The present steam generating facilities in the Engineering Laboratory are overage and require a considerable expenditure for repairs. The 100-psig operating pressure of the existing boiler limits laboratory demonstrations and experiments.

The installation of a 250-psig steam source would permit operation of existing equipment at design conditions. The installation of a steam source near 600 psig would permit future installation of an educational steam turbine unit to regain leadership in the field of heat engineering.

A steam source exists on the O. S. C. campus that will serve as a source of steam near 600 psig. The source of such steam is the campus heating plant. The problem of connecting the source and the utilizer provides the challenge of this thesis.

The existing utilities tunnel system can serve as a route to carry a pipe line to connect the heating plant and the engineering laboratory. The route follows the existing tunnel to a point near Dearborn Hall. A split-tile conduit must be laid to complete the connection to the Engineering Laboratory.

The minimum pipe size for the desired results was computed to be two-inch schedule 80 seamless steel pipe. Pressure drops were sufficiently low and still permitted standard expansion joints. Sufficient insulation was provided to maintain superheated steam at the outlet in the laboratory. Traps and flash tanks were provided to permit removal of condensate from the proposed line.
Sufficient gradient was maintained in the piping design to cause the condensate to collect at the trap points. Sufficient pipe guides, hangers, and anchors were provided to result in proper operation of the expansion joints.

In the laboratory a reducing valve was specified that would control steam pressure to that desired in a particular engine or turbine. A desuperheater was specified to permit control of steam temperature above saturation. Relief valves were specified that will provide for protection of low pressure lines should errors be made in valve operation. Proper valves, traps, drips and piping were specified to facilitate connecting the existing facilities with the proposed units.

The estimated sum of $45,116.00 was determined as the appropriation required to install the minimum of equipment, to modernize the present laboratory facilities and provide for planned additions.
HIGH-PRESSURE STEAM SERVICE FOR
O.S.C. ENGINEERING LABORATORY

by

James Edward Lynch

A THESIS
submitted to
OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of
MASTER OF SCIENCE

June 1953
APPROVED:

Professor of Mechanical Engineering
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Date thesis is presented May 15, 1953
Typed by Dorothy Ehrichs
ACKNOWLEDGMENTS

The author wishes to express a heartfelt vote of thanks to Mr. Richard A. Adams, General Superinten­dent of the Physical Plant Department at Oregon State College for use of cost records, maps and blueprints, and for drafting room facilities. Without the fine spirit of cooperation shown, this thesis would never have been completed. The following members of this department have contributed greatly in preparing the final result: Mr. Otto H. Meyer, for past records of labor costs of pipework; Mr. James L. Rundall, for tracing and inking of drawings; Mr. Irvin W. Barklow, for the patience shown in reproducing the drawings accompanying this thesis.

The following concerns supplied quotations on the major items of equipment to be proposed for installation: R. H. Brown and Co., Howard Nielson Company, Foster Wheeler Corporation, and Unistrut Portland Company. These firms performed a great service in supplying current prices on equipment that could not be obtained otherwise. The author expresses to each a sincere thanks.

The author acknowledges permission of the Solar Aircraft Company to reprint copyrighted material on Sola-Flex Expansion Joints. The use of this material has served to introduce a relatively new product.

The author wishes to thank professors Arthur D. Hughes and Milosh Popovich for direction and advice in planning the proposed modernization program for the heat power division of the Mechanical Engineering Department.

The author wishes to thank Professor Olaf G. Paasche for photographs of existing equipment in the present utilities tunnel. The inconveniences suffered while taking these photos will save others a trying effort in such an unbearably warm location.
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INTRODUCTION TO THE PROBLEM

Developments in the field of Mechanical Engineering have been quite notable in the last twenty years. One of the major branches, Heat Engineering, has made great strides in utilizing the recent metallurgical advances. The newer materials and improvements in steel have permitted high temperature and high pressure cycles to be used in modern steam power plants. The resulting gains in thermal efficiency have halved the fuel consumption in central stations in the last twenty-five years. Oregon State College has been a leader in this field from an academic standpoint and the staff has every hope that it will remain so. To continue to hold this position it is essential that adequate laboratory facilities be maintained to demonstrate the principles discussed in the classroom. This thesis will be devoted to the professional design of a minimum modernization program.

To solve the problem herein stated, it was necessary to analyze the existing laboratory facilities
and evaluate them individually. After analyzing the existing equipment and receiving the Mechanical Engineering Department's future plans it was decided that three pressure ranges should be provided for future use. The older reciprocating steam engines and one of the two steam turbines will give satisfactory performance on existing steam conditions of 100 psig. The existing Ames Unaflow steam engine and the existing Terry Steam Turbine will operate nearer to design point when steam is supplied at 250 psig. No equipment presently being utilized requires a higher pressure. The third pressure range was chosen as a compromise with the following as factors: first cost, availability in laboratory size, operating and maintenance cost, and finally, use of other facilities on the campus.

In addition to the modernization problems, a more pressing one was encountered—the present boiler was installed as original equipment in the Engineering Laboratory. The design of this boiler indicated that it had no value as an educational unit and only questionable value as a source of steam for the present 100-psig range. The experience of the author in the field of steam engineering leads to one definite initial step—remove this boiler. If this boiler were removed, a
new steam source must be obtained for each pressure range. If the highest pressure and temperature conditions to be used are satisfied, the lower conditions can be obtained by a combination of reducing valve and desuperheater.

In choosing a pressure range it was necessary to judge recent and past developments in the field. In 1930 the use of 400 to 450-psig steam pressure was adopted with temperatures of 700 to 750°F. More recent developments have led to large plants using pressures as high as 1800 psig and temperatures of 1050°F are not uncommon. Smaller plants, such as lumber mills, have lagged behind partly from lack of competent operating personnel. A moderate-sized plant such as the Eugene Water and Electric Board found 600 psig and temperatures of 750 to 900°F as being a satisfactory compromise using first cost, return on investment, and available personnel as criteria. A laboratory following the first example would be twenty years behind time when installed. The higher pressure-temperature ranges are not available in such small sizes except at high cost and must be ruled out. A unit in the 600 psi and 750 to 900°F range appeared as a most acceptable compromise in that equipment exists in this range at a reasonable
first cost and relatively low maintenance cost. This also opened another alternative as the Oregon State College heating plant was considering a new steam generator operating at or near the proposed steam conditions.

Any of the possible choices of steam generation required the use of a pressure reducing station, a dewuperheater with temperature control equipment and a water source at operating pressure.

If a boiler was the optimum unit, it was desired that such a unit have automatic controls. The present unit was operated by the college heating plant until recently. No regular operator has been supplied since the Engineering Laboratory was connected to the central heating system. Serious inconveniences have occurred in the past when scheduling use of the boiler. One of the heating plant personnel was dispatched to operate the boiler for the laboratory sessions. Close coordination between the two departments involved has served to prevent friction in the past. Part of the harmony has resulted from the fact that the Superintendent of Heating being a part-time member of the Mechanical Engineering Department. A foresighted attitude on the part of all concerned has resulted in the exclusion of any system in which a fireman need be brought in for
laboratory sessions. The automatic boiler thus became the only one considered. Fuels for such a unit must of necessity be either commercial fuel oil or gas. Gas was considered as the most probable cheap fuel source of the next ten years.

A strong alternative presented itself when the Physical Plant of the college chose to install a modern power plant as part of the heating modernization program. The boiler chosen was designed for operation at 600 psia and 740°F. This design condition was quite reasonable for use on the site of the heating plant. A considerable distance was involved and this distance factor reduced the initial advantage of eliminating purchase of a boiler by adding a high labor charge for piping. Ultimately the latter method was chosen and this thesis presents the solution to the problems encountered.
CHOICE OF HIGH PRESSURE STEAM SOURCE

The choice of steam source presented a considerable difficulty as no rough estimate was available based on past experience in this locality. To estimate the cost of such a facility it was necessary to rough out the design, estimate the labor cost from previous steam line work, and do a "take-off" to obtain the bill of materials for cost purposes. To get cost estimates for a boiler, it was necessary to write manufacturers for quotations on the unit most nearly meeting the specifications of our future laboratory facilities.

Either design required considerable background work. Previous Mechanical Engineering Laboratory reports were read and analyzed to obtain the maximum steam flow for a design point. The present Terry Turbine produced a result that appeared to be the maximum for future use. That unit required 2000 lb of steam per hour with initial pressure at 100 psig and exhausting to atmosphere. When operating on its design pressure of 250 psig, there should be a reduction of twenty-five percent in steam consumption. This leaves a maximum flow of 1500 lb per hour.
To modernize the laboratory, an educational unit is the most desirable addition for the department to purchase and install. A more detailed description of this unit is given in one of the following paragraphs. Such units are manufactured by General Electric Company and the Westinghouse Electric and Manufacturing Company. The cost of these units is prohibitive at the present time, but their steam requirements were estimated and included in the basic design point.

The department owns two surplus turbine generators manufactured by Westinghouse. These units were designed for use by the United States Navy and are 60-kw units. They are 120-240 volt three wire-DC machines. The steam consumption for this unit was guaranteed at 29.2 lb per kw-hr when operating at 60-kw output and supplied with steam, dry and saturated, at 200-psig and exhausting at 5 in Hg absolute pressure. Under test conditions the unit attained a steam rate of 27.56 lb per kw-hr when supplied with the above steam and exhaust conditions. This results in a total steam consumption of 1750 lb per hr under guarantee conditions. The unit is designed to operate safely when supplied with steam at 300-psig and a final
temperature of 750°F. A slight reduction in steam consumption should result under these conditions. Rough calculations permit 15 percent reduction in steam rate to be used as an estimating figure. A flow rate of just under 1500 lb per hr for each machine is required.

To demonstrate all the types of turbine steam-flow arrangements, it is essential that two identical turbines be used and that they be piped to operate in series or parallel to steam flow, with superheated or saturated steam and to operate condensing or non-condensing. The two existing turbine generator units could have been adapted to fulfill these needs. After a thorough study of the needs of such a unit, these units were deemed a minimum: two surface condensers each equipped with a condensate pump and a single stage air ejector, two sets of resistors to dissipate the electric energy, weigh tanks for condensate and cooling water plus scales for each condenser and the controls for each generator to control output. To purchase this equipment in parts was considered as financially impossible at this time and was dropped from further consideration.
The educational unit manufactured by General Electric Company is complete as a unit and consists of two 20-kw units plus all required controls and equipment. No figures were available on which to base steam consumption, but 35 lb per kw-hr is a high rate for small turbines in this pressure range and was used for design purposes. The maximum steam flow for parallel operation is then for 40-kw and results in a steam rate of 1400 lb per hour. This, with the previous figure from the Terry Turbine unit, will permit a normal flow rate of 1500 lb per hour to be used as the basic design point. With an anticipated increase in enrollment that might result in scheduling two steam laboratories at the same period the flow rate was checked for changes required for 3000 lb per hour and the design was modified to provide for this occurrence.

