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STATEMENT OF PROBLEM

Evaluate design requirements and limitations of:

a) Steam Generating Equipment
b) Main Coolant Piping and Valves
c) Main Coolant Pumps

ABSTRACT

In order to obtain the most economical layout of the main heat transfer loop system, a parametric study was performed for the following reactor and steam turbine cycle conditions:

Reactor:

Thermal Output: 160,000 kwt

Fuel Element	#4	#6
Reactor Outlet Temp.	670 F	684.5 F
Reactor Inlet Temp.	610 F	610.0 F
Δt	60 F	74.5 F
Organic Flow Rate (total)	17.8×10^6 lbs/hr	14.4×10^6 lbs/hr

Steam Conditions at Turbine Throttle:

a) 600°F - 800 psig
1000 psig
1200 psig

b) 650°F - 800 psig
1000 psig
1200 psig

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Since the reactor thermal power was held constant at 160,000 kw for all study cases, the gross turbine outputs and steam flows varied with estimated gross turbine cycle efficiencies as follows:

Case	1	2	3	4	5	6
Steam Conditions	p = 1200 psig t = 650 F	1000 psig 650 F	1200 psig 600 F	800 psig 650 F	1000 psig 600 F	800 psig 600 F
FW	410 F	400 F	410 F	380 F	400 F	380 F
Gross Turbine Output, kw	55,200	54,000	53,300	53,200	52,000	52,400
Total Steam Flow, lbs/hr	621,000	602,000	660,000	577,000	631,000	600,000

On the basis of these organic coolant and steam flows, single and two-loop systems and various types of steam generators were investigated. Consideration was given to steam generator requirements for a 300 Mwe plant for which the present design is a prototype.

The results of this study show that vertical and horizontal steam generators with organic on the tube side exhibit definite size limitations. With high steam pressures and large organic flow rates, the tube sheet diameter and thickness becomes too large for practical application. For this reason, except for a few marginal cases in the 800 and 1000 psig steam pressure range, most conditions would require two vertical type steam generators for a 50 Mwe plant, as shown in Table I. Inasmuch as this would result in an excessive number of steam generators for power stations in the 200-300 Mwe range, a steam generator with organic on the tube side was ruled out.

In aiming at a single loop system for a 50 Mwe plant, in order to attain a four-loop system for a 300 Mw station, a horizontal shell and tube type steam generator with the organic on the shell side was selected. The unit has a forced-water-circulation system and a separate steam drum for steam-water separation.

In multiple loop systems the most economical arrangement consists of one main organic coolant pump per loop. For the single loop layout, two half-size pumps in parallel arrangement have been selected for increased safety and reliability.

DISCUSSION

1. Vertical Steam Generator

This unit is a shell and tube type heat exchanger with a vertical U-tube bundle, with organic coolant on the tube side and water and steam on the shell side. Natural circulation of the water is effected by a shroud construction around the tube bundle, whereby a primary separator at the top of the tube bundle separates the steam-water mixture.

The steam side design pressures used for the study are 1350, 1150 and 950 psig, corresponding to turbine throttle pressures of 1200, 1000 and 800 psig. Boiler heat transfer surfaces were calculated for the various steam pressures, organic coolant flows and plotted against reactor temperature differences to cover a wide range of possible combinations as indicated in Fig. 1. The diagram is based upon a reactor inlet temperature of 610°F. Since the superheater surface is relatively small for 600°F and 650°F temperature, it has very little effect on the over-all boiler heating surface as shown in the diagram and can therefore be neglected in the comparison.

For each of the organic flow rates selected for further study, namely 17.8×10^6 lbs/hr and 14.4×10^6 lbs/hr, 5/8" OD tubes and 3/4" OD tubes were considered with a maximum organic velocity of 12 fps. Using the heat transfer surface required for each case, the tube sheet thickness, tube bundle length, shell thickness and over-all height of the unit were calculated. Normally, the ligament between tubes in the tube sheet is 1/4"; however as the tube sheet thickness increases, larger ligaments are required. For tube sheet thickness over 18", a 3/8" ligament is used commercially.

