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WRITTEN BY A. T. Stell	**ATOMICS INTERNATIONAL** *A Division of North American Aviation, Inc.* **TECHNICAL DATA RECORD**	TDR NO. 4093
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GROUP Analytical Engineering		LEDGER ACCT. 3621
UNIT Heat Transfer		SUB-ACCT. 4966
APPROVED BY: D. F. Casey (SUPERVISOR) D.F. Casey	PROGRAM HNPF	TWR 00880
OTHER	PROJECT System Analysis	DATE August 10, 1959
		PAGE 1 OF 92

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SUBJECT:

Steady State Thermal Behavior of HNPF Sodium Heat Transfer System

CONTENTS:

I STATEMENT OF PROBLEM

Investigate the performance of the HNPF sodium heat transfer components in order to determine the steady state, part load characteristics under various operating conditions.

II SUMMARY OF RESULTS

The complete steady state temperature distributions, variations of flow rates and heat transfer coefficients throughout the sodium heat transfer systems as functions of reactor load are shown in Figures 7 through 16.* Each Figure consists of a set of curves describing the thermal performance of the heat transfer systems for all operating conditions analyzed. The thermal behavior of the sodium heat transfer system assuming the reactor outlet temperature and turbine throttle steam pressure and temperature constant has been studied for the following operation conditions:

1. Operation with constant superheater outlet steam temperature
2. Operation with equal flow rates in the primary and secondary loops over the entire load range
3. Operation with reactor inlet temperature varied linearly with the primary sodium flow rate.

Part-load characteristics of the expected sodium and steam temperatures, flow rates and heat transfer coefficients with the restrictions of Condition 1 and 2 above, are presented in Figures 7 and 8 and Figures 9 and 10, respectively. These curves

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* Note: When reference is made to a set of curves, one figure number is mentioned only. A particular curve is referred to as Fig. 7b, 9d,. etc.

are calculated for three feedheaters in service and a fouled steam generator with fouling factors of 0.0005 and 0.0010 for the evaporator and superheater respectively.

Part load characteristics of the many variables mentioned above with the restriction of Condition 3 are presented in Figures 13 through 16. Several cases were investigated for this method of operation, since it represents the actual features of the presently designed primary flow rate control and is therefore of greater importance. These cases are noted below with the appropriate figure numbers.

Feedheaters in service	Condition of Steam Generator	Figure No.
3	clean	13
4	clean	14
3	fouled	15
4	fouled	16

The computer program developed for calculation of the heat transfer system variables for Condition 1 is presently available for use under Production Deck No. 3W-071. The code for Condition 2 and 3 is available under Production Deck No. 3W-082. These decks are on file at the EDPM Department of the Rocketdyne Division.

Each set of curves consist of six graphs in the following sequence:

> The first graph shows the sodium and steam temperature variations with load, while the second graph depicts the variations with the reactor load of the primary sodium flow rate, steam flow rate, primary to secondary flow rate ratio, bypass flow rate and the bypass as a percentage of the evaporator steaming rate. The third graph shows the variation in evaporator and superheater heat loads and the ratio of these heat loads with the reactor thermal load. The remaining three graphs show the overall heat transfer coefficients of the three sodium heat transfer components in one loop of the system.
>
> Figures 11 and 12 present the load characteristics of the system when the reactor temperature differential is held constant at 338°F. In other words the reactor inlet temperature is held constant at 607°F rather than varied linearly with the primary sodium flow rate as in Condition 3. The linear variation of the reactor inlet temperature with the primary flow rate was based on the relationship
>
> $$T_{nri} = 560 + .50 \frac{W_{n,p}}{W_{n,p_N}} \qquad \text{(Reference 1)}$$
>
> where W_{n,p_N} represents the primary flow rate at normal full load operation.

With reference to this last mentioned condition, it is seen that the temperature variations over the load range are in general far more sensitive to the condition of the steam generator than it is to the feed water temperature. Therefore, feed water temperature is not donsidered suitable for purposes of control and plant operation with 4 feed heaters is recommended except at very low loads to improve the overall efficiency of the plant.

The evaporator will produce more steam when operating with 4 feed heaters due to the higher feed water temperature. Therefore the evaporator pressure will be higher if the same turbine throttle steam pressure is to be maintained. In fact, when comparing the temperature profiles of Fig. 15a and Fig. 16a it is seen that the evaporator temperature increases from 530 F to 532 F at 250 Mw when using the 4th feed heater and thus the evaporator pressure will increase from 885 psia to 900 psia, the corresponding saturation pressures.