With 600-psia being a standard pressure in power plant work, it was deemed well to adapt this pressure range to the laboratory facilities. Several letters of inquiry were sent to boiler manufacturers of high-pressure units. Only one firm, Foster Wheeler Corporation, manufactures a unit that could be considered. The unit proposed consisted of a package unit boiler including the required boiler mountings plus forced draft fan, fuel oil pump and automatic combustion
control. The unit did not include a boiler feed pump. Two such pumps are required by law for safety reasons. The estimated cost was $25,000 at the factory with freight to be paid by the purchaser. The unit did not have a superheater and was too large for such small loads as laboratory use demands. This unit was designed for a normal rating of 10,000 lb per hour of saturated steam at 825-psig. The unit was designed for either oil or natural gas firing. Previous operating experience convinced the author that the unit was unacceptable as a boiler is difficult to control when operating at less than 20 percent of rating. A small change in setting produces too high a percentage change and overcorrection occurs. Any boiler requires routine maintenance and attention. Brickwork would be renewed at approximately four-year intervals. The cost for labor and materials is approximately $1000.00 at present prices. Since no superheater is included in the basic design it was necessary to get estimates on such a unit. The same manufacturer offered one that was suitable for a price of $8850.00 f.o.b. Dansville, N.Y. The first cost, plus operating and maintenance cost throughout the life of the equipment eliminated it from consideration on a cost basis.
Difficulty of control at low flow left much to be desired and the possibility of purchasing a boiler was dropped and the other alternative investigated to the point of a complete design.

The previously-mentioned alternative consisted of using steam generated at the college Heating Plant and piped into the Engineering Laboratory. The boiler was designed for 600-psia and 740°F final temperature. A major design problem was involved in connecting the two buildings to give suitable steam conditions and keep costs at a minimum.

Several routes could be followed in laying a steam line between these two points. Sheet No. 1 of the enclosed drawings is a plot map showing the final routing. The most direct route traversed is approximately 1900 ft in distance.

The Physical Plant Department recently completed the first loop, of three, of a Utilities Tunnel System. The new tunnel contains the steam lines for heating and the condensate return lines. Permission for use of existing space in this tunnel was received and can be utilized where no present or future conflict occurs. The future lines were designed in advance and the locations to be occupied are known by the author.
The only logical method of connecting the source and the laboratory includes using the Armory Tunnel to Jefferson Street. Three main routes contained possibilities from this point. The most direct route would necessitate either a tunnel, or the cheaper split-tile conduit with drains, to eliminate water seepage and manholes at expansion joints to permit maintenance and inspection. The cost could easily amount to $20.00 per foot for labor and still not permit good access for proper maintenance. The grades encountered on this terrain are such that larger pipe would be required to permit condensate to flow against the steam down to a trap point. Serious water hammer with possible fracture of pipe would result from neglecting this factor.

The first route seriously considered included use of the east part of the tunnel loop. Either half of the loop is about equally distant from the Mines Building. The east half has more changes in direction than the west half causing additional expansion joints to be used for the same distance traversed.

Two routes were considered in connecting the Apperson Way Tunnel with the laboratory. One route involved placing a steam line either through or under
the Mines Building, under the Engineering Quadrangle to the west end of the Engineering Laboratory. To place the line under the Mines Building would result in a very expensive undertaking plus the nuisance factor to the Physics Department located in the basement and loss of parking area while laying the line.

An alternate route involves a split-tile conduit between Shepard Hall and Dearborn Hall, along the west end of Dearborn Hall to the north end of the building, east to a point directly south of the SW corner of the Engineering Laboratory and north to enter the building as indicated on the Plot Map. This route is free of conflict underground and can be considered as a permanent location. The addition to the Engineering Laboratory would not cause this line to be removed or relocated. This location was chosen since it was considered as the one point that would not interfere with future excavation. This latter choice shortened the length of line for the west side of the loop and increased it for the east side.

The west half of the loop has a distinctly favorable profile as it permitted a minimum use of
steam traps. Except for the section on Jefferson Street from Armory Way to 22nd Street all of this run is downhill. This small section has a sufficient up-grade to permit counter flow of condensate when it occurs.

A change in elevation of 15.6 in. per thousand feet of pipe permits a water velocity of 1 ft per sec as an open channel. This will maintain a dry steam line. This can be accomplished by grading downhill between pipe anchors and expansion joints then running the pipe up to the ceiling and continuing the downhill run. Each low point is then trapped to a flash tank and then is again trapped to the existing return mains.
METHODS USED IN CALCULATING 
HEAT TRANSFER AND PRESSURE DROP

The two problems of heat transfer and pressure drop were handled simultaneously. Reynold's analysis was used for pressure drop calculations. These were checked by the less accurate, but more commonly used Babcock Formula. For the film coefficient on the inside of the pipe Nusselt's analysis was used. For the film coefficient on the outside surface an empirical method was used as velocities were extremely small and temperature differences difficult to obtain accurately.

Nusselt's analysis of forced convection makes use of two dimensionless ratios. Included in this analysis is Reynold's Number.

The variables in the Reynold's Number are:
density of fluid; diameter of pipe; velocity of fluid and dynamic viscosity. Pressure drop is a function of this number. The symbols used with this analysis are:

\[ \rho = \text{Density in lb/ft}^3 \]
\[ D = \text{Inside diameter of pipe in feet} \]
\[ v = \text{Velocity of fluid in ft/hr} \]
\[ \mu = \text{Dynamic viscosity in lb/ft-hr} \]
\[ \phi = \text{Function symbol (Greek phi)} \]
\[ \Delta P_f = \text{Pressure drop lb/ft}^2 \]
\[ L = \text{Length of pipe in feet} \]

The Reynolds analysis is then expressed in this manner: (1 p 367)

\[ \frac{\Delta P_f D}{v^2 L P} = \phi \left( \frac{P D v}{\mu} \right) \]

Nusselt's analysis is an expression of equality between Nusselt's dimensionless ratio for film coefficient and a product of Reynold's Number and another dimensionless ratio of Prandtl's. The symbols used with this analysis are:

Nusselt's:  
- \( h \) = Film coefficient Btu/ft\(^2\)-hr-F
- \( D \) = Diameter of film surface in ft
- \( k \) = Thermal conductivity of fluid Btu/hr-ft

Reynold's:  
- \( \rho \) = Density lb/ft\(^3\)
- \( D \) = Diameter of pipe ft
- \( v \) = Velocity of fluid ft/hr
- \( \mu \) = Dynamic viscosity lb/ft-hr

Prandtl's:  
- \( C_p \) = Specific heat of fluid Btu/hr-F
- \( \mu \) = Dynamic viscosity lb/ft-hr
- \( k \) = Thermal conductivity Btu/hr-ft
Experimental constants have been introduced that indicate the influence of each of the quantities on the final result. The equation of equality is normally expressed in this manner: (2 p 113)

$$\frac{hD}{k} = 0.023 \left( \frac{\rho Du}{\mu} \right)^{0.8} \left[ \frac{C_p \mu}{k} \right]^{0.3}$$

for a process in which the fluid is being cooled by an outside source (in our case the atmosphere).

Two possibilities were explored for solution of the heat transferred from the outside surface to the atmosphere. The first calculations were undertaken from an analysis in Elements of Heat Transfer and Insulation by Jacob and Hawkins. This analysis separated the two means of heat transfer into the two components of importance—convection and radiation. The convection transfer was based on velocity of air movement adjacent to the pipe exterior. The radiation loss was based on the Stefan–Boltzmann Law. This involves the difference of the fourth power of the absolute temperature of the surface radiating and the fourth power of the absolute temperature of the surrounding medium receiving heat. The result using
this method was inaccurate. Resulting temperature differences between the hot surface and the air was of the order of five degrees fahrenheit and velocities of air proved to be extremely small. This method was abandoned to the more easily handled method of an emperical equation common to heat transfer. It was assumed that the primary heat transferred occurred by free convection and that loss to radiation was a minimum secondary quantity. The form of this emperical equation for horizontal pipe lines is:

\[
h = 0.22 \left( \frac{\Delta t}{D} \right)^{0.25}
\]

where \( h \) = film coefficient Btu/sqft-hr-F

\( \Delta t \) = temperature difference from surface to still air

\( D \) = surface diameter in ft

The above method is recommended by Jacob and Hawkins for design purposes and has been indicated to be a minor factor in the final analysis of heat loss in this instance.

Between the two films the heat is transferred by conduction through the pipe walls and any insulation being used. The choice of insulating material
and quantity to be used were affected by several factors. The steam line has a primary purpose of serving a laboratory where quality of steam is an important factor. If superheat can be maintained throughout the length of the line several advantages occur. These are:

1. the purchase of a superheater can be delayed until additional finances are available,
2. fewer traps are required, reducing first cost, as no condensate would be present in the lines after steam begins to flow, and
3. smaller pipe can be utilized where water hammer is not a problem. Smaller pipe results in slightly higher velocities. These considerations led to a thicker layer of insulation than standard practice dictates. This line is much longer than normal power plant lines and was considered on its own merits. Normal engineering practice was referred to as a check on reasonableness of conclusions.

The temperature of the steam entering the line at the heating plant will be between 730 and 750°F. This temperature range requires a durable insulating material adjacent to the pipe. The most common and readily obtainable insulation is a mixture of diatomaceous earth and asbestos. Johns-Manville produces such a material under the trade name of "Superex".
It is durable and quite resistant to high temperatures and has a low value of thermal conductivity. A value of 0.03 Btu/hr-ft-F was used in these calculations. The pipe was to be covered with a two-inch thickness of insulation. The standard insulation composed of 85 percent magnesia and 15 percent asbestos was recommended for the second layer, also two inches, followed by canvas wrapping to complete the job. A value for thermal conductivity of 0.037 Btu/hr-ft-F was used for the "85% mag", the trade name for 85 percent magnesia. Several other combinations were tried and computed for anticipated results and either failed to give the desired superheat as a result of being too thin or didn't reduce heat loss by sufficient increments to warrant the additional cost.

To obtain the heat transferred throughout the length of the pipe line, it was necessary to get a composite coefficient of heat transfer. The flow conditions in the line are turbulent, permitting the conditions of the variables for the inside film coefficient to be taken as those of the stream. The heat lost in the film can then be expressed as \( q \), heat loss, is equal to the product of \( h \), the film coefficient, \( A \), the inside area of the pipe and \( \Delta t \),
the temperature drop through the film. The equation is written \( q = HA\Delta t \)

To compute the loss through any pipe or cylinder the equation: (2 p 34)

\[
q' = \frac{2\pi k (\Delta t)}{\ln \frac{r_2}{r_1}}
\]

\( \ln \) symbol for natural logarithm

\( r_2 \) and \( r_1 \) = outside and inside radii of the cylinder. The remaining symbols are as in the previous equations.

