

AN ENGINEERING DESIGN OF
LABORATORY EQUIPMENT FOR CRUDE
OIL AND MULTI-COMPONENT HYDROCARBON
STEAM-DISTILLATION TESTS

By

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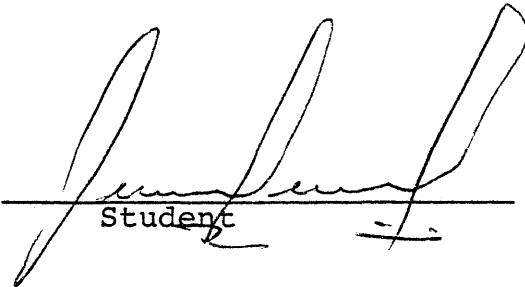
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An Engineering Report submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Engineering in Petroleum Engineering.

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ABSTRACT

A completely satisfactory theory of steam distillation of multi-component hydrocarbon systems has not been developed for steam flood oil recovery. To further investigate this process for crude oil steam distillation, an equipment design for laboratory steam distillation test has been completed.

In this report, an engineering design has been made for a steam distillation cell and steam generator with heater and insulation specifications. For steam distillation cell, both hemispherical and flat-plate heads were considered.

Design factors considered also included various steam flow rates, sample sizes and different hydrocarbon compositions.

ACKNOWLEDGEMENTS

The financial assistance provided by Texaco Petroleum Company, Ecuadorian Division, is greatly appreciated.

Professor C. H. Wu's advice and suggestions are very much appreciated. Special thanks are due to Professors D.M. Bass, Jr. and E. D. Sloan for their helpful suggestions and for serving on the thesis committee.

Thanks are extended to Colorado School of Mines for the facilities provided to complete this report.

INTRODUCTION

Steam distillation (1, 3, 6, 7, 10, 12)* is a term applied to a distillation process with open steam, i.e. the steam is in direct contact with the distillation system (hydrocarbons) in either a batch or semi-batch operation. The presence of steam and water phase in the hydrocarbon system reduces the hydrocarbon partial pressure, consequently, induces the vaporization of hydrocarbon components at a temperature lower than the boiling point of the hydrocarbon.

Early experimental work demonstrated that steam is an effective oil displacement agent. The pioneering work of Willman et al (13) provided much useful information on the mechanisms of steam flood including steam distillation. When steam is injected continuously into an oil bearing formation, oil is expelled mainly by three major mechanisms; the most important of these three mechanisms is steam distillation, the other two being thermal expansion and amplification of the in-situ forces such as gravity segregation and internal fluid pressures due to the reduction in viscosity caused by the elevated temperature.

The present report is concerned with an engineering design of the steam distillation cell and its supporting equipment. This equipment will be suitable for laboratory steam distillation study on single-component, multi-component hydrocarbon mixtures, and on crude oils.

*References at the end of this report.

REVIEW OF STEAM DISTILLATION

Theory of Steam Distillation

Carey's (5) study of steam distillation phenomena show that the presence of a liquid water phase in the distillation cell can be analyzed with the phase rule; $\phi + F = C + 2$, where ϕ is the number of phases, F is the degree of freedom of the system, C is the number of components in the system. If no liquid water is present there are two components, (assuming one hydrocarbon) with two degrees of freedom. So, by the phase rule, the partial pressure of steam is equal to the difference between the total pressure and the partial pressure of the volatile component. If water is present as liquid phase, there are three phases and two components hence one degree of freedom. In this case the distillation pressure is equal to the sum of vapor pressures of the volatile component and the vapor pressure of the water at the distillation temperature.

Hengstenbeck (12) and Robinson (6) also described the steam distillation of organic materials with high boiling points by assuming immiscibility between the two phases. These authors presented a generalized steam requirement equation as:

$$\frac{L}{S} = \frac{Y_b}{Y_s} = \frac{p_i}{p_s} = \frac{p_i}{P_t - p_i} \dots \dots \dots (1)$$

L = Liquid hydrocarbon in the cell, moles

S = Steam required in the process, moles

Y_b = Mole fraction in the vapor (base component)

Y_s = Mole fraction of steam in the vapor

p_i = Partial pressure of the organic material, psia

p_s = Partial pressure of the steam, psia

P_t = Total pressure of the system, psia

If equilibrium is attained and a liquid water phase is not present in the distillation cell, the partial pressure of the organic material p_i is equal to its vapor pressure, while the partial pressure of the steam is equal to the total pressure (P_t) minus the partial pressure of the organic material. If a liquid water phase is present, the partial pressure of water would be the vapor pressure of water.

If the system comprises of a multi-component mixture the partial pressure of the mixture is the sum of the partial pressures of each component, assuming that Raoult's law is valid. The expression for pressure can be written as:

$$p_i = P_i X_i \dots \dots \dots (2)$$

p_i = is the partial pressure of the ith component, psia

X_i = is the mole fraction in the organic liquid

P_i = vapor pressure of the pure ith component, psia

If the mixture consists of several components having appreciable amount of volatile material, then combining equation (2) with the differential form of equation (1) will

result in the following:

$$\frac{ds}{dl} = \frac{P_t - p_i}{P_i}$$

$$\int ds = \int \frac{P_t - \sum P_i X_i}{\sum P_i X_i} dl \dots \dots \dots (3)$$

The mathematical model developed by Holland and Welch (7) is much more comprehensive. Details of the derivation are shown in Appendix 1. The model is for steam distillation of multi-component mixtures, assuming that the semi-batch process is carried out at constant pressure and temperature, so that the partial pressure of the steam in the vapor is less than the saturation pressure of steam at a given constant temperature. This assumption assures the absence of liquid water in the distillation cell.

Holland and Welch's equation is presented as:

$$\sum_{i \neq s,r} \frac{L^{\circ}_i}{B_i} \left[1 - \left(\frac{L_b}{L^{\circ}_b} \right)^{B_i} \right] + L^{\circ}_r \ln \frac{L^{\circ}_b}{L_b} = \frac{E_b P_b}{\pi} [L^{\circ} - L + S] \dots (4)$$

L°_i = Moles of volatile component i th in the cell

B_i = $\frac{E_i}{E_b} \times d_i$

E_i = Vaporization efficiency of component i ; $E_i = p_i^s / P_i X_i^s$

E_b = Vaporization efficiency of the volatile component selected as the base component.

d_i = P_i^s / P_b^s = Relative Volatility

- L_b = Moles of the volatile component selected as the base component at any time when $t = 0$, $L_b = L^{\circ}_b$
 L°_r = Moles of non-volatile components in the cell at all times
 Π = Total pressure of the distillation psia
 L = Moles of volatile components in the cell at any time when $t = 0$, $L = L^{\circ}$
 S = Moles of steam used during the time interval of $t = 0$, to $t = t$
 p_i = Partial pressure of component i in the vapor at any time
 P_i = Vapor pressure of the pure component i at the temperature of the cell, psia
 P_b = Vapor pressure of the pure component selected as the base component at the temperature of the cell, psia

Steam Distillation in Porous Media

The process of oil recovery by steam can be visualized by considering steam injection into a very long porous medium, initially saturated with oil and connate water. The oil in the immediate vicinity of the injection end is partially displaced and pushed down stream. A fraction of the oil is left behind the steam front. The advancing steam gradually condenses into hot water, because of heat losses to the matrix, connate water, oil in place, and the overburden and underburden formation. This condensation generates a hot water bank. The hot water forced downstream by the steam displaces oil, and the temperature of the water gradually declines to the original reservoir temperature. From

this point on the displacement process proceeds as it would in a conventional water flood. Thus, in a large linear or radial flow pattern, five zones can be observed from the injection well to the producing end. These zones are:

1. The steam zone
2. The solvent bank
3. The hot water bank
4. The oil bank
5. Undisturbed temperature zone

Many authors (9, 13, 21, 22, 24, 25, 26, 28, 29, 31, 32, 33) have discussed the mechanisms of oil displacement in these zones.

Early experimental work demonstrated that steam is an effective oil displacement agent; the pioneering work of Willman et al (13) provided much useful information on the mechanisms of steam flooding. He estimated the oil recovery due to steam distillation mechanism to range from 5% to 19% of the original oil in place for many crude oils at steam temperatures of 380-500°F.

Ozen (24) and Quinones (31) estimated that 5% to 10% of the heavy oil recovered by a steam flood could be attributed to steam distillation. Also Ozen (24) predicted as much as 65.9% of oil recovery for some light oils could be attributed to the same mechanism.

Johnson et al (28) conducted two experiments in which superheated steam was injected into an unconsolidated core (saturated with oil) under isothermal superheated conditions. They found that the oil vaporized by steam depended on the amount of steam contacting the immobile oil and it increases as the volatility of the oil and the steam injection temperature are increased. They developed a method for calculating the amount of oil distilled in the steam zone; which involved the

1. Amount of steam condensed at the steam front.
2. Amount of oil left behind the hot water front, and available for vaporization.
3. The fraction of oil distilled as a function of the volume of steam produced per unit volume of oil available for vaporization.

This fraction of oil distilled was computed by using Cook et al computer program (27). Basically, this program flashes the incremental volumes of gas through a series of cells initially containing equal oil volumes. Vaporization is determined by assuming the residual oil left in each cell after the incremental gas volume has passed through all of the cells and comparing this sum with the oil initially present.

Quinones (31) work is concerned with an investigation of steam distillation for a single component, multi-component hydrocarbon mixtures, (n-octane, n-decane, n-dodecane), and

crude oil; in order to develop a procedure for predicting oil recovery by steam distillation. The laboratory work is divided in three parts, one set of experiments were conducted at atmospheric pressure, the second set at elevated pressures and temperatures (max 75 psi and 365°F), and finally special runs in an unconsolidated cylindrical core, in order to investigate the extent of steam distillation. Two steam distillation prediction methods were developed in this study, one based on the vapor pressure concept which means using ideal gas and liquid solutions, and the other based on the non-ideal solution, using K-values.

Wu and Brown (34) performed laboratory tests to measure crude oil steam distillation yields and determined the effect of process parameter changes in the steam distillation process. These experiments were carried out in a cylindrical vertical cell. They used saturated and superheated steam on crude oils between 9 and 36° API. These experiments were carried out at pressures ranging from 200 to 500 psig, and steam temperatures from 387 to 600°F. They found that crude oil composition controls steam distillation results; and that these results appear to be independent of steam injection rate, initial oil volume, and porous media studies. They concluded that a ratio of cumulative water condensed to initial oil volume, V_w/V_{oi} , is an important parameter for correlating steam distillation results.

APPLICATION OF STEAM DISTILLATION

Steam distillation is commonly used in many petroleum and food refining processes. Examples of some of these processes are distillation of thermally unstable or reactive materials at the boiling temperature, a material which cannot be distilled by indirect heating even under low pressure because of high boiling point, or when direct-fired heaters cannot be used because of danger.

Although a great variety of methods have been proposed for rendering edible oils odorless and testless, the objective can be accomplished by steam distillation. Steam distillation is also used in the manufacture of margarine fats and in converting cottonseed oil to an edible oil (3). In the petroleum industry a steam distillation process is used in the stripping of crude oil. Steam distillation is also observed in steam flooding an oil reservoir.

PROPOSED STEAM DISTILLATION EQUIPMENT

It is proposed that the equipment shown in Figure 1 with description and specifications listed on Table 1 and 2 be used for future steam distillation tests. Water is pumped into the generator where it is heated to 400°F and the steam generated is channeled into a steam distillation cell (SDC) containing hydrocarbons at a temperature of 382°F. The over-heads (hydrocarbon, steam) from the steam distillation cell are forced through a condenser. The condensed liquid hydrocarbons and water are separated in a liquid separator. The volumes of the separated water and hydrocarbons are determined. The hydrocarbon composition is analyzed by a chromatograph which is shown in Figure 2 and Table 3.

PROPOSED HYDROCARBON SAMPLES
FOR STEAM DISTILLATION TESTS

The hydrocarbons proposed for steam distillation evaluation are n-pentane, n-heptane, n-octane, n-decane, and crude oils. Although, the system will permit the use of other types of hydrocarbons if desired. The physical properties of these hydrocarbons are shown in Table 4.

DESIGN OF STEAM DISTILLATION CELL (SDC)

Entrainment and SDC Size

The size of the steam distillation cell (SDC) is based on the results obtained from entrainment calculations. The specifications of the SDC are: area 81.07 cm^2 , critical mass flux $2.44 \text{ gr/min. cm}^2$, free space from the liquid level to the top 60.96 cm , and critical steam injection rate 3.29 gr/sec . The procedure and results of these calculations are shown in Appendix 2. Calculations were also made by considering the rate of vaporization, sample size and steam injection rate in a steam distillation cell. Presented in Table 5, 6 and 7 are the results of these calculations.

