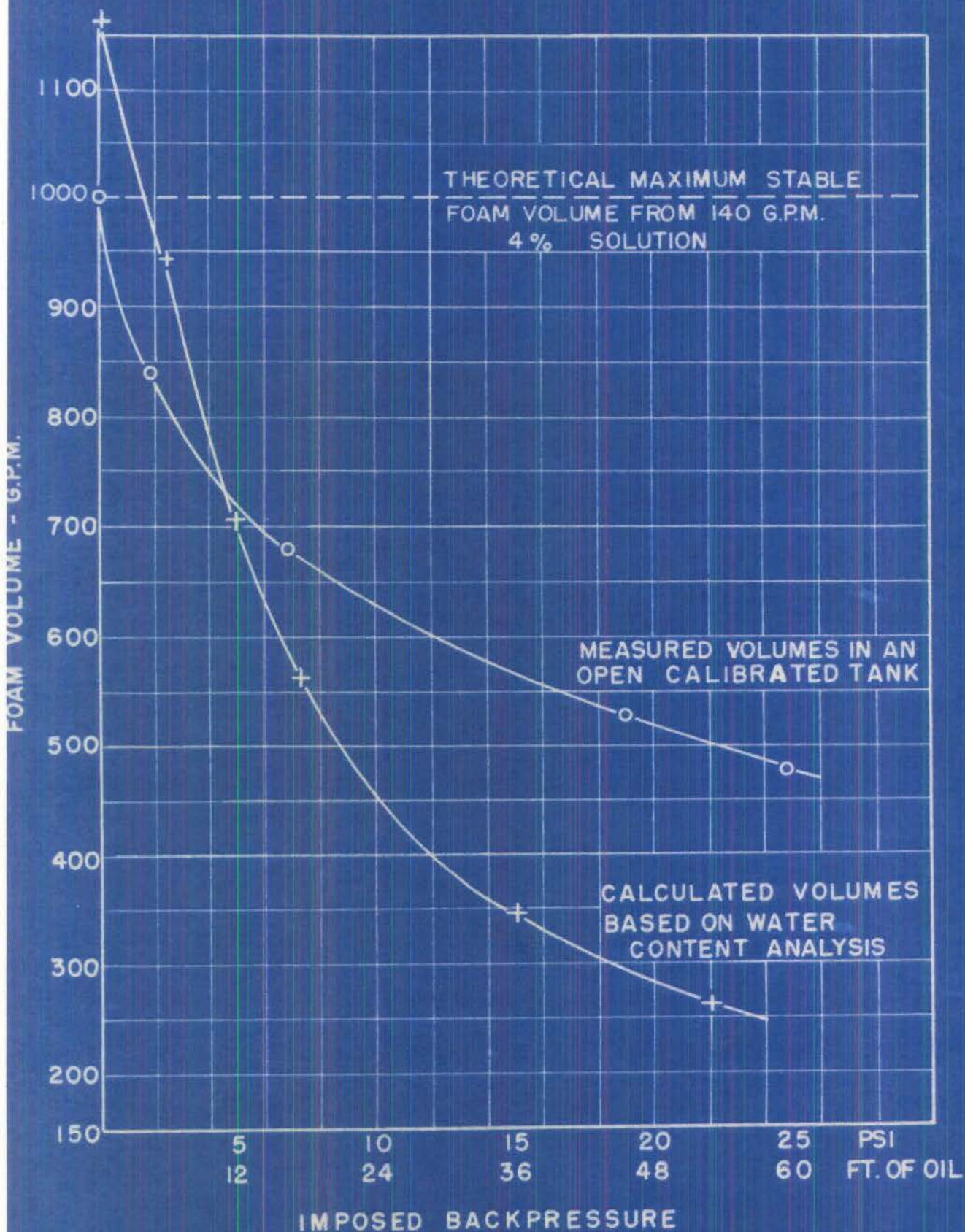
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PLATE 5