The heat loss, \( q \), is the same quantity in each equation. The various temperatures from the center of the stream to the air were designated in this manner:

- \( t_1 \) = temperature of steam in pipe.
- \( t_2 \) = temperature at inside surface of pipe.
- \( t_3 \) = temperature at outside surface of pipe and inside surface of diatomaceous earth insulation.
- \( t_4 \) = temperature at outside surface of diatomaceous earth and inside surface of 85 percent magnesia.
- \( t_5 \) = temperature at outside surface of 85 percent magnesia.
- \( t_6 \) = temperature of surrounding air.
To solve for heat loss the equations for each temperature drop were combined in this manner:

\[ q = h A (t_1 - t_2) \] stream to wall

\[ q = \frac{2\pi k(t_2 - t_3)}{\ln \frac{r_3}{r_2}} \] through steel wall of pipe

\[ q = \frac{2\pi k(t_3 - t_4)}{\ln \frac{r_4}{r_3}} \] through diatomaceous earth

\[ q = \frac{2\pi k(t_4 - t_5)}{\ln \frac{r_5}{r_4}} \] through 85% magnesia

\[ q = 0.22 \left( \frac{t_5 - t_6}{D} \right)^{0.25} \] outside surface to air

The first four equations can be rearranged and re-written in terms of \( t_1-t_5 \) as all these equations are first degree equations. This leaves two equations that can be solved by substituting values of \( t_5 \) and getting simultaneous solution for \( q \). By plotting a curve of \( t_5 \) versus \( q \) it was then possible to isolate the heat loss per foot of pipe for values of \( t \) and \( t_6 \). The last two variables were difficult to establish and will vary considerably. The design point was
chosen for a condition of maximum steam temperature and minimum normal tunnel temperature. The entering temperature was taken at 750°F and the lowest air to be encountered when operating was 100°F. This will produce a maximum heat loss as the temperature difference reaches a maximum at such time.

To compute pressure drops and heat losses it was necessary to assume that conditions of equilibrium had been reached and that steam flow was constant. It was also necessary to compute these losses for actual flow rates as heat loss per hour increases with velocity, but not as rapid an increase as the flow rate. This results in a reduced heat loss per pound of steam flowing. Pressure drop increases with flow rate, but at a much more rapid rate. A rough approximation would state that the pressure drop varies as the square of the flow rate.

Several pipe sizes and thicknesses of insulation were used in various combinations in the initial calculations. The method of approach was similar and only smooth calculations are used in this thesis. Two-inch Schedule 80 pipe (ID = 1.94" OD = 2.375") with two inches of diatomaceous earth and two inches of 85 percent magnesia were used as the design condition.
A length of pipe of 2545 ft was determined and calculations performed in the manner herein described. The pressure drop and heat loss per foot of pipe was computed based on inlet conditions. This was applied to the entire length and an end condition established. This condition could not be true, but gave a trial end condition. As the distance from the entrance became greater the temperature and pressure would drop. With this reduction in pressure there is an accompanying drop in specific volume (the superheat range being maintained). The reduction in temperature reduces the tendency to transfer heat, the lower specific volume reduces velocity and will reduce both the film coefficient and rate of pressure drop. An arithmetic mean condition of pressure and temperature between inlet conditions and assumed outlet conditions was used to compute the heat lost and pressure drop. When calculations verified the assumed final condition of pressure and temperature the assumed mean condition was accepted as being sufficiently accurate to be used as a design basis. Two flow rates were used, 1500 lb per hour and 3000 lb per hour. A flow rate of 6000 lb per hour was checked and indicated an
excessive velocity. Such high velocities cause erosion of steam lines.

The resulting calculations indicated the desired condition of moderate pressure drop and attainment of moderate superheat at the outlet end would be achieved with the chosen pipe and insulation combination. With a flow rate of 1500 lb per hour the final conditions were computed as 569 psig and 555F, which is 60F of superheat. For a flow rate of 3000 lb per hour the end condition of 530 psig and 622F was computed which is 146F of superheat.
PIPE EXPANSION AND SOLUTION

Molecules of solids increase in activity with an increase in temperature. In most materials this causes an increase in dimension with temperature. Steel has been observed since its inception as a structural material. The commonly accepted engineering value of 0.0000065 ft increase per ft of length per degree fahrenheit temperature rise was not considered accurate enough and was only used as a check. Holborn and Day's formula accounts for the expansion not being a linear function of temperature change.

The symbols used are:

\[ L_t = \text{length at some temperature } t^\circ F. \]
\[ L_0 = \text{length at } 32^\circ F. \]
\[ a, b = \text{experimental constants.} \]

for steel \( a = 0.00621 \)
\[ b = 0.00162 \]

The form of the equation as used is: (1 p 370)

\[ L_t = L_0 \left[ 1 + a \left( \frac{t-32}{1000} \right) + b \left( \frac{t-32}{1000} \right)^2 \right] \]

It was considered as quite justified that expansion be calculated as closely as data permits. The use of the more accurate data permitted closer tolerances on expansion joints.
Expansion in each run of steam line was computed on the temperatures prevailing in that line. The expansion joints were then placed to operate at certain maximum temperatures. The design was originally based on 1500 lb per hour and changed to permit the increase in expansion caused by the higher final temperature encountered with 3000 lb per hour flow rate.

Several methods of absorbing expansion were investigated. The method most commonly used in steam power plants has been the use of pipe loops. The existing tunnel system limited the diameter of such loops to somewhat less than six feet. The length and number of individual runs of piping ruled this method out during preliminary calculations and price schedules confirmed this at a later date.

Various methods of pipe bends using corrugated pipe and bellows type joints were then investigated. None was found to meet ASME standards for pressure-temperature rating in the operating range to be used. The use of slip joints was then investigated and units manufactured by the American District Steam Company of Tonawanda, N.Y. were found to meet this standard. Several months later the Sola-Flex
Expansion Joint was encountered. This unit is a bellows type joint made of stainless steel. It was designed for such uses as exhaust manifolds in aircraft. Post-war development has found this unit being used in refineries and power plants. It has many advantages for this type of operation. The first four photographs are of this type expansion joint. One major advantage is low cost where small amounts of expansion need be relieved. In the size required in this project a joint with 0.688" traverse costs $51.80 f.o.b. San Diego and one of 5.5" traverse costs $79.10. The unit is made of individual bellows (2.125" ID and 6.375" OD) welded to form a complete unit. The units vary in weight from 22 lb for the smaller to 29 lb for the larger of two examples used here. This is about one-half the weight of the smallest slip joint of the type required. The Sola-Flex joint contains no packing which removes consideration for location in a manhole when used in conduit. The latter property led to the choice of this joint for use in the split-tile conduit.

In the long straight runs in the tunnel, the use of slip joints with a total expansion traverse
of 16" per unit resulted in a slight gain directly in cost with a big indirect gain as the use of many anchors and guides could be eliminated when one double slip joint could replace three bellows joints in certain big runs.
DESIGN PROBLEMS

The first four sections of this thesis have covered the problem in general terms plus details of the major theoretical portion of the design. The practical considerations can transfer the engineers conception of a general idea to a possible reality. In addition to being a pipeline designed as a carrier of a hot fluid, steam, it must also be structurally sound, to exist, and be capable of being maintained by workmen. In addition, such a unit must not interfere with existing or future heating lines as they are the prime purpose of the tunnel system.

The proposed steam line must be designed for on and off operation. This will produce "warming up" and "shutting down" periods. During "warm up" periods the condensate lying in the lines must be easily removed at convenient intervals. The easiest method to accomplish this is to place the pipe on a slope or gradient to permit the water to flow to a low point or points. Steam traps, complete with by-pass arrangements and strainer, must be installed at such points to remove this water. The cheapest method to return the condensate to the heating plant consists
of running the discharge line from the trap to the existing return lines. The release of hot water under pressure approaching 600 lb per sq in will result in some flash to steam. If sufficient quantity of steam entered the return line a build-up of pressure would prevent the gravity return system from operating. If the trap failed and permitted continuous flow of steam into the return main there is a possibility of overloading the vacuum return pump with the same effect as a vapor lock. Neither is likely to occur, but must be accounted for to produce a design that will result in a safe installation. To obtain the desired result the trap discharges into a section of four-inch pipe that permits the hot water to flash into steam and acts as a condenser. (see photograph Fig. 5) The flash tank has a drain connection at its low point (see detail drawing, sheet No. 7) and a trap permitting flow of water into the return line at low pressure.

Any such design must be structurally sound. The pipe line is essentially a beam with a uniform load consisting of the weights of pipe and insulation plus pipe and possibly some water. The greatest
depth of water permitted was taken at one-half inch to prohibit water hammer. The deflection allowed required a support at approximately 15-foot intervals. The existing support structure is on 14-ft centers and will permit more favorable structural stability than is necessary.

Water hammer is a serious problem in steam line design and was approached in three ways. (1) Sufficient traps were placed where major elevation changes occurred to permit removal of water collected at these points. (2) Maintaining a design in which the superheat range would be involved eliminates condensation while steam is flowing at design rates of flow. Low flow rates will result in condensation toward the outlet end. (3) To facilitate flow of condensate the pipe line was designed for a minimum grade of 15.6 in. per 1000 ft. This was computed on the basis of an open channel to maintain a flow of one foot per second when no steam is flowing. The line was graded for natural flow to be in the same direction as the steam flow except from Armory Way to 22nd Street in the Jefferson Street Tunnel. The natural grade will keep the line dry when not operating. A major trap point was proposed for the
beginning of this run of pipe. A run of pipe was begun near the ceiling of the tunnel and continued at the designed grade through expansion joints to a point where the line was near the floor. At the last anchor point provision was made for a trap and a long radius elbow directed the line to the ceiling again where the grade was again resumed and the next run designed (see tunnel profile drawings Nos. 2, 3, 4, and 5).

The existing steam lines are supported on patented structural shapes manufactured by Unistrut Products Company. The name Unistrut is their trade name and copyright. Unistrut structural shapes have been designated on the detail drawings and will be referred to by name when required.

When steam piping is designed for expansion the thrust due to movement and pressure within the line must be absorbed. To prevent an unbalanced movement of pipe between two expansion joints anchors were used. An anchor is a device that holds a particular point of a pipe line rigid causing expansion to occur in both directions away from the point. The use of anchors forces each expansion joint to perform the task for which it is designed. Anchors
require bracing to a large mass to prevent movement. In this design the thrust is to be absorbed by angel bracing the anchors into the tunnel walls or floor as convenience dictates for the erector. Expansion joints are to be braced in like manner (see detail sheet, drawing No. 7 and photograph Fig. No. 6).

A pipe line must rest on a low-friction base to reduce distortion of the pipe. Unistrut rollers (see drawing No. 6, photograph Fig. 7) have given excellent service on the existing tunnel and have the additional facility of being easily fabricated in place. Every third roller-guide should include both upper and lower rollers to help prevent distortion.

Pipe alignment guides are required within four feet of each expansion joint to prevent any non-axial movement near the expansion joint. This assures maximum use of the joint and prevents harmful wear to moving parts in the Adsco slip joint or overstress of one side in the Sola-Flex Bellows joint.