Proposed Materials for SDC

The proposed material specification for this SDC are tabulated in Table 8. The preference for stainless steel, SS-304, is based on the fact that it has minimum corrosion, high tensile stress and relatively high thermal conductivity than other available materials.

Design of the Two Ends of the SDC

Calculations were made for designing hemispherical and flat-plate heads. Based on these calculations the hemispherical heads are proposed for this design due to the fact that for a constant shell thickness and maximum stress

one unit of thickness required in the hemispherical heads, will require five units of thickness in the case of flat ends. The procedure for these calculations are shown in Appendix 4 and 5.

Heater Tapes and Insulations

The design of steam distillation heater tapes entails the consideration of heat transfer from the heater tape to 1) content of the cell (water and hydrocarbons), 2) the cell itself and 3) the insulator.

A conventional static heat balance calculation shows that a heater tape design to supply 3,586 BTU/hr is required for the specified cell temperature (382°F).

The insulation should use an asbestos with a thermal conductivity of .113 BTU/(hr ft°F). The calculation procedure for the heater tapes and insulation are shown in Appendix 7.

Specifications of the Cell

A summary of SDC design specifications are tabulated in Table 9.

STEAM GENERATOR DESIGN

The steam generator is designed to maintain a temperature of 400°F. The cell is made of stainless steel cylinder; 4 inches diameter, one foot long, and .0369 inches thickness at a maximum generator pressure of 1500 #/in². The pellets inside the steam generator (Figure 7) are proposed to be 1/4 inch in diameter and are positioned six inches from the bottom of the cell. The insulating material is an asbestos with thermal conductivity of about .113 BTU/(hr °F ft).

The calculation procedure and specifications for the heat coil capacity, steam generator, and steam generator insulation are included in Appendices 8 and 9, and Tables 10 and 11.

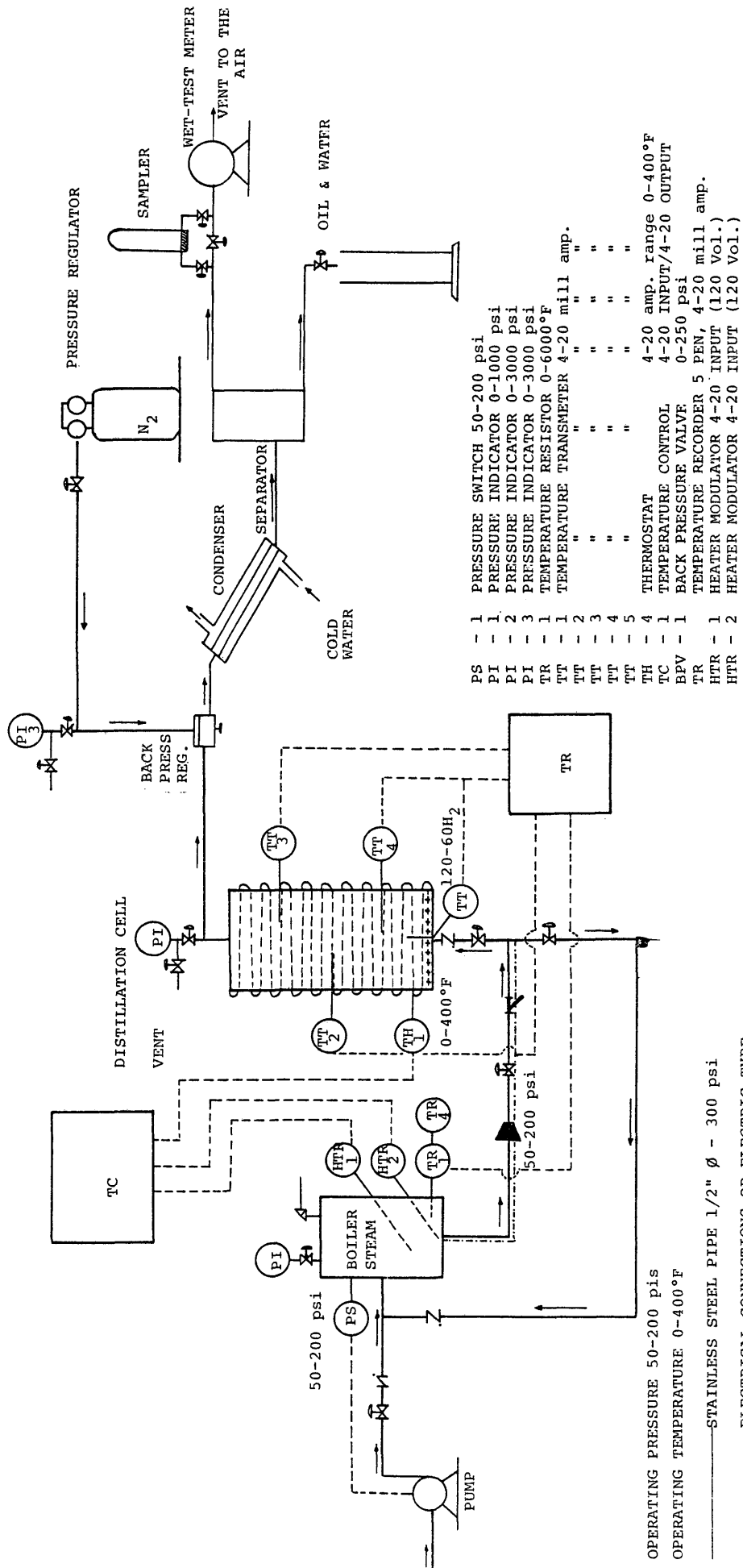
SUMMARY AND CONCLUSIONS

1. An equipment design for laboratory steam distillation tests has been completed. The steam distillation cell is designed based on the results obtained from the entrainment and SDC size calculations. The SDC specifications are as follows:

Cross sectional area 81.07 cm^2 , hydrocarbon volume 383 cm^3 , critical steam injection 3.29 gr/sec , critical mass flux $2.44 \text{ gr/min. cm}^2$.
2. The following conclusions can be made from the entrainment calculations:
 - a) With constant flow rate of steam and constant vaporization flow rate of hydrocarbons, the required time for distillation increases with increasing sample size.
 - b) With constant vaporization flow rate of hydrocarbons, and constant sample size the time required for distillation decreases as the steam flow rate increases.
 - c) For constant steam injection rate and constant sample size, the time required for steam distillation decreases as the light end fraction of the sample increases.
3. A conventional static heat balance calculation show that a heater with a capacity to supply $3,586 \text{ BTU/hr}$ is required.

4. The insulator should use an asbestos with a thermal conductivity of .113 BTU/(hr ft°F).
5. The steam generator system is designed to maintain a temperature of 400°F. The cell is made of cylindrical stainless steel cylinder with 4 inches diameter, one foot long, and .0369 inches thickness at a maximum generator pressure of 1500 psia.

FIGURE 1
STEAM DISTILLATION FLOW DIAGRAM



OPERATING PRESSURE 50-200 ps
OPERATING TEMPERATURE 0-400°F

STAINLESS STEEL PIPE 1/2" Ø - 300 psi

ELECTRICAL CONNECTIONS OR ELECTRIC TYPE

- PS - 1 PRESSURE SWITCH 50-200 psi
- PI - 1 PRESSURE INDICATOR 0-1000 psi
- PI - 2 PRESSURE INDICATOR 0-3000 psi
- PI - 3 PRESSURE INDICATOR 0-3000 psi
- TR - 1 TEMPERATURE RECORDER 0-6000°F
- TT - 1 TEMPERATURE TRANSMITTER 4-20 mill amp.
- TT - 2 " " " " " "
- TT - 3 " " " " " "
- TT - 4 " " " " " "
- TT - 5 " " " " " "
- TH - 4 THERMOSTAT 4-20 amp. range 0-400°F
- TC - 1 TEMPERATURE CONTROL 4-20 INPUT/4-20 OUTPUT
- BPV - 1 BACK PRESSURE VALVE 0-250 psi
- TR - TEMPERATURE RECORDER 5 PEN, 4-20 mill amp.
- HTR - 1 HEATER MODULATOR 4-20 INPUT (120 Vol.)
- HTR - 2 HEATER MODULATOR 4-20 INPUT (120 Vol.)

FIGURE 2
BASIC BLOCK DIAGRAM OF DUAL COLUMN GAS CHROMATOGRAPH

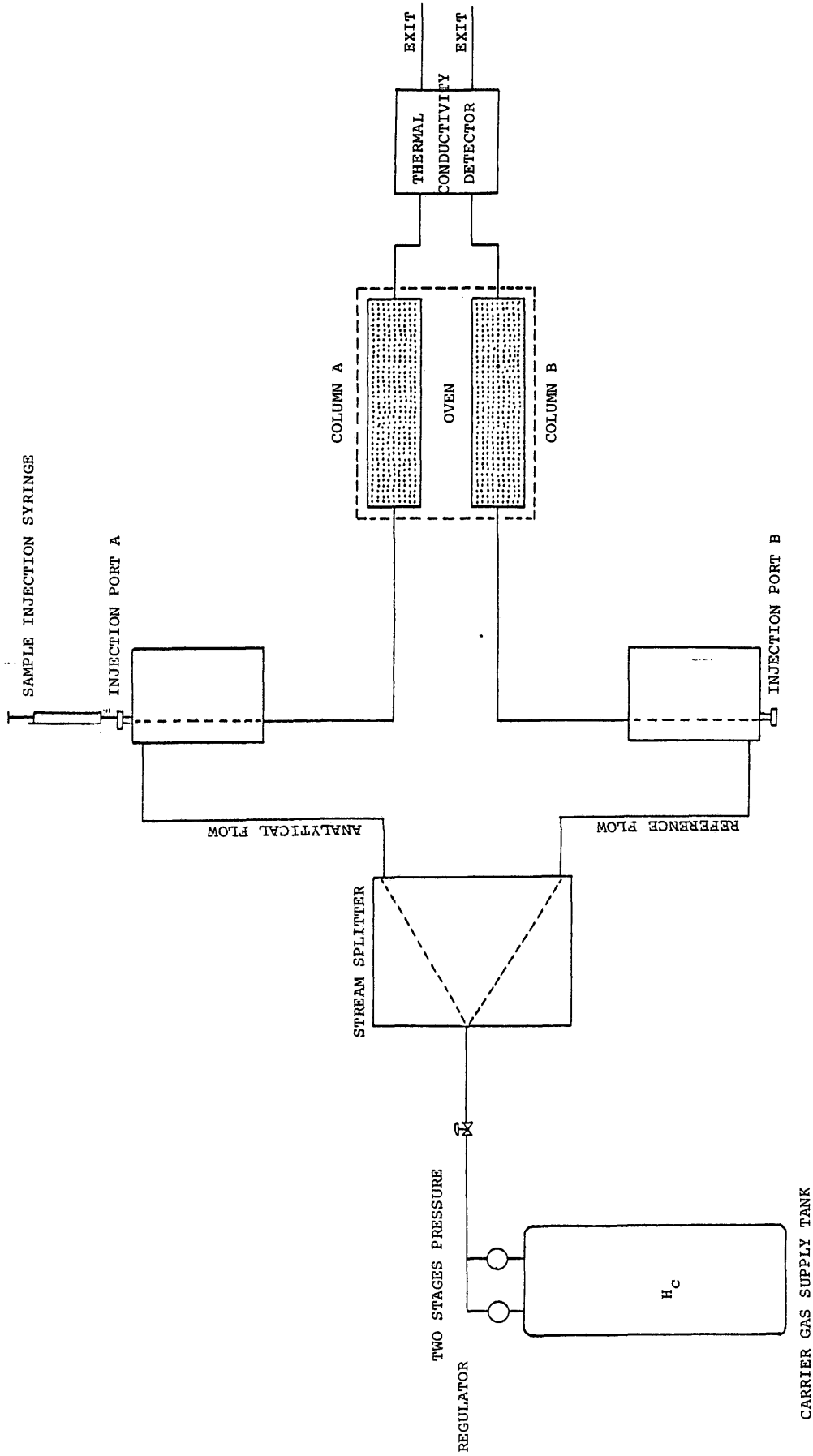
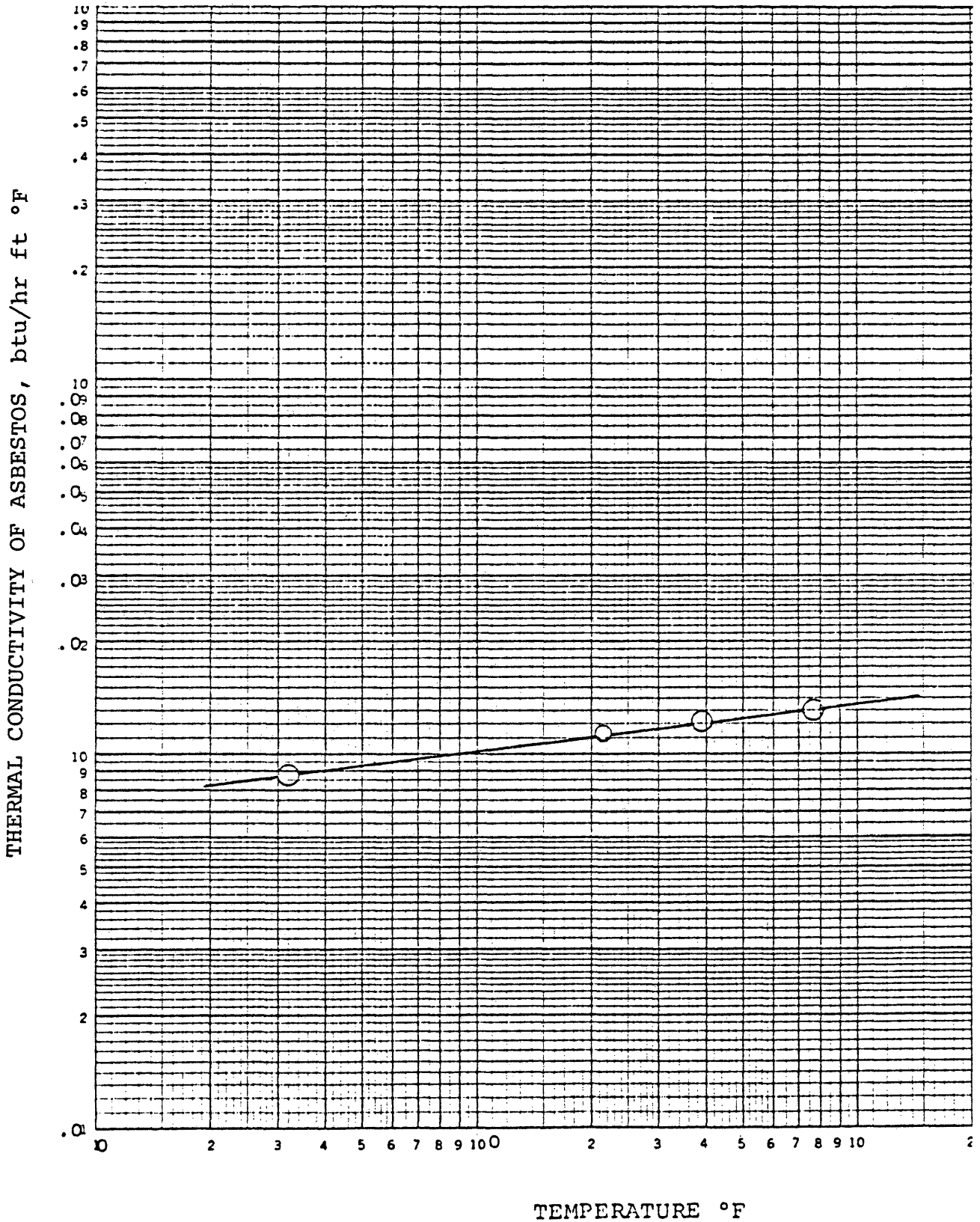