The bypass flow rate into the attemporator is not affected by the feed water temperature. However, it is rather sensitive to the condition of the steam generator. A clean superheater produces much higher temperature steam and thus more saturated steam bypass is required to reduce the turbine steam temperature to a reasonable value. For a clean steam generator this bypass flow rate exhibits a maximum of 28,000 lb/hr at about 210 Mw reactor output (See Fig. 14b). If the steam generator is in fouled condition however, this maximum bypass flow rate would be reduced to 22,800 lb/hr at a reactor load of 155 Mw (see Fig. 15b).

The primary to secondary sodium flow rate ratio does not depend upon feed water temperature either; however, it appears that gradual fouling of the steam generator will tend to reduce this ratio, particularly at higher loads. In general it may be stated therefore that the consequences of fouling of the steam generator for the same reactor load for the last mentioned operating condition are as follows:

Decrease of superheater sodium inlet temperature
Decrease of superheater steam outlet temperature
Decrease of evaporator sodium inlet temperature
Increase of evaporator sodium outlet temperature
Decrease of superheater bypass flow rate
Increase of secondary sodium flow rate
Decrease of evaporator heat transfer coefficient
Decrease of superheater heat transfer coefficient

Primary flow rate and steam flow rate are not influenced by fouling of the steam generator.

The influence of higher feed water temperature on the sodium heat transfer system at the same reactor power when operating under condition 3 is as follows:

Decrease of superheater steam outlet temperature
Decrease of evaporator sodium inlet temperature
Increase of steam flow rate
Decrease of evaporator heat load
Increase of superheater heat load
Increase of superheater heat transfer coefficient

Sodium hot leg temperatures, maximum bypass flow, and primary flow rate do not change with higher feed water temperature. The secondary sodium flow rate will change very slightly however, due to a higher evaporator temperature.

The constant superheater outlet steam temperature operation (Fig. 7) shows unique features in temperature and flow rate profiles as compared with the profiles of other operating conditions. Immediately evident is the tendency of the superheater inlet and outlet sodium temperatures to decrease with load (Fig.7a). Also it appears to be the only condition studied where the primary sodium flow rate is smaller than the secondary sodium flow rate (Fig. 7b). This is not surprising, however, when considering the much larger reactor temperature difference created by the fairly rapid drop in reactor sodium inlet temperature, being forced down by the decreasing temperature approach at the cold end of the intermediate heat exchanger.

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III. METHOD OF CALCULATION

General Assumptions

In the solution of the problem, the following assumptions are included or implied:

1. Specific heat for sodium is a constant
2. The IHX, and superheater are true counter flow heat exchangers
3. The evaporator bulk water temperature is constant at any one heat load
4. There is no moisture carry over to the superheater
5. Sodium temperature and flow rates are the same in all three loops
6. Sodium flow is turbulent at all flow rates
7. Thermal properties of steam can be approximated to a good degree of accuracy by a polynomial representation of the temperature range under consideration
8. The turbine system will absorb the entire reactor thermal output at any time
9. The superheated steam from the superheater and the saturated steam from the evaporator will be perfectly mixed within the attemporator.

In order to study the steady state behavior of the many thermodynamic variables of the sodium heat transfer system, a set of simultaneous equations was devised to describe the characteristics of the system under part load conditions. The sodium heat transfer system under consideration is one of the three heat transfer loops of the Hallam Nuclear Power Facility, shown schematically on Figure 1. For the sake of mathematical convenience the system was divided into four components; evaporator, superheater, attemporator, and intermediate heat exchanger. It is then possible to express the thermal performance of these components in terms of the temperatures and flow rates, which are the dependent variables of the system. The only independent variable of the system is the reactor thermal power considering the steam pressure and temperature at the turbine throttle as well as the reactor outlet sodium temperature constant. The remaining system variables will adjust themselves as dictated by the operating procedure under consideration, the reactor thermal power and the heat transfer and thermodynamic relationships expressed by the equations.

The system equations, 13 in number, are now set up relating these variables in terms of one another and may in principal be solved for each value of Q_r (the reactor thermal power) when the restrictions on the system have been decided. The equations are expressed in transcendental form for solution on the digital computer.

In particular, the variable thermodynamic functions must be represented by polynomials, in order to obtain fairly accurate representation over the entire range of interest.