Split-tile conduit is a common method of placement where low pressure steam lines are used for heating. Several types of conduit systems have been used on the O.S.C. campus. The fundamental
requirements are: a covering to prevent the seepage of moisture near the steam line, a base to hold pipe supports, anchors, guides, and expansion joints, and lastly sufficient drainage to carry moisture away. The split-tile conduit shown in sheet No. 7 of the included drawings is a successful one in use on the campus. This conduit is the cheapest successfully used to date. Sola-Flex Expansion Joints in this conduit will provide a reduction of maintenance that resulted in the elimination of manholes in this design. The conduit is graded to eliminate the need for the use of steam traps in this section of the line. A continuous grade was chosen to enter the Engineering Laboratory sufficiently above the floor level to permit installation of valves and a trap and by-pass system. At no point will the conduit be dangerously close to the surface although the line will be only 18 inches below ground level near the Quonset Hut, G-3. At one point the line will be ten feet below ground. This depth was caused by a rise in ground elevation near the middle of the run. No serious difficulty should be encountered, but an extra precaution must be exercised while excavating and laying pipe and conduit in this one area. A
typical cross section is shown on sheet No. 5.

In fabrication the use of arc welding is preferred. Arc welding is the cheapest and most easily performed method of fabrication. In large diameter pipes the use of flanges is important to permit removal of sections of pipe or fittings for repair purposes. In small lines such as this proposed line the use of welded joints provides few worries as small lines can be readily cut with an acetylene torch and replaced by welding a similar section in place. The operation described is a common one and requires a very minimum of outage time to perform.
ENGINEERING LABORATORY CHANGES

The present boiler is over age, requires a considerable expenditure for maintenance, and is inadequate for the future needs of the Mechanical Engineering Laboratory. The third reason just stated is sufficient reason for installing this proposed change. The first two reasons are sufficient to recommend removal of the existing boiler, the two feed pumps, vacuum-return pump, and surge tank associated with this unit.

The removal of this equipment provides sufficient space to install all that is recommended as a base proposal. The removal would require an expenditure of approximately $750.00 for welders to cut the steel into smaller sections and for laborers to remove the brickwork, steel and sections of headers and steam drum after cutting into small enough pieces to be removed. The Physical Plant Department on the campus would provide the most reasonable source of labor for such a job where destruction and removal is involved.

The proposed steam line was designed to enter the existing boiler pit through the west wall about
three feet above the floor level. This constitutes a low point and steam trap and by-pass was provided for. No flash tank was provided as no return line is available and all traps must discharge into the sewer. A stop valve is provided to isolate the line and permit repairs in the laboratory while steam pressure is on the main. Valves are provided for flow through a future superheater or straight through to the first branch point as desired. The first branch point divides flow to either a future educational steam turbine unit (see drawing No. 6 for arrangement of piping) or to a Fischer reducing valve. The proposed reducing valve as quoted by R.H. Brown and Co. provides for an air-operated pilot valve and wall-mounted valve positioner to permit close control of pressure. The unit proposed provides for closure of the valve on failure of air supply. Existing compressed air is adequate for this unit.

Flow from the reducing valve is directed through a venturi-type desuperheater by Schutte and Koerting with a Taylor temperature controller to maintain constant steam quality as laboratory conditions dictate. A relief valve capable of relieving
3000 lb per hour of steam at 250-psig was provided for between the reducing valve and desuperheater. This size is adequate as the orifice size of the reducing valve will permit only that quantity of steam flow in an emergency. From the desuperheater branches are provided, with valves, for connection to the existing 100-psig line and to a proposed 250-psig line. A relief valve is provided in the 100-psig line to prevent damage if the pilot controls are improperly set. The relief valve specified is capable of discharging 3000 lb per hour also. The 250-psig relief valve must be piped to the roof with a drip provided and the line so graded that the line will be completely drained by the drip. This drip must be free of all restrictions including valve or pet cock. The 100-psig relief valve shall be connected to discharge into the existing atmosphere line. The 250-psig line must be continued through the second floor to connect the Ames Uniflow Engine and the Terry Turbine. No rigid pipe hangers are to be provided, but rather the use of flexible supports are specified. The pipe is laid out with bends in such directions to provide movement in all three planes. This eliminates expansion joints where
short runs are provided. A heavy base and steel slip-plate should be provided at the point where the 250-psig line forms a riser to connect with the new horizontal run above. This provides for the weight of the one major length of pipe involved. The possible use of spring hangers is a frill that could be added but has not been included here.

No provision is made for a 600-psia relief valve. The generating source is adequately protected and no excess pressure can be built up in this line (except for a hydrostatic test) therefore no relief valve need be provided.

A small pump and motor must be supplied to provide water for the desuperheater. The flow rate is to be 0.5 gallons per minute. A total head of about 700 feet is anticipated. If efficiency is figured as 30 percent overall a motor of 1/3 horsepower is adequate and cost is estimated at $150.00 installed with a relief valve.
ALTERNATES AND FUTURE ADDITIONS

One subtractive alternate is included. This alternate provides for elimination of the valves for connecting a future superheater and substitutes short nipples with caps welded to tees. The cap could be burned off and valves welded in at a later date. The 600-psi line to the future turbine location could be left out and a similar nipple placed in the tee at this connection. A saving could be realized by these eliminations. No recommendation is made either way on this alternate.

The first addition to be recommended includes either a General Electric Company or Westinghouse Electric and Manufacturing Company educational steam turbine unit. This type unit would serve to bring the existing laboratory up to date and provide adequate laboratory investigation of steam turbine cycles as discussed in classroom lectures.

The second addition to be recommended consists of a gas-fired superheater with automatic temperature control to maintain a constant temperature. In addition a pressure reducing valve should be installed with the educational unit to provide a constant
pressure of approximately 550 psig maximum down to any desired minimum to account for pressure drop with flow and to permit reduced pressure operation.

A third addition consists of disconnecting the 250-psig and 100-psig lines and adding a separate reducing valve and desuperheater. The same pump can serve both desuperheaters if capacity is doubled at a very slight extra cost as the proposed pump is quite small. The addition of this third item is a frill that can offer complete flexibility, but the author doubts the advisability of operating three steam laboratory sections at one and the same time.

The first addition is a necessity to modernize the laboratory facilities. The second addition completes the modernization program to give accurate pressure-temperature control over a wide range of steam rates.

The basic design consists in only that which is considered to be a necessity in the next five years to maintain existing laboratory facilities in operation.
BILL OF MATERIALS FOR
TUNNEL SYSTEM PROPER AND CONDUIT

2545 ft Schedule 80 Seamless Steel
f.o.b. Portland, Oregon,
@ $69.25/100ft
$1762.00

16 Long Radius Elbows
f.o.b. Corvallis, Oregon,
@ $2.65
41.40

23 Anchor Bases by Solar Aircraft
f.o.b. San Diego, California
@ $21.75
500.25

23 Pipe Guides by Solar Aircraft
f.o.b. San Diego, California
@ $21.75
500.25

6 Double Expansion Joints by
American District Steam Company
8" traverse each end
f.o.b. North Tonawanda, New York
@ $248.00
1488.00

Sola-Flex Stainless Steel Bellows
Type Expansion Joint by Solar Aircraft, f.o.b. San Diego, Calif.
1 with 2.75" expansion @ $65.80
1 with 3.438" expansion @ $69.70
6 with 4.125" expansion @ $73.60
2 with 4.813" expansion @ $77.50
1 with 5.5" expansion @ $81.40
Total
813.50

10 3/4" Gate Valves 600# Standard
Hancock 903 EW or 903 AW
@ $21.25
212.50

5 1/2" Globe Valves Hancock
533 CP or 533 EP
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P-1000

250 Double Axle 2-roller Pipe Supports  
Unistrut U-879A

1600 P-1008 Unistrut Clamping Nuts 3/8"

1600 3/8" Cap Screws

200 Unistrut P-1331 4-hole Shelf 
Brackets

400 Unistrut P-1186 Closed Angle 
Connections

400 Unistrut Open Angle Connections

40 Unistrut P-3254 Concrete Inserts

Quotation for all Unistrut Materials $ 2883.65

2545 ft Insulation 2" of Suprex and 2 1/8" 
85% Magnesia from E. J. Bartells 
Company $3.564 plus 4% for clips, 
wheat paste, canvas wrapping, etc. 
Total $3.70

Labor, Split Tile, Drainage, Pea Gravel 
etc. for 445 ft of Split Tile Conduit 
@ $11.50/ft $5120.00

Labor for 2100 ft of Tunnel @ $6.00/ft $12600.00
# BILL OF MATERIALS AND LABOR FOR
WORK IN ENGINEERING LABORATORY

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FREIGHT

6 Adsco Expansion Joints from North Tonawanda, N. Y. to Corvallis, Ore. @ $5.40/100 lb  $ 29.16

Fisher Reducing Valve, Fisher Control Valve, Taylor Controller-Recorder, and Schutte and Koerting Desuperheater from Cornwell Heights, Penn. to Corvallis, Ore. 200 lb @ $9.15/100 lb  18.30

11 Sola-Flex Expansion Joints, 23 anchor bases and 23 pipe guides from San Diego, Calif. to Corvallis, Ore. 645 lb @ $2.50/100 lb  16.08

Total Estimates All Items  $40,333.16

10% Contingency Fund  4,033.32

Funds Required for Project  $44,366.48
Fig. No. 1

Above: Typical weld end Sola-Flex Expansion Joint as specified for use in Split-Tile Conduit.

Below: Cut-a-way section to show construction of bellows as used in Sola-Flex Expansion Joints.
THE SPAN

THE CANTILEVERED CONTOUR GIVES YOU THIS

FREE POSITION

COMPRESSED POSITION

EXPANDED POSITION

Fig. No. 2

Typical contour of bellows in Sola-Flex Expansion Joint. Note: both inside and outside diameters do not change throughout design range of expansion.
Fig. No. 3

Above: Two Sola-Flex joints welded to form a double joint is then welded to a Solar Anchor Base.

Below: The type anchor base to be used throughout the proposed pipe line.
Illustration shows Standard Sola-Flex Pipe Guide. Order by Pipe Size.

(Pat. Pending)

Fig. No. 4
Fig. No. 5

Typical Flash Tank as used in existing Utilities System.
Fig. No. 6

Expansion Joint with support structure and bracing system used in existing tunnel. A similar arrangement was specified for the proposed installation.
Fig. No. 7

Typical roller type pipe hanger used in existing tunnel. Similar hangers are specified for the proposed installation.
DESCRIPTION OF NOTATION POINTS ON DRAWINGS


2. Sola-Flex Joint 5.5" traverse plus an anchor base. Guide 4' from joint.

3. Adsco double expansion joint 16" total traverse. Guide 4' from each end.

4. Adsco double expansion joint 16" total traverse. Guide 4' from each end.

5. Anchor base.

6. Anchor base, bucket trap and flash tank, change in elevation.

7. Flash tank with 3 Barco swing joints in connection to return line.

8. Anchor base.


10. Anchor point with trap and flash tank.

11. Adsco double expansion joint 16" total traverse. Guide 4' from each end.

12. Anchor point.

13. Adsco double expansion joint 16" total traverse. Guide 4' from each end.
15. Anchor base.
16. Anchor base, bucket trap and flash tank; connect flash tank to return line with 3 Barco swing joints.
17. Two Sola-Flex joints, with anchor base, welded to form double joint 4.125" traverse each end with guides 4' from each end.
18. Two Sola-Flex joints with anchor bases. Long radius elbow between guides 4' from joint. 4.125" traverse each.
19. Two Sola-Flex joints, anchor base between. Guides 4' from each joint. 4.125" traverse.
20. One Sola-Flex joint with anchor base. Guide 4' from joint. 2.75" traverse.
22. Two Sola-Flex joints with anchor bases; long radius elbow between. 4.813" traverse each. Guides 4' from each joint.
23. Anchor base and long radius elbow.
CONCLUSIONS

The conclusions from the work performed in preparing this thesis consist of a summary of the results of design calculations plus price quotations of materials required and estimates of labor costs. The need of a steam source to continue operation of the existing laboratory facilities compels, as a minimum, that the existing boiler be replaced with a steam generator or other supply source. Continuation of the present low pressure system as the design point places the present leadership as an educational institution in jeopardy. A higher pressure-temperature range will provide the modern facilities desired.