FIGURE 3

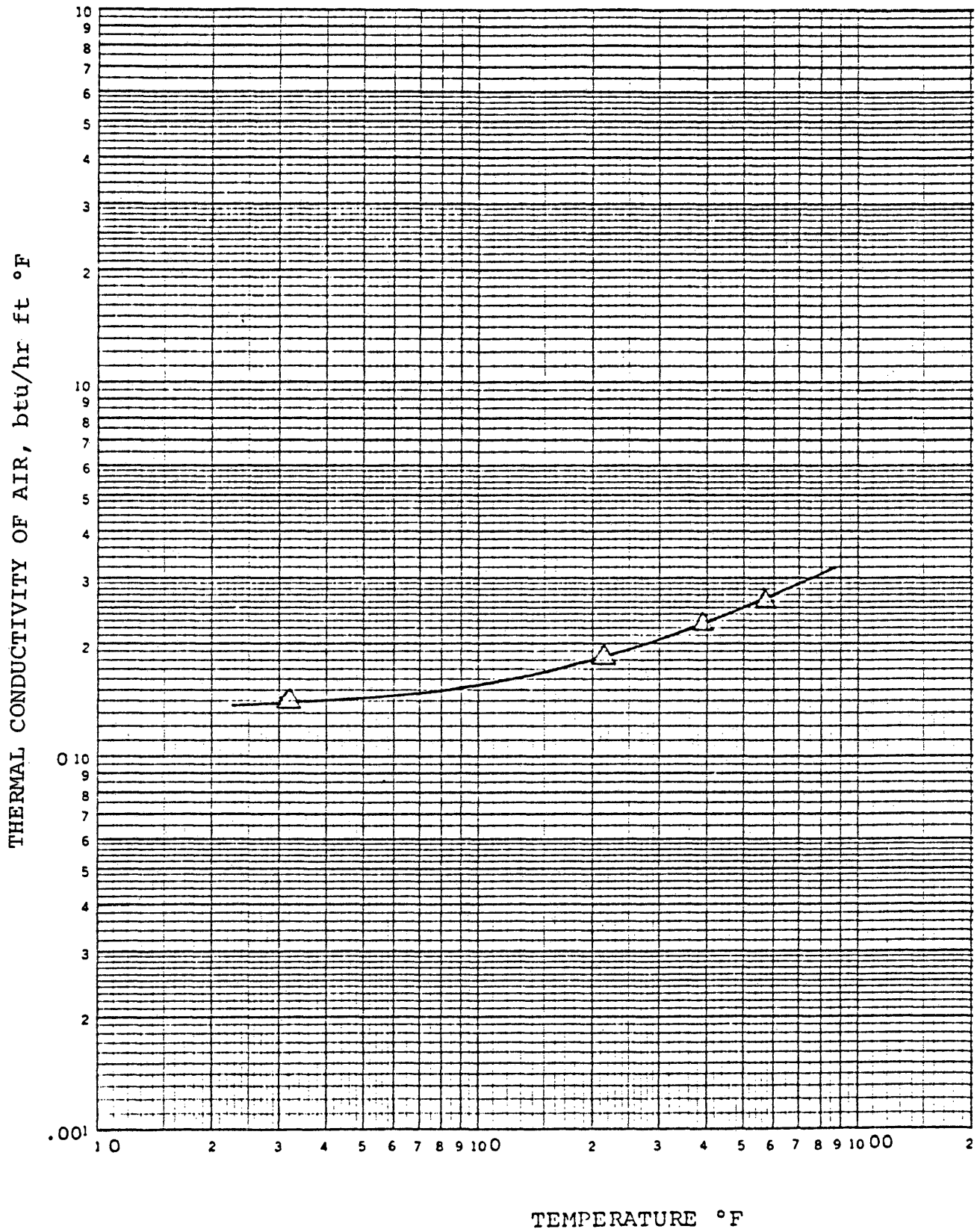
ASBESTOS THERMAL CONDUCTIVITY VS TEMPERATURE



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FIGURE 4

AIR THERMAL CONDUCTIVITY VS TEMPERATURE



SS-304 THERMAL CONDUCTIVITY Vs TEMPERATURE

(Stainless Steel-304)

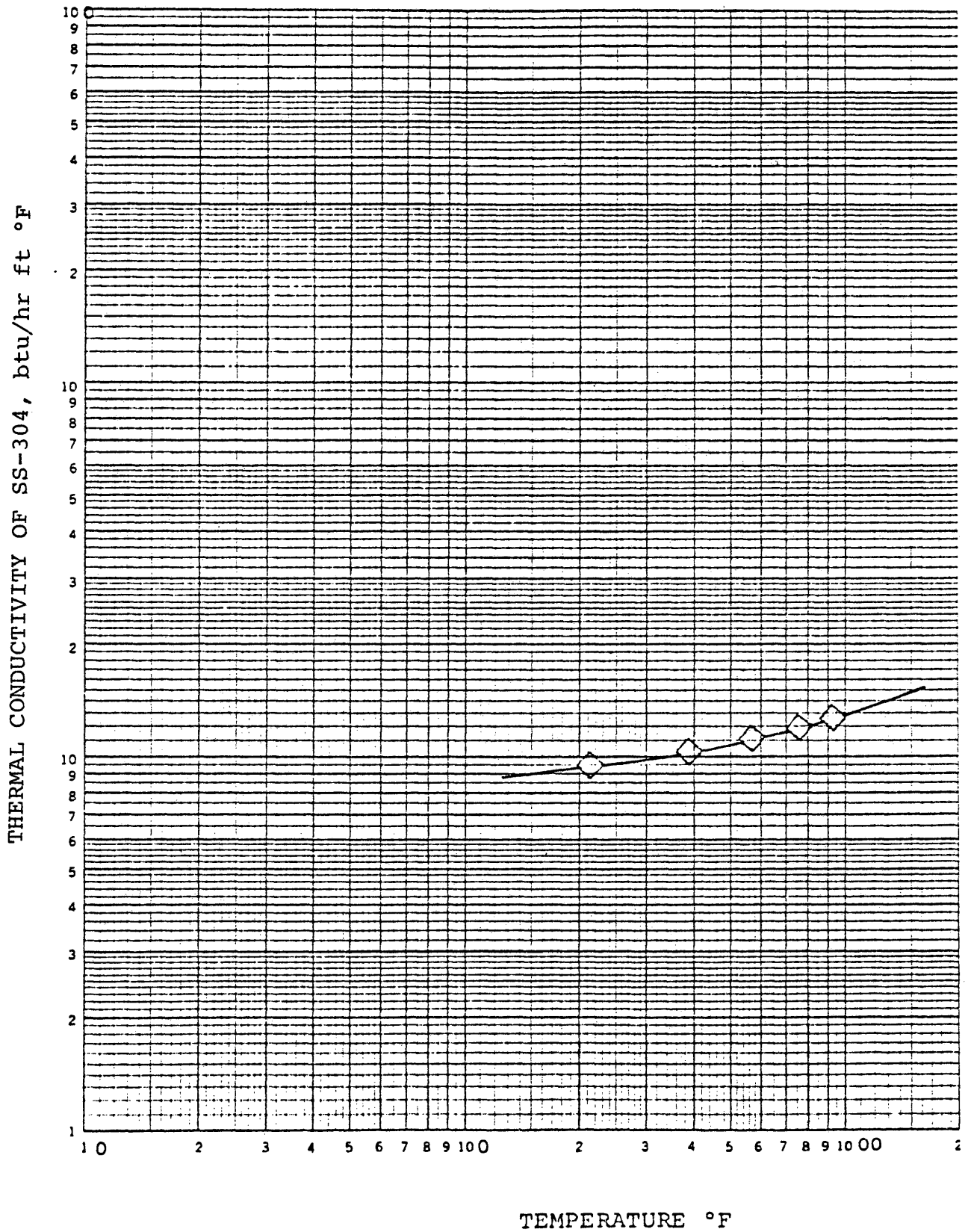
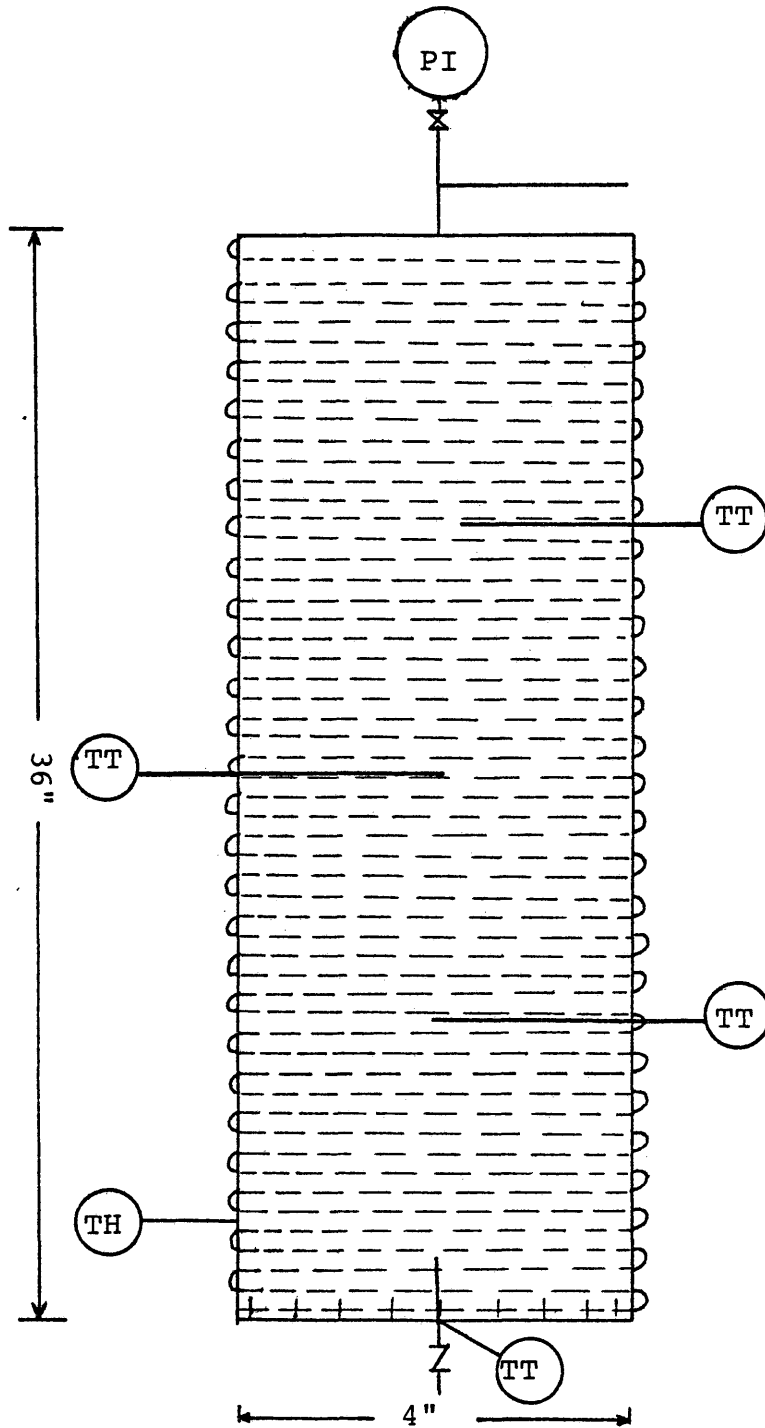