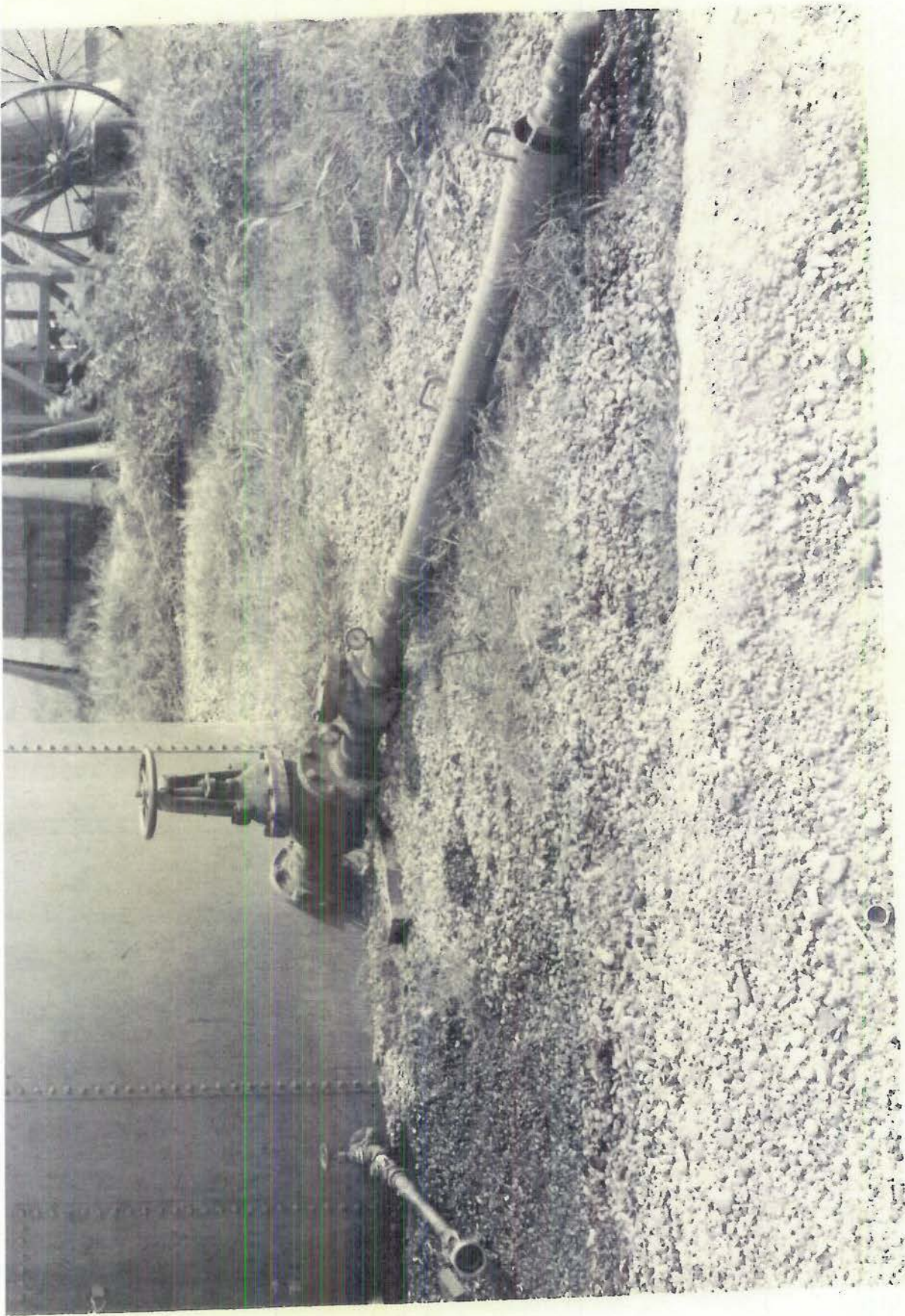


CALIBRATED FOAM VOLUME MEASURING TANK SHOWING BRANCHPIPE IN TEST POSITION

CAPACITY NO. 10 BRANCHPIPE
WHEN OPERATED AGAINST
IMPOSED PRESSURE



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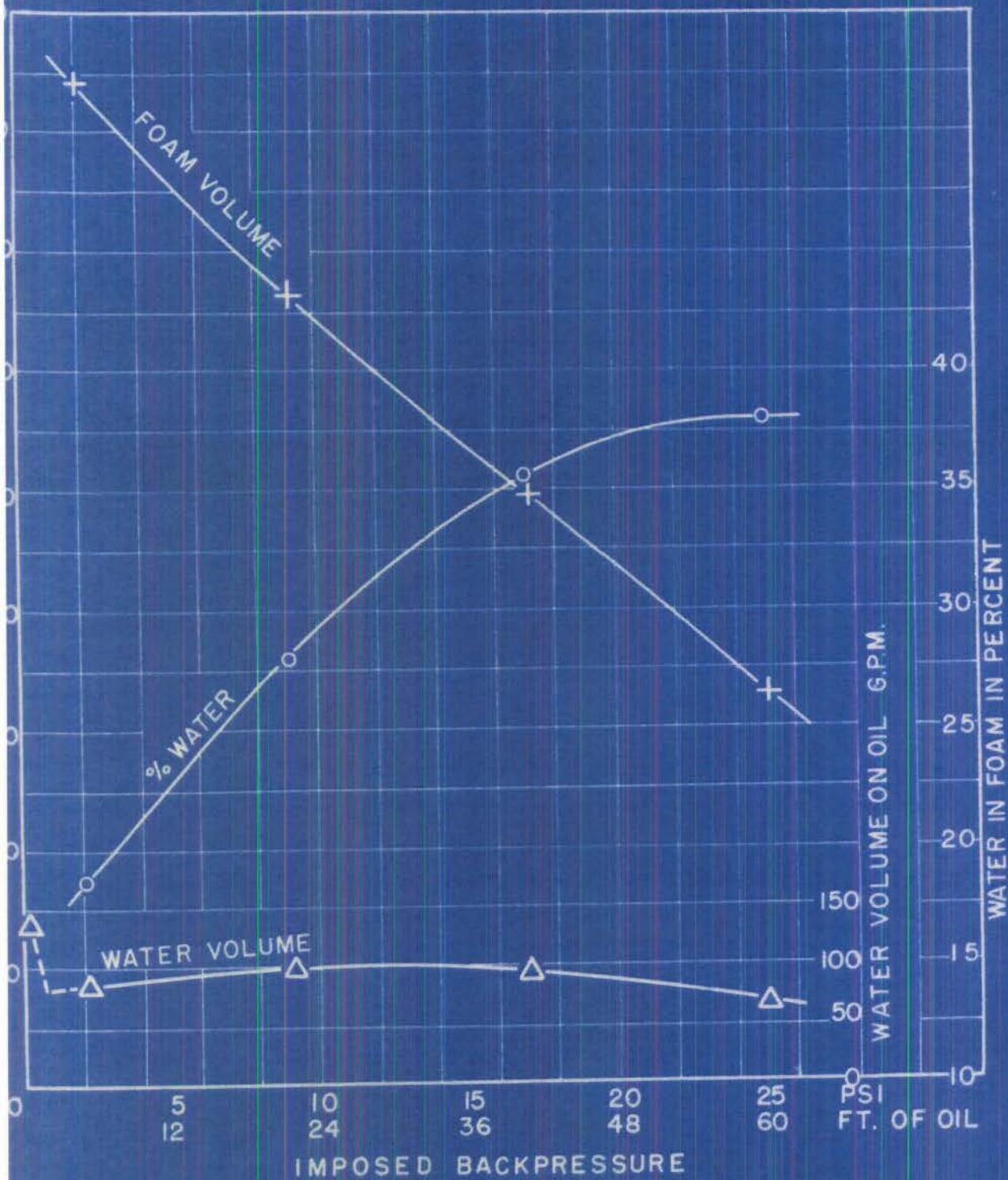


ATTACHMENT OF #10 BRANCHPIPE & AMERICAN PLAYPIPE TO 100 BARREL
BOLTED STEEL TANK CONTAINING A FIVE FOOT OIL DEPTH

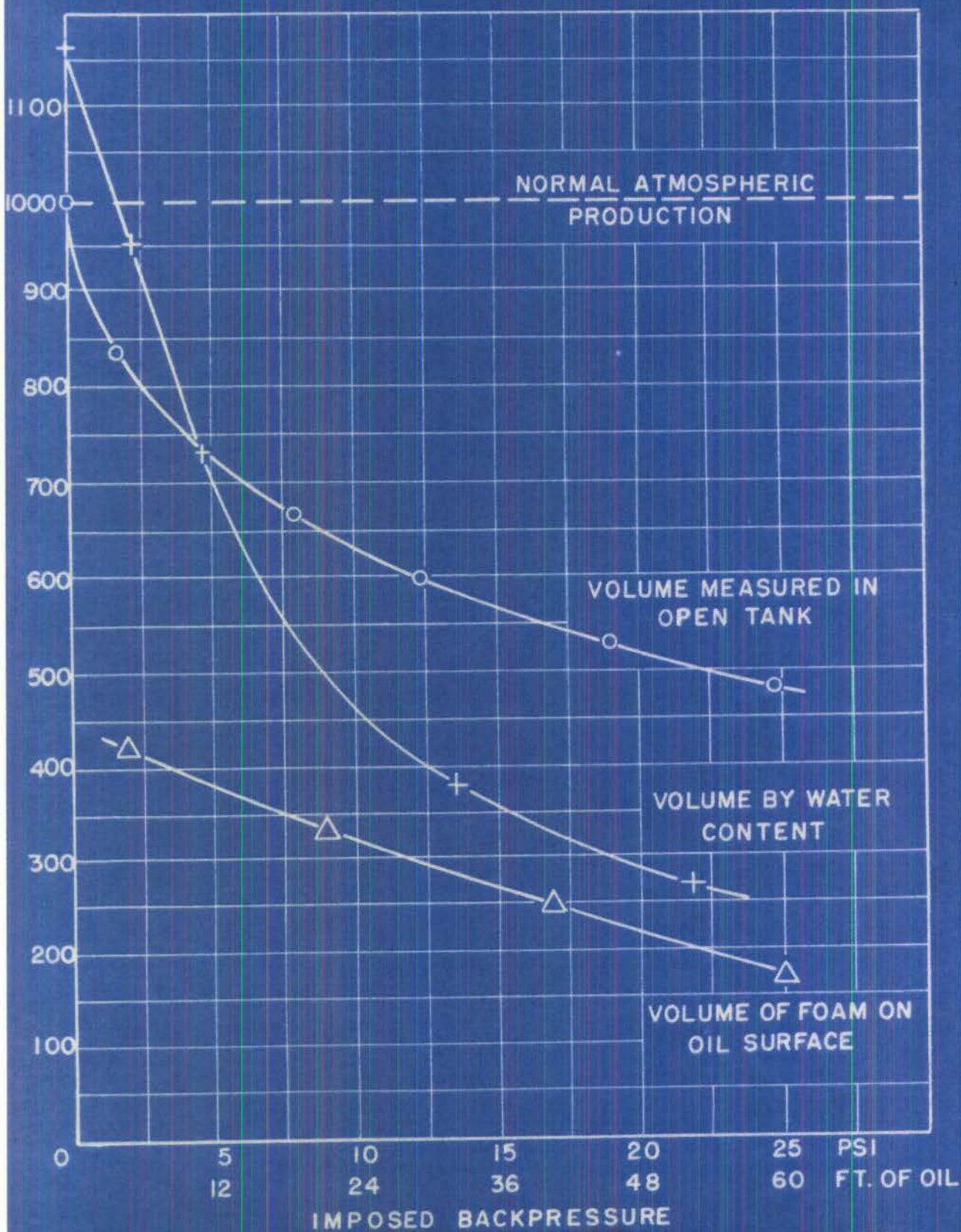
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PLATE 7