A pressure range of 600 psig was chosen as a representative of modern practice within the practical limit of existing and planned facilities. The purchase of a suitable steam generator becomes quite difficult as few manufacturers care to produce small units of this type. The Foster Wheeler Corporation delivered the only quotation on a steam generator. The sum was $25,000.00 f.o.b. New York. The unit has a capacity approximately three times greater than the laboratory requirements. The proposed unit was
without superheater or boiler feed pumps. A price of $8,850.00 f.o.b. New York was quoted for a gas-fired superheater. The latter unit did not include firebrick or insulation. The last item would increase the cost by another $2,000.00. An additional cost for erection was not included. Two boiler feed pumps would add enough to the total cost to result in a first cost near or above the cost of a steam line to obtain steam from the existing campus heating plant.

The total estimated cost of $40,333.16 with a contingency fund of 10% would result in a required appropriation of $44,366.48 to install the proposed system. These figures cover all material, labor, excavation, etc. An additional sum of approximately $750.00 would be required to remove the existing boiler. The removal could be done by cutting all tubes with an acetylene torch and removing in sections, eliminating removal of an existing wall as need be done to install a new boiler.

The final total appropriation for the base design installed is $45,116.48. The result of installing this base design will permit the installation of a future educational turbine generator unit.
with a minimum of piping. The laboratory facilities will then be a standard to maintain leadership in engineering education. The future addition of all alternates proposed will provide for any future enrollment should cause arise for a great increase in interest in Mechanical Engineering as a profession.
BIBLIOGRAPHY


APPENDIX I
THESIS FINAL FORM CALCULATIONS

Pressure Drop

Initial Conditions  600-psi at 750F

Flow Rate is 1500#/hr

\[ v = \frac{1500(1.1324)(144)(4)}{3600(1.94)(1.94)(\pi)} \]

\[ v = 23.0 \text{ fps} = 1380 \text{ ft/min} \]

\[ \frac{N}{Re} = \frac{1.94(23)(10^6)}{12(1.1324)(18.5)} \]

\[ \frac{N}{Re} = 177,600 \]

\[ \frac{\Delta P}{D} = 0.00032 \]

\[ \frac{\Delta P}{v^2 L \rho} = 0.00032(23)(23)(2545)(12) \]

\[ \frac{\Delta P}{(1.94)(144)(1.1324)} \]

\[ \Delta P = 16.4 \text{ psi} \]

Check by Babcock Formula

\[ \Delta P = 0.0001321 \left( \frac{W^2}{y d^5} \right) (1 + \frac{5.6}{d}) \]
\[ \Delta P = 0.0001321 \left( \frac{1500^2}{60} \right) \left( \frac{2700}{1.1324} \right) \left( 1 + \frac{3.6}{1.94} \right) \left( 1.945 \right) \]
\[ \Delta P = 0.0001321 \left( \frac{625}{2700} \right) \left( \frac{1.324}{2.857} \right) \]
\[ \Delta P = 26.2 \text{ psi} \]

Heat Losses

Flow Rate 1500#/hr

Initial Conditions 600-psia 750F

Pipe Schedule 80 2" nominal size

Film Coefficient \( \frac{hD}{k} = 0.023 \left[ \frac{VDP}{\mu} \right]^{0.8} \left[ \frac{\mu CP}{k} \right]^{0.3} \)

\[ v = \frac{1500 \times 1.1324 \times 144 \times 4}{3600 \times 1.94 \times 1.94 \pi} \]
\[ v = 23.0 \text{ fps} \]

\[ \frac{hD}{k} = 0.023 \left[ \frac{VDP}{\pi} \right]^{0.8} \left[ \frac{CP \mu}{k} \right]^{0.3} \]

\[ h \left( \frac{1.94}{12 \times 0.0033} \right) = 0.023 \left[ \frac{23.0 \times 1.94 \times 10^6}{12 \times 1.1324 \times 18.5} \right]^{0.8} \]
\[ \left[ \frac{0.56 \times 18.5 \times 3600}{10^5 \times 3.3} \right]^{0.3} \]
\[
h = 0.023(12)(0.0033) \left[ \frac{23(1.94)(10^6)}{12(1.1324)(18.5)} \right]^{0.8} \[ \frac{0.56(18.5)(3600)}{10^8 (3.3)} \]^{0.3} \\
h = 0.000469 (177,600)^{0.8} (11.3)^{0.3} \\
h = 0.000469 (177.6 \times 1000)^{0.8} (2.07) \\
h = 0.000469 (2.07) (62.8)(252) \\
h = 15.4 \text{ Btu/hr ft}^2 \text{ F} \\

For 2" Diatomaceous Earth plus 2" 85% Magnesia \\
k for steel \ 24.5 (2-3) \\
k for D-E \ 0.03 (3-4) \\
k for 85% Mag \ 0.037 (4-5) \\

Outside Air in Tunnel at 100°F for one foot of length \\
\[ q = h A (t_1 - t_2) \]
\[ q = 15.4 \frac{1.94}{12} \pi (t_1 - t_2) \]
\[ q = 7.82 (t_1 - t_2) \]

\[
t_2 - t_5 = \frac{q'}{2m} \left[ \frac{\ln \frac{r_3}{r_2}}{k_{2-3}} + \frac{\ln \frac{r_4}{r_3}}{k_{3-4}} + \frac{\ln \frac{r_5}{r_4}}{k_{4-5}} \right] \\
q' = 2m (t_2 - t_5) \\
\left( \frac{\ln \frac{r_3}{r_2}}{k_{2-3}} + \frac{\ln \frac{r_4}{r_3}}{k_{3-4}} + \frac{\ln \frac{r_5}{r_4}}{k_{4-5}} \right) \]
\[ q' = \frac{2\pi (t_2 - t_5)}{\left( \frac{\ln \frac{2.375}{1.94}}{24.5} + \frac{3.187}{0.03} + \frac{\ln 5.187}{3.187} \right)} \]

\[ q' = \frac{2\pi (t_2 - t_5)}{\left( \frac{\ln 1.225 + \ln 2.69 + \ln 1.628}{24.5 + 0.03 + 0.037} \right)} \]

\[ q' = \frac{2\pi (t_2 - t_5)}{(0.00829 + 33 + 13.17)} \]

\[ q' = \frac{2\pi (t_2 - t_5)}{46.18} \]

\[ q' = (t_2 - t_5)(0.1391) \]

\[ q = 7.82 (t_1 - t_2) \]

\[ t_2 - t_5 = \frac{q}{0.1391} \]

\[ t_2 - t_5 = 7.19 q \]

\[ t_1 - t_2 = \frac{q}{7.82} \]

\[ t_1 - t_2 = 0.128 q \]

\[ t_1 - t_5 = 7.32 q \]

\[ q = 0.1365 (t_1 - t_5) \]
From 5 to 6 (Outside Air at 100F)

\[ h = 0.42 \left( \theta / A \right)^{0.25} \quad (4, \text{sec. 3, p 29}) \]

\[ h = 0.42 \frac{(t_5 - t_6)^{0.25}}{(10.375)^{0.25}} \]

\[ h = \frac{0.42}{1.795} (\Delta t)^{0.25} \]

\[ h = 0.232 (\Delta t)^{0.25} \]

\[ h = 0.22 \left( \frac{\Delta t}{D} \right)^{0.25} \]

\[ h = 0.22 \Delta t^{0.25} \left( \frac{12}{10.375} \right)^{0.25} \]

\[ h = 0.22 \Delta t^{0.25} (1.157)^{0.25} \]

\[ h = 0.22 \Delta t^{0.25} (1.0371) \]

\[ h = 0.228 \Delta t^{0.25} \]

These are essentially equal

\[ q = h A (\Delta t) \]

\[ q = 0.23 \left( 10.375 \pi \right) (\Delta t)^{1.25} \]
\[ q = 0.1365 \ (t_1 - t_5) \quad t_1 = 750^\circ F \]
\[ q = 7.5 \ (t_5 - t_6)^1.25 \quad t_6 = 100^\circ F \]
\[ q_1 = 0.1356 \ (750 - t_5) \]
\[ q_2 = 7.5 \ (t_5 - 100)^1.25 \]

<table>
<thead>
<tr>
<th>( t_5 )</th>
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<th>( q_2 )</th>
</tr>
</thead>
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<tr>
<td>110</td>
<td>87.4</td>
<td>133.3</td>
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<td>88</td>
<td>56</td>
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<td>85.5</td>
</tr>
<tr>
<td>106</td>
<td>87.9</td>
<td>70.5</td>
</tr>
</tbody>
</table>

\( t_5 = 107^\circ F \) when \( t_6 = 100^\circ F \)

Heat Loss is 87.8 Btu/ft hr

Total Loss is 2545 \((87.8) = 224,000 \text{ Btu/hr}\)

Condition at Laboratory

1379.6 - 149.3 = 1230.3

Conditions 569-psig and 518F

Since the film coefficient depends on the quality and \( \Delta t \) will drop, the final temperature will probably be about 550F.
To check for average conditions

582-psia at 650°F

\[
\frac{hD}{k} = 0.023 \left[ \frac{v \Delta P}{\mu} \right]^{0.8} \left[ \frac{C_p \mu}{k} \right]^{0.3}
\]

\[
v = \frac{1500(144)(4)(1.045)}{3600 (1.94)(1.94)\pi}
\]

\[v = 21.2 \text{ fps}\]

\[
h = \frac{0.023 (0.0034)}{1.94} (12) \left[ \frac{21.2(1.94(10^6))}{12(1.045)(17.5)} \right]^{0.8}
\]

\[
= \left[ \frac{0.6 (17.5)(3600)}{10^3 (3.4)} \right]^{0.3}
\]

\[h = 0.000483 (187,300) 0.8 \quad (11.11)^{0.3}
\]

\[h = 0.000483 (65.5)(252) (2.06)
\]

\[h = 16.42
\]

\[q = 16.42 \frac{1.94}{12} \pi (t_1 - t_2)
\]

\[q = 8.34 (t_1 - t_2)
\]

\[q = (t_2 - t_5) (0.1391)
\]

\[t_2 - t_5 = 7.19q\]
\[ t_1 - t_5 = 7.31 \, q \]

\[ q_2 = 7.5 \, (t_5 - t_6)^{1.25} \]

\[ q_1 = 0.1369 \, (t_1 - t_5) \]

