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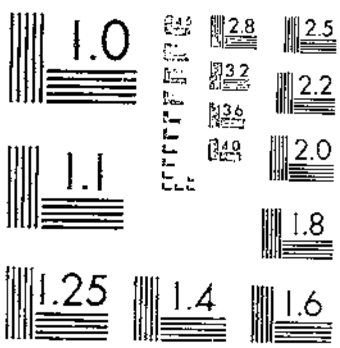

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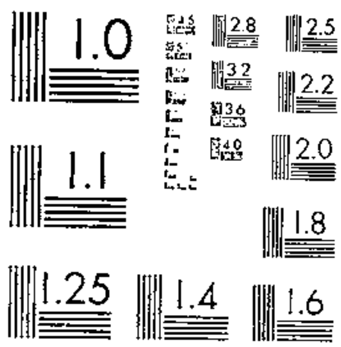

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APPLICATION OF STEAM IN THE STERILIZATION OF SOILS

By Arthur H. Senner

Associate mechanical engineer, Division of Structures, Bureau of Agricultural Engineering

CONTENTS

INTRODUCTION

Soil sterilization [1] as a means of protecting a crop against certain soil-borne diseases is practiced by greenhouse vegetable growers throughout the country. It is also an effective method of combating the nematode, and for the control of certain insects which pass part of their life cycle in the soil. Vegetable growers generally sterilize the soil once a year; it is advantageously done in midsummer between crops. Sterilization of soil by steam is considered the most effective and most economical method.

The earliest use of steam for soil sterilization apparently dates back to 1893. At that time W. N. Rudd, of Greenwood, Ill., effected sterilization by placing soil in a large bin and admitting steam through perforated pipes located at the bottom of the bin. Since that early application of steam sterilization the technic has pro-

[1] The term "sterilization" is not strictly correct since all the micro-organisms are not necessarily killed.

68836°—34——1

gressed through several stages of development, each apparently showing marked improvement over the preceding one.[2]

COMMON METHODS OF STEAM STERILIZATION

THE STEAM RAKE OR HARROW

The steam rake or harrow is one of the earliest devices utilized for soil sterilization. A framework of pipe is made of a size and shape to fit the beds, and into these pipes are screwed teeth, made of small-size pipe, similar to the teeth of a coarse rake. These pipes which form the so-called "teeth" are closed at the ends by flattening. The steam is emitted through small holes drilled through the pipe teeth near the lower end. The small pipes are about 6 inches long and placed about 6 inches apart in each direction; they are forced into the soil to the desired depth of sterilization. The apparatus is supplied with steam by means of a hose, and the steam finds its way into the soil through the small holes referred to above. Generally there are either two rakes used in a single house or four rakes operated in pairs, end to end, in adjoining houses. The rake ordinarily consists of three main pipes which run crosswise of the house. During the operation, a heavy canvas cover is laid on the beds to prevent the rapid escape of steam.

THE BURIED-PIPE SYSTEM

In the buried-pipe method several perforated pipes of about 1½-inch size are connected to a common header and buried to a depth of about 6 inches. After the bed has been sterilized the pipes are taken up and used in another bed. The perforations are one-eighth or three-sixteenths of an inch in diameter, spaced 12 to 15 inches apart along the bottom of the pipe. When steam is turned on the beds are covered with a heavy canvass to retain the heat and steam. The number and length of the pipes are determined by the size and shape of the beds but, of course, are limited by the available boiler capacity. This method of sterilization is effective but the labor required to bury and change the pipes is large. Time can be saved by utilizing two sets of pipes, one set being moved to a new location while the steam is turned on in the other.

THE INVERTED-PAN SYSTEM

In the inverted-pan system an inverted pan is placed over the soil to be sterilized and steam is admitted to the pan at a pressure

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[2] For more complete descriptions of the practical details of soil sterilization, see the following publications:

BESSEY, E. A. ROOT-KNOT AND ITS CONTROL. U.S. Dept. Agr., Bur. Plant Indus. Bull. 217, 78 pp., illus. 1911.

——— and BYARS, L. P. THE CONTROL OF ROOT-KNOT. U.S. Dept. Agr. Farmers' Bull. 648, 19 pp., illus. 1915.

BROWN, H. D., BALDWIN, I. L., and CONNER, S. D. GREENHOUSE SOIL STERILIZATION. Ind. Agr. Expt. Sta. Bull. 266, 27 pp., illus. 1922.

GODFREY, G. H. ROOT-KNOT: ITS CAUSE AND CONTROL. U.S. Dept. Agr. Farmers' Bull. 1345, 27 pp., illus. 1923.

JOHNSON, J. STEAM STERILIZATION OF SOIL FOR TOBACCO AND OTHER CROPS. U.S. Dept. Agr. Farmers' Bull. 1629, 14 pp., illus. 1930.

NEWHALL, A. G. CONTROL OF ROOT-KNOT NEMATODE IN GREENHOUSES. Ohio Agr. Expt. Sta. Bull. 451, 60 pp., illus. 1930.

——— and CHUPP, C. SOIL TREATMENTS FOR CONTROL OF DISEASES IN THE GREENHOUSE AND THE SEEDBED. N.Y. Cornell Agr. Coll. Ext. Bul. 217, 59 pp., illus. 1931.

only slightly above atmospheric. The pan is generally made from 6 to 9 inches deep. The size and shape of the pans vary according to the size and arrangement of the beds in the greenhouse. The pans used in practice today vary in area from approximately 30 square feet to about 110 square feet. Some of the larger and heavier pans are raised by a mechanical hoisting device and transferred from one position to another by some form of conveyor. The pans are usually made of metal varying from 20-gage to 14-gage material. The type which is transported manually is of course provided with lifting handles.

THE BURIED-TILE SYSTEM

There is apparently a definite trend toward the use of buried drain-tile laid with open joints. Steam is admitted to the tile by means of a pipe header which is in turn fed by the steam-distribution system. There are two general tile methods, the temporary system and the permanent system. In the temporary system several lines of tile are buried at a time. After sterilization of a plot is completed and the tile are cool enough to be handled, they are dug up and used over and over in similar fashion until the entire area to be sterilized has been covered. The tile ordinarily used is common 3- or 4-inch drain-tile and is laid to a depth of approximately 14 inches and spaced approximately 18 inches on centers.