The results of these calculations are summarized in Table 1, showing the requirements for two steam generators in parallel where a single unit is impractical. In all cases with one steam generator, the tube sheet requirements are abnormally high. Experience has shown that heavy tube sheets may be a source of trouble due to possible high stress concentrations when welding thick tube sheets to moderately thin shells. Many heat exchanger failures have been traced to stress corrosion at the tube-to-tube sheet joint.

The steam generator manufacturers contacted recommend that tube sheets be limited to 14" thickness, however one supplier has built a unit with an 18" tube sheet thickness successfully. Note that the thicknesses listed in Table I were calculated using the TEMA formula. These values may increase if a rigorous stress analysis was performed. Steam generator designs requiring thicknesses of 18" and above are considered impractical and are not recommended until more experience becomes available.

Since most of the designs employing a single unit show nonacceptable tube sheet thicknesses, several modifications of the vertical steam generator were studied. By using two steam generators in parallel arrangement in a single loop, or one steam generator each in two loops, reasonable size units can be expected.

However, in determining the requirements for a 300 Mwe plant and adopting the vertical design discussed, this may result in 12 units and 6 loops. For a 1000 psig turbine throttle pressure condition, studies were made using a 4-loop design with two steam generator units in parallel per loop. This resulted in a 114" OD shell and 20" tube sheet thickness for a 5/8" OD tube and 106" OD shell and 18.5" tube sheet thickness for a 3/4" tube. Thus, the larger tube diameter shows some advantage, however the final selection would depend on a hazard analysis postulating a rupture of a tube and determining the relative relief capacities required.

In order to reduce the tube sheet thickness, consideration was given to the use of low chrome-alloy materials. At a design temperature of 750°F for the steam generator, low carbon steel SA 266 II has an allowable stress of 14,750 psi. By substituting $2\frac{1}{4}$ Cr $\frac{1}{2}$ Moly, SA 182 F22 material with an allowable stress of 17,500 psi for low carbon steel, the required tube sheet thickness is reduced approximately 9%. However, based upon manufacturers' experiences with this material, the question remains whether it can be forged to meet rigid ultrasonic specifications for the thicknesses and diameters required.

In view of the inherent limitations of flat tube sheets, other alternates were investigated. One possibility is the arrangement of two horizontal headers in the bottom portion of a vertical steam generator from which the tubes emanate. For the 1000 psig steam pressure case and with a reactor Δt of 60°F, two 36" headers, approximately 7" thick and 96" long, would be required. The tubes would have to be bent near the header and band type supports would be required for the tube bundle. However, this design introduces certain manufacturing problems and presents difficulties in the location and repair of leaks, hence this design does not appear attractive.

Another possibility is the use of an elliptical or hemispherical tube sheet. Preliminary calculations show that a 14" thick ellipse, 120" in diameter, is required for the above case, assuming a stress concentration factor of 2. The forging required makes this design questionable.

2. Horizontal Steam Generators

One of the main reasons for the large diameter tube sheet in a single vertical steam generator is the large organic flow through the tubes. In order to obtain reasonable pressure drops, the velocity of the organic through the tubes has been limited to 12 fps, thus making the number of tubes dependent upon the throughput. In some of the cases under consideration, this results in large diameter tube sheets and short tube bundle lengths.

A more balanced diameter-to-length ratio can be obtained with the organic on the shell side and the steam and water on the tube side. A natural circulation boiler of this type does not appear practical for this application in a containment vessel. In view of the low pressure drop required through the boiler tubes for circulation, the steam drum would have to be at some substantial elevation above the boiler to meet the necessary head requirement. For this reason a single forced circulation type steam generator has been tentatively selected for the prototype plant. In this unit 2 half-capacity forced circulation pumps take boiler water from a conventional steam drum and pump it through the tube system of the boiler where it is partly converted into steam. Steam-water mixture separation takes place in the horizontal steam drum, which is equipped with centrifugal type separators and steam drying equipment.

For the 1000 psig/650°F turbine case, 602,000 lbs/hr steam are produced. With a water circulation ratio of 4:1, the boiler vessel diameter is reduced to approximately 76 inches, requiring a tube sheet thickness of approximately 13 inches. Although this unit requires a separate steam drum 60" OD, 30' long, the shell thickness is materially reduced due to the lower design pressure on the organic side. The recirculation pumps require a total of 120 horsepower.