CAPACITY OF NO. 10 BRANCHPIPE
WHEN OPERATED AGAINST
IMPOSED PRESSURE AND THROUGH
FIVE FEET OF OIL



ISOLATION OF LOSSES OCCURRING
WITH NO. 10 WHEN OPERATED
AGAINST BACKPRESSURE AND
THROUGH FIVE FEET OF OIL





EXPERIMENTAL TEST FIRE TANK

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PLATE 10

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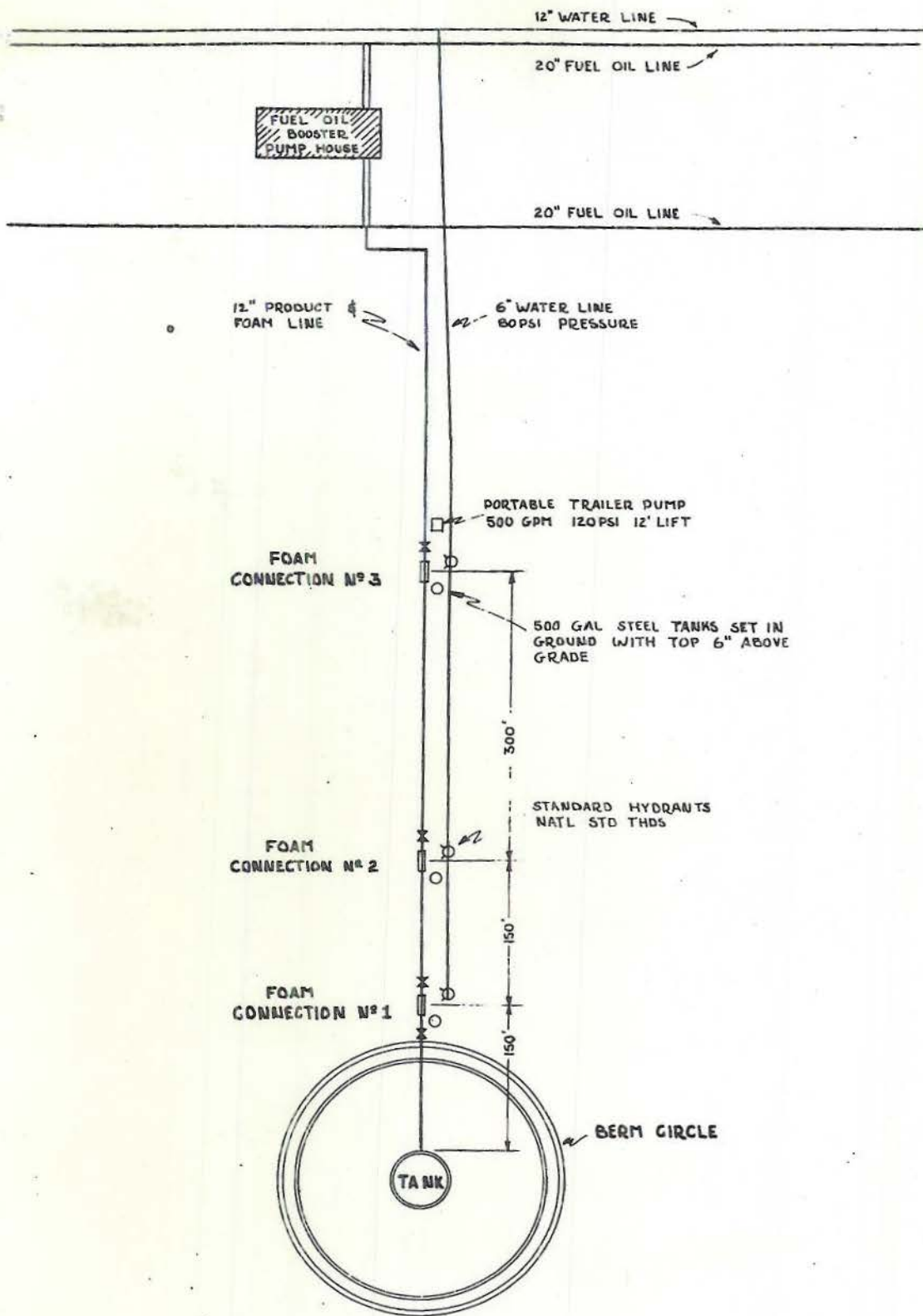
PLATE II