In the permanent system, the tiles are buried and permitted to remain in the soil indefinitely. After years of service it may become necessary to reset some of the tile or to replace some which have become broken due to the effect of excess steam pressure or other cause. Both 3- and 4-inch tile have been used with apparently equal success. The buried-tile system entails the highest initial outlay but the labor required for the process is the least of the several systems.

PHYSICAL PRINCIPLES INVOLVED IN STEAM STERILIZATION

The factors of steam pressure and moisture content of the steam are introduced into almost every discussion of soil sterilization. While some investigators and greenhouse operators have regarded high-pressure steam[3] as essential for satisfactory soil sterilization, this view is not borne out by the known physical properties of steam. Regardless of the initial pressure of the steam, its final pressure when it comes in contact with the soil is always approximately atmospheric. That is, whether the harrow, buried-pipe, inverted-pan or buried-tile plan be used, the pressure of the steam at the point where it is applied for sterilization is only slightly above atmospheric, and for all practical purposes the final pressure may be regarded as atmospheric and its temperature as 212° F., also there is comparatively little moisture in the steam after it expands to the lower pressure. While steam at 150 pounds gage pressure, for instance, is hotter than steam at 10 pounds gage, the steam in either case returns to approximately 212° F. when the pressure is released. In addition, the heat contained in a pound of water in the form of steam is changed very little by raising the pressure.

[3] By high-pressure steam in this connection is meant a boiler steam pressure of 100 to 150 pounds per square inch. Such pressures when judged by the standards of modern power-plant practice are of course decidedly low.

OBJECTS OF INVESTIGATION

The principal objects of this investigation were to find the effect of initial steam pressure on the final moisture content of the soil, the final temperature of the soil, and the quantity of steam needed.

Another point of interest is the effect of the available horsepower on the task of sterilization. For example, the Bureau of Agricultural Engineering has frequently been asked whether there is any appreciable difference in the total amount of steam required to sterilize when a comparatively large boiler horsepower is utilized for a relatively short period as compared with a lesser boiler horsepower when applied for a longer period. Also it is important to know the effect of the rate of steam flow on the resulting pressure of the steam in the tile or under the pan. With a given size and weight of pan and with a given set of soil conditions, the quantity of steam which may be passed under the pan in a unit of time, without heaving the pan, has a definite limit. This limit is reached when the upward force of the steam equals the weight of the pan plus the force of friction of the earth in contact with the pan. In practice, additional weights are generally placed on the corners of the pan.

The pressure developed in the tile is of importance because, as will be demonstrated subsequently, the steam piping system feeding the tile beds can be designed more intelligently when the terminal pressure of the steam is known.

In dealing with saturated steam the maximum attainable soil temperature is definitely limited by the pressure in the tile or under the pan. Some operators have attempted in vain to attain relatively high soil temperatures. From the properties of steam, however, it can readily be seen that in order to attain higher soil temperatures the steam must be superheated [4] to a temperature which is higher than that which corresponds to the pressure in the tile under the pan. The effects of superheated steam on the final moisture content of the soil, the time required, and quantity of steam necessary were studied to a limited degree.

The sizing of distribution mains is evidently important to the man confronted with the design and installation of a steam soil-sterilization system. The test layout described later was therefore designed to yield certain data which would prove of value in a rational design of the piping system.

TEST LAYOUT [5]

The tests were conducted out of doors on a plot of selected soil consisting of a brown fine sandy loam mixed with well-rotted horse manure, so as to approximate a soil frequently found in greenhouses. The mixing was done thoroughly and uniformly with a revolving

[4] Superheated steam is steam, the temperature of which has been raised to a higher degree than that of saturated steam corresponding to its pressure. Steam is superheated by the addition of heat to the steam when it is not in the presence of water in the liquid form. For example in the separately fired superheater used in these tests, the steam after leaving the boiler was passed through an additional set of coils which was heated by an oil burner. Thus the temperature was raised as high as 535° F., which is considerably higher than the temperature corresponding to the pressure at which the steam was generated.

[5] The work was done at the U.S. Naval Engineering Experiment Station, Annapolis, Md., Capt. H. R. Greenlee, officer in charge. The excellent cooperation received from Captain Greenlee and his staff contributed largely to the satisfactory conduct of the work.

bucket-type concrete mixer. Between tests the soil was conditioned by spading and by breaking up the lumps.

The testing bed (fig. 1) was divided into two major sections. Plots 1 to 3, inclusive, were utilized for the tile studies and plots 4 to 12 for studies with the inverted pan. The steam was generated by an oil-fired boiler and maintained constant at the various pressures as required by the conditions of test. The superheater was piped in such

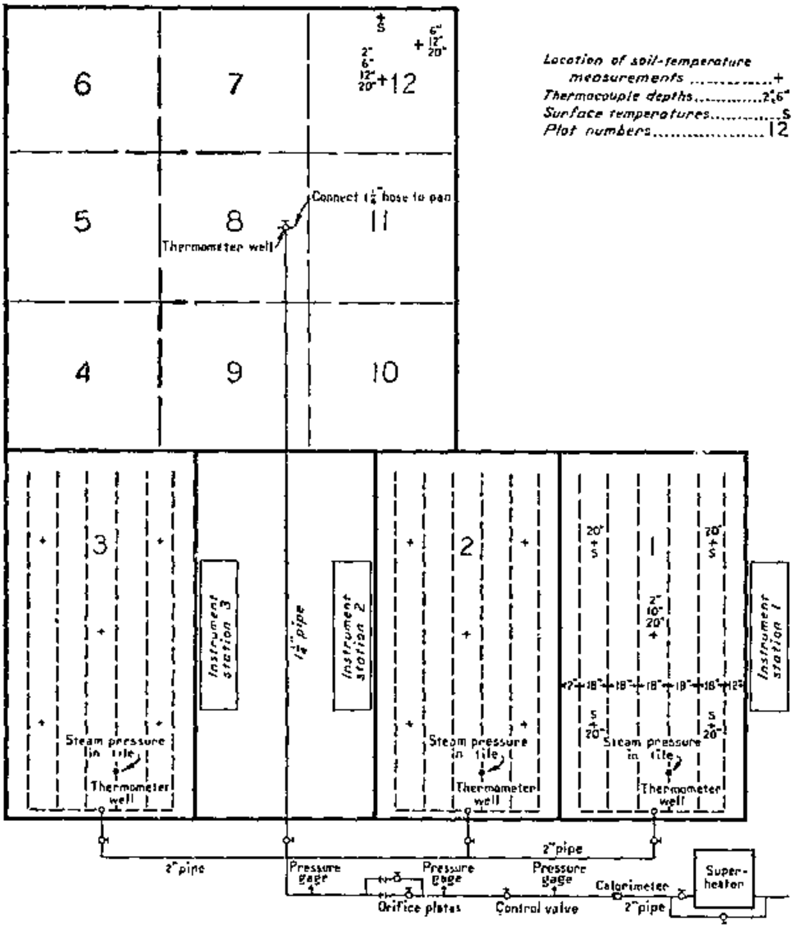

FIGURE 1.—Layout of test plots. Soil temperatures were taken alike in plots 1, 2, and 3, and alike in plots 4, 6, and 12.