As mentioned previously, one of the main criteria in selecting a 50 Mwe steam generator is to project the requirements for a 300 Mwe plant. A preliminary investigation was made of a 4-loop design with one horizontal forced-circulation type steam generator in each loop and for 1000 psig steam conditions at the turbine throttle. This resulted in a boiler vessel 106" in diameter, approx. 40' long, and a tube sheet thickness of 18.5" for 5/8" OD tubes. By changing to 3/4" OD tubes, the diameter of the shell can be reduced to 85", however the over-all length would increase to 50'. The steam drum in each of the four loops would have to handle 900,000 lbs/hr steam and its dimension would be approximately 60" OD, 40' long.

3. Layout of Vertical and Horizontal Steam Generator Concepts

A preliminary layout was made to determine the primary containment vessel size for a 300 Mwe plant for either one of the two concepts. It was found that no material difference in containment vessel size exists, either for two vertical steam generators per loop or one horizontal forced circulation boiler per loop with a separate steam drum above the reactor operating floor.

4. Main Heat Transfer Loop Piping

In conjunction with the preceding steam generator evaluation for single and two loop systems, a brief study was made of the heat transfer loop piping requirements for layout purposes and for obtaining cost information. The latter was incorporated into the preliminary over-all plant optimization and cost studies as reported in TDR 6627.

As the basis for the evaluation, the following assumptions were made:

a) The organic coolant velocity in the main loop pipe should not exceed 18 ft/sec.

b) The length of main coolant piping was estimated at 200 feet.

c) The equivalent length of the pipe, blocking valves, elbows and other fittings in each loop was estimated to be 500 feet for pressure drop calculations.

d) The total organic pressure drop across the superheater and boiler unit was estimated to be 30 psi.

e) The pressure drop across the steam generator bypass control valve and the flowmeter was estimated at 5 psi.

f) The main coolant pump efficiency was estimated at 80%.

The relationship between organic flow rate and reactor temperature difference for single and two-loop systems is indicated in Fig. 2. Superimposed on this diagram are the various pipe sizes required in order to stay within the velocity limits and pressure drop conditions stated above. This information was used to obtain the main coolant pump power requirements for the steam cycles discussed in TDR 6627.

5. Main Coolant Pumps

Since the main coolant pumps are an integral part of the primary reactor coolant loop and steam generator system, the type pump to be selected may essentially affect the over-all layout and size of the containment vessel.

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In order to make the containment vessel as small as possible, it is necessary to keep the space required for the piping between reactor vessel and steam generator at a minimum. In view of the relatively large diameter (24" to 36") of the main coolant pipes, it is important that large thermal expansion loops be avoided. This can be accomplished by using suitable expansion joints, and by selecting a pump design that will not require excessive changes in the runs of suction and discharge piping.

Previous studies have revealed that vertical type pumps lend themselves to simpler pipe layouts than horizontal pumps for larger capacity plants. Furthermore, the possibility exists that a vertical pump can be arranged with flexible supports to allow movement with the pipes. Indications are that vertical pumps are more expensive than horizontal ones; however, studies have shown that this price disadvantage may be offset by the greater flexibility in layout and some other resultant savings.

In addition to these layout requirements, two other features are considered of prime importance: the ease of maintenance on bearings and seals and the application of a type of mechanical seal to prevent outleakage of possibly radioactive coolant into the atmosphere.

Various types of pumps have been offered by manufacturers with the bearings arranged on the inside of the pump proper and lubricated by the coolant. In view of the poor lubricating properties of the organic coolant and a lack of operating experience with this type bearing, it is not under consideration at this time, although it would lead to a simple pump design.

In order to prevent outleakage of coolant, present pump designs incorporate a conventional double mechanical seal pressurized by fresh coolant leaking both ways. There is confidence that this type of seal system will perform as expected, and a test program is in progress to furnish back-up information and operational experiences.

Therefore, the pumps selected for the prototype plant contain the above features and are suitable for large power plant applications.