1m. 40s. AFTER FOAM START

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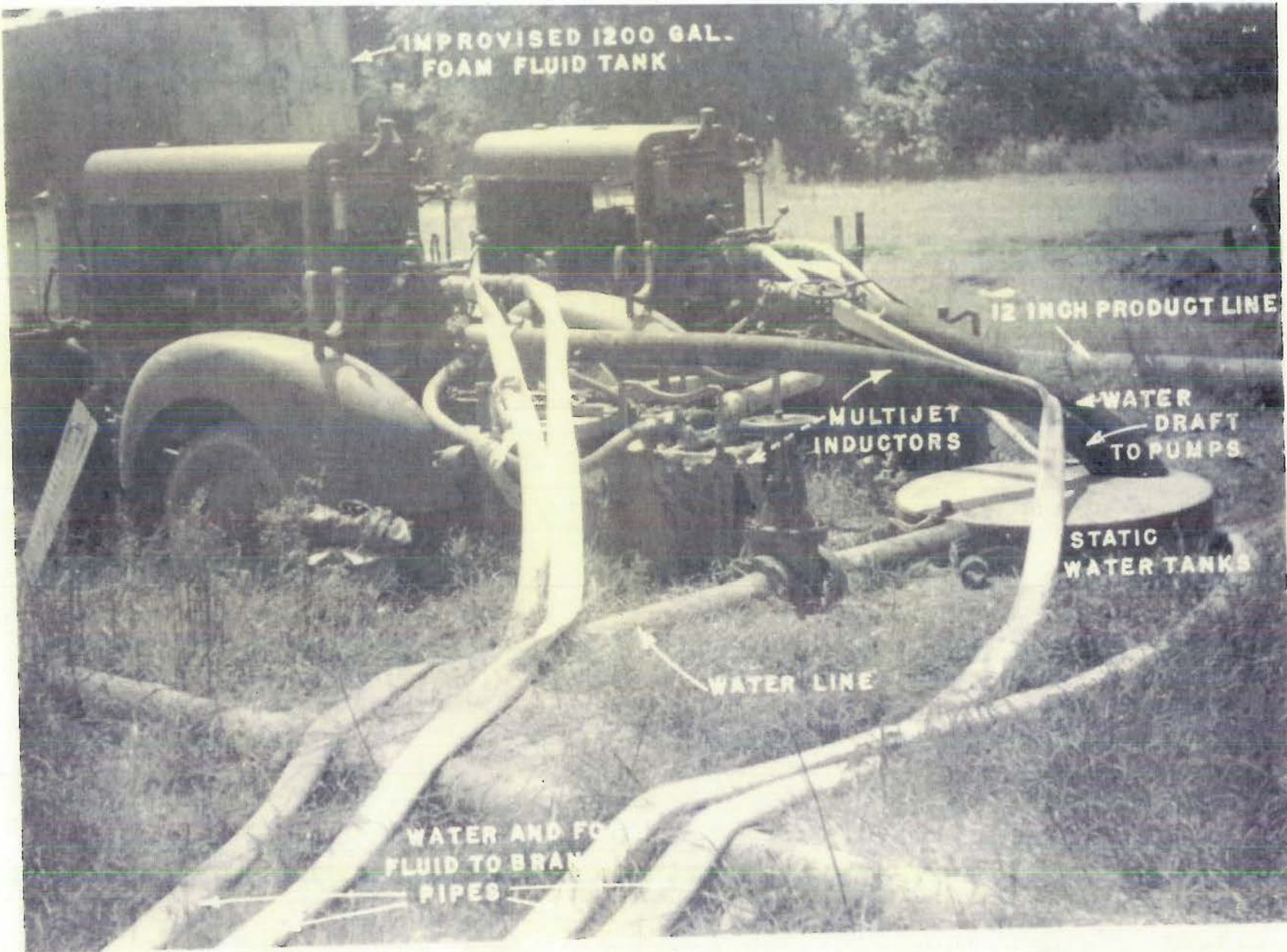
PLATE 12



TEST TANK LAYOUT AT PENNIMAN SITE

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PLATE 14



INSTALLATION OF PUMPS AND FOAM FLUID INDUCTORS NEAR FORCING BRANCHPIPES

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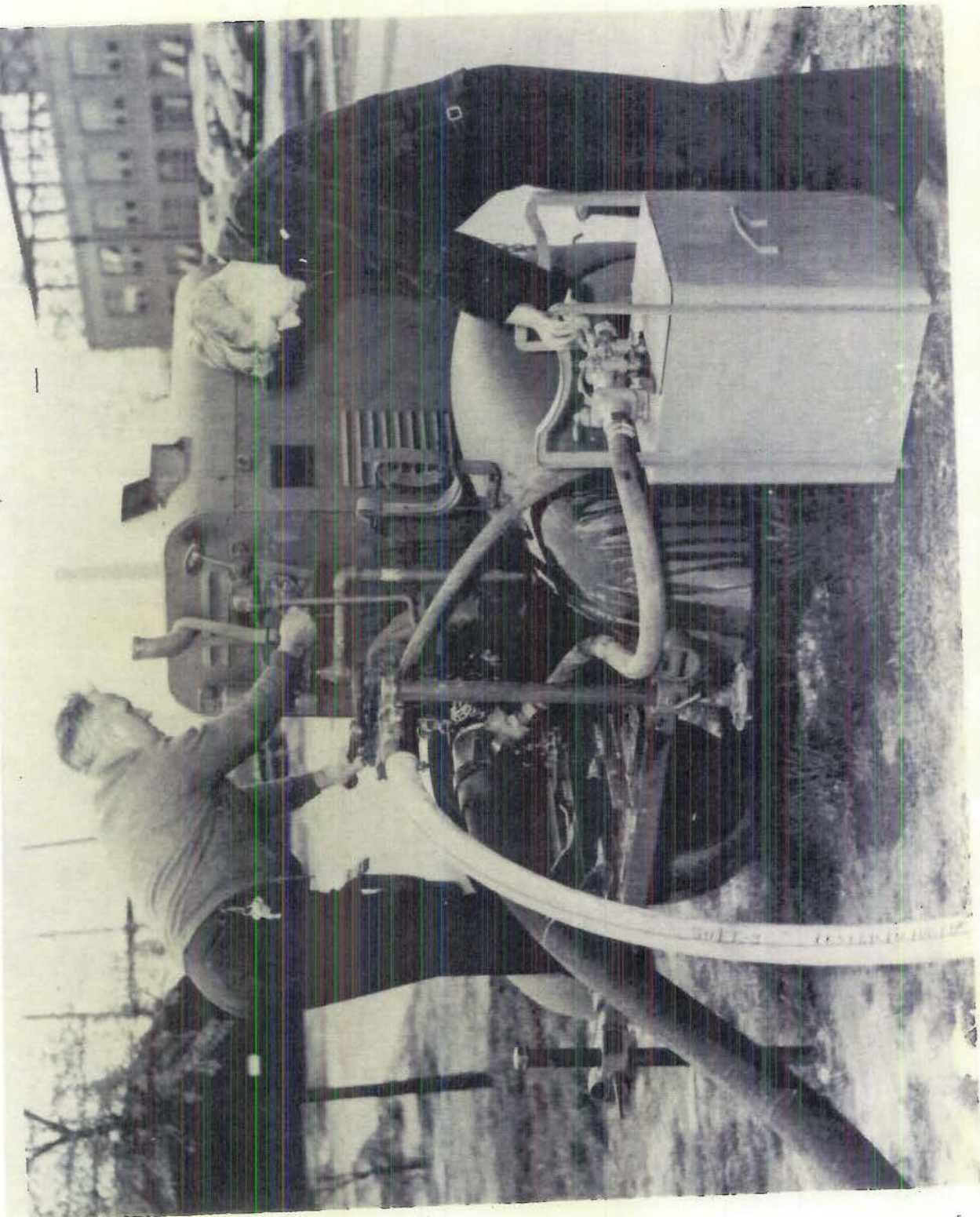
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PLATE 15 :