a manner that the steam could be passed through it or by-passed around it. The superheater had ample capacity to raise 1,200 pounds of steam per hour to a temperature of 700° F. As may be seen in figure 1, the steam was supplied by a 2-inch pipe and delivered to each of the sterilizing beds by the same size line. Adequate provision was made for valving off any of the individual sterilizing beds. A separate 1¼ inch line, also valved, was provided to deliver the steam to the pan plots. The moisture content of the steam delivered during the test was determined by means of a standard throttling calorimeter located as shown. The line pressure was determined at the point between the calorimeter and the control valve by means of a calibrated test gage. The quantity of steam supplied was computed from a knowledge of the drop in pressure across calibrated orifices installed as shown. This method of measuring the flow of steam proved simple and accurate.

In most instances the pressure after the orifice was less than the so-called "critical back pressure" and the flow could therefore be calculated by means of the simple Napier formula, an explanation of which will be found in any standard textbook of thermodynamics or a mechanical engineering handbook.

The temperature of the steam was determined by means of mercury thermometers at each of the three headers feeding the tile plots and at the end of the 1¼-inch line serving the pan plots. Four-inch tile was laid 18 inches on centers, as indicated in figure 1. It was buried to a depth which gave a 14-inch cover at the steam-supply end and pitched down about 1 inch in 20 feet in the direction of flow of

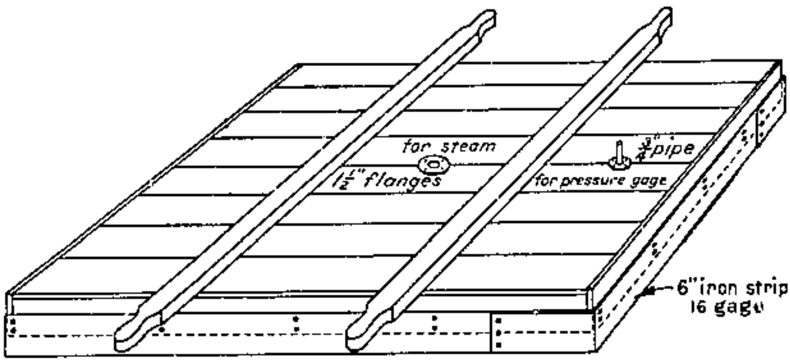

FIGURE 2.—Detail of soil-sterilizing pan used.

the steam. The tile plots were separated by 1-inch planks set on edge in the soil. Each of the tile plots contained 190 square feet of soil area and the pan plots, while not actually separated by means of planks as in the case of the tile, were subdivided as indicated in order that record could be made of the particular plot of soil sterilized during any particular test. Soil-temperature determinations were made by means of thermometers and copper-constantan thermocouples placed in the positions indicated and at the respective depths designated in figure 1.

In addition to the several pressure readings taken on the steam line, the pressures in the tile headers were also determined by means of mercury manometers. In addition to the thermocouples which were placed in the soil at the points indicated above, one couple was used to determine the temperature of the steam under the pan.

Details of the pan used for this investigation are shown in figure 2. The frame of the pan was made of 1-inch boards, was 7 feet square and 6 inches deep, lined on the inside with 24-gage galvanized iron, and had a flange on the outside of 16-gage iron extending 3 inches below the wooden sides.

METHOD OF TEST

It is obvious that a limited experiment like this one, consisting of only 22 separate tests, could not cover all the possible practical conditions involved. However, effort was made to duplicate most of the experiments on at least two different soil plots in order to obtain check data. For example, tests 1 and 2 (table 1) were both made at 20 boiler horsepower with steam supplied at a pressure approximately 8 pounds per square inch gage, but test no. 1 was conducted on plot no. 1 while test no 2 was conducted on plot no. 2. Similarly, when experimenting with the inverted pan, tests nos. 14 and 15 were both made at approximately 10 horsepower with steam at a pressure of 8 pounds per square inch gage, but test no. 14 was conducted on plot no. 12 while test no. 15 was conducted on plot no. 6.

TABLE 1.—*Results of tests of sterilization of soil*

TILE

Test no.	Date of test	Plot no.	Boiler power utilized (approximate)	Ratio of square feet of sterilized plot area to boiler horsepower	Pressure of steam in supply main	Temperature of steam entering tile or pan	Time required to attain desired soil temperatures [1]	Steam flow per hour	Steam utilized to attain desired soil temperatures [2]	Steam required per square foot of sterilized plot	Coal required per square foot of sterilized plot	Steam pressure in tile or under pan	Temperature of saturated steam corresponding to tile or pan pressure	Maximum soil temperature attained during sterilization	Quality of steam supplied, in percentage of dryness	Air temperature	Soil moisture: Initial	Soil moisture: Final	Soil moisture: Increase
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
			Horsepower		*Pounds*	° *F.*	*Hours*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	° *F.*	° *F.*	*Pct.*	° *F.*	*Pct.*	*Pct.*	*Pct.*
1	Aug. 16	1	20	9.5	8	213	4.97	626	3,210	16.9	2.1	0.20	213	212	99	85	13.7	18.0	4.3
2	Aug. 19	2	20	9.5	9	213	3.93	618	2,460	12.9	1.6	.20	213	213	99	81	13.7	17.6	3.9
3	July 18	3	20	9.5	138	212	4.50	607	2,710	14.2	1.8	.23	213	212	95	88	-----	-----	-----
4	July 25	1	20	9.5	140	212	4.75	578	2,860	15.1	1.9	.13	212	212	96	85	-----	-----	-----
5	Aug. 5	2	40	4.8	20	217	1.50	1,186	2,280	12.0	1.5	.43	213	212	99	90	14.4	16.7	2.3
6	Aug. 10	3	40	4.8	26	222	3.47	1,309	4,750	25.1	3.2	.94	215	214	98	85	17.4	22.0	4.6
7	Aug. 25	1	40	4.8	28	[3] 428	2.42	1,301	3,370	17.7	2.4	.24	(3)	321	-----	87	15.5	18.1	2.6
8	July 29	2	40	4.8	80	217	1.84	1,249	2,360	12.4	1.6	.46	214	212	96	88	13.1	17.5	4.4
9	Aug. 1	3	40	4.8	84	219	2.62	1,249	4,060	21.3	2.7	.65	214	214	96	86	14.8	18.8	4.0
10	July 26	3	40	4.8	138	218	2.50	1,210	3,325	17.5	2.2	.62	214	212	95	83	10.5	18.5	8.0
11	Sept. 12	2	40	4.8	140	220	2.06	1,235	2,670	14.0	1.8	.81	215	214	95	79	16.2	21.3	5.1
12	Sept. 16	3	40	4.8	144	220	3.68	1,268	4,530	23.8	3.0	.93	215	213	95	76	14.2	17.7	3.5
13	Sept. 20	1	60	3.2	135	227	1.31	1,760	3,090	16.3	2.1	.36	213	212	97	80	13.0	16.8	3.8