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There are three such thermodynamic functions required for the solution of the system equations. They are approximated by 2nd order polynomials obtained from a least-square curvefit based on 7 points of the thermodynamic data to be represented. A 2nd order curvefit was chosen in favor of a higher order polynomial to avoid the occurrence of extremities in the curves between the points. These thermodynamic functions are: the saturated steam temperature and enthalpy in the evaporator, and the feed water enthalpy entering the evaporator. On Figures 2 and 3, the saturated steam temperature and enthalpy variation respectively, have been plotted as a function of the evaporator steaming rate in lb/hr. These curves have been obtained by combining the temperature and enthalpy variations with the saturation pressure from the steam tables and the assumption that the evaporator pressure increases with the square of the steam flow rate.

In order to keep the number of thermodynamic functions to a minimum the saturated liquid enthalpy in the evaporator was assumed to be smaller than the saturated water temperature T_{se} by a constant value. This assumes the specific heat of the liquid to be constant, which is quite acceptable when the temperature changes are small (Reference 5). The variation of feed water temperature or rather enthalpy with thermal load is plotted on Figures 4 and 5, being derived from the best available steam plant cycle heat balance data available at present (Reference 1).

System Equations & Component Representation

The thermal behavior of the system was described by the following set of equations pertaining to the four heat transfer components in the system. For each component in the circuit, the heat and mass balance equations were written, together with the characteristic equations representing the steady state response. These equations are as follows:

Evaporator

1. $Q_e = W_{n,s} \, Cp_n \, (T_{nei} - T_{neo})$

2. $\frac{1}{U_e} = X_1 \, W_{n.s}^{-0.4} + Y_1 \left(\frac{Q_e}{A_e}\right)^{-0.587} + Z_1$

3. $\frac{U_e A_e}{W_{n,s} Cp_n} = \ln \frac{T_{nei} - T_{se}}{T_{neo} - T_{se}}$

4. $Q_e = W_{se} \; H_{seo} - H_{fw} + PCBD. \, W_{se} \, H_{sat} - H_{fw}$

Superheater

5. $Q_s = W_{n,s}Cp_n (T_{nsi} - T_{nei})$

6. $Q_s = W_{ss} (C_{71} T_{sso} - C_{72}) = W_{ss}Cp_s (T_{sso} - T_{se})$

7. $\frac{U_sA_s}{W_{n,s}Cp_n} - \frac{U_sA_s}{W_{ss}Cp_s} = \ln \frac{T_{nsi} - T_{sso}}{T_{nei} - T_{se}}$

8. $\frac{1}{U_x} = X_3 \; W_{n,s}^{-0.6} + Y_3 \; W_{n,p}^{-0.4} + Z_3.$

Attemporator

9. $W_{ss}Cp_s (T_{sso} - T_{se}) = W_{se}(H_{sao} - H_{seo}).$

IHX

10. $Q_r = Q_e + Q_s = W_{n,p}Cp_n (T_{nro} - T_{nri})$

11. $Q_r = W_{n,s}Cp_n (T_{nsi} - T_{neo})$

12. $\frac{U_xA_x}{W_{n,p}Cp_n} - \frac{U_xA_x}{W_{n,s}Cp_n} = \ln \left(\frac{T_{nro} - T_{nsi}}{T_{nri} - T_{neo}}\right)$

13. $\frac{1}{U_x} = X_3W_{n,s}^{-0.6} + Y_3 \; W_{n,p}^{-0.4} + Z_3$

The constants for these equations are identified and listed in the Appendices and may be fixed at any reasonable value depending on the description of the heat transfer system under study.

Evaporator Representation

From a heat transfer point of view, the evaporator is the simplest heat exchanger of the four (the attemperator is a mixing devise rather than a heat exchanger), due to the fact that one fluid is changing phase and therefore the evaporator has approximately isothermal tube walls at any one heat load.