<table>
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<td>100.9</td>
</tr>
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<td>74.2</td>
<td>85.5</td>
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<tr>
<td>106</td>
<td>74.4</td>
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<td>105</td>
<td>74.5</td>
<td>56</td>
</tr>
<tr>
<td>106.5</td>
<td>74.3</td>
<td>78 , \text{Btu/lb}</td>
</tr>
</tbody>
</table>

Use 106F \, 74.4 \, \text{Btu/lb}

Total loss 2545 (74.4) = 180,300 \, \text{Btu/lb}

Loss/\text{lb}= 120 \, \text{Btu/lb}

Final Conditions = 1379. - 120 = 1259

566 \, \text{psig and.} \, 555F \, \text{This is 60F Superheat}

The estimate was well within the accuracy of the other data.
Pressure drop check

\[ N_{Re} = 187,300 \]

\[ \frac{\Delta P_{fD}}{\rho v^2 L} = 0.0003 \]

\[ \Delta P = \frac{0.0003(\xi_1 \xi_2)(\xi_1 \xi_2)(2700)(12)}{(1.045)(1.94)(144)} \]

\[ \Delta P = 14.95 \text{ psi for 2700 ft} \]
For 2545 = 14.1 psi

Check for temperatures from pipe center to surface (hottest point)

Temp of inside surface
\[ q = h A (t_1 - t_2) \]

\[ 87.8 = 7.54 (750 - t_2) \]

\[ 750 - t_2 = \frac{87.8}{7.54} \]

\[ t_2 = 750 - 116 \]

\[ t_2 = 733.4 \text{F} \]

Temp of outside surface
\[ q = \frac{2\pi (t_2 - t_3)}{0.00829} \]
\[
87.8 = \frac{2\pi(738.4 - t_3)}{2\pi} \\
738.4 - t_3 = 0.1155F \\
t_3 = 738.3F \\
\]

For temp at junction of insulation
\[
87.8 = \frac{2\pi (738.3 - t_4)}{33} \\
738.3 - t_4 = \frac{87.8 (33)}{2\pi} \\
738.3 - t_4 = 462 \\
t_4 = 276F \\
\]

Outside temp
\[
87.8 = \frac{2\pi (276 - t_5)}{13.17} \\
276 - t_5 = \frac{87.8 (13.17)}{2\pi} \\
t_5 = 92F \\
\]

Using 3000 #/hr flow rate
\[
v = 46 \text{ fps} = 2760 \text{ feet per minute} \]
\[ N_{Re} = 355,200 \]

\[ \frac{\Delta P_f D}{\nu \cdot L \cdot \rho} = 0.00028 \]

\[ \Delta P = \frac{0.00028 \cdot (46)(46)(2550)(12)}{1.94 (144)(1.1324)} \]

\[ \Delta P = \underline{57.3 \text{ psi}} \text{ drop} \]

\[ \frac{h_D}{k} = 0.023 \left[ \frac{\nu D_p}{\mu} \right] 0.8 \left[ \frac{C_p \mu}{k} \right] 0.3 \]

\[ \frac{h (1.94)}{12(0.0033)} = 0.023 \left[ \frac{46(1.94)(10^6)}{12(1.1324)(18.5)} \right] 0.8 \]

\[ \left[ \frac{0.56(18.5)(3600)}{10^3 (3.3)} \right] 0.3 \]

\[ h (49) = 0.23 \cdot (355.200)^{0.8} \cdot (11.28)^{0.3} \]

\[ h (49) = 0.023 \cdot (110)(250)(2.07) \]

\[ h = \frac{0.023(110)(250)(2.07)}{49} \]

\[ h_{1-2} = 26.75 \text{ Btu/ft}^2 \text{ hr F} \]

\[ q = 26.75 \cdot \frac{1.94\pi}{12} \cdot (t_1 - t_2) \]

\[ q = 13.58 (t_1 - t_2) \]
\[ t_1 - t_2 = \frac{q}{13.58} \]

\[ t_1 - t_2 = 0.0727 \, q \]

\[ t_2 - t_5 = 7.19 \, q \]

\[ t_1 - t_5 = 7.263 \, q \]

\[ q = 0.1378 \, (t_1 - t_5) \]

\[ q = 7.5 \, (t_5 - t_6)^{1.25} \]

\[ t_1 = 750^\circ F \quad t_6 = 100^\circ F \]

\[ q_1 = 0.1378 \, (750 - t_5) \]

\[ q_2 = 7.5 \, (t_5 - 100)^{1.25} \]

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<tr>
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<td>56.2</td>
</tr>
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</table>
Use $107^\circ F$ as base $\Delta h = 87.8$ Btu/ft hr

Total loss is 213,000 Btu/hr

Final conditions $\frac{213000}{3000} = 71$ Btu/# loss

Outlet conditions 543-psia at 622°F

Estimated actual final conditions 545 at 635°F

Avg conditions then 570-psia at 690°F

\[ v = \frac{3000(144)(4)(1.095)}{3600(1.94)(1.94)n} \]

\[ v = 44.5 \text{ feet per second} \]

\[ N_{Re} = \frac{1.94(44.5)(10^6)}{12(1.095)(17.5)} \]

\[ N_{Re} = 375,000 \]

\[ \Delta P = \frac{0.000289(44.5)(2550)(12)}{1.94(144)(1.095)} \]

\[ \Delta P = 55.5-\text{psi} \]

\[ \frac{hD}{k} = 0.023 \left[ \frac{vD\rho}{\mu} \right]^{0.8} \left[ \frac{C_p}{k} \right]^{0.3} \]
\[
\frac{h (1.94)}{12(0.0032)} = 0.023 \left[ \frac{44.5(1.94)(10^6)}{12(1.095)(17.5)} \right]^{0.8} \left[ \frac{0.6(17.5)(3600)}{10^3 (3.2)} \right]^{0.3}
\]

\[
h (50.5) = 0.023 (375,000)^{0.8} (11.81)^{0.3}
\]

\[
h = \frac{0.023}{50.5} (252)(114)(2.097)
\]

\[
h = 27.45 \text{ Btu/ft hr F}
\]

\[
q = 27.45 \frac{1.94m}{12} (t_1 - t_2)
\]

\[
q = 13.92 (t_1 - t_2)
\]

\[
t_1 - t_2 = 0.0718 q
\]

\[
t_2 - t_5 = 7.19 q
\]

\[
t_1 - t_5 = 7.26 q
\]

\[
q_1 = 0.1378(t_1 - t_5)
\]

\[
q_2 = 7.5 (t_5 - t_6)^{1.25}
\]

Ends Up 545-psia at 622F

Temp Drop From Steam To Pipe Wall (hot end)

\[
750 - t_2 = 0.0727(37.8)
\]
\[ t_2 = 750 - 87.8(0.0727) \]
\[ t_2 = 750 - 6.32F \]
\[ t_2 = 744F \]

(mid point)
\[ t_2 = 690 - 87.8(0.0718) \]
\[ t_2 = 690 - 6.32F \]
\[ t_2 = 684F \]
\[ t_2 = 622 - 87.8(0.071) \]
\[ t_2 = 618 - 6.24 \]
\[ t_2 = 616F \]

If Temp Drop Varies Linearly As Distance
\[ \frac{750 - 622}{2423} = 0.0528F \text{ drop/ft of pipe} \]

Heat Loss in Terms of Length and Flow Rate for 3000#/hr
\[ \frac{87.8}{3000} = 0.0293 \text{ Btu/ft lb hr} \]

If Pressure Drop Varies As The Length
\[ \frac{56}{2423} = 0.0231 \text{ psi per foot of length} \]
Pipe Line Deflections

Weight per foot of length

Pipe 2" schedule 80

\[ p = 474-486 \, \text{#/ft}^3 \]  
(5, sec 1 p 7)

\[
W = \frac{486 \pi}{4(144)} \left(2.375^2 - 1.94^2\right)
\]

\[
W = \frac{486 \pi}{4(144)} \left(5.65 - 3.765\right)
\]

\[
W = \frac{486 \pi}{4(144)} (1.89)
\]

\[ W = 5.0 \, \text{#/ft} \]

Diatomaceous Earth

\[ p = 30\, \text{#/ft}^3 \]

\[
W = \frac{30 \pi}{4(144)} \left(6.375^2 - 5.65\right)
\]

\[
W = \frac{30 \pi}{4(144)} \left(40.7 - 5.65\right)
\]

\[
W = \frac{30 \pi}{4(144)} (35.05)
\]

\[ W = 5.73 \, \text{#/ft} \]

85% Magnesia

\[ p = 17\, \text{#/ft}^3 \]
Assuming water to a depth of 0.35" if the curve shape is parabolic the max deflection for this condition is 0.5"

\[
\sin \alpha = \frac{0.97 - 0.35}{0.97}
\]

\[
\sin \alpha = \frac{0.62}{0.97}
\]

\[
\sin \alpha = 0.639
\]

\[
\alpha = 39.45^\circ
\]

\[
\theta = 100.50^\circ
\]

\[
\theta = 1.754 \text{ radians}
\]

A = \frac{r^2}{2} (\theta - \sin \theta)

A = \frac{(0.97)^2}{2} (1.754 - 0.983)
A = 0.47 (0.771)
A = 0.362 sq in
W = \frac{0.362}{144} (62.4)
W = 0.007 \#/ft
Total weight per foot is 17.1 \#/ft

Pipe Deflections

This situation is so close to a fixed beam of uniform loading that this will be used as the basis for design.

\[ y = \frac{wl^4}{384EI} \quad (6 \text{ p 196}) \]

I for a cylinder is \[ \frac{\pi}{4} [ r_2^4 - r_1^4 ] \]

\[ I = \frac{\pi}{64} (2.375^4 - 1.94^4) \]

\[ I = \frac{\pi}{64} (31.8 - 14.15) \]

\[ I = \frac{\pi(17.6)}{64} \]

\[ I = 0.864^4 \]

For 14 ft Span

\[ y = \frac{17.1 (168^4)}{384(30)(10^6)(0.864)} \]

\[ y = 0.1363'' \]

If Full of Water

\[ w = 16.94 + (1.94)^2 \frac{\pi}{(144) 4} (62.4) \]
\[ w = 16.94 \pm 1.84 \]
\[ w = 18.78 \]
\[ y = \frac{18.78(168)^4}{384(30\times10^6)(0.864)} \]
\[ y = 0.15" \]
\[ Ss = \frac{Mc}{I} = \frac{18.78(168)^2}{12(0.864)(2)(2.375)} \]
\[ Ss = \frac{Mc}{I} = \frac{18.78(168)^2(2.375)}{12(0.864)(2)} \]
\[ Ss = \frac{Mc}{I} = 6,080 \text{ psi} \]