PAN

Test no.	Date of test	Plot no.	Boiler power utilized (approximate)	Ratio of square feet of sterilized plot area to boiler horsepower	Pressure of steam in supply main	Temperature of steam entering tile or pan	Time required to attain desired soil temperatures [1]	Steam flow per hour	Steam utilized to attain desired soil temperatures [2]	Steam required per square foot of sterilized plot	Coal required per square foot of sterilized plot	Steam pressure in tile or under pan	Temperature of saturated steam corresponding to tile or pan pressure	Maximum soil temperature attained during sterilization	Quality of steam supplied, in percentage of dryness	Air temperature	Soil moisture: Initial	Soil moisture: Final	Soil moisture: Increase
14	Aug. 22	12	10	4.9	8	222	-----	312	-----	-----	-----	0.10	212	213	99	87	14.9	20.0	5.1
15	Aug. 24	6	10	4.9	8	221	1.65	329	488	10.0	1.3	.04	212	213	99	84	12.3	18.9	6.6
16	Sept. 23	12	10	4.9	75	225	-----	309	-----	-----	-----	.13	212	197	96	79	-----	-----	-----
17	Sept. 21	6	10	4.9	155	227	4.40	338	1,340	27.3	3.5	.08	212	214	97	81	17.7	24.2	6.5
18	Aug. 12	12	20	2.5	22	239	.75	609	617	12.6	1.6	.12	212	212	99	80	14.5	19.5	5.0
19	Sept. 6	6	20	2.5	27	[3] 421	.79	626	470	9.6	1.3	.13	(3)	212	-----	78	13.4	14.5	1.1
20	Aug. 9	12	20	2.5	83	[3] 535	.50	611	297	6.0	.9	.14	(3)	214	-----	87	7.7	10.0	2.3
21	July 20	4	20	2.5	140	239	-----	619	-----	-----	-----	.05	212	210	95	87	-----	-----	-----
22	July 28	6	20	2.5	143	239	1.84	618	1,030	21.0	2.7	.08	212	212	97	91	-----	16.2	-----

[1] Desired temperature for tile method 212° F. at all points and for pan method 180° at depth of 12 inches.
[2] Total quantity of steam has been adjusted to 80° F. initial soil temperature.
[3] Superheated steam.

As may be seen in table 1, during the tile tests the boiler output was 20, 40, or 60 horsepower; which is to say that from 3.2 to 9.5 square feet of ground area were sterilized per boiler horsepower. This probably represents a range such as is found in practice. The steam pressure for the several runs varied from as low as 8 pounds to 144 pounds. The area of ground sterilized at one time by means of the buried tile was always 9 feet 6 inches by 20 feet, or 190 square feet.

In all the tests the steam flow was controlled and measured by means of a calibrated orifice placed in the line. This orifice served the same purpose as does the control valve in a practical installation. The size of the orifice was predetermined by calculation based upon a knowledge of the pressures on each side of the orifice. The pressure before the orifice in each instance was, of course, the line or boiler pressure as tabulated in column 6 of table 1.

The general method in the case of the tile tests was as follows: Steam was admitted to the soil after all thermocouples and other instruments were in place and the sterilizing bed had been covered with building paper. Readings of soil temperatures were taken at regular intervals. The duration of the intervals depended principally upon the rate of temperature change taking place in the soil. This rate was, of course, higher when the larger boiler horsepowers were employed. The beds were heated until all the thermocouples and thermometers reached equilibrium or maximum temperature, the length of time depending principally upon the horsepower employed. The steam pressure, temperature, and calorimeter readings were made every half hour since these did not generally vary to any significant extent. There was a special orifice for each set of conditions of steam pressure and rate of steam flow.

When superheated steam was supplied, the steam was passed through the superheater and the temperature of the superheated steam was controlled by regulation of the oil burner. During the superheat test steam temperatures as high as 535° F. were employed. (To attain this temperature without superheat would require a pressure of about 900 pounds.)

The control and measurement of steam flow when using the inverted pan was similar to that described for the tile tests. It was assumed in the case of the pan, however, that practical sterilization had been attained when the soil reached an average temperature of 180° F. at depth of 12 inches. This would probably be necessary for nematode control, but would be excessive for simple weed elimination as practiced by tobacco growers. Readings of steam pressures and temperatures were taken as in the case of the tile tests. Because of the more rapid rise in soil temperatures, particularly near the surface, it was necessary to take readings at closer time intervals when sterilizing with the inverted pan than was required in the case of the buried tile. The manipulation of the superheater was the same as that described for the tile method. The weight of the pan was augmented by 100-pound weights placed on each corner. This served to hold the pan down and minimized the escape of steam.