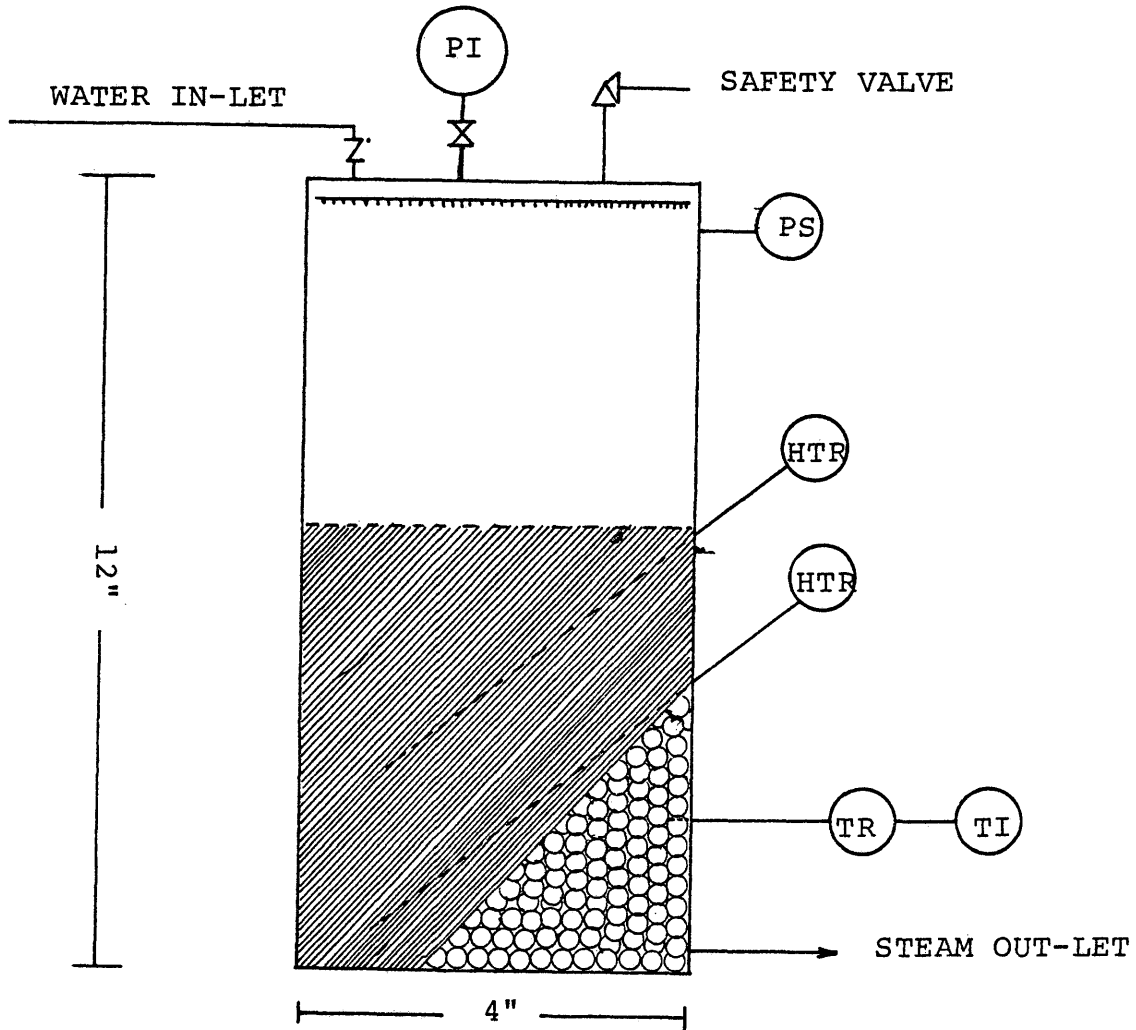
FIGURE 6

STEAM DISTILLATION CELL



- TT TEMPERATURE TRANSMETER
 PI PRESSURE INDICATOR
 TH THERMOSTAT
 --- ELECTRIC TAPE HEATERS
 ++ DEFFUSER PLATE

FIGURE 7
STEAM GENERATOR



- PI PRESSURE INDICATOR
- PS PRESSURE SWITCH
- HTR HEATER
- TR TEMPERATURE REGULATOR
- TI TEMPERATURE INDICATOR
- OO STAINLESS STEEL PELETS

TABLE 1

PROPOSED STEAM DISTILLATION EQUIPMENT

1. Water pump
2. Steam generator
3. Steam distillation cell
4. Temperature controller
5. Temperature resistor
6. Temperature transducer
7. Heat modulator
8. Thermostat
9. Pressure indicators
10. Temperature indicators
11. Back pressure regulator
12. Condenser
13. Separator
14. Samplers
15. Wet test meter
16. Gas chromatograph
17. Pipe and fittings
18. Heaters

TABLE 2
SPECIFICATIONS AND PRICES FOR SUPPORTING EQUIPMENT

<u>Units</u>	<u>Materials</u>	<u>Size</u>	<u>Working Pressure</u>	<u>Catalog</u>	<u>Price \$</u>	<u>TOTAL</u>
10	Valves	1/2"	50-400 PSI	SS-1458	28.00	280.00
6	Elbows	1/2"	50-400 PSI	SS-810-9	10.30	61.80
6	Tees	1/2"	50-400 PSI	SS-810-3	15.50	93.00
7	Unions	1/2" - 3/8"	50-400 PSI	SS-810-6	7.80	54.60
2	Red. Unions	1/2"	50-400 PSI	SS-810-6-6	8.70	17.40
40	Tubing	1/2"	50-600 PSI	SS	ft/1.66	66.40
10	Fittings	1/2"	50-600 PSI	SS	set/4.00	40.00
1	Pre. Indicator	1/2"	0-1000 PSI	G-1536-2	42.00	42.00
1	Pre. Indicator	1/2"	0-1000 PSI	G-1536-2	42.00	42.00
1	Pre. Indicator	1/2"	0-300 PSI	G-5000	25.35	25.35
1	Back Pres. Regulator	1/2"	0-250 PSI	BPR-40-1P	150.00	150.00
1	Steam Regulator	1/2"	50-250 PSI	VC-214-P	84.90	84.90
1	Steam Trap	1/2"	0-250 PSI	VC-345-1	172.00	172.00
3	Check Valve	1/2"	0-300 PSI	VC-1100-36	16.00	48.00
40	Pipe Insulation	1/2"	--	--	ft/1.05	42.00
3	Cell Insulation	4 1/2"	--	--	ft/1.75	7.00
1	Heating Tape	1/2" - 144"	115 Vol(0-500°F)	3111-12	25.90	25.90
2	Heating Tape	4 3/4"-120"	115 Vol(0-900°F)	3107-10	46.50	93.00
1	Voltage Cont.		115 Vol.	2503-SCR	59.75	59.75
1	Temp. Controller			F8703-1	347.00	347.00

TABLE 3
SPECIFICATIONS AND PRICES FOR ANALYSIS EQUIPMENT

SYRINGES

<u>CAPACITY ML.</u>	<u>DESCRIPTION</u>	<u>HAMILTON NO.</u>	<u>ORDERING NO.</u>	<u>PRICE \$</u>
500	Fixed Needle 22GA	750-N	9301-0034	18
100	Fixed Needle 2822GA	710-N	9301-0028	18
25	Fixed Needle 2822GA	702-N	9301-0022	18
10	Fixed Needle 26GA	701-N	9301-0021	18
5	Fixed Needle 26GA	75-N	9301-0175	18

CONNECTORS

<u>UNIT</u>	<u>DESCRIPTION</u>
2	2-3287-1

COLUMNS

<u>UNIT</u>	<u>DESCRIPTION</u>	<u>LENGTH</u> (ft)	<u>CATALOG ORDER NO.</u>	<u>PRICE \$</u>
1	10% SP - 1000 on 100/120 Chromosorb WAW	10	01-2173	70
1	10% Carbowax 20M on 80/100 Chromosorb WAW	20	01-2196	100

TABLE 4
PROPOSED HYDROCARBONS SAMPLES FOR STEAM DISTILLATION TESTS

NAME	COMPOUND FORMULA	MOLECULAR WEIGHT	BOILING POINT OF	DENSITY		CRITICAL PROPERTIES			Hvo @ 25°C Kcal/Mole
				°API	SG. 60/60°F	°F	P ATM.		
n-Pentane	$\text{CH}_3-(\text{CH}_2)_3-\text{CH}_3$	72.147	96.9	92.7	.631	5.25	386.5	32.6	6.395
n-Heptane	$\text{CH}_3-(\text{CH}_2)_5-\text{CH}_3$	100.210	204.2	74.2	.688	5.73	512.5	26.8	8.748
n-Octane	$\text{CH}_3-(\text{CH}_2)_6-\text{CH}_3$	114.240	258.2	68.6	.707	5.89	565.0	24.6	9.919
n-Decane	$\text{CH}_3-(\text{CH}_2)_8-\text{CH}_3$	142.290	345.2	61.3	.734	6.11	654.0	22.0	12.276
Crude Oils	--	--	--	15-35	.9659	.849	--	--	--

TABLE 5

SUPERFICIAL VELOCITY IN SDC
For 100 CM³ Sample Volume

	12,000 cm ³ /hr					8,000 cm ³ /hr					6,000 cm ³ /hr									
Rate Of*																				
Vaporization (%/hr)	5	10	20	30	30	5	10	20	30	30	5	10	20	30	30	5	10	20	30	30
SDC Superficial Velocity (cm/hr)	148.08	148.14	148.27	148.39	148.39	98.74	98.80	98.93	99.05	99.05	74.07	74.13	74.26	74.28	74.28					
Calculated Time to Complete a run (hrs)	11.27	5.36	2.82	1.87	1.87	16.91	8.45	4.22	2.81	2.81	22.54	11.26	5.12	3.74	3.74					
Area = 81.07 cm;	Free Space above the liquid = 83.48 cm (32.87")																			
Liquid Level = 7.96 cm (3.13"); U =	$\frac{\text{Flow rate of steam} + \text{flow rate of Hydrocarbons}}{\text{Cross Sectional Area.}}$																			

* Percent of initial hydrocarbon volume.

TABLE 6
 SUPERFICIAL VELOCITY IN SDC
 For 383 CM³ Sample Volume

STEAM INJECTION RATE	12,000 cm ³ /hr					8,000 cm ³ /hr					6,000 cm ³ /hr				
Rate Of* Initial Vaporization (%/hr)	5	10	20	30	30	5	10	20	30	30	5	10	20	30	30
SDC Superficial Velocity (cm/hr)	148.25	148.49	148.96	149.44	149.44	98.92	99.15	99.62	100.09	100.09	74.25	74.48	74.96	75.43	75.43
Calculated time to Complete a run (hrs)	8.22	4.11	2.05	1.36	1.36	12.33	6.15	3.06	2.03	2.03	16.42	8.18	4.07	2.69	2.69
Area = 81.07 cm ² ;	Free Space above the Liquid = 60.96 cm (24")														
Liquid Level = 30.48 cm (12"); U =	Flow rate of steam + flow rate of Hydrocarbons Cross Sectional Area.														

* Percent of initial hydrocarbon volume.