The heat balance of any point in the evaporator gives:

$$W_{n,s}Cp_n\,dt = -U_e\,(t - T_{se})\,dA_e$$

or

$$\int_{T_{nei}}^{T_{nxi,s}} \frac{dt}{t - T_{se}} = -\int_{0}^{A_e} \frac{U_e dA}{W_{n,s}Cp_n}$$

which upon integration yields

$$\ln \frac{T_{nei}-T_{se}}{T_{neo}-T_{se}} = \int_{0}^{A} \frac{U_e dA}{W_{n,s}Cp_n}$$

Admittedly, the thermal conductance U is a function of the tube length as U depends on the local heat flux which is greater at the hot end than at the cold end of the evaporator. However, assuming a constant specific heat of sodium, an average thermal conductance U may be calculated such that

$$\int_{0}^{A} U_A dA = UA.$$

This value of U was found to be 570 Btu/ft^2/°F/hr at design conditions for fouled condition (Reference 2). Thus

$$\ln \frac{T_{nei}-T_{se}}{T_{neo}-T_{se}} = \frac{U\,A}{W_{n,s}Cp_n}$$

Although U_A may be averaged in this manner to make integration of

$$\int_{0}^{A} UdA$$

possible, U will also vary with the sodium flow rate and the average heat flux in the evaporator. This is the dependency of U with reactor thermal power that must be found.

The overall thermal conductance (U_e), may be expressed as follows:

$$\frac{1}{U_e} = R_s + R_b + R_t + R_f.$$

The tube resistance R_t and the fouling resistance R_f are constants. R_t may be calculated from physical data, and R_f is as provided in AI's steam generator specifications AT5-354 (Reference 11). The sodium resistance R_s varies with the sodium flow rate $W_{n,s}$ according to

$$R_s = \frac{A_o}{A_i h_{na}}$$

and $h_{na} = .625\ Pe^{0.4}$

while the boiling resistance varies with the average heat flux Q_e across the evaporator according to $R_b = 1/h_b$,

$$h_b = 110\ t_b^{1.42} \quad \text{(Reference 4)}$$

and

$$\frac{q_e}{A_e} = h_b\ t_b.$$

After some algebraic manipulation, inserting the known constants of evaporator tube design and using an average value for the thermal diffusivity of sodium α, in

$$P_e = \frac{v.d.}{\alpha},$$

the equation for the thermal conductance U, reduces to:

$$\frac{1}{U_e} = 0.0518\ W_{n,s}^{-0.4} + 0.1439\ \left(\frac{Q_e}{A_e}\right)^{-0.587} + 14 \times 10^{-4}.$$

Another relation describes the sodium enthalpy loss in the evaporator namely

$$Q_e = W_{n,s}\ Cp\ (T_{nei} - T_{neo}) \text{ or}$$

$$Q = W_{n,s}\ Cp\ (T_{nei} - T_{se}) \quad (1 - e^{-\frac{UA}{WCp}})$$

where the term $1 - e^{-\frac{UA}{WCp}}$ represents the effectiveness of the evaporator. This sodium enthalpy loss must equal the enthalpy gain of the feed water heater to its saturation value and the heat of evaporation at the evaporator pressure, or,

$$Q_e = W_{se}\ (H_g - H_{fw}) + PCBD\ W_{se}\ (H_{sat} - H_{fw}).$$

The second term of this equation allows for a certain amount of continuous evaporator blowdown which is necessary to maintain a reasonable impurities level in the evaporator.

Superheater Representation

While equation 5 is self explanatory, equation 6 is not quite so obvious. This relationship eliminates a nodal iteration procedure ordinarily required since the specific heat of steam (Cp_s) varies markedly with temperature and very slightly with pressure and thus with flow rate. For the particular system under study, the superheater outlet steam pressure and temperature are permitted to vary over a very limited range while the steam flow rate may vary from zero to full flow. The writer found that for this limited range of superheater outlet steam temperature, the steam enthalpy rise in the superheater may be represented by a linear function of the outlet temperature with remarkable accuracy. The steam enthalpy rise variation includes the slight pressure changes in the superheater due to variable steam flow rates. This relationship is shown on Figure 6. Equation 6 defines the variable Cp_s very simply as a continuous function of steam enthalpy. This method facilitates computer coding, as the solution to the entire problem requires iteration on one variable at a time only, rather than two simultaneously and eliminates an iteration subroutine which would otherwise be necessary.

Equation 7 describes the superheater effectiveness in terms of the respective flow rates, temperatures and thermal conductance in a similar manner as described for the evaporator.