68896°—34——2

DISCUSSION OF TEST RESULTS

The test results are presented in table 1 and in figures 3 to 5 inclusive. The tests are arranged in table 1 in order of increasing boiler horsepower supplied as well as increasing pressure of steam supplied. For example, tests nos. 1 to 4, inclusive, are tile tests for all of which approximately 20 boiler horsepower was supplied but the steam pressures in the supply line varied thus, 8 pounds for test no. 1, 9 pounds for test no. 2, 138 pounds for test no. 3, and 140 pounds for test no. 4. Then during tests nos. 5 to 12, inclusive, approximately 40 boiler horsepower was supplied with the steam pressure increasing again from 20 pounds for test no. 5 to 144 pounds for test no. 12. It is important to note that during test no. 7 superheated steam at 428° F. temperature was supplied. In test no. 13, 60 horsepower was supplied at a steam pressure of 135 pounds.

Tests nos. 14 to 22 were conducted with the inverted pan. Again the tests are grouped in order of increasing boiler horsepower and increasing steam pressures. In test no. 19 superheated steam at a temperature of 421° F. was supplied and in test no. 20 steam at a temperature of 535° was supplied.

The curves in figure 3 illustrate the rise in temperature of several of the plots when sterilized by means of the tile and inverted pan and when supplied with steam at various pressures and horsepower ratings. The temperatures plotted for the several depths are averages of the readings taken for the respective depths. As stated above, sterilization was considered complete when all the readings reached 212° F.; in the case of the tile method and when an average temperature of 180° had been attained at a depth of 12 inches in the inverted-pan tests. It will be noted that the deeper thermocouples come up to temperature quicker than do the shallower ones when the tile method is employed, whereas the reverse is true when the inverted-pan method is employed. This of course is because the steam first comes into contact with the soil at a depth considerably below the surface in tile sterilization, whereas it is fed down from the surface in pan sterilization. The greater inherent effectiveness of the buried-tile method is obvious from a consideration of the method of introduction of steam to the soil. A measure of the completeness of penetration of the steam through the soil when using the tile method can be gotten by simply measuring the temperature of the soil at the surface by means of an ordinary mercury thermometer having an upper limit above 212°. If the surface temperature is 212° in a number of places well distributed over the plot, it is certain that the soil between the tile and the surface is also 212°. Also, the steam will have penetrated below the tile to a certain depth, depending upon the degree of compactness.

The difference in the effectiveness of the tile and pan methods of sterilization should be kept clearly in mind, especially in considering the relative fuel costs. The former method sterilizes deeper and heats the soil to a higher average temperature, therefore it is only natural that more fuel will be required by the tile method than by the pan method.

EFFECT OF PRESSURE OF STEAM SUPPLIED ON FINAL TEMPERATURE OF STERILIZED SOIL

In the discussion of the physical principles involved in soil sterilization by the methods used in ordinary greenhouse and outdoor bed practice, it was pointed out that theoretically the maximum soil temperature should be approximately 212° F. because the steam always expands to a final pressure of about atmospheric when

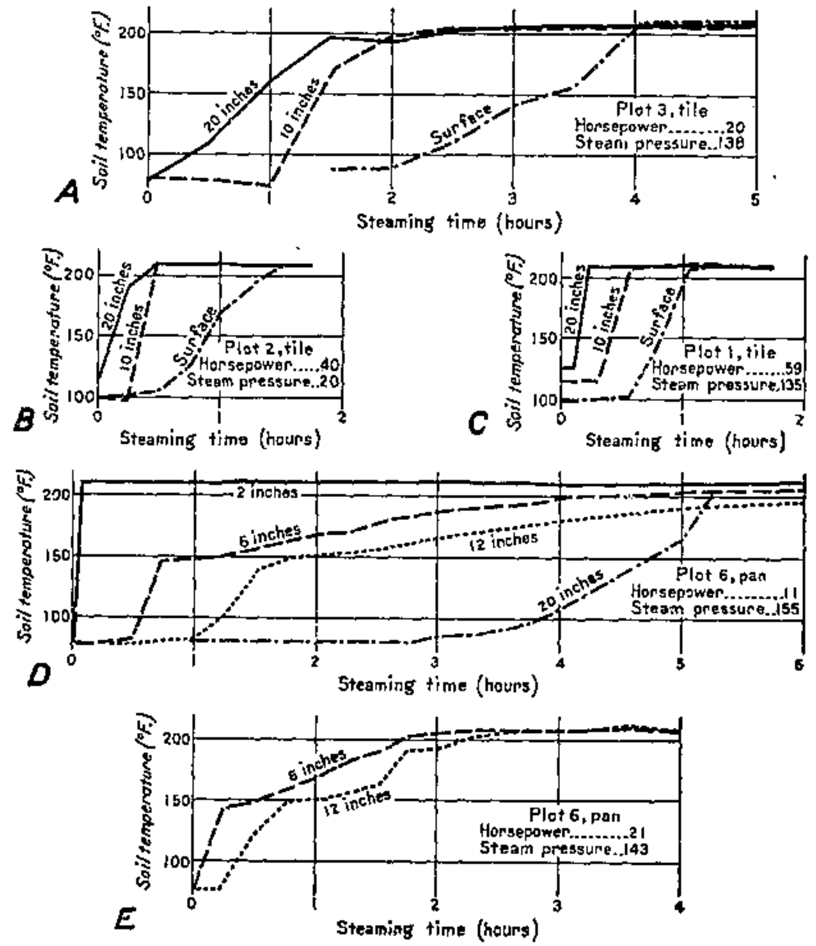

Figure 3.—Rise of soil temperature during sterilization: *A*, Tile test, 20 horsepower; *B*, tile test, 40 horsepower; *C*, tile test, 59 horsepower; *D*, pan test, 11 horsepower; *E*, pan test, 21 horsepower.

released in the soil. Also it was shown that even with relatively high initial steam pressures the final temperature would still be approximately 212°.

Column 15 in table 1 and the curves presented in figure 3 show that the test work bears out the theoretical deductions regarding maximum attainable soil temperatures. Except for test no. 7 when superheated steam at a temperature of 428° F. was supplied, the highest soil temperature reading was 214°, and in about one-half the tests the maximum temperature attained was 212°. Taking into consideration the probable experimental error it can be said that for all practical purposes the maximum soil temperature attainable is 212°.