TABLE 7

SUPERFICIAL VELOCITY IN SDC
For 478 CM³ Sample Volume

	12,000 cm ³ /hr			8,000 cm ³ /hr			6,000 cm ³ /hr					
Rate Of*	5	10	20	5	10	20	5	10	20	30		
Vaporization (%/hr)												
SDC Superficial Velocity (cm/hr)	148.32	148.61	149.20	149.79	98.98	99.27	94.86	100.45	74.31	74.60	75.19	75.78
Calculated Time to Complete A run (hrs)	7.19	3.59	1.79	1.19	10.78	5.37	2.67	1.77	14.36	7.15	3.55	2.34

Area = 81.07 cm²; Free Space above the Liquid = 53.34 cm (21")
 Liquid Level = 38.10 cm (15"); $U = \frac{\text{Flow rate of steam + flow rate of Hydrocarbons}}{\text{Cross Sectional Area.}}$

* Percent of initial hydrocarbon volume.

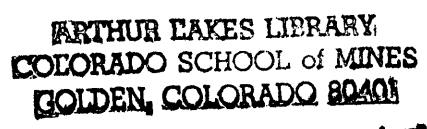


TABLE 8
MATERIAL SPECIFICATION FOR SDC

TYPE OF MATERIAL:	Stainless Steel (SS-304)		
CARBON CONTENT:	.08% max.		
Mn:	2.0% max.		
Si:	1.0%		
Cr:	18-20%		
Ni:	8-12%		
DENSITY:	7.9 gr/cm ³		
SPECIFIC HEAT:	.12 BTU/#°F (32-212°F)		
THERMAL CONDUCTIVITY:	°F	K	BTU/(hr·ft ² ·°F)
	212	9.4	
	392	10.3	
	572	11.0	
	752	11.8	
	932	12.5	
YIELD STRENGTH:	30-35,000 #/in ²		
TENSILE STRESS:	77,500 #/in ² (400°F)		
AMS:	-5639A		
ASTM:	-A-269-GIT		

* See plot in Figure 5

TABLE 9
SPECIFICATIONS OF THE SDC

TYPE OF MATERIAL:	SS-304
MAXIMUM CELL PRESSURE:	700 #/in ²
YIELD STRENGTH:	30-35,000 #/in ²
TENSILE STRESS:	77,500 #/in ² (400° F)
SHELL THICKNESS:	1/8 in.
HEMISPHERICAL HEAD THICKNESS:	1/16 in.
INSIDE DIAMETER:	4.000 in.
HEIGHT:	36. in.
THERMAL CONDUCTIVITY:	Figure 3, 4, 5, BTU(hr ft ⁰ F)
INSULATOR:	2 in. asbestos
WORKING PRESSURE RANGE:	50-200 #/in ²
TEMPERATURE RANGE:	282-382° F
HEAT FLOW REQUIRED:	3585.93 BTU/hr
HYDROCARBON VOLUME SDC:	.0873 ft ³
WATER VOLUME SDC:	.0014 ft ³
FREE LEVEL ABOVE LIQUID SDC:	24 in.

TABLE 10
MATERIAL SPECIFICATIONS FOR STEAM GENERATOR

OUTSIDE DIAMETER:	4.500 in.
INSIDE DIAMETER:	4.00 in.
HEIGHT:	12 in.
TYPE OF MATERIAL:	Stainless Steel (SS-304)
CARBON CONTENT:	.08% max.
Mn:	2.0% max.
Si:	1.0%
Cr: :	18-20%
Ni:	8-12%
DENSITY:	7.9 gr/cm ³
SPECIFIC HEAT:	.12 BTU/# ^o F (32-212 ^o F)
THERMAL CONDUCTIVITY:	^o F K BTU/(hr ft ^o F)*
	212 9.4
	392 10.3
	572 11.0
	752 11.8
	932 12.5
YIELD STRENGTH:	30-35,000 #/in ²
TENSILE STRENGTH:	77,500 #/in ² (400 ^o F)
AMS:	-5639A
ASTM:	-A-269-GIT

* See plot in Figure 5.

TABLE 11
STEAM GENERATOR SPECIFICATION

TYPE OF MATERIAL:	SS-304
MAXIMUM PRESSURE:	1500 #/in ² max.
YIELD STRENGTH:	30-35,000 #/in ²
TENSILE STRESS:	77,500 #/in ² (400°F)
SHELL THICKNESS:	1/4 in.
HEMISPHERICAL HEAD THICKNESS:	1/8 in.
INSIDE DIAMETER:	4.0000 in.
THERMAL CONDUCTIVITY:	See Figure 3
HEIGHT:	12.0 in.
INSULATOR:	3.0 in asbestos
MAXIMUM TEMPERATURE:	400°F
WATER SUPPLY:	1-10 cm ³ /min.
GENERATOR EFFICIENCY:	95%
ENTALPY:	1201 BTU/# at 250 #/in ² and 400°F
HEAT FLOW REQUIRED X SF 2:	3344.58 BTU/hr.
PELLETS DIAMETER:	1/4 in.

APPENDIX 1

DERIVATION OF THE HOLLAND AND WELCH EQUATION

A semi batch steam distillation is of the differential type in that the vapor is continuously withdrawn and condensed. The temperature of the vessel is maintained at a constant value by an indirect heat source (tape heaters). The equations which describe the process are derived by utilizing an over-all material balance during a time interval of Δt .

The accumulation of component "i" in the vessel during the time interval from t to $(t + \Delta t)$ is the number of moles of the component at time $(t + \Delta t)$ less the number of moles of the component at time t .

$$\begin{array}{l} \text{Accumulation of} \\ \text{Component i in the} \\ \text{Vessel} \end{array} = (L_t X_i)_{t+\Delta t} - (L_t X_i)_t \dots (1)$$

$$\begin{array}{l} \text{Accumulation of} \\ \text{Component i in the} \\ \text{Vessel} \end{array} = t \frac{d}{dt} (L_t X_i)_{t+\Delta t} \dots (2)$$

Equation (2) is obtained by the theorem of the mean of differential calculus.

$$\begin{array}{l} \text{Depletion of Component} \\ \text{i in the Vessel} \end{array} = t \frac{d}{dt} (L_t X_i)_{t+\Delta t} \dots (3)$$

In the above expressions "i" is not corresponding to steam so $i \neq s$. Let the average flow rate of vapor for volatile components plus steam during the time interval Δt be denoted by \bar{r} , and \bar{y} the average value of the mole fraction

of any component i in the vapor during the same period of time. Then the depletion of the i component from the vessel during the time Δt will be

$$\text{Depletion of Component } i \text{ during the time } \Delta t = \bar{y} \bar{r} \Delta t \dots \dots \dots (4)$$

Now replace equation (4) into (3)

$$- \frac{d}{dt} (L_t X_i)_{t+\epsilon \Delta t} = \bar{y} \bar{r} \Delta t \dots \dots \dots (5)$$

$$- \frac{d}{dt} (L_t X_i)_{t+\epsilon \Delta t} = \bar{y} \bar{r} \dots \dots \dots (6)$$

$$\lim_{t \rightarrow 0} - \frac{d}{dt} (L_t X_i)_{t+\epsilon \Delta t} = \bar{y} \bar{r}$$

$$- \frac{d}{dt} (L_t X_i) = y_i r \dots \dots \dots (7)$$

but $r = \frac{d(V + S)}{dt} \dots \dots \dots (8)$

and $L_t X_i = L_i \dots \dots \dots (9)$

Then, replacing (8) and (9) into (7)

$$- \frac{dL_i}{dt} = y_i \frac{d}{dt} (V + S) \dots \dots \dots (10)$$

V is related to L_t by an over-all material balance.

$$L^\circ + L^\circ_r = L + L^\circ_r + V \dots \dots \dots (11)$$

$$L^\circ_t = L_t + V \dots \dots \dots (12)$$

$$V = L^\circ_t - L_t \dots \dots \dots (13)$$

Replacing (13) into (10)

$$- \frac{dL_i}{dt} = y_i \frac{d}{dt} (L^\circ_t - L_t + S)$$

$$- \frac{dL_i}{dt} = y_i \left[\frac{dL^\circ_t}{dt} - \frac{dL_t}{dt} + \frac{dS}{dt} \right]$$

$$- \frac{dL_i}{dt} = Y_i \left[-\frac{dL_t}{dt} + \frac{dS}{dt} \right] \dots \dots \dots (14)$$

For any component except steam, using Dalton's and Raoult's Law:

$$Y_i = \frac{p_i}{\pi} = \frac{E_i P_i X_i}{\pi}$$

$$p_i = \frac{P_i X_i}{\pi}$$

$$L_t X_i = L_i$$

$$Y_i = \frac{E_i P_i X_i L_t}{\pi L_t} = \frac{E_i P_i L_i}{\pi L_t} \dots \dots \dots (15)$$

E_i is the vaporization efficiency of component i in the same manner, if we write equations (14) and (15) in terms of the base component we have:

$$- \frac{dL_b}{dt} = Y_b \left[-\frac{dL_t}{dt} + \frac{dS}{dt} \right] \dots \dots \dots (16)$$

$$Y_b = \frac{E_b P_b L_b}{\pi L_t} \dots \dots \dots (17)$$

Now divide (14) by (16) and replace (15) and (17),

$$\frac{- \frac{dL_i}{dt}}{- \frac{dL_b}{dt}} = \frac{Y_i \left[-\frac{dL_t}{dt} + \frac{dS}{dt} \right]}{Y_b \left[-\frac{dL_t}{dt} + \frac{dS}{dt} \right]}$$

$$\frac{dL_i}{dL_b} = \frac{Y_i}{Y_b} \dots \dots \dots (18)$$

$$\frac{dL_i}{dL_b} = \frac{Y_i}{Y_b} = \frac{E_i P_i L_i / \pi L_t}{E_b P_b L_b / \pi L_t}$$

$$\frac{dL_i}{dL_b} = \frac{E_i P_i L_i}{E_b P_b L_b} \dots \dots \dots (19)$$

$$d_i = \frac{P_i}{P_b}$$

$$\frac{dL_i}{dL_b} = \frac{E_i}{E_b} d_i \frac{L_i}{L_b} \dots \dots \dots (20)$$

$$B_i = \frac{E_i}{E_b} d_i$$

$$\frac{dL_i}{dL_b} = B_i \frac{L_i}{L_b} \dots \dots \dots (21)$$

$$\frac{dL_i}{L_i} = B_i \frac{dL_b}{L_b}$$

$$\int_{L_i^0}^{L_i} dL_i = B_i \int_{L_b^0}^{L_b} dL_b$$

$$\ln \frac{L_i}{L_i^0} = B_i \ln \frac{L_b}{L_b^0}$$

$$L_i = L_i^0 \left(\frac{L_b}{L_b^0} \right)^{B_i} \dots \dots \dots (22)$$

Since L_t is equal to the sum of the L_i terms, where $i \neq s$, so,

$$L_t = \sum_{i \neq s} L_i^0 \left(\frac{L_b}{L_b^0} \right)^{B_i} \dots \dots \dots (23)$$

The non-volatile components have been included for $i = r$

$$B_r = 0, L_i^0 = L_r^0$$

Substituting equation (23) into equation (16) and replacing Y_b by its equivalent, given by equation (19), gives

$$\frac{-dL_b}{dt} = Y_b \left[\frac{-dL_t}{dt} + \frac{d_s}{dt} \right]$$

$$Y_b = \frac{E_b P_b L_b}{L_t}$$

$$\frac{-dL_b}{dt} = \frac{E_b P_b L_b}{L_t} \left[\frac{-dL_t}{dt} + \frac{d_s}{dt} \right]$$

$$L_t \frac{dL_b}{L_b} = \frac{E_b P_b}{L_t} \left[\frac{dL_t}{dt} - \frac{d_s}{dt} \right] dt$$

$$L_t \frac{dL_b}{L_b} = \frac{E_b P_b}{L_t} \left[dL_t - d_s \right] \dots \dots \dots (24)$$

$$\int_{L^{\circ}_b}^{L_b} L_t \frac{dL_b}{L_b} = \frac{E_b P_b}{\pi} \int_{L^{\circ}}^L dL_t - \frac{E_b P_b}{\pi} \int_0^s d_s \dots (25)$$