The pump is a conventional vertical, single stage mixed flow type with overhung impeller, double mechanical seal and a bearing assembly external to the pumped fluid. Each of the two pumps is rated at 20,000 gpm flow and a total differential head of 240 ft. The pump is direct driven by a vertical 1500 HP, 4160 volt, 3 phase, 60 cycle induction motor with closed forced ventilation. This type of cooling system is considered adequate and results in considerable cost savings over an explosion-proof motor.

TABLE I

Steam Pressure at Turbine Throttle	1200 psi		1000 psi		800 psi	
Design Press. for Steam Generator/ Turbine	1350 psi	750°F	1150 psi	750°F	950 psi	750°F
Use of 1 Steam Generator						
Steam Temperature - °F	650 & 600	650 & 600	650 & 600	650 & 600	650 & 600	650 & 600
Organic ΔT(Reactor Inlet 610°F)	60	74.5	60	74.5	60	74.5
Flow Rate (Organic)	17.8×10^6	14.4×10^6	17.8×10^6	14.4×10^6	17.8×10^6	14.4×10^6
Org. Flow Velocity ft/sec	12	12	12	12	12	12
No. of 5/8" Tubes/Dia.Tube Sheets**	6830/120"	5500/110"	6830/120"	5500/110"	6830/120"	5500/110"
No. of 3/4" Tubes/Dia.Tube Sheets**	4200/109"	3390/101"	4200/109"	3390/101"	4200/109"	3390/101"
Heating Surface Required	40,000	39,000	27,600	27,200	20,400	21,000
Tube Sheet Thickness 5/8"/3/4"** TEMA Formula (carbon steel constr.)	22.8"*/20.7"*	20.9"*/19.2"*	21"*/19.1"*	19.2"*/17.7"*	19"*/17.3"*	17.5"*/16.1"*
Dia. Tube Sheet/Tube Sheet Thickness for 5/8" Tube***			135"/23.6"	124"/21.7"	135"/21.5"	124"/19.6"
Dia. Tube Sheet/Tube Sheet Thickness for 3/4" Tube***			121"/21.5"	113"/19.8"	121"/19.4"	113"/18.1"
Tube Bundle Length 5/8"/3/4"Tubes				/22'6"	11'*/14'*	13.5'*/17'
Shell Thickness 5/8"/3/4"				/4.2"*	/3.7"	3.7"/3.4"
Over-All Height of Unit				/38'	/30'	29'7"/32'8"
Use of 2 Steam Generators						
Heating Surface ft²	20,000	19,500	13,800	13,600	10,200	10,500
No. of Tubes 5/8"	3415	2750	3415	2750	3415	2750
No. of Tubes 3/4"	2100	1695	2100	1695	2100	1695
Tube Sheet Diameter 5/8"	84"	78"	84"	78"	84"	78"
Tube Sheet Diameter 3/4"	80"	75"	80"	75"	80"	75"
Tube Sheet Thickness 5/8"/3/4"	16"/15.2"	14.8"/14.2"	14.7"/14"	13.6"/13.1"	13.4"/12.8"	12.4"/11.9"
Tube Bundle Length 5/8"/3/4"	20'/25.5'	24.5'/30.5'	14'6"/18'	17'/22'6"	11'/14'	13.5'/17'
Shell Thickness	4"/3.8"	3.6"/3.6"	3.5"/3.3"	3.2"/3.1"	2.9"/2.7"	2.7"/2.6"
Over-All Height of Unit 5/8"/3/4"	35'/41'	39'/45'	29'/32'6"	31'5"/37'	25'8"/28'5"	28'10"/31'2"