In the case of superheated steam, the maximum soil temperature attained was 321° F. This temperature was attained, however, only after a comparatively long steaming time, 27 hours actual steaming in a 5-day period. The time to reach 212° was 2.42 hours only. Since the sterilizing was done only during the day it is not possible from these tests to determine how much time would have been required if the steaming had been continuous. Actually the steaming was done on 5 consecutive days, thus 3.5 hours on the first day, 6 hours on the second day, 6 hours on the third day, 5.5 hours on the fourth day, and 6 hours on the fifth day. Between each day's steaming the plot had 18 hours of cooling which no doubt greatly increased the time required to reach the maximum temperature of 321°. However, regardless of the practical value of sterilizing with superheated steam it has been proved conclusively that the only way to attain soil temperatures in excess of 212° is by the use of superheated steam.

EFFECT OF PRESSURE OF STEAM ON MOISTURE CONTENT OF SOIL

During the process of soil sterilization by means of steam as ordinarily applied in the tile or pan methods, the soil obviously becomes wetter. It is believed by some growers and investigators that the pressure of the steam supplied affects the increase in moisture content of the soil during the process. Specifically they believe that if steam at relatively low pressure is supplied, the soil becomes excessively wet and puddled during the process and the thoroughness of the sterilization is impaired. From a consideration of the properties of steam this belief could not be justified, but, in order to learn the effect of steam pressure on soil moisture, careful determinations of the moisture content of the soil both before and after sterilization were made. The soil-moisture data are presented in columns 18, 19, and 20 of table 1. There was no material difference in the increase of the soil-moisture content when sterilizing with low-pressure steam as compared with high-pressure steam. Consider the case of plot no. 6, when sterilized with steam supplied at 10 horsepower. The increase in moisture content when supplied with steam at 8 pounds is approximately 6.5 percent and practically the same increase is shown when steam at 150 pounds is supplied. The additional data presented for plots 2 and 3 show that there is no material difference in the increase in moisture content of the soil regardless of the pressure of the steam supplied. From column 19, table 1 it can also be seen that the final moisture content of the soil was never very high, the maximum for the tile method being 22 percent and for the inverted-pan being about 24 percent. This amount of soil moisture prevailing after sterilization is not objectionable.

EFFECT OF PRESSURE OF STEAM SUPPLIED ON QUANTITY OF STEAM REQUIRED FOR STERILIZATION

Some growers believe that a high initial steam pressure will somehow permit sterilization to be completed in a shorter time and with

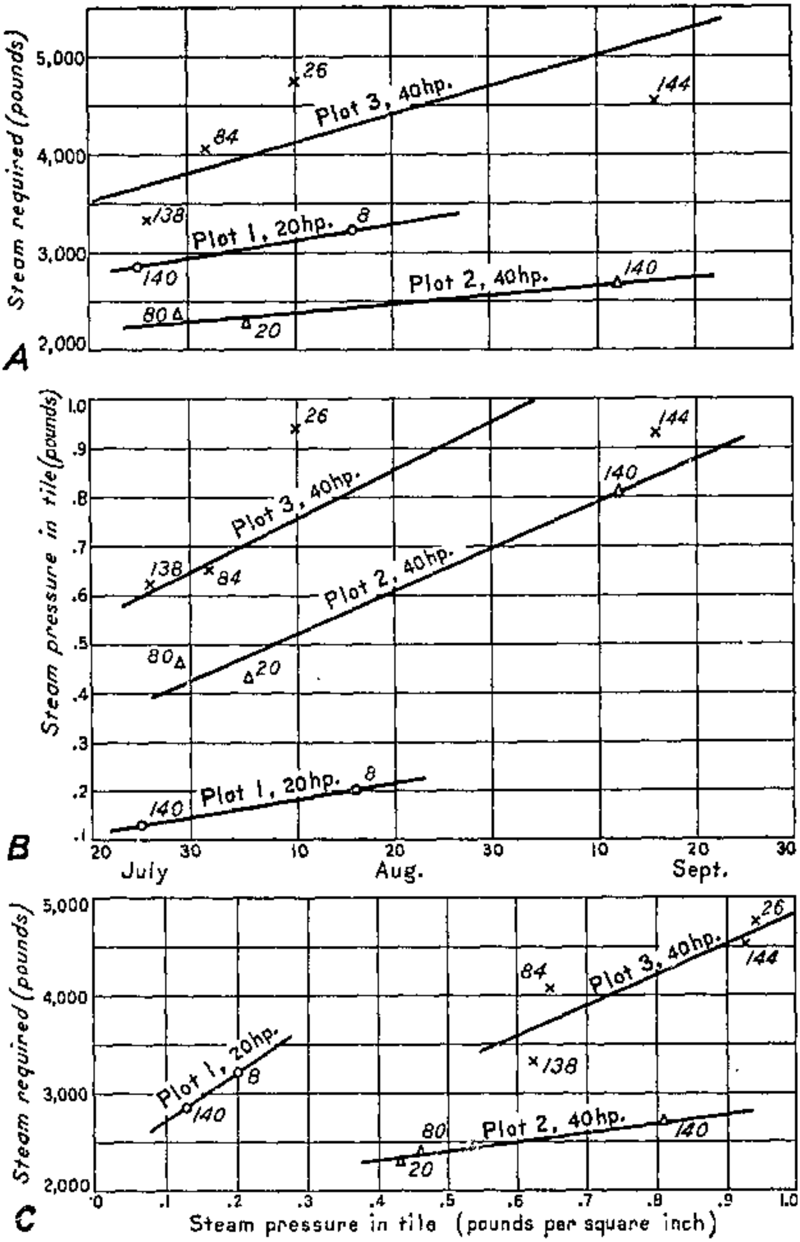

FIGURE 4.—Changes in steam required and in steam pressure in tile during progress of tests, also relation between tile pressure and steam required: *A*, Increase of steam required with time; *B*, Increase of pressure in tile with time; *C*, relation between steam required and steam pressure in tile. (Numbers adjacent to plotted points indicate steam pressure in main.)

less total steam demand than would be required if the initial steam pressure were low, even though the steam were supplied to the soil at the same rate.