Using equation (23) and replacing on the left-hand side of the equation (25)

$$\int_{L^{\circ}_b}^{L_b} L_t \frac{dL_b}{L_b} = \int_{L^{\circ}_b}^{L_b} \sum_{i \neq s, r} L^{\circ}_i \left(\frac{L_b}{L^{\circ}_b} \right)^{B_i} \frac{dL_b}{L_b} + \int_{L^{\circ}_b}^{L_b} L^{\circ}_r \left(\frac{L_b}{L^{\circ}_b} \right)^{B_r} \frac{dL_b}{L_b}$$

$$\int_{L^{\circ}_b}^{L_b} \sum_{i \neq s, r} L^{\circ}_i \left(\frac{L_b}{L^{\circ}_b} \right)^{B_i} \frac{dL_b}{L_b} + \int_{L^{\circ}_b}^{L_b} L^{\circ}_r \left(\frac{L_b}{L^{\circ}_b} \right)^{B_r} \frac{dL_b}{L_b} =$$

$$\frac{E_b P_b}{\pi} \int_{L^{\circ}}^L dL_t - \frac{E_b P_b}{\pi} \int_0^s d_s$$

$$\frac{L^{\circ}_i}{L^{\circ}_b} \int_{L^{\circ}_b}^{L_b} L_b^{B_i-1} dL_b + L^{\circ}_r \int_{L^{\circ}_b}^{L_b} \frac{dL_b}{L_b} = \frac{E_b P_b}{\pi} \int_{L^{\circ}}^L dL_t -$$

$$\frac{E_b P_b}{\pi} \int_0^s d_s$$

$$\frac{L^{\circ}_i}{L^{\circ}_b} \left[\frac{L_b^{B_i}}{B_i} \right]_{L^{\circ}_b}^{L_b} + L^{\circ}_r \left[\ln L_b \right]_{L^{\circ}_b}^{L_b} = \frac{E_b P_b}{\pi} \left[L_t \right]_{L^{\circ}}^L - \frac{E_b P_b}{\pi} \left[s \right]_0^s$$

$$\frac{L^{\circ}_i}{L^{\circ}_b B_i} \times \frac{1}{B_i} [L_b^{B_i} - L^{\circ}_b B_i] + L^{\circ}_r [\ln L_b - \ln L^{\circ}_b] =$$

$$\frac{E_b P_b}{\pi} [L - L^{\circ}] - \frac{E_b P_b}{\pi} [S - 0]$$

$$\frac{L^{\circ}_i}{B_i} \left[\frac{L_b^{B_i}}{L^{\circ}_b B_i} - \frac{L^{\circ}_b B_i}{L^{\circ}_b B_i} \right] + L^{\circ}_r \ln \frac{L_b}{L^{\circ}_b} = \frac{E_b P_b}{\pi} [L - L^{\circ}] - \frac{E_b P_b}{\pi} S$$

$$\frac{L^{\circ}_i}{B_i} \left[\left(\frac{L_b}{L^{\circ}_b} \right)^{B_i} - 1 \right] + L^{\circ}_r \ln \frac{L_b}{L^{\circ}_b} = \frac{E_b P_b}{\pi} [L - L^{\circ} - S]$$

$$\frac{L^{\circ}_i}{B_i} \left[1 - \left(\frac{L_b}{L^{\circ}_b} \right)^{B_i} \right] + L^{\circ}_r \ln \frac{L_b}{L^{\circ}_b} = \frac{E_b P_b}{\pi} [L^{\circ} - L + S] \dots (26)$$

$$\sum_{i \neq s, r} \frac{L^{\circ}_i}{B_i} \left[1 - \left(\frac{L_b}{L^{\circ}_b} \right)^{B_i} \right] + L^{\circ}_r \ln \frac{L_b}{L^{\circ}_b} = \frac{E_b P_b}{\pi} [L^{\circ} - L + S]$$

ASSUMPTIONS ON THE HOLLAND AND WELCH EQUATION

1. The steam batch distillation is carried out at constant pressure and temperature.
2. The partial pressure of the steam in the vapor from the distillation apparatus is less than the saturation pressure of steam at a given constant temperature; this makes sure the absence of liquid water in the distillation apparatus.
3. The vapor obtained by boiling the liquid is at equilibrium with the liquid.
4. The steam semi-batch distillation will be carried out under dynamic conditions.
5. The mixture at the equilibrium conditions must obey Raoult's law.
6. The non-volatile components are considered miscible with the volatile components.
7. The total pressure in the system is maintained constant by increasing the flow rate of the steam.

APPENDIX 2

ENTRAINMENT AND SDC SIZE

Entrainment is the upward displacement of liquid particles caused by the dynamic action of the vapor. Entrainment may be defined as the quantity of liquid carried upward by the vapor per unit time.

The effects of entrainment in fractionating equipment are largely the impairment of color, loss of liquid overhead as in oil absorbers, increase in the quantity of liquid flowing from plate to plate due to abrupt changes in the vapor load, and decrease in plate efficiency.

Souders and Brown (2) found that entrainment could be the result of two distinct effects of the flowing vapor, the actual carrying of droplets by the rising vapor and the throwing of liquid particles by the dynamic action of vapor jets. The first effect is a function of the mass velocity of the vapor, the densities of the liquid and vapor, the diameter of the particle, and agglomeration of individual particles into large masses. The entrainment produced by the throwing of liquid particles is a function of the kinetic energy of the vapor jets, which, in turn, depends upon the density and the linear velocity of escape of the vapor, and is closely related to the spacing between plates.

The resistance of a sphere in a moving stream is given by:

$$F_a = K U \sqrt{\frac{\pi}{2}} D u + k d_2 \frac{\pi D^2}{4} u^2 \dots \dots \dots (1)$$

F_a = Total force on drop, #

K, k = Empirical Constants

U = Viscosity of Fluid, cp

D = Diameter of Particle, in

d_2 = Density of Fluid, #/ft³

u = Linear velocity of vapor, ft/sec

In a fractionating column the first term on the right could be neglected, since the viscosity of the vapor is very small (.01 - .001)cp.

$$F_a = K d_2 \frac{\pi D^2}{4} u^2 \dots \dots \dots (2)$$

The force of gravity less buoyancy on a spherical particle, is

$$F_g = \frac{\pi D^3}{6} (d_1 - d_2)g \dots \dots \dots (3)$$

d_1 = Density of the particle, #/ft³

g = Acceleration of gravity, ft/sec²

When the force of gravity is equal to the resistance to the moving vapor, the particle remains suspended.

$$F_a = F_g$$

$$K d_2 \frac{\pi D^2}{4} u^2 = \frac{\pi D^3}{6} (d_1 - d_2)g$$

$$u^2 = \frac{2}{3} \frac{K}{D} \left(\frac{d_1}{d_2} - 1 \right) g \dots \dots \dots (4)$$

g, K and D are constant

$$B = \sqrt{\frac{2Kg}{3D}} \dots \dots \dots (5)$$

So the suspending velocity is

$$u = \sqrt{\frac{2gK}{3D}} \times \sqrt{\frac{d_1}{d_2} - 1}$$

$$u = B \sqrt{\frac{d_1}{d_2} - 1} \dots \dots \dots (6)$$

u = ft/sec.

Since mass velocity of the vapor is

$$W = u \frac{ft}{sec} \times d_2 \frac{\#}{ft^3}$$

$$= u \frac{ft}{\frac{sec \times 1 \text{ hr}}{3600 \text{ sec}}} \times d_2 \frac{\#}{ft^3}$$

$$= 3600 u d_2 \frac{\#}{hr \cdot ft^2} \dots \dots \dots (7)$$

$$W = 3600 \sqrt{\frac{2gK}{3D}} \times \sqrt{\frac{d_1}{d_2} - 1} d_2 \frac{\#}{hr \cdot ft^2}$$

$$C = 3600 \sqrt{\frac{2gK}{3D}}$$

$$W = C d_2 \sqrt{\frac{d_1}{d_2} - 1} \dots \dots \dots (8)$$

<u>Column Pressure</u> (PSIA)	<u>Spacing Plate</u>	<u>C*</u> ft/hr
14.697 (212°F)	12"	235
190 (377.51°F)	21"	400
465 (459.59°F)	24"	440

By assuming these conditions we have

$$d_1 = \text{Density of Oil Max.} = .90 \times 62.4 \frac{\#}{ft^3} = 56.16 \frac{\#}{ft^3}$$

$$\text{Med.} = .80 \times 62.4 \frac{\#}{ft^3} = 49.92 \frac{\#}{ft^3}$$

$$\text{Min.} = .70 \times 62.4 \frac{\#}{ft^3} = 43.86 \frac{\#}{ft^3}$$

*For Commercial Natural Gas Absorber.

d_2 = Density of Steam

Superheated Conditions		Density
465 (459.59°F)	V = .9985 ft ³ /#	1.0015 #/ft ³
190 (377.51°F)	V = 2.404 ft ³ /#	.4160 #/ft ³
14.697 (212°F)	V = 26.80 ft ³ /#	.0373 #/ft ³

Maximum mass velocity of the vapor

$$W = 440 \frac{\text{ft}}{\text{hr}} \times 1.0015 \frac{\#}{\text{ft}^3} \sqrt{\frac{56.16 \frac{\#}{\text{ft}^3}}{1.005 \frac{\#}{\text{ft}^3}} - 1} = 3270.28 \frac{\#}{\text{hr ft}^2}$$

Medium Value

$$W = 400 \frac{\text{ft}}{\text{hr}} \times .4160 \frac{\#}{\text{ft}^3} \sqrt{\frac{49.92 \frac{\#}{\text{ft}^3}}{.4160 \frac{\#}{\text{ft}^3}} - 1} = 1815.21 \frac{\#}{\text{hr ft}^2}$$

Minimum mass velocity of the vapor

$$W = 235 \frac{\text{ft}}{\text{hr}} \times .0373 \frac{\#}{\text{ft}^3} \sqrt{\frac{43.68 \frac{\#}{\text{ft}^3}}{.0373 \frac{\#}{\text{ft}^3}} - 1} = 299.83 \frac{\#}{\text{hr ft}^2}$$

24" free space from the liquid level.

$$3270.28 \frac{\#}{\text{hr ft}^2} \times \frac{1}{60 \frac{\text{min}}{\text{hr}}} \times \frac{454 \text{ gr}}{\#} \times \frac{1}{(30.48)^2 \frac{\text{cm}}{\text{ft}}} = 26.64 \text{ gr/min cm}^2$$

21" free space from the liquid level

$$1815.21 \frac{\#}{\text{hr ft}^2} \times \frac{1}{60 \frac{\text{min}}{\text{hr}}} \times \frac{454 \text{ gr}}{\#} \times \frac{1}{(30.48)^2 \frac{\text{cm}}{\text{ft}}} = 14.78 \text{ gr/min cm}^2$$

12" free space from the liquid level

$$299.83 \frac{\#}{\text{hr ft}^2} \times \frac{1}{60 \frac{\text{min}}{\text{hr}}} \times \frac{454 \text{ gr}}{\#} \times \frac{1}{(30.48)^2 \frac{\text{cm}}{\text{ft}}} = 2.44 \text{ gr/min cm}^2$$

Cross sectional area of the distillation cell

$$A = \frac{\pi D^2}{4} = \frac{3.1416}{4} (4 \text{ in} \times 2.54 \text{ cm/in})^2 = 81.07 \text{ cm}^2$$

The critical mass flux is $299.83 \frac{\#}{\text{hr ft}^2} = 2.44 \text{ gr/min cm}^2$

Taking this value to calculate the critical steam injection rate in the linear steam flood cell:

$$2.44 \frac{\text{gr}}{\text{min cm}^2} \times 81.07 \text{ cm}^2 = 197.81 \text{ gr/min}$$

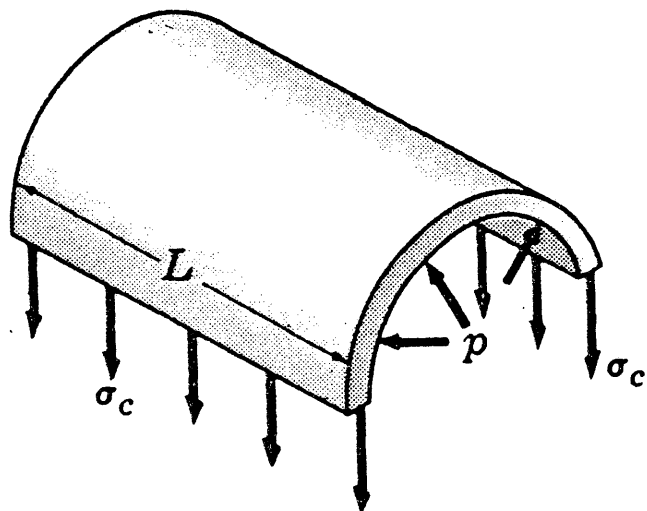
or 3.29 gr/sec.

Assumptions

1. The space between the free liquid level and the top of the cell is assumed as the distance between plates.
2. Based on assumption 1., values of C from Souder's paper were used for theoretical calculations.
3. The steam injected into the distillation cell is superheated.
4. The injected steam remains as steam inside of distillation cell.
5. The steam injected in the distillation cell covers the entire cross sectional area of the cell.
6. The mass velocity of the vapor calculated represents the maximum injection rate for a particular plate spacing; any increase in the injection rate will cause entrainment.
7. The liquid particle sizes are constant.