The thermal conductance of the superheater (U_s) can be expressed as follows:

$$\frac{1}{U_s} = R_{Na} + R_t + R_s + R_f \ .$$

In a similar fashion as described previously for the evaporator the tube metal and fouling resistance (R_t and R_f) are constant. R_t may be determined from physical data and R_f is given in AI's specification No. AT5-354 (Reference 11). The tube side sodium resistance is equal to the sodium resistance in the evaporator multiplied by the 0.4 power of the ratio of the number of tubes in the evaporator and superheater as the tubes used in both these units are identical. The tube side film resistance in the superheater is thus known. A survey of the literature on shell side heat transfer reveals that the shell side film coefficient (h) in orifice baffled heat exchangers varies with the 0.6 power of the mass flow rate of the shell side fluid and in this case is proportional to the 0.6 power of the steam flow rate.

Admittedly, the shell side film coefficient depends also on the Prandtl number of the superheated steam which strictly speaking would vary with the local temperature and to a slight degree also pressure in the superheater.

It may be shown however, that its influence is not significant as compared with the Reynnolds number and within the scope of this work, the Prandtl number was considered constant.

Thus the equation for the thermal conductance reduces to

$$\frac{1}{U_s} = X_2 W_{n,s}^{-0.4} + Y_2 W_{ss}^{-0.6} + Z_2$$

and after substituting the values for the constants:

$$\frac{1}{U_s} = 0.0559 W_{n,s}^{-0.4} + 6.35 W_{ss}^{-0.6} + 1910^{-4}.$$

The proportionality factor Y_2, was selected at 6.35 to give a U_s of 175 at the design flow rate (for fouled condition) as claimed by the steam generator manufacturer (Reference 2).

Attemporator Representation

Where a total of four equations is necessary to describe the heat transfer in each of the other three components, only one can be written for the attemporator. This equation represents the heat and mass balance of the steam enthalpy and flow rates entering and leaving the attemporator. The enthalpy of the steam (and thus the temperature when the pressure is constant) to the turbine is fixed at a constant value.

Equation 9 is thus self-explanatory. It states that the enthalpy rise of the steam flow through the superheater equals the enthalpy difference of the total steam flow between evaporator outlet and turbine throttle inlet. This is readily seen to be true when one realizes that the superheater is the only component between the evaporator and the turbine that increases the steam energy content.

IHX Representation

While equations 10 and 11, describe the sodium enthalpy change in the IHX on the primary and secondary side, equation 12 expresses the heat balance between the two media in the IHX and is similar to equation 7 derived for the superheater. The overall heat transfer coefficient (U_x) is stated in terms of primary and secondary sodium flow in Equation 13. If

$$\frac{1}{U_x} = R_p + R_s + R_t$$

where R_t is the constant tube metal resistance, then the shell side film coefficient may be assumed to vary with the 0.6 power of the secondary flow, while the tube side film resistance would vary with the 0.4 power of the primary sodium flow. As the resistances are inversely proportional to the film coefficients, one may write

$$\frac{1}{U_x} = X_3 W_{n,p}^{-0.4} + Y_3 W_{n,s}^{-0.6} + Z_3$$

As Z_3 and X_3 are fairly accurately known Y_3 was selected to give a value of $U = 1145$ at

$$W_{n,p} = W_{n,s} = 3.0 \times 10^{-6} \text{ lbs/hr}$$

as quoted by the manufacturer of this component (Reference 7).

IV COMPUTER SOLUTIONS

As stated earlier, the 13 system equations expressing 15 variables as functions of one another (when implying constant steam conditions to turbine) cannot be solved unless at least two variables are chosen as fixed values. The reactor sodium outlet temperature is obviously one of these fixed values and the second restriction may be selected in accordance with the desired operating procedure.

In order to analyse the subject heat transfer system under the three operating conditions described under "Summary of Results" of this TDR, it was necessary to develop two computer codes, which were programmed in Fortran for the IBM 709 digital machine.

One of the two computer codes solves the complete heat transfer system when constant superheater steam outlet temperature is desired. The other computer program solves the heat transfer system when the flow rate or temperatures are controlled in the primary loop and is therefore applicable when part load characteristics of the plant must be studied under the provision of operating procedure No. 2 and 3 as outlined in the "Summary of Results" in this TDR.

When operating with constant superheater outlet steam temperature, the need for an attemporator no longer exists and therefore that particular program had to be different for that operating condition, while the superheater outlet steam temperature must be specified. Moreover, it is not immediately possible to compute the primary sodium flow rate from the reactor thermal load, as can be done for the other two operating procedures.

1. Operation with constant steam temperature at superheater outlet

For computer solutions of this condition, some of the equations were combined in such a manner as to make solution of the steam flow rate immedately possible. It is seen from Equation 6 that for this case, the superheater load is linear with the steam flow rate and this combined with Equation 4, the steam flow rate may be quickly computed.