**Lengths of Individual Runs**

- **Heating Plant to Point 1**: 50 ft
- **Point 1 to Point 6**: 623 ft
- **Point 6 to Point 10**: 260 ft
- **Point 10 to Point 16**: 815 ft
- **Point 16 to Point 18**: 225 ft
- **Point 18 to Point 20**: 230 ft
- **Point 20 to Point 21**: 45 ft
- **Point 21 to Point 22**: 90 ft
- **Point 22 to Point 23**: 80 ft
If the Temperature Drop is Linear in the Line

\[
\frac{740 - 500}{2423} = 0.1^\circ F \text{ drop per foot}
\]

Expansion in Unit #1 (based on zero at 32°F)
Length is 50 ft \hspace{1cm} \text{Temp drop is 5°F}

\[
t_{\text{avg}} = 737.5 \text{ ft} \hspace{1cm} t_2 = 735°F
\]

\[
\Delta L_1 = 50 \left(0.00621 \cdot (0.7055) + (0.7055)^2 \cdot 0.00162\right)
\]

\[
= 50 \left(0.00438 + 0.000806\right)
\]

\[
= 50 \left(0.00519\right)
\]

\[
= 0.259 \text{ ft} = 3.11''
\]

Expansion to 70°F (Base Temp)

\[
\Delta L^1 = L(0.00621 \cdot (0.038) + (0.038)^2 \cdot 0.00162)
\]

\[
= L(0.000236 + 0.00000234)
\]

\[
= L(0.000238)
\]

For Unit #1 \hspace{1cm} = 0.0119 \text{ ft}

Net Expansion \hspace{1cm} = 0.247 \text{ ft} = 2.965''

Unit #2 Length 623 ft \hspace{1cm} \text{Temp drop} = 62.3°F

\[
t_{\text{avg}} = 704°F \hspace{1cm} t_3 = 673°F
\]
\[ \Delta L_2 = 623 \left(0.00621 \cdot (0.672) + (0.672)^2 \cdot (0.00162)\right) \]
\[ = 623 \left(0.00417 + 0.000731\right) \]
\[ = 623 \cdot 0.00489 \]
\[ = 3.055 \text{ ft} \quad = 36.6" \]
\[ \Delta L_2 = 0.1482 \]

Net Expansion = 2.907 ft = 34.9"

Unit #3 Length 260 ft  Temp Drop = 26°F
\[ t_{avg} = 660°F \]
\[ \Delta L_3 = 260 \left(0.00621 \cdot (0.628) + (0.628)^2 \cdot (0.00162)\right) \]
\[ = 260 \left(0.0039 + 0.00064\right) \]
\[ = 260 \cdot 0.00454 \]
\[ = 1.18 \text{ ft} \quad = 14.17" \]
\[ \Delta L_3 = 260 \cdot 0.000238 = 0.0618 \]

Net Expansion = 1.12 ft = 13.34"

Unit #4 Length 815 ft  Temp Drop 81.5°F
\[ t_{avg} = 606°F \quad t_5 = 565°F \]
\[ \Delta L_4 = 815 \left(0.00621 \cdot (0.574) + (0.574)^2 \cdot (0.00162)\right) \]
\[ = 815 \left(0.003565 + 0.000534\right) \]
\[ = 815 \cdot 0.004099 \]
\[ = 3.34 \text{ ft} \quad = 40.1" \]
\[ \Delta L_4 = 815 \cdot 0.000238 = 0.194 \]
Net Expansion = 3.146 ft = 37.8"

Unit #5  Length 225  Temp drop 22.5F

\[ t_{avg} = 554F \quad t_8 = 543F \]

\[ \Delta L_5 = 225 \left( 0.00621 \times 0.522 \right) + (0.522)^2 \left( 0.00162 \right) \]

\[ = 225 \left( 0.00324 + 0.000441 \right) \]

\[ = 225 (0.00368) \]

\[ = 0.828 \text{ ft} = 9.94" \]

\[ \Delta L^I = 225 (0.000238) = 0.0536 \text{ ft} \]

Net Expansion = 0.775 ft = 9.3"

Unit #6  Length 244  Temp Drop 24.4F

\[ t_{avg} = 531F \quad t_7 = 519F \]

\[ \Delta L_6 = 244 \left( 0.00621 \times 0.499 \right) + (0.499)^2 \left( 0.00162 \right) \]

\[ = 244 (0.0031 + 0.000404) \]

\[ = 244 (0.0035) \]

\[ = 0.855 \text{ ft} = 10.25" \]

\[ \Delta L^I = 244 (0.000238) = 0.0531 \text{ ft} \]

Net Expansion = 0.797 ft = 9.57"

Unit #7  Length 35  Temp Drop 3.5F

\[ t_{avg} = 517F \quad t_8 = 515F \]

\[ \Delta L_7 = 35 \left( 0.00621 \times 0.485 \right) + (0.485)^2 \left( 0.00162 \right) \]

\[ = 35 \left( 0.00301 + 0.000381 \right) \]

\[ = 35 (0.00339) \]

\[ = 0.1187 \text{ ft} = 1.423" \]
\[ \Delta L_l = 35(0.000238) = 0.00833 \]

Net Expansion = 0.1104 ft = 1.327

Unit #8 Length 90 ft Temp Drop 9°F

\[ t_{avg} \quad 511^\circ F \quad t_9 \quad 506^\circ F \]

\[ \Delta L_8 = 90 \left( 0.00621 \times 0.479 \right) + (0.479)^2(0.00162) \]
\[ = 90 \left( 0.002975 + 0.000372 \right) \]
\[ = 90 \times 0.003347 \]
\[ = 0.301 \text{ ft} = 3.61" \]

\[ \Delta L_l = 90 \times 0.000238 = 0.0214 \text{ ft} \]

Net Expansion = 0.28 ft = 3.36"

Unit #9 Length 81 Temp Drop 8°F

\[ t_{avg} \quad 502^\circ F \quad t_{10} \quad 498^\circ F \]

\[ \Delta L_9 = 81 \left( 0.00621 \times 0.47 \right) + (0.47)^2(0.00162) \]
\[ = 81 \left( 0.00292 + 0.000358 \right) \]
\[ = 81 \times 0.00328 \]
\[ = 0.266 \text{ ft} = 3.18" \]

\[ \Delta L_l = 81 \times 0.000238 = 0.0193 \]

Net Expansion = 0.247 ft = 2.97"
### Expansion Requirements Using Sola-Flex Expansion Joints

<table>
<thead>
<tr>
<th>Unit #1</th>
<th>50 ft</th>
<th>2.965&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.438&quot;</td>
<td>$69.70</td>
</tr>
<tr>
<td></td>
<td>2 anchor base</td>
<td>43.50</td>
</tr>
<tr>
<td></td>
<td>1 pipe guide</td>
<td>21.75</td>
</tr>
<tr>
<td>Unit #2</td>
<td>623 ft</td>
<td>34.9&quot;</td>
</tr>
<tr>
<td></td>
<td>2 at 5.5&quot;</td>
<td>$162.80</td>
</tr>
<tr>
<td></td>
<td>5 at 4.813&quot;</td>
<td>387.50</td>
</tr>
<tr>
<td></td>
<td>8 anchors</td>
<td>174.00</td>
</tr>
<tr>
<td></td>
<td>7 guides</td>
<td>152.25</td>
</tr>
<tr>
<td>Unit #3</td>
<td>260 ft</td>
<td>13.43</td>
</tr>
<tr>
<td></td>
<td>2 at 4.813&quot;</td>
<td>$155.00</td>
</tr>
<tr>
<td></td>
<td>1 at 4.125</td>
<td>73.60</td>
</tr>
<tr>
<td></td>
<td>4 anchors</td>
<td>87.00</td>
</tr>
<tr>
<td></td>
<td>3 guides</td>
<td>65.25</td>
</tr>
<tr>
<td>Unit #4</td>
<td>815 ft</td>
<td>37.8&quot;</td>
</tr>
<tr>
<td></td>
<td>6 at 5.5&quot;</td>
<td>$488.40</td>
</tr>
<tr>
<td></td>
<td>1 at 4.813&quot;</td>
<td>77.50</td>
</tr>
<tr>
<td></td>
<td>8 anchors</td>
<td>174.00</td>
</tr>
<tr>
<td></td>
<td>7 guides</td>
<td>152.25</td>
</tr>
<tr>
<td>Unit #5</td>
<td>225 ft</td>
<td>9.3&quot;</td>
</tr>
<tr>
<td></td>
<td>2 at 4.813&quot;</td>
<td>$155.00</td>
</tr>
<tr>
<td></td>
<td>3 anchors</td>
<td>65.25</td>
</tr>
<tr>
<td></td>
<td>2 guides</td>
<td>43.50</td>
</tr>
<tr>
<td>Unit #6</td>
<td>244 ft</td>
<td>9.57&quot;</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>2 at 4.813&quot;</td>
<td></td>
<td>$155.00 (9.626&quot;)</td>
</tr>
<tr>
<td>3 anchors</td>
<td></td>
<td>65.25</td>
</tr>
<tr>
<td>2 guides</td>
<td></td>
<td>43.50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$3205.15</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit #7</th>
<th>35 ft</th>
<th>1.327&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 at 1.375</td>
<td></td>
<td>$58.00 (3.438&quot;)</td>
</tr>
<tr>
<td>2 anchors</td>
<td></td>
<td>43.50</td>
</tr>
<tr>
<td>1 guide</td>
<td></td>
<td>21.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit #8</th>
<th>90 ft</th>
<th>3.36&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 at 3.438&quot;</td>
<td></td>
<td>$69.70 (3.438&quot;)</td>
</tr>
<tr>
<td>2 anchors</td>
<td></td>
<td>43.50</td>
</tr>
<tr>
<td>1 guide</td>
<td></td>
<td>21.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit #9</th>
<th>81 ft</th>
<th>2.97&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 at 3.438&quot;</td>
<td></td>
<td>$69.70 (3.438&quot;)</td>
</tr>
<tr>
<td>2 anchors</td>
<td></td>
<td>43.50</td>
</tr>
<tr>
<td>1 guide</td>
<td></td>
<td>21.75</td>
</tr>
</tbody>
</table>

Total $3205.15
Expansion Modified For 3000 #/hr Flow Rate

Unit #1 50 ft

\[ P_1 = 600\text{-psia at 750°F} \quad h_1 = 1379.6 \]

\[ \Delta P = 1.15 \]

\[ \Delta h = 1.47 \]

\[ t_2 = 748 \]

\[ t_{\text{avg}} = 749 \]

\[ \Delta L_1 = 50 \left( 0.00621 (0.717) + 0.00162 (0.717)^2 \right) \]

\[ = 50 \left( 0.00445 + 0.000832 \right) \]

\[ = 0.264 \text{ ft} \]

\[ = 3.165 \text{ in} \]

Expansion above 70°F \[ L(0.000238) \]

\[ 50(0.000238) = 0.0119 \text{ ft} \]