APPENDIX 3

STEAM DISTILLATION CELL THICKNESS



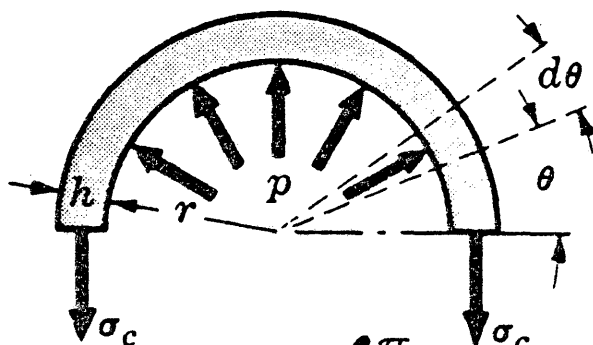
σ_c = Circumferential Stress

P = Pressure

h = Wall Thickness

r = Radius

L = Length



$$\sum F_v = -2 \sigma_c h L + \int_0^{\pi} PrL \sin \theta d\theta = 0$$

$$-2 \sigma_c h L + PrL \int_0^{\pi} \sin \theta d\theta = 0$$

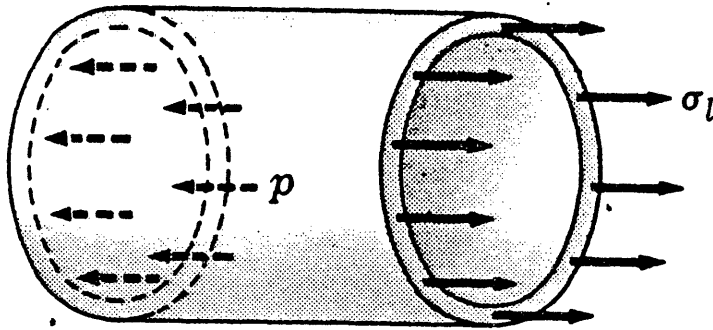
$$-2 \sigma_c h L = -PrL \left[-\cos \right]_0^{\pi}$$

$$2 \sigma_c h = Pr \left[-\cos \pi + \cos 0^\circ \right]$$

$$2 \sigma_c h = Pr (1 + 1)$$

$$2 \sigma_c h = 2 Pr$$

$$\sigma_c = \frac{Pr}{h}$$



$$\sum Fh = -P\pi r^2 + 2\pi rh\sigma_l = 0$$

$$2\pi rh\sigma_l = P\pi r^2$$

$$2h\sigma_l = Pr$$

$$\sigma_l = \frac{Pr}{2h}$$

Since the circumferential stress is twice the longitudinal stress, it is the critical one for design purposes and it must not exceed the allowable working stress 30,000 PSI (yield point) with a safety factor of 2.

$$L = 36 \text{ in.}$$

$$h = ?$$

$$r = 2 \text{ in.}$$

$$\frac{30000 \text{ \#/in}^2}{2} = \frac{700 \text{ \#/in}^2 \times 2 \text{ in.}}{h}$$

$$h = \frac{700 \text{ \#/in}^2 \times 2 \text{ in.} \times 2}{30000 \text{ \#/in}^2} = .0933 \text{ in.}$$

$$h = .0933 \text{ in thick.}$$

*Type SS-304 Cr(18%) Ni(8%), ASTM A269-GIT

APPENDIX 4

SDC HEMISPHERICAL HEADS

By the basic relationships for thin cylindrical shells under, internal pressure it is shown that the induced circumferential stress is equal to the pressure times the diameter divided by twice the shell thickness (page 25). As the pressure increases and the shell thickness increases, the stress distribution across the thickness become non-uniform and some correction is required. So the modified equation as given by the ASME unfired pressure code, Section VIII, 1962, page 25 is:

$$h = \frac{Pr}{fE - .6P} \dots \dots \dots (1)$$

In equation (1) the allowable tensile stress, f , must be modified by a joint efficiency, E .

According to ASME code, when steel is jointed by double butt welding and fully radiographed has a joint efficiency of 1.0. If the welded joints are not radiographed, the joint efficiency is only .70 and if spot radiographic examination is used the joint efficiency is .85.

$$h = \frac{Pr}{fE - .6P}$$

$$h = \frac{700 \text{ \#/in}^2 \times 2 \text{ in.}}{77500 \text{ \#/in}^2 \times 1.0 - .6 \times 700 \text{ \#/in}^2}$$

$$h = \frac{1400 \text{ in.}}{77500 - 420} = \frac{1400 \text{ in.}}{77080} = .0182 \text{ in.}$$

$h = .0182 \text{ in.}$ thickness of the shell

$h = .0182 \text{ inches}$

The 1962 ASME code gives the following equation for calculating the thickness of thin-walled ($h \leq .35 r$) spherical shells, which also applies to hemispherical heads. In this case the $.6P$ in equation (1) is replaced by $.2P$:

$$h = \frac{Pr}{2fE - .2P} \dots \dots \dots (2)$$

$$h = \frac{700 \text{ \#/in}^2 \times 2 \text{ in}^2}{2 \times 77500 \text{ \#/in}^2 - .2 \times 700 \text{ \#/in}^2}$$

$$h = \frac{1400 \text{ in.}}{155000 - 140} = \frac{1400 \text{ in.}}{154860} = .0090 \text{ in.}$$

$h = .0090 \text{ in}$ thickness of the head

APPENDIX 5

SDC FLAT-PLATE HEADS

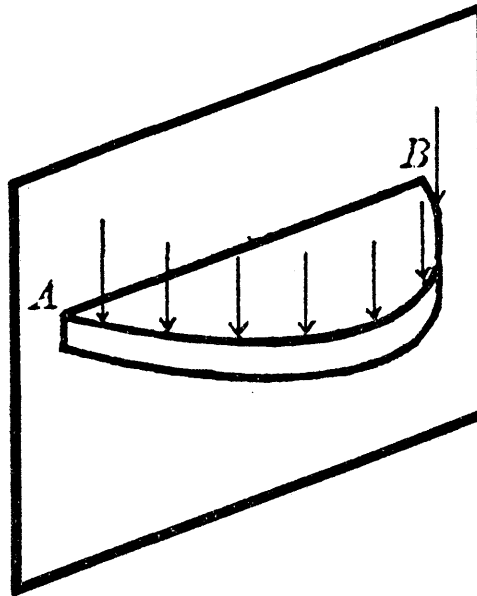
When a flat plate is supported at its boundary and loaded by forces applied at right angles to its surface, flexure takes place just as it does in the case of a beam. But the flexure of a flat plate presents a more difficult problem than that of a beam, since the curvature is not confined to parallel planes. The one considered here is analogous to the simple theory of flexure in beams.

We assume that the plate is of uniform thickness and that the deflection of the middle surface is small compared with the thickness of the plate. The plane midway between the faces of the plate is referred to as the middle-plane, or, when deformed, the middle-surface of the plate. It is also assumed that this surface is not extended. We also assume that elements of the plate originally straight and perpendicular to the middle-plane remain straight and become perpendicular to the middle-surface when strained. We neglect normal stresses across planes parallel to the middle surface.

Consider a flat, circular plate of homogeneous material, which bears a uniform load, pound force per unit area, since the edge of the plate is assumed rest freely on a circular rim with a slightly smaller circle than the plate.

The strain calculated is greater than if the plate was fixed at the edges. Consequently, the formula deduced here will give the maximum stress.

The following figure shows half of a diametral section of the plate. The half of the plate is considered as a cantiliver.



Then r is the radius of the plate, the total load is $\frac{\pi r^2}{2} \times W$, and resultant is applied at the center of gravity of the semi-circle, which is at a distance $\frac{4r}{3\pi}$ from AB. Similarly, the resultant of the supporting forces at the edge of the plate is $\frac{\pi r^2}{2} \times W$, and is applied at the center of gravity of the semi-circumference, which is at a distance of $\frac{2r}{\pi}$ from AB.

$$\text{Total load semicircle} = \frac{\pi r^2}{2} \times W$$

$$\text{Center of gravity semicircle} = \frac{4r}{3\pi} \quad (\text{from AB})$$

$$M_{1AB} = F_i \times d_1$$

$$M_{1AB} = \frac{\pi r^2}{2} \times W \times \frac{4r}{3\pi} = \frac{2r^3W}{3}$$

$$M_{1AB} = \frac{2}{3} r^3 W$$

$$\text{Forces at the edge} = \frac{\pi r^2}{2} W$$

Center of gravity of semicircumference $\frac{2r}{\pi}$ (from AB)

$$M_{2AB} = F_2 \times d_2$$

$$M_{2AB} = \frac{\pi r^2}{2} W \times \frac{2r}{\pi} = r^3 W$$

$$M_{2AB} = r^3 W$$

The total external moment M at the support is

$$M_{tAB} = M_{2AB} - M_{1AB}$$

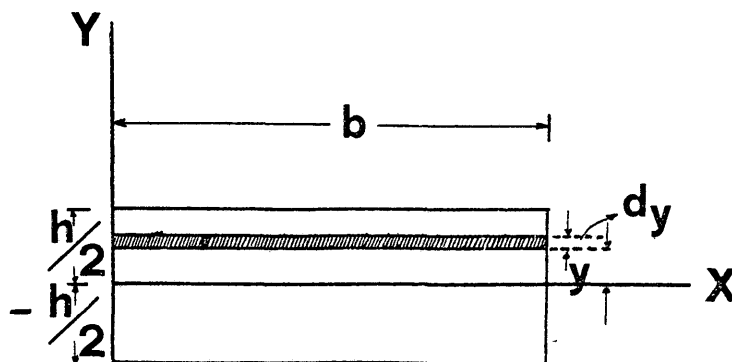
$$M_{tAB} = r^3 W - \frac{2}{3} r^3 W$$

$$M_{tAB} = \frac{r^3 W}{3}$$

Assuming that the stress at any point of the plate is independent of the distance of this point from the center, so we can apply the fundamental formula used in the theory of beams.

The stress due to the external moment M is given by:

$$P = \frac{Me}{I} \dots \dots \dots (1)$$



The moment of inertia $I \times G$ about X-axis passing through the centroid is given by $I \times G = \int y^2 da$. The element is selected such that y is a constant for all points in the element, as shown in the shaded area.

$$I \times G = \int y^2 da \dots\dots\dots (2)$$

$$da = bdy \dots\dots\dots (3)$$

$$I \times G = \int_{-h/2}^{h/2} h^2 bdy \dots\dots\dots (4)$$

$$= b \int_{-h/2}^{h/2} y^2 dy$$

$$= b \left[\frac{y^3}{3} \right]_{-h/2}^{h/2}$$

$$= \frac{b}{3} \left[\left(\frac{h}{2}\right)^3 - \left(-\frac{h}{2}\right)^3 \right] = \frac{b}{3} \left[\frac{h^3}{8} + \frac{h^3}{8} \right]$$

$$= \frac{2bh^3}{24} = \frac{bh^3}{12}$$

$$I \times G = \frac{bh^3}{12} \dots\dots\dots (5)$$

Replacing in (1)

$$P = \frac{Me^3}{bh^3/12}$$

If the thickness of the plate is denoted by h

$$e = \frac{h}{2} \dots\dots\dots (6)$$

$$M_{tab} = \frac{r^3 W}{3} \dots\dots\dots (7)$$

$$P = \frac{r^3 W/3 \times h/2}{bh^3/12}$$

$$b = 2r$$

$$P = \frac{r^3 W/3 c h/2}{2r h^3/12}$$

$$P = W \left(\frac{r}{h}\right)^2 \dots \dots \dots (8)$$

$$\frac{30000 \text{ \#/in}^2}{2} = 700 \text{ \#/in}^2 \frac{r_i^2}{h^2}$$

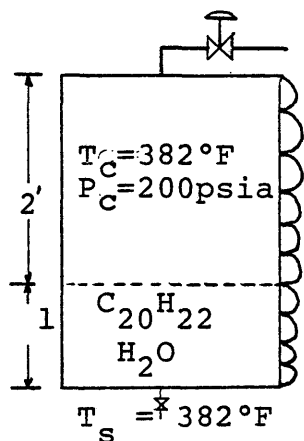
$$h^2 = \frac{700 \text{ \#/in}^2 \times r_i^2 \times 2}{30000 \text{ \#/in}^2}$$

$$h = \sqrt{\frac{2 \cdot 700 \text{ \#/in}^2 r_i^2}{30000 \text{ \#/in}^2}} = \sqrt{\frac{2 \times 700 \times 4 \text{ in}^2}{30000}}$$

$$h = .432 \text{ in}$$

APPENDIX 6

SDC HEATER DESIGN



$$T_c = \text{Temp. of the cell} = 382^\circ F$$

$$P_c = \text{Press. of the cell} = 200 \text{ psia}$$

$$T_s = \text{Temp. of Steam} = 382^\circ F$$

$$\text{Vol. Hc.} = .0873 \text{ ft}^3$$

$$\text{Vol. H}_2\text{O} = .0014 \text{ ft}^3$$

Data Required.