With the evaporator and superheater thermal load known, the sodium flow rate in the secondary loop is found with the use of Equations 1, 2, 3, 6, 7, and 8. Finally, Equations 10, 12 and 13 determine the primary sodium flow rate and the reactor sodium inlet temperature. Now all the variables are known and plotted against the reactor thermal load (Q_r). On Figures 7 and 8, the temperature profiles, flow rate variations and heat transfer coefficient profiles are shown as a function of reactor load.

2. Operation with constant balanced sodium flow rates

When the sodium flow rates are always balanced, the steam temperature will rise at lower loads. The steam temperature to the turbine is controlled at a constant value through bypassing some of the saturated steam from the evaporator around the superheater and mixing this saturated steam with the superheated steam leaving the superheater.

For this condition a new variable is introduced viz, the steam flow rate through the superheater, since the evaporator steaming rate is not equal to the steam flow rate in the superheater. However, it is readily verified for this case that the superheater thermal load depends on the evaporator steaming rate only and therefore, when combining Equations 6 and 9 with the evaporator load statement of Equation 4, the evaporator steaming rate may readily be computed.

To find the secondary sodium flow rate, a different procedure must be used than the one employed in the previous case, as the steam flow rate in the superheater is not known yet and therefore Equations 6, 7, and 8 cannot be used to compute the secondary sodium flow rate. The method of attack is now to make use of the fact that for balanced flow rates in the IHX, the MTD in the IHX is equal to the temperature difference at the hot end (or cold end) of the IHX. This affords a relationship which states that the sodium inlet temperature to the superheater is dependent on the secondary sodium flow rate only. However, as the evaporator and thus also the superheater thermal load are known, Equations 1, 2, and 5 may be combined to give a second relationship stating the superheater sodium inlet temperature as a function of the secondary sodium flow rate. Equating the superheater sodium inlet temperature from these two equations, a transcedental equation results which was solved for the secondary sodium flow rate.

To complete the problem, the superheater steam flow rate was computed from Equations 6 and 7, and all unknowns are now determined under the conditions stated by this operating procedure. It is possible that f for higher than normal loads, the stipulated steam flow rate would become greater than the evaporator steaming rate. As the absurdity of a negative superheater bypass flow is obvious, a test was build in the program such that in the event that this occurs, the sodium and steam flow rates are recomputed to give a superheater bypass flow equal to zero while the steam temperature to turbine will be lower than initially required. On Figures 9 and 10, the temperature and heat transfer coefficient profiles with the flow rate variations are shown as a function of reactor load.

3. Operation with controlled reactor sodium inlet temperature

While the aforementioned cases are definitely of academic interest, the solution to the problem under the restrictions of this case is far more important, as the control and protective system for the Hallam Nuclear Power Facility is designed to regulate the primary sodium flow rate as a function of the sodium inlet temperature to the reactor. Therefore, this operating condition has been investigated for either 3 or 4 feed heaters in service as well as for clean and fouled heat transfer components.

The control function which programs the primary flow rate with the reactor sodium inlet temperature in a closed loop system, may be any arbitrary function; however, as the presently designed control system is based on a linear relationship, the code was developed to accommodate linear functions. A minor change in the program is necessary when using control functions other than linear.

This third condition is an extension of the criteria discussed under condition 2, and logically its description runs parallel to that of condition 2. The only exception being that when considering the thermal equilibrium of the IHX, a different relationship exists between the sodium inlet temperature to the superheater and the secondary sodium flow rate, as the MTD of the intermediate heat exchanger no longer equals the temperature difference at its hot or cold end as in the previous case. Inspection of Equation 10 reveals however, that when the reactor sodium inlet temperature is expressed as a function of the primary sodium flow rate, both are dependent on the reactor thermal load and may be readily computed.