Net Expansion = 0.252 ft = 3.025 in

Unit #2 623 ft \[ \Delta p = 14.4 \text{ psi} \]

\[ P_3 = 585 \]

\[ \Delta h = 18.27 \text{ Btu/#} \]

\[ h_3 = 1360 \quad t_3 = 714 \quad t_{\text{avg}} = 731°F \]

\[ \Delta L_2 = 623 \left( 0.00621 (0.699) + (0.699)^2 (0.00162) \right) \]

\[ = 623 \left( 0.00434 + 0.000792 \right) \]

\[ = 623 (0.00513) \]

\[ = 3.195 \]

\[ = 38.4 \text{ in} \]

\[ \Delta L_{70} = 623(0.000238) = 0.1482 \]

\[ \Delta L' = 3.047 \text{ ft} = 36.6 \text{ in} \]
Unit #3  260 ft  \( \Delta P = 6\text{-psi} \)  
\( \Delta h = 7.62 \text{ Btu/#} \)

\[ P_4 = 579 \quad t_4 = 700F \quad t_{\text{avg}} = 707F \]

\[ \Delta L_3 = 260(0.00621(0.675) + (0.675)^2(0.00162)) \]
\[ = 260(0.00419 + 0.000737) \]
\[ = 260(0.00493) \]
\[ = 1.282 \text{ ft} \]
\[ = 15.4 \text{ in} \]

\[ \Delta L_{70} = 260(0.000238) = 0.0618 \text{ ft} \]

\[ \Delta L_{\frac{1}{3}} = 1.22 \text{ ft} \quad = 14.65 \text{ in} \]

Unit #4  815 ft  \( \Delta P = 18.82 \)
\( \Delta h = 23.9 \text{ Btu/#} \)

\[ P_5 = 560 \quad t_5 = 656F \quad t_{\text{avg}} = 678F \]

\[ \Delta L_4 = 815 \left((0.00621(0.646) + (0.646)^2(0.00162))\right) \]
\[ = 815 \left((0.00401 + 0.000675)\right) \]
\[ = 815 \left((0.00469)\right) \]
\[ = 3.82 \text{ ft} \]
\[ = 45.9 \text{ in} \]

\[ \Delta L_{70} = 815(0.000238) = 0.194 \text{ ft} \]

\[ \Delta L_{\frac{1}{4}} = 3.626 \text{ ft} \quad = 45.5 \text{ in} \]

Unit #5  225 ft  \( \Delta P = 5.2\text{-psi} \)
\( \Delta h = 6.6 \text{ Btu/#} \)

\[ P_L = 555 \quad t_6 = 645F \quad t_{\text{avg}} = 673F \]
\[ \Delta L_5 = 225 \left( 0.00621 \left( 0.641 \right) + (0.641)^2 (0.00162) \right) \]
\[ = 225 \left( 0.00398 + 0.000665 \right) \]
\[ = 225 \left( 0.004645 \right) \]
\[ = 1.045 \text{ ft} \]
\[ = 12.53 \text{ in} \]

\[ \Delta L_{70} = 225 \left( 0.000238 \right) = 0.0536 \]

\[ \Delta L_5 = 0.9914 = 11.9 \text{ in} \]

Unit #6  
\[ \Delta P = 5.64 \]
\[ \Delta h = 7.15 \]

\[ P_7 = 549.4 \quad t_7 = 635 \text{F} \quad t_{avg} = 640 \]
\[ h_7 = 1.07 \text{ ft} \]
\[ = 12.82 \text{ in} \]

\[ \Delta L_6 = 244 \left( 0.00621 (0.608) + (0.608)^2 (0.00162) \right) \]
\[ = 244 \left( 0.00378 + 0.0006 \right) \]
\[ = 244 \left( 0.00438 \right) \]
\[ = 1.07 \text{ ft} \]
\[ = 12.82 \text{ in} \]

\[ \Delta L_{70} = 244 \left( 0.000238 \right) = 0.0681 \text{ ft} \]

\[ \Delta L_6 = 1.012 = 12.13 \text{ in} \]

Unit #7  
\[ \Delta P = 0.808 \]
\[ \Delta h = 1.027 \]

\[ P_8 = 548.6 \quad t_8 = 632 \quad t_{avg} = 634 \]
\[ h_8 = 1314 \]

\[ \Delta L_7 = 35 \left( 0.00621 (0.602)^2 (0.00162) \right) \]
\[ = 35 \left( 0.003735 + 0.000587 \right) \]
\[ = 35 \left( 0.00432 \right) \]
= 0.151 ft
= 1.81 in

\[ \Delta L_7 = 0.143 \text{ ft} = 1.72" \]

Unit #8 90 ft \( \Delta P = 2.08 \)
\( \Delta h = 2.64 \)

\( P_9 = 546.5 \quad t_9 = 628 \quad t_{\text{avg}} = 630^\circ F \)

\( h_9 = 1311.5 \)

\[ \Delta L_8 = 90 (0.00621 (0.598) + (0.598)^2 (0.00162)) \]
\[ = 90 (0.00372 + 0.00058) \]
\[ = 90 (0.0043) \]
\[ = 0.387 \text{ ft} \]
\[ = 4.65 \text{ in} \]

Net = 4.38 in

Unit #9 81 ft \( \Delta P = 1.87-\text{psi} \)
\( \Delta h = 2.37 \text{ B/#} \)

\( P_{10} = 544.7 \quad t_{10} = 622^\circ F \quad t_{\text{avg}} = 625^\circ F \)

\( h_{10} = 1309.1 \)

\[ \Delta L_9 = 81 (0.00621(0.593) + (0.593)^2 (0.00162)) \]
\[ = 81 (0.00366 + 0.00057) \]
\[ = 81 (0.00425) \]
\[ = 0.344 \text{ ft} \]
\[ = 4.13 \text{ in} \]
## Alternate Proposal For 3000 #/hr Flow Rate
### Using Sola-Flex Joints

<table>
<thead>
<tr>
<th>Unit</th>
<th>Diameter (in)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>3.025&quot; (3.438)</td>
<td>$69.70</td>
</tr>
<tr>
<td></td>
<td>Requires 3.438&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 anchor bases</td>
<td>$43.50</td>
</tr>
<tr>
<td></td>
<td>1 pipe guide</td>
<td>$21.75</td>
</tr>
<tr>
<td>#2</td>
<td>36.6&quot; (37.126&quot;)</td>
<td>$407.00</td>
</tr>
<tr>
<td></td>
<td>Requires 5 at 5.5&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 at 4.813&quot;</td>
<td>$155.00</td>
</tr>
<tr>
<td></td>
<td>8 anchors</td>
<td>$174.00</td>
</tr>
<tr>
<td></td>
<td>7 guides</td>
<td>$152.25</td>
</tr>
<tr>
<td>#3</td>
<td>14.65&quot; (15.126&quot;)</td>
<td>$81.40</td>
</tr>
<tr>
<td></td>
<td>Requires 1 at 5.5&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 anchors 2 at 4.813&quot;</td>
<td>$155.00</td>
</tr>
<tr>
<td></td>
<td>3 guides</td>
<td>$87.00</td>
</tr>
<tr>
<td>#4</td>
<td>43.5&quot; (44&quot;)</td>
<td>$651.20</td>
</tr>
<tr>
<td></td>
<td>Requires 8 at 5.5&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 anchors</td>
<td>$195.75</td>
</tr>
<tr>
<td></td>
<td>8 guides</td>
<td>$174.00</td>
</tr>
<tr>
<td>#5</td>
<td>11.9&quot; (12.375&quot;)</td>
<td>$220.80</td>
</tr>
<tr>
<td></td>
<td>Requires 3 at 4.125&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 anchors</td>
<td>$87.00</td>
</tr>
<tr>
<td></td>
<td>3 guides</td>
<td>$65.25</td>
</tr>
</tbody>
</table>
Unit #6  12.13"  (12.375")
  Requires 3 at 4.125  $220.80
  4 anchors  87.00
  3 guides  65.25

Unit #7  1.72"  (2.063")
  Requires 1 at 2.063"  61.90
  2 anchors  43.50
  1 guide  21.75

Unit #8  4.38"  (4.813")
  Requires 1 at 4.813"
  2 anchors  43.50
  1 guide  21.75

Total  $3591.75

Alternate Using 3000#/hr Flow Rate And Adsco Expansion Joints Where Price Differential Warrants It

Unit #2  36.6"

  2 double expansion joints by Adsco  
  8" traverse each end  $496.00
  1 Sola-Flex at 5.5"  81.40
  4 Adsco #10 guides  180.00
  1 Solar guide  21.75
  4 anchors  87.00

Total  $866.15
Possible saving in valves, traps and return system swing joints.

Unit #3  14.65"

Use 1 adsco 16" traverse  $ 248.00
2 anchors  45.50
2 guides  90.00

$ 381.50

By Solar  $388.65

Unit #4  43.5"

3 Adsco at 16" traverse  $ 744.00
4 anchors  87.00
6 guides  270.00

$1101.00

By Solar  $1020.95

Unit #5  11.9"

One Adsco double 16" traverse  $ 248.00
2 anchors  87.00
2 guides  90.00

$ 425.00

By Sola-Flex  $373.05

Use Sola-Flex
Assuming Pipe is 1/2 full of water and a velocity of one foot per second

\[ A = \frac{\pi r^2}{2} \quad \text{wetted perimeter} = \pi r \]

\[ D^1 = \frac{A}{wp} = \frac{\pi r^2}{2\pi r} = \frac{r}{2} \]

\[ D^1 = 0.37 = 0.0808 \text{ ft} \]

\[ v = \frac{(1.486 R^{0.67} s^{0.5})}{r} \quad (4 \text{ sec} 2 \text{ p} 15) \]

\[ l = \frac{1.486 (0.0808)^{0.67}}{0.01} s^{0.5} \]

\[ l = \frac{1.486 (0.187)}{0.01} s^{0.5} \]

\[ \frac{0.01}{1.486 (0.187)} = s^{0.5} \]

\[ s^{0.5} = 0.036 \]

\[ s = 0.0013 \]

Slope = 0.0156 \text{ in/ft} = 15.6 \text{ in/1000 ft}
Pressure Drop For 2" Schedule 80 Pipe With Flow Rate of 6000 #/hr

\[ N_{Re} = 177,600 \ (4) = 710,400 \ (v = 92) \]

\[ \Delta P_{fD} \over \nu^2 \rho = 0.00027 \]

\[ \Delta P_f = \frac{0.00027(92)(2545)(12)}{(1.94)(144)(1.324)} \]

\[ \Delta P = 220.7 \text{ psi} \]

Velocity is 5520 ft/min and will not be too erosive for short time use.

Film Coefficient

\[ h = 0.000469 \ (710,400)^{0.8} \ (2.07) \]

\[ h = 0.000469 \ (2.07)(252)(190) \]

\[ h = 45.5 \text{ Btu/sq ft hr } ^{\circ}F \]

\[ T_1 - t_2 = 0.0215 \text{ q} \]

\[ t_2 - t_5 = 7.19 \text{ q} \]

\[ t_1 - t_5 = 7.21 \text{ q} \]

\[ q_1^f = 0.1388 \ (t_1 - t_5) \quad t_1 = 750^\circ F \]

\[ q_2^f = 7.5 \ (t_5 - t_6)^{1.25} \quad t_6 = 100^\circ F \]
This causes little change in heat loss

Conditions 380-psia and approx 500F
APPENDIX II