* Not Practical
** Using 1/4 inch ligaments
*** Using 3/8 inch ligaments

FIG. 1

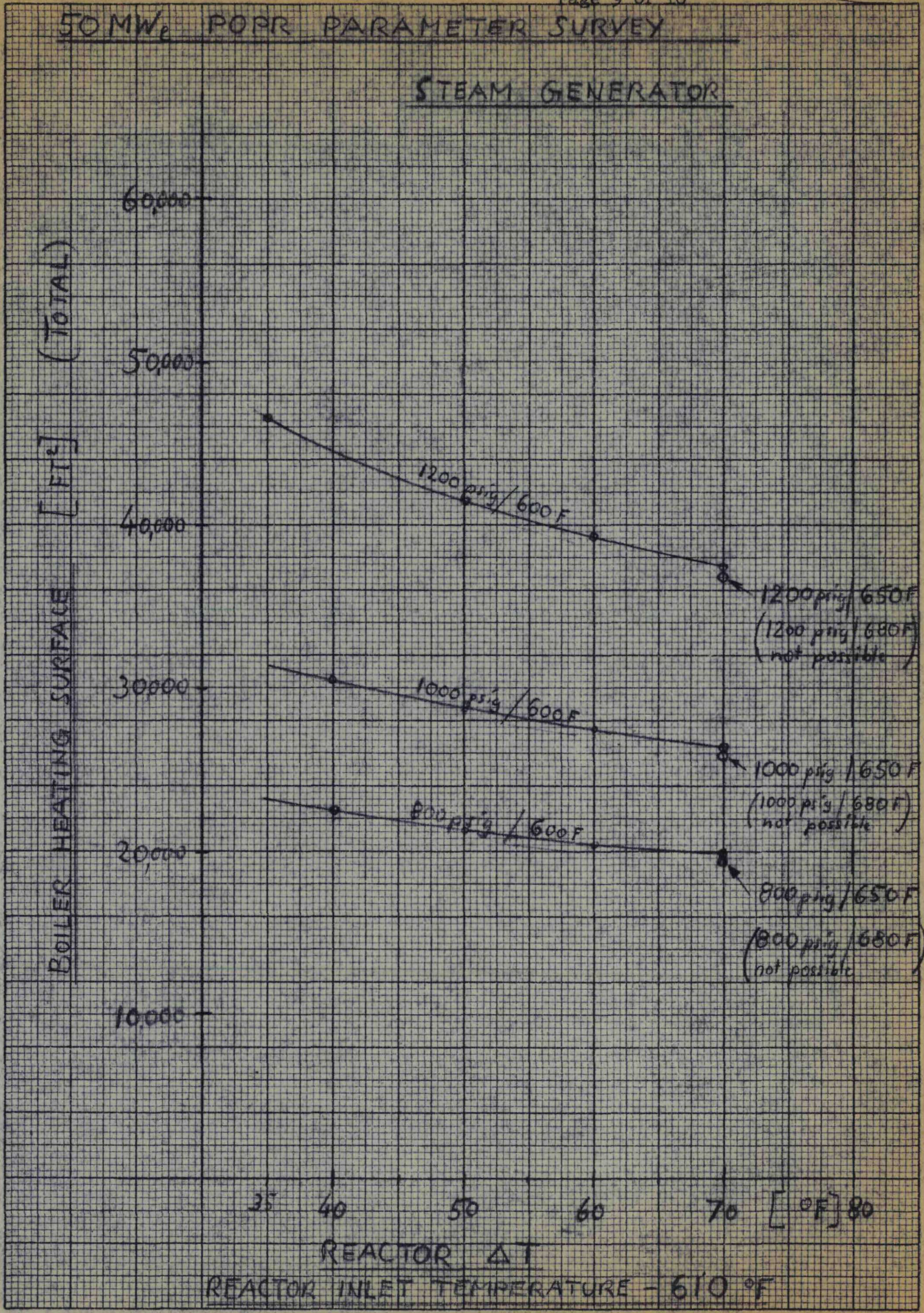
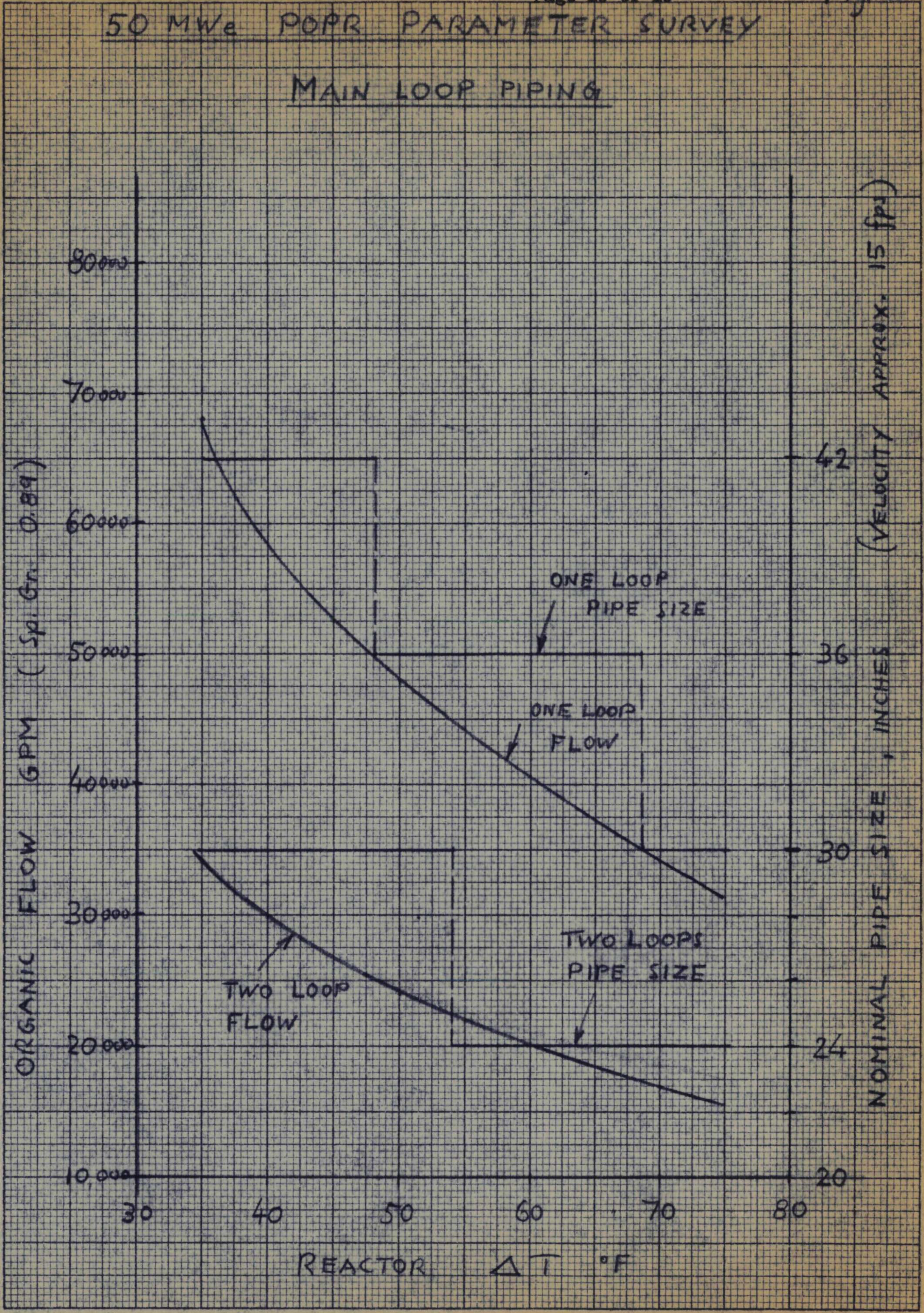

50 MWe POPR PARAMETER SURVEY
STEAM GENERATOR
BOILER HEATING SURFACE [FT²] (TOTAL)
60,000
50,000
40,000
30000
20,000
10,000
1200 psig / 600 F
1200 psig / 650 F
(1200 psig / 680 F not possible)
1000 psig / 600 F
1000 psig / 650 F
(1000 psig / 680 F not possible)
800 psig / 600 F
800 psig / 650 F
(800 psig / 680 F not possible)
35
40
50
60
70
[°F]
80
REACTOR ΔT
REACTOR INLET TEMPERATURE - 610 °F

Fig. 2


50 MWe POPR PARAMETER SURVEY
MAIN LOOP PIPING
ORGANIC FLOW GPM (Sp. Gr. 0.89)
80000
70000
60000
50000
40000
30000
20000
10,000
NOMINAL PIPE SIZE, INCHES (VELOCITY APPROX. 15 fps)
42
36
30
24
20
ONE LOOP
PIPE SIZE
ONE LOOP
FLOW
TWO LOOPS
PIPE SIZE
TWO LOOP
FLOW
30
40
50
60
70
80
REACTOR ΔT °F