It is first desirable that the reader have in mind the physical facts presented in figure 4 in order to understand why certain test points do not fall in line. Figure 4, *A* shows that there was a gradual increase in the steam demand during the progress of the test. The increase in steam demand for plots 1, 2, and 3 with the passage of time is clearly shown. This was due no doubt to an increase in the compactness of the soil just above the tile. An increase in the compactness of the soil above the tile naturally resulted in the loss of a relatively greater amount of steam into the subsoil and a consequent increase in the amount of steam required for sterilization of the upper soil. Figure 4, *B* shows how this gradual increase in compactness of the soil above the tile increased the steam pressure in the tile. The characteristics for plots 1, 2, and 3 are again presented in this series of graphs. Figure 4, *C* in turn shows the relation between tile pressures and steam demands for plots 1, 2, and 3, in each of

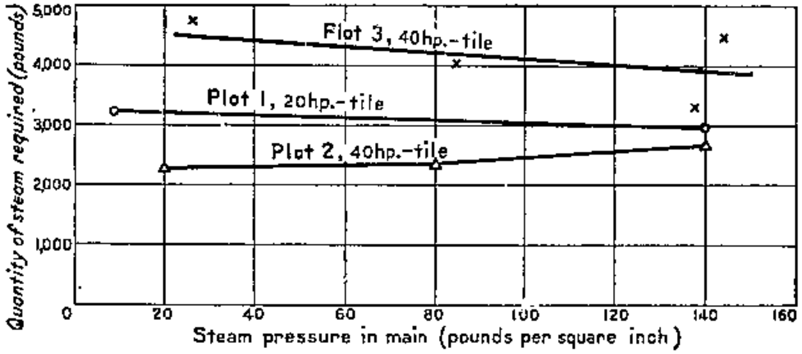

FIGURE 5.—Effect of various steam pressures on quantity of steam used.

which plots the rate of steam input was fixed. By further correlation, which is not presented, it was proved conclusively that the steam pressure in the supply main had no effect on this change in tile pressure or steam demand during the progress of the test.

There was no apparent increase or decrease in the steam demand as the steam pressure in the main was varied (fig. 5, plot no. 3). The departure of some of the points from the curve drawn can be explained by references to figure 4 where it is seen that for the tests conducted late in the season the steam demand was relatively high, while during the early stages of the work the demand was relatively low. This is believed to be due to the compacting of the soil as the season progressed. Taking these facts into consideration it can be concluded that each of the three graphs for the tile tests can be considered practically horizontal and there is therefore no loss or gain in steam demand resulting from the use of high-pressure steam.

EFFECT OF BOILER HORSEPOWER ON QUANTITY OF STEAM REQUIRED

In the cases of both plots nos. 1 and 3 an increase in boiler horsepower shows an increase in the quantity of steam required. In the case of plot no. 6 when sterilizing by means of the pan an increase in boiler horsepower resulted in a decrease in the quantity of steam required. The increase in the case of the tile may be explained by the fact that as the steam input to the tile is increased, the pressure in the tile is increased and a relatively greater amount of steam is forced down into the deeper soil. There is no apparent reason for decrease in steam demand upon increasing the horsepower in the case of the pan test. It must be clearly understood, however, that even though more steam may be required to utilize the higher boiler horsepower per unit of area in the case of the tile method, there is a time saving which must be taken into consideration when making an estimate of the relative merits of high and low boiler horsepower per unit of soil sterilized. More tests would be required to demonstrate conclusively that the characteristic shown for plot no. 6 holds in general.

EFFECT OF BOILER HORSEPOWER ON STEAM PRESSURE IN TILE AND UNDER PAN

The question of steam pressure in the tile and under the inverted pan is of interest for two principal reasons: (1) Because only a fairly limited pressure can be withstood by either the tile or inverted pan; (2) because some knowledge of the final pressure of the steam must be had for an intelligent design of the piping or steam-distribution system for soil sterilization. The pressure under the pan in the case of plot no. 6 (table 1) remained nearly constant while the boiler horsepower input to the pan was doubled. This probably means that the pan heaved up when 20 horsepower was introduced and a larger quantity of steam was wasted to the atmosphere. On the other hand, the pressure in the tile tests shows the expected increase with an increase in the boiler horsepower input. For example, in plot no. 3, the tile pressure increased from 0.23 pound at 20 boiler horsepower input to 0.62 pound at 40 boiler horsepower input. Correspondingly, in plot no. 1, the tile pressure increased from 0.13 pound at 20 boiler horsepower to 0.36 pound at 60 boiler horsepower input. The tile pressure for plot no. 3 is about twice that for plot no. 1, which explains the higher steam demand for plot no. 3. The higher tile pressure might plausibly be due to a more compact soil above the tile in the case of plot no. 3; this would result in relatively more steam being driven downward with the accompanying increase in time required to attain desired temperatures at the shallower depths. Under all conditions of steam input covered by this investigation, the tile pressure and pan pressure were at all times very low—in fact considerably less than 1 pound.

It is of interest to note that there was a general increase in the steam pressure in the buried tile during the progress of the investigation indicating a steady increase in the compactness of the soil above the tile, probably caused by rains, and by walking on the tile beds. This is shown clearly in figure 4, A and has been discussed in a preceding section.

HORSEPOWER REQUIRED PER UNIT OF SOIL STERILIZED

The grower or greenhouse operator who sterilizes soil by means of steam is sometimes confronted with the problem of determining the relation between boiler horsepower available for soil sterilization and the size of the plot to be sterilized at one time. In the case of the pan the amount of steam which can be fed into a given pan has a pretty definite limit, depending principally upon its weight. For example with the 7- by 7-foot pan used in these tests, only 20 boiler horsepower could be utilized without heaving even though an additional weight of 400 pounds was placed on the pan. There is no such practical limitation in the case of the tile method.

From the data recorded in table 1 it is obvious that if a relatively small area is sterilized with a given horsepower the time required will be short, whereas if a relatively large area is sterilized the time required will be longer. The largest ratio employed in these tests when utilizing the buried tile was approximately 10 square feet of soil per horsepower. Sterilization at this ratio required from 4 to 5 hours for completion. When the time required for preparing the bed for sterilization is taken into consideration it can be seen that just about one complete working day will be required for a given plot. Roughly 1 square yard per boiler horsepower can therefore be assumed as a practical maximum ratio of soil area to boiler horsepower for the tile method. The maximum ratio in the case of the inverted pan is limited generally by the total weight of the pan, and any weights which may be added to the pan. The weight of the pan is in turn limited by the ability of an ordinary crew to manipulate it. The greatest horsepower input which was permissible with the pan used in these tests gave a ratio of about 2.5 square feet of soil to 1 boiler horsepower. For the ordinary pan handled by a small crew 3 square feet of soil area per boiler horsepower should prove feasible in most cases.