$$\text{Mass of Water} = 40 \text{ cm}^3 \times 1 \text{ gr/cm}^3 \times \frac{1 \#}{454 \text{ gr}} = .0881 \text{ \# of water}$$

$$\text{Mass of } C_{10} = .0873 \text{ ft}^3 \times .734 \times 62.4 \frac{\#}{\text{ft}^3} = 3.9985 \text{ \# of } C_{10}$$

$$\text{Specific gravity } C_{10} = .734 \text{ from Table 4}$$

$$\text{Specific heat } C_{10} = .504 \text{ BTU/\#}^\circ F \text{ Reference (5) at } 345^\circ F$$

$$\text{Specific heat } H_2O = 1.015 \text{ BTU/\#}^\circ F \text{ Reference (5) at } 212^\circ F$$

$$\text{Heat of vaporization } H_2O = 1203 \text{ BTU/\# at } 200 \text{ psia } 382^\circ F \text{ (5)}$$

$$\text{Specific Volume } H_2O = 2.321 \text{ ft}^3/\# = .4308 \text{ \#/ft}^3 \text{ at } 200 \text{ psi } 382^\circ F \text{ (5)}$$

$$\text{Heat of vaporization } C_{10} = 9.388 \text{ Kcal/mole at } 200 \text{ psi } 382^\circ F \text{ (5)}$$

$$\text{Free volume above liquid} = r^2 L = 3.1415 \times \left(\frac{2}{12}\right)^2 \text{ ft}^2 \times 2 \text{ ft} = .1745 \text{ ft}^3$$

$$P_{vH_2O} = 200 \text{ psi at } 382^\circ F \text{ (vapor pressure, } H_2O)$$

$$P_{vC_{10}} = 29.40 \text{ psi at } 382^\circ F \text{ (vapor pressure, } C_{10})$$

$$P_t \text{ (total pressure)} = 200 + 29.40 = 229.40 \text{ psia}$$

$$Y_{H_2O} = \frac{200}{229.4} = .8718 \text{ mole fraction}$$

$$Y_{C_{10}} = \frac{29.4}{229.4} = .1282 \text{ mole fraction}$$

Moles H₂O in vapor space

$$PV = nRT$$

$$N_{H_2O} = \frac{PV}{RT} = \frac{.1745 \text{ ft}^3 \times 200 \text{ psi}}{10.73 \text{ ft}^3 \times \text{psi}/\# \text{mole } ^\circ\text{F} \times 842^\circ\text{F}}$$

$$N_{H_2O} = .0039 \text{ moles}$$

Moles C₁₀ in vapor space

$$N_{C_{10}} = \frac{PV}{RT} = \frac{.1745 \text{ ft}^3 \times 29.4 \text{ psi}}{10.73 \text{ ft}^3 \times \text{psi}/\# \text{-mole } ^\circ\text{F} + 842^\circ\text{F}}$$

$$N_{C_{10}} = .0006 \text{ moles}$$

Energy required

$$\text{for water} = \text{moles} [(\text{Cp}\Delta\text{T})_{\text{Li}_b} + \text{LHV}_{\text{at } 382^\circ}]$$

$$= M_{H_2O} \text{Cp}\Delta\text{T} + M_{VLHV}$$

$$= .0881\# \times 1.015 \text{ BTU}/\# \text{ } ^\circ\text{F} (212 - 60)^\circ\text{F} + .0039 \times 18\# \times 1203 \frac{\text{BTU}}{\#}$$

$$= 13.592 \text{ BTU} + 84.45 \text{ BTU} = 98.043 \text{ BTU}$$

$$= 98.043 \text{ BTU} \times 4/\text{hr} = 396.17 \text{ BTU/hr}$$

$$\text{for C}_{10} = \text{moles} [(\text{Cp}\Delta\text{T})_{\text{Li}_b} + \text{LHV}_{\text{at } 382^\circ}]$$

$$= M_{C_{10}} \text{Cp}\Delta\text{T} + M_{VLHV}$$

$$= 3.9985\# \times .504 \frac{\text{BTU}}{\# \text{ } ^\circ\text{F}} \times (345.2 - 60)^\circ\text{F} + .006 \text{ mole} \times 9.388 \frac{\text{K cal}}{\text{mole}} \times \frac{\text{BTU}}{.252 \text{ Kcal}}$$

$$= 574.75 \text{ BTU} + .0224 \text{ BTU} = 575 \text{ BTU}$$

$$= 574.77 \text{ BTU} \times 4/\text{hr} = 2300 \text{ BTU/hr}$$

The last calculations assume that we have liquid water and liquid decane present in a three phase system and these energy is supplied by a heater with a capacity obtained by using a safety factor of 4:

Q_H = Capacity of the heater

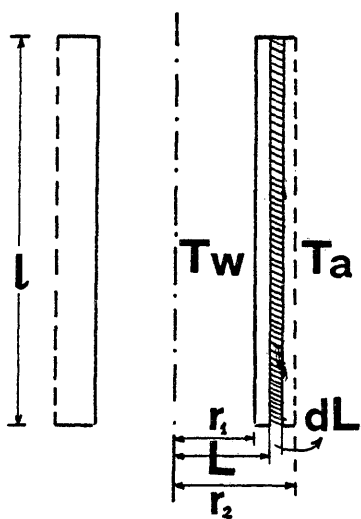
Q_{H_2O} = 396.17 BTU/hr

Q_{ClO} = 2300 BTU/hr

Q_{loss} = 875.28 BTU/hr

Q_H = $Q_{H_2O} + Q_{ClO} + Q_{loss}$
= (396.17 + 2300 + 875.28) BTU/hr
= 3586 BTU/hr

APPENDIX 7
INSULATOR CALCULATIONS



$$A = 2\pi lL$$

$$\frac{q}{A} dL = -K dT$$

$$q dL = -2\pi lLk dT$$

$$q \int_{r1}^{r2} \frac{dL}{L} = -2\pi lK \int_{T1}^{T2} dT$$

$$q \left[\ln L \right]_{r1}^{r2} = -2\pi lK t \left[\right]_{T2}^{T1}$$

$$q \ln \frac{r2}{r1} = 2\pi lK (T2 - T1) \dots (1)$$

Equation (1) gives an approximate solution of heat loss, a more accurate solution will include K/htr_2 which compensates for heat losses due to convection and radiation.

$$q \left[\ln \frac{r2}{r1} + \frac{K}{htr_2} \right] = 2\pi lK (T2 - T1) \dots (2)$$

$$q = \frac{2\pi lK (T2 - T1)}{\ln \frac{r2}{r1} + \frac{K}{htr_2}}$$

Logarithmic - mean temperature

$$T_{log} = \frac{T1 - T2}{\ln T1/T2} \quad \begin{matrix} T1 = TW = 400^\circ F \\ T2 = Tair = 80^\circ F \end{matrix}$$

$$T_{\text{Log}} = \frac{(400 - 80)^\circ\text{F}}{\ln 400/80} = \frac{320^\circ\text{F}}{1.6094} = 198.83^\circ\text{F}$$

From Figure 3 read the corresponding value of K at mean log temperature

$$K_{\text{avg}} \text{ at } 198.83^\circ\text{F} = .113 \text{ BTU}/(\text{hr ft } ^\circ\text{F})$$

$$r_1 = 2.25 \text{ in} \qquad \text{Insulation Thickness} = 2 \text{ in}$$

$$r_2 = 4.25 \text{ in}$$

$$ht = 1.68 \text{ BTU}/(\text{hr ft}^2 \text{ } ^\circ\text{F})$$

$$l = 1 \text{ ft}$$

$$T_{\text{air}} = 80^\circ\text{F}$$

$$T_W = 400^\circ\text{F}$$

$$q = \frac{.113 \text{ BTU}/\text{hr ft } ^\circ\text{F} \times 2 \times 3.1416 \times 1 \text{ ft} \times (400-80)^\circ\text{F}}{\ln 4.25 \text{ in}/2.25 \text{ in} + (.113 \text{ BTU}/\text{hr ft } ^\circ\text{F} \times 12/1.68 \text{ BTU}/\text{ft}^2 \times \text{hr } ^\circ\text{F} \times 4.25 \text{ in})}$$

$$q = \frac{.113 \text{ BTU}/\text{hr} \times 2 \times 3.1416 \times 1 \times (400-80)}{\ln 4.25/2.25 + (.113 \times 12/1.68 \times 4.25)}$$

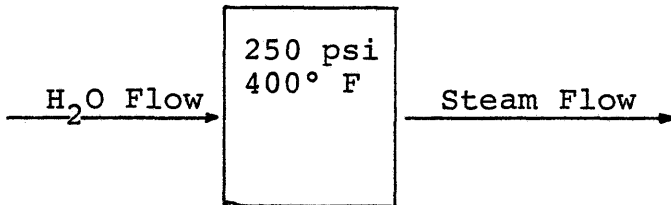
$$q = \frac{227.2 \text{ BTU}/\text{hr ft of Length}}{.6360 + 1899} = 275.0922 \text{ BTU}/\text{hr ft of Length}$$

$$q_{\text{Total}} = 275.0922 \frac{\text{BTU}}{\text{hr} + \text{ft of Length}} \times 3 \text{ ft Length} = 875.2767 \text{ BTU}/\text{hr}$$

$$q_{\text{Total}} = 875.28 \text{ BTU}/\text{hr}$$

APPENDIX 8

STEAM GENERATOR DESIGN



Water Supply 1 cc/min - 10cc/min

$$10 \frac{\text{cm}^3}{\text{min}} \times 60 \frac{\text{min}}{\text{Hr}} = 600 \text{ cm}^3/\text{Hr}$$

$$600 \frac{\text{cm}^3}{\text{Hr}} \times \frac{1 \text{ gal}}{3785.43 \text{ cm}^3} = .1585 \text{ gal/Hr}$$

Boiler efficiency = 95%

$$.1585 \text{ gal/Hr} \times 8.345 \text{ \#/gal} = 1.3227 \text{ \#/Hr}$$

Entalpy at 250 psi = 1201.1 BTU/#
400 °F

$$\frac{1.3227 \text{ \#/Hr} \times 1201.1 \text{ BTU/\#}}{.95} = 1672.29 \text{ BTU?Hr}$$

$$1672.29 \frac{\text{BTU}}{\text{Hr}} \times \frac{\text{WATT hr}}{3.412 \times \text{BTU/hr}} = 489.98 \text{ WATT-hr}$$

$$979.96 \text{ WATT-hr} \quad 1 \text{ Kw-hr}$$

Pipe characteristics

Type	SS-304	AMS 5639A
Grade	Cr (18%) Ni (8%)	Size 4.000 x .500
ASTM	A-269-61T	B & WM Ht N ^o 27034

APPENDIX 9

STEAM GENERATOR INSULATION CALCULATIONS

$$q = \frac{2 \text{ lK} (T_1 - T_2)}{\ln r_1/r_2 + (K/ht) r_2}$$

Logarithmic - mean temperature

$$T_{\text{Log}} = \frac{(T_1 - T_2)^\circ\text{F}}{\ln T_1/T_2} \quad \begin{array}{l} T_1 = T_w = 400^\circ\text{F} \\ T_2 = T_{\text{air}} = 80^\circ\text{F} \end{array}$$

$$T_{\text{Log}} = \frac{(400 - 80)^\circ\text{F}}{\ln 400/80} = \frac{320^\circ\text{F}}{1.6094} = 198.83^\circ\text{F}$$

From Figure 3 read the corresponding value of K at mean-log temperature.

$$K_{\text{avg}} \text{ at } 198.83^\circ\text{F} = .113 \text{ BTU/hr/ft}^2/\circ\text{F/ft}$$

$$r_1 = 2.25 \text{ in} \quad \text{Insulation thickness} = 3 \text{ in}$$

$$r_2 = 5.25 \text{ in} \quad l = 1 \text{ ft}$$

$$ht = 1.68 \text{ BTU/hr/ft}^2/\circ\text{F} \quad T_{\text{air}} = 80^\circ\text{F}$$

$$T_w = 400^\circ\text{F}$$

$$q_{\text{Total}} = \frac{.113 \text{ BTU/hr ft }^\circ\text{F} \times 2 \times 3.1416 \times 1 \text{ ft} \times (400 - 80)^\circ\text{F}}{\ln 5.25 \text{ in}/2.25 \text{ in} + (.113 \text{ BTU/hr ft }^\circ\text{F} \times 12/1.68 \text{ BTU/hr ft}^1/\circ\text{F} \times 5.25 \text{ in})}$$

$$q_{\text{Total}} = \frac{.113 \text{ BTU/hr ft of length} \times 2 \times 3.1415 \times 1 (40-80)}{\ln 5.25/2.25 + (.113/1.68 \times 5.25)} =$$

$$\frac{225.2 \text{ BTU/hr ft of length}}{.8473 + .1537}$$

$$q_{\text{Total}} = \frac{227.2}{1.001} \text{ BTU/hr ft of length} + 1 \text{ ft} = 226.97 \text{ BTU/hr}$$

$$q_{\text{Total}} = 226.97 \text{ BTU/hr}$$

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