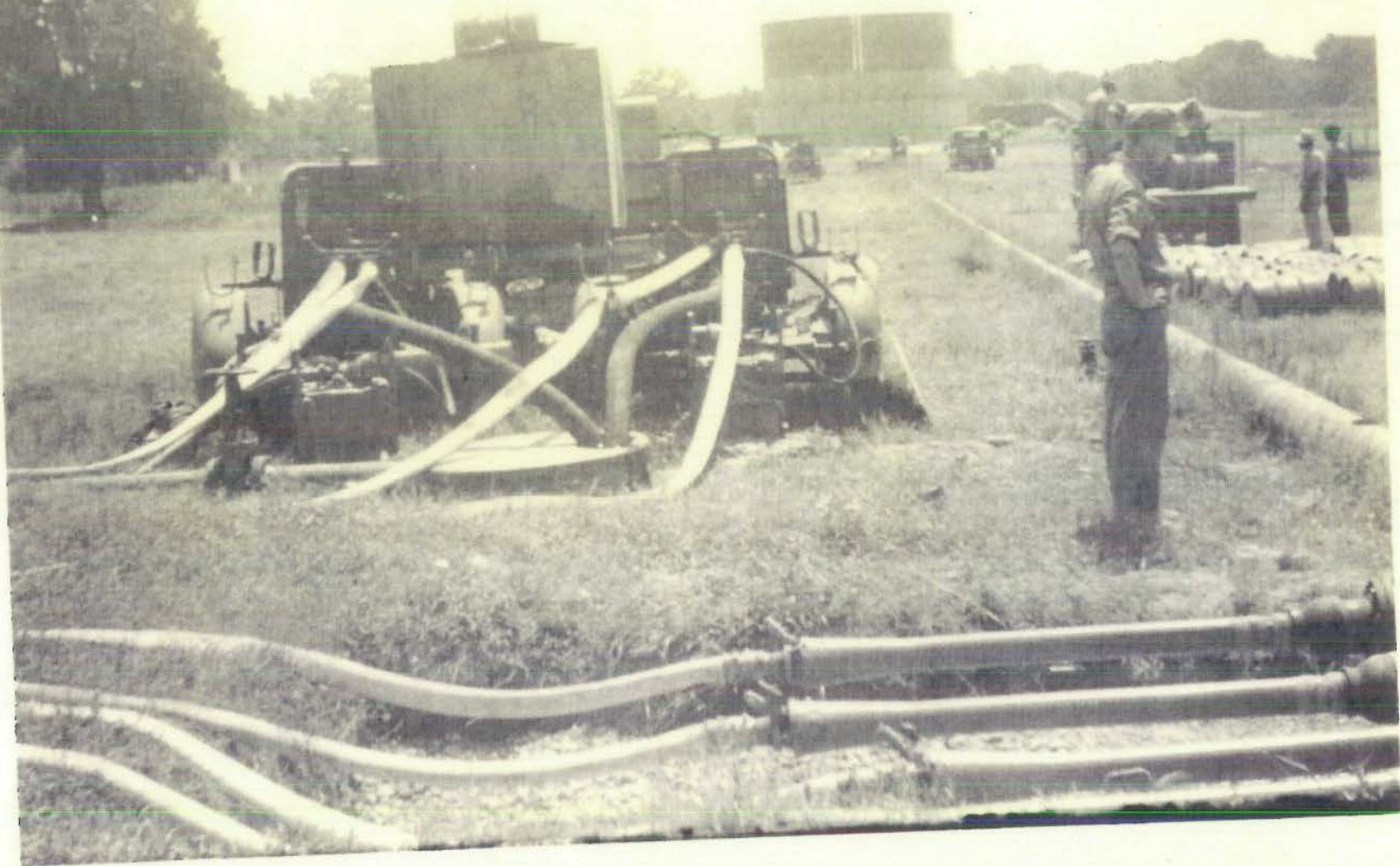
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PLATE 16

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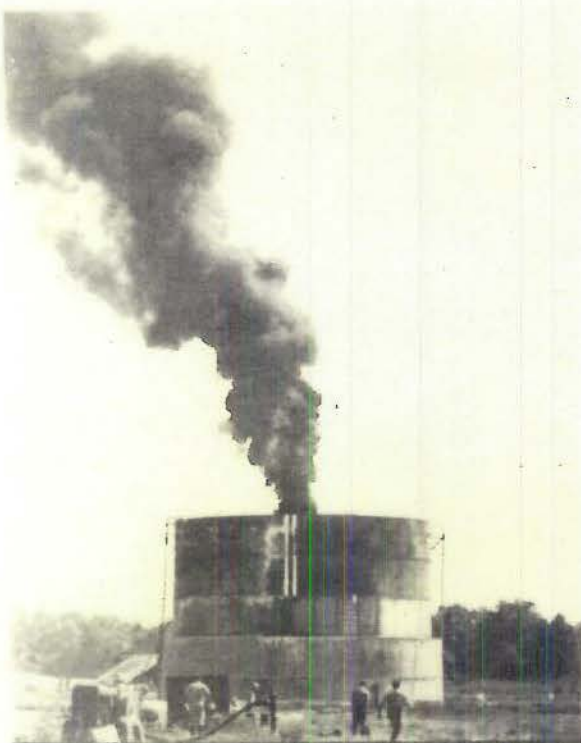


SUBSURFACE FOAM APPLICATION INSTALLATION SHOWING 600-FT. PRODUCT LINE TO TANK

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PLATE 17

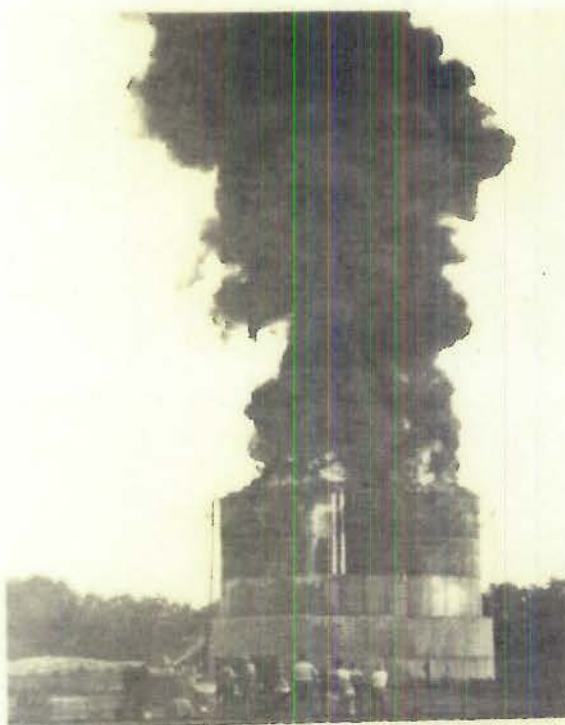
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A. Ignition of oil with gasoline.
Note heat-indicating paint.
Auxiliary fire crew in foreground