Since the labor requirements in the pan method are relatively important the object is to sterilize as quickly as possible and therefore to use as low a ratio of soil area to boiler horsepower as feasible. On the other hand the labor requirement with the permanent buried tile is not relatively important and the objective is rather to handle a larger area of soil per boiler horsepower. The boiler horsepower is one of the important limiting factors in the case of tile sterilization.

COAL REQUIRED PER SQUARE FOOT OF STERILIZED PLOT

The coal required per square foot of sterilized plot is given in column 12 of table 1. The average value for the buried-tile method is about 2 pounds of coal per square foot. The average value for the inverted pan (attaining a temperature of 180° F. at a depth of 12 inches) is also about 2 pounds. This value checks very closely with figures obtained from growers who have kept accurate cost records for greenhouse-soil sterilization. However, 2 pounds of coal per square foot is undoubtedly more than ordinarily is used for the partial sterilization employed in connection with tobacco-seed beds.

PIPING

The following discussion, together with table 2, illustrates a method of design of steam supply mains for soil-sterilization purposes. Suppose that it is desired to determine the size of main required to convey the sterilizing steam for a greenhouse range in which the farthest plot is approximately 500 feet from the boiler and in which 250 boiler horsepower is to be utilized with steam at an initial pressure of 150 pounds. From table 2 it is readily seen that a 3-inch main would be necessary. The distance from the boiler to the farthest plot should of course be measured along the course of the pipe itself rather than in a straight line.

TABLE 2.—*Sizes of steam mains and boiler horsepower for soil sterilization in greenhouses*

Boiler horsepower	Size of pipe required in—							
	Mains 500 feet long where the boiler pressure is—				Mains 1,000 feet long where the boiler pressure is—			
	10 pounds	50 pounds	100 pounds	150 pounds	10 pounds	50 pounds	100 pounds	150 pounds
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
10	2	1¼	1	1	2½	1½	1¼	1¼
15	2½	1½	1¼	1	3	2	1¼	1¼
25	3	2	1¼	1¼	3½	2½	1½	1½
35	3½	2½	1½	1½	3½	2½	2	1½
50	3½	2½	2	1½	4	3	2½	2
75	4	3	2½	2	5	3½	2½	2
100	5	3½	2½	2	5	4	3	2½
150	6	4	3	2½	6	5	3½	3
200	6	5	3½	3	8	5	4	3½
250	8	5	3½	3	8	6	5	3½
300	8	6	4	3½	10	8	5	4
350	8	6	5	3½	12	8	6	5
400	10	6	5	4	12	8	6	5

Since it has been demonstrated that low-pressure steam may be used very effectively for soil sterilization, it is feasible to use the steam-heating mains as distribution pipes for such low-pressure sterilizing steam. In this case it is not a matter of sizing the pipes but rather determining the amount of the available boiler capacity which may be handled by the existing mains. The capacity of a heating main is greatly increased over that required for heating purposes when utilized to convey steam for sterilization because the back pressure ordinarily imposed by the heating system is removed and the steam is allowed to pass freely into the soil. In fact it is safe to assume that the carrying capacity is thus increased approximately four times. To illustrate the method of handling the steam when the heating mains are utilized for distribution, consider the case of a range of eight greenhouses, 35 feet wide and 125 feet long, each requiring approximately 15 boiler horsepower for heating. Let it be assumed also that a 150-horsepower boiler is used to supply the heating steam. Since as stated above the heating-line capacity can safely be increased four times to determine the sterilizing-steam capacity, steam to the extent of approximately 60 boiler horsepower can be conveyed to each of the houses by the existing heating mains for the purpose of soil sterilization. Thus one-half the available boiler capacity can be passed into a given house for the purpose. If it be desired to utilize the entire boiler capacity and sterilize the entire range in a relatively short time the steam could be delivered to two of the houses and sterilization could be done simultaneously in each. If it is assumed that 1 square yard of soil is to be sterilized per boiler horsepower it can readily be seen that about one-eighth of each of the two houses can be sterilized at a given time if the entire normal boiler capacity is employed. When special lines are used to carry low-pressure steam for soil sterilization they should be sized in accordance with the data given in table 3 in a manner similar to that outlined for the high-pressure steam example given above.

TABLE 3.—*Number of branch lines or headers equivalent to various main and branch sizes*

Size of main (inches)	Number of buried-tile lines that can be used when size of branch pipe or header is—						
	½ inch	¾ inch	1 inch	1¼ inches	1½ inches	2 inches	2½ inches
¾	2	1					
1	4	2	1				
1¼	7	4	2	1			
1½	11	5	3	2	1		
2	20	10	5	3	2	1	
2½	31	15	8	4	3	2	1
3	54	26	15	7	5	3	2
3½	78	38	21	11	7	4	3
4		52	29	15	10	5	3
5			50	25	17	9	6
6				40	27	15	9
8					55	30	19
10						52	33
12							52

It is necessary that a certain amount of care be given to the sizing of the branch lines leading from the main supply line to the buried tile. Referring to table 3 let it be assumed that a 4-inch supply line is being used to carry steam which is to be distributed to 11 buried-tile lines and it is desired to determine the proper size of branch line to each tile line. Entering at 4 in the first column of table 3, and reading across horizontally to 10, which is the closest number to the 11 lines assumed in the example, and then moving up vertically to the top line we find that each branch line should be 1½ inches in size. Similarly if the main is 2 inches in diameter and there are 10 tile lines we find that each branch line should be three-fourths of an inch in diameter.

CONCLUSIONS

In the experiments herein reported the following conclusions seem warranted:

It is not possible to obtain a soil temperature in excess of about 212° F. without the use of superheated steam.

The moisture content of the soil increases during sterilization but the increase is not materially affected by variations in steam pressure.

Increasing the initial steam pressure does not decrease the quantity of steam required to sterilize the soil.

The pressure of the steam under the pans remains constant at the various boiler horsepowers due to heaving of the pan and increased escape of steam into the air as the boiler horsepower is increased. The pressure in the tile increases as the boiler horsepower is increased.

With the tile method roughly 1 square yard of soil may be sterilized per boiler horsepower. With the pan method 3 square feet per boiler horsepower may be sterilized.

About 2 pounds of coal are required per square foot of soil surface with both the tile and pan methods.

The capacity of a steam heating main is greatly increased when used to convey steam for sterilization because of the absence of appreciable back pressure.

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