In the development of this computer program a linear relationship between reactor sodium inlet temperature and primary sodium flow rate is assumed of the form

$$T_{nri} = Cf_1 + Cf_2 \frac{W_{n,p}}{W_{n,pN}} \qquad \text{(Reference 1)}$$

The question now remains as to what the primary sodium flow rate is at full load ($W_{n,pN}$), as

$$\frac{Cf_2}{W_{n,pN}}$$

will establish the slope of the linear function. This full load primary flow rate depends on the reactor sodium outlet temperature as well as the full reactor load and in order to make the program suitable for higher reactor sodium outlet temperatures and thermal loads, the linear function in question was rewritten into the form

$$T_{nri} = S\, W_{n,p} + N$$

where $n = Cf_1$ and $S = \dfrac{Cf_2\, Cp_n\, T_{nro} - (Cf_1 + Cf_2)}{RNP \; 1.13 \; 10^6}$

For the solution of the problem, the quantities Cf_1, Cf_2 and RNP, (the normal full load reactor power in Mwt) must be furnished as additional input data. To study the thermal behavior of the sodium heat transfer system with a constant reactor temperature drop it is merely required to state $Cf_2 = 0$ and Cf_1 will then represent any constant reactor sodium inlet temperature as may be desired.

Combination of equation 10, 11, 12 and 13 with the known linear control function of reactor sodium inlet temperature in terms of the primary sodium flow rate, readily establishes a relationship expressing the sodium inlet temperature to the superheater as a function of the secondary sodium flow rate. Equating this expression with the relationship mentioned under condition 2 obtained by algebraic manipulation of equation 1, 2, and 6, the secondary sodium flow rate is computed from the resulting transcendental equation. The remainder of the program is identical to that discussed under condition 2. On Figures 13 through 16 the temperature and heat transfer coefficient profiles with the flow rate variations are shown as a function of reactor load.

As pointed out, conditions 2 and 3 differ only in the relationship between the superheater sodium temperature and the secondary sodium flow rate, therefore both cases may be calculated with the same computer program.

An indication in the input data is required as to whether operating condition 2 or 3 needs to be computed. The program will then insert the appropriate equations pertaining to the condition under consideration. The constants Cf_1 and Cf_2 are used for this purpose and when specifying $Cf_1 = Cf_2 = 0$, all the computations will be made with the restrictions of equal primary and secondary flow rates over the load range.

V. REFERENCES AND APPENDICES

A. References and Acknowledgments

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The programming for the IBM 709 was ably performed by P. Inman of AI Dept. 758.

B. Nomenclature

T_{se} = Evaporator saturated steam (or liquid) temperature, °F

T_{sso} = Superheater outlet steam temperature, °F

T_{nei} = Evaporator sodium inlet temperature or (superheater sodium outlet temperature, °F

T_{neo} = Evaporator sodium outlet temperature, °F

T_{nsi} = Superheater sodium inlet temperature, °F

T_{nri} = Reactor sodium inlet temperature, °F

T_{nro} = Reactor sodium outlet temperature, °F

$W_{n,p}$ = Primary sodium flow rate, lbs/hr

$W_{n,s}$ = Secondary sodium flow rate, lbs/hr

W_{se} = Evaporator steaming rate, lbs/hr

W_{ss} = Superheater steam flow rate, lbs/hr

U_e = Overall evaporator heat transfer coefficient Btu/°F-ft^2-hr

U_s = Overall evaporator heat transfer coefficient Btu/°F-ft^2-hr

U_x = Overall IHX heat transfer coefficient, Btu/°F-ft^2-hr

Q_e = Evaporator thermal load, Btu/hr

Q_s = Superheater thermal load, Btu/hr

Cp_n = Specific heat of sodium, Btu/°F-lb

Cp_s = Specific heat of steam, Btu/°F-lb

C_{71} = Superheater steam enthalpy function coefficient, Btu/°F-lb

C_{72} = Superheater steam enthalpy function constant, Btu/lb

X = Proportionality constant for tube side heat transfer

Y = Proportionality constant for shell side heat transfer

Z = Tube resistance

PCBD = Evaporator blowdown as percent of steaming rate

Cf_1 = Reactor inlet temperature control function constant, °F

Cf_2 = Reactor inlet temperature control function coefficient, °F

RNP = Design capability of reactor in tmw

RTMW = Reactor thermal load in tmw

H_{sao} = Enthalpy of superheated steam to turbine, Btu/lb

H_{sat} = Enthalpy of saturated liquid in evaporator, Btu/lb

H_{seo} = Enthalpy of saturated steam to superheater, Btu/lb

H_{fw} = Enthalpy of feedwater to evaporator, Btu/lb

A_e = Evaporator heat transfer surface, ft^2

A_s = Superheater heat transfer surface, ft^2

A_x = IHX heat transfer surface, ft^2

Appendix A

Description of input data required by the program

There are two types of input data necessary to solve a particular problem of interest.