B. Fire after about 3 min.
burning time.



C. Six min. after ignition.
Note vapor path to center.

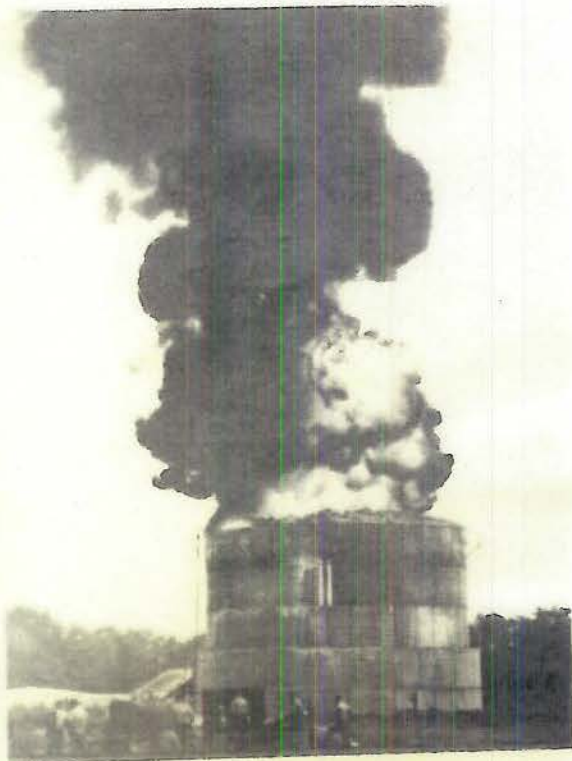


D. About 10 min. after ignition.
Flame line visible at bottom of
top ring.

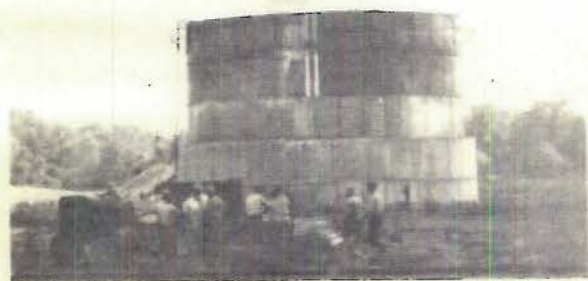
DECLASSIFIED

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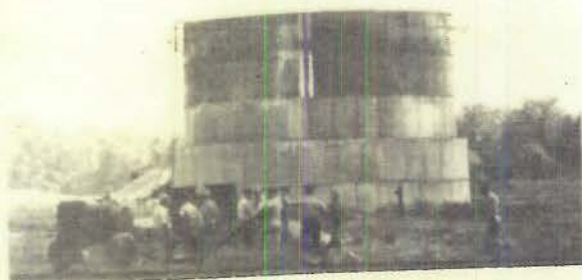
LIBRARY
PAWL RESEARCH LABORATORY



A. Appearance of flames after 15 min. burning. Foam applied.



B. Foam applied for 6.5 min. Some fire at rear of tank top.



C. Foam applied for about 7 min.



D. Tank after foam had been applied for 8 min.

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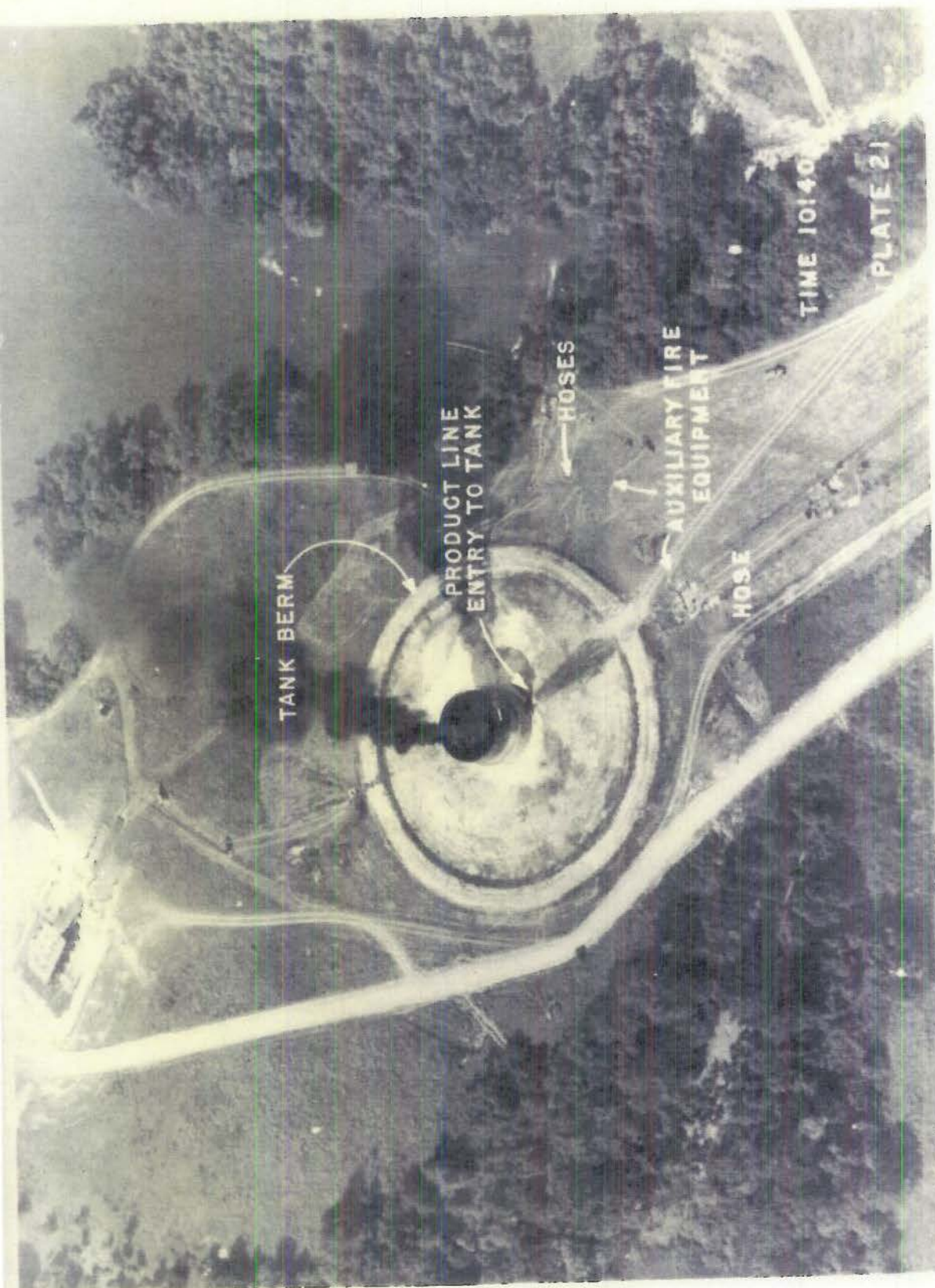


A. Appearance of surface of oil after excess foam had covered fired area.



B. Closeup of disturbed foam blanket (above) showing setup of foam one hour after generation.

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TIME 10:40

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PLATE 21



TIME 10:42

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PLATE 22

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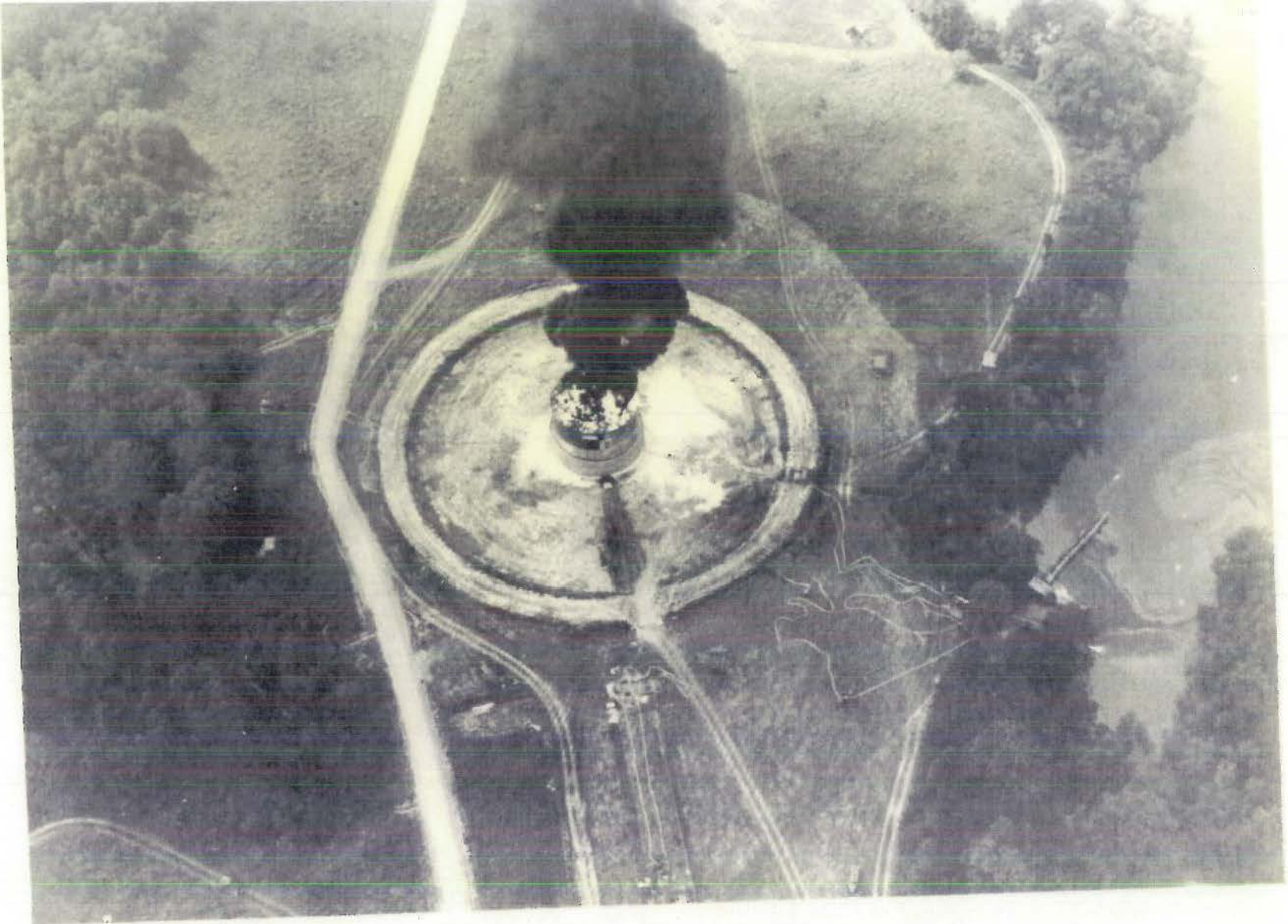


TIME 10:43

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PLATE 23

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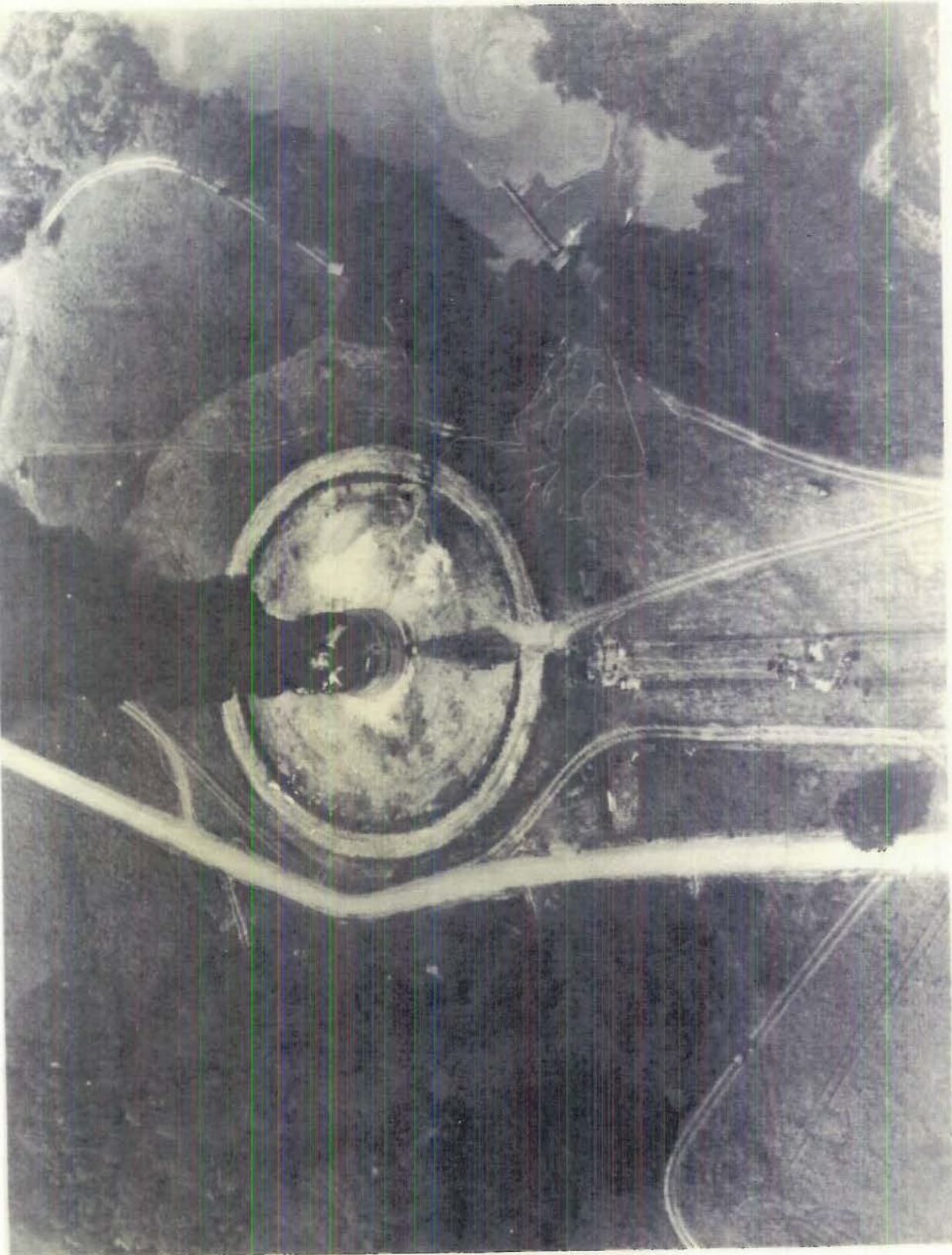


TIME 10:55 (FOAM START)

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PLATE 24

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TIME 10:59

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PLATE 25

DECLASSIFIED



TIME 11:01.5

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PLATE 26

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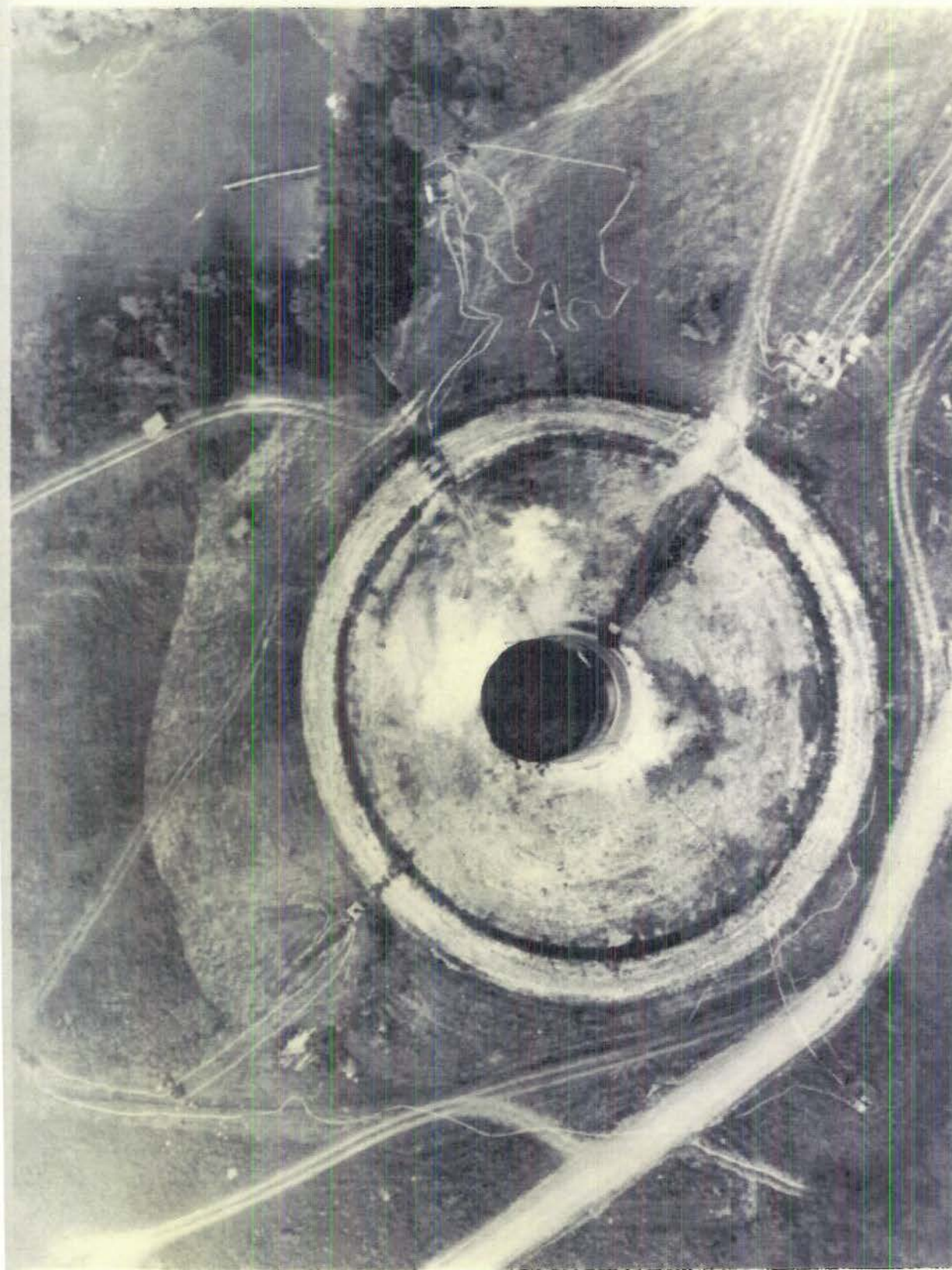


TIME 11:02.5

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PLATE 27

DECLASSIFIED

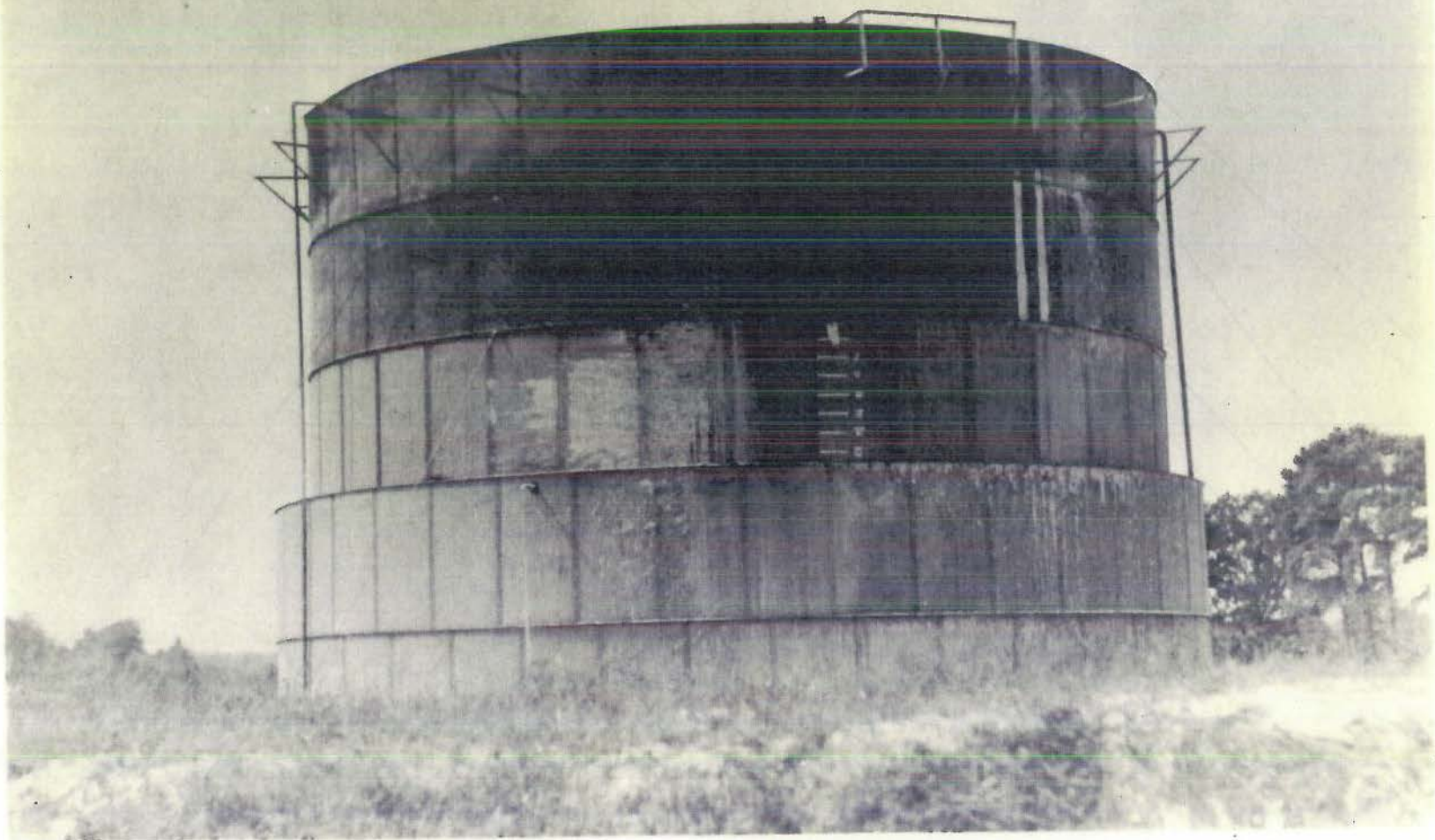


TIME 11:05

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PLATE 28

DECLASSIFIED



PHOTOGRAPH OF TANK AFTER FIRE

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