1. General input data describing the size of the components, reactor thermal load and sodium outlet temperature, condition of heat transfer surfaces and thermodynamic relations describing variations of feed water temperature, evaporator temperature and saturated steam enthalpy with load as well as the two constants of the linear relationship between the steam enthalpy increase in the superheater and the steam outlet temperature.

   Most of this thermodynamic information is available from the Steam Tables once the turbine throttle pressure and the full load evaporator pressure have been decided upon. The feedwater temperature variation with load may be estimated from turbine heat balance calculations.

2. Specific input data pertaining to the operation procedure one wishes to investigate and is in addition to the input data described above. The specific input data consists of only 5 inputs, namely Cf_1, Cf_2, RNP, H_{sao} and T_{sso}. For Case 1, the steam temperature leaving the superheater (T_{sso}) must be specified. For Case 2, the enthalpy of

the turbine steam must be selected, while the quantities Cf_1, Cf_2, and RNP should be put equal to 0, which will instruct the computer to use only that part of the program appropriate for the solution of the problem when the sodium flow rates in the IHX are balanced at all loads.

When the solution of Case 3 is desired, the quantities Cf_1, Cf_2 and RNP must be given together with the turbine steam enthalpy. The reactor inlet temperature profile with primary sodium flow rate is now determined and the computer will solve the remaining variables over the load range.

Appendix B

Statement of calculation procedures to determine the flow rates, temperatures and heat transfer coefficients for each method of operation

1. Operation with constant steam temperature at the superheater outlet

Combination of equations 1 and 6, solves for W_{se}, as T_{sso} is given as input data and $W_{se} = W_{ss}$

Thus:

$$W_{se} = W_{ss} = \frac{Q_r}{(H_{seo} - H_{fw}) + PBCD\ (H_{sat} - H_{fw}) + C_{71}\ T_{sso} - C_{72}}$$

This equation will rapidly converge to the correct value of W_{se}.

When combining equations 1, 3, 5, 6, and 7, one may write after some manipulation:

$$\frac{Q_e}{Q_s} \quad 1 - e^{-\frac{U_s A_s}{W_{n,s} Cp_n}\left(\frac{W_{n,s} Cp_n}{W_{se} Cp_s} - 1\right)} = \left(1 - e^{-\frac{U_e A_e}{W_{n,s} Cp_n}}\right)\left(\frac{W_{n,s} Cp_n}{W_{se} Cp_s} - 1\right)$$

This transcendental equation permits calculation of $W_{n,s}$ from the known value of W_{se} and the same reactor thermal load. With the secondary sodium flow rate and the steam flow rate known, the sodium temperatures in the secondary loop are computed by means of the appropriate equations.

The evaporator temperature T_{se} is known as a function of the evaporator pressure and thus the steam flow rate.

Further:

$$T_{nei} = T_{se} + \frac{Q_e}{W_{n,s} Cp_n \left(1 - e^{-U_e A_e / W_n Cp_n}\right)} \qquad \text{Equations 1 and 3}$$

$$T_{neo} = T_{nei} - \frac{Q_e}{W_{n,s} Cp_n} \qquad \text{Equation 1}$$

$$T_{nsi} = T_{nei} + \frac{Q_e}{W_{n,s} Cp_n} \qquad \text{Equation 5}$$

Finally, the primary sodium flow rate $W_{n,p}$ is computed by combining equations 10, 11 and 12 to yield:

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$$e^{\frac{U_x A_x}{W_{n,p} Cp_n}\left(1 - \frac{W_{n,p}}{W_{n,s}}\right)} = \frac{T_{nro} - T_{nsi}}{T_{nro} - T_{neo} \quad Q_r / W_{n,p} Cp_n}$$

and $T_{nri} = T_{nro} - \frac{Q_r}{W_{n,p} Cp_n}$ (T_{nro} is input)

Equations 2, 8, and 13, relate the value of the heat transfer coefficients to the steam and sodium flow rates and are thus also defined.

This completes the solution of the temperatures and flow rates with the constant superheater outlet steam temperature conditions.

2. Operation with constant balanced sodium flow rates

If constant steam temperature at the turbine throttle is desired, the attemporator must be used to reduce the higher superheater outlet steam temperature to the constant value specified at the turbine throttle. This introduces a new unknown flow rate W_{ss}, the superheater steam flow rate, as the steam flow through the superheater no longer equals the evaporator steaming rate.

However, when combining the attemporator relation (Equation 9) with Equations 4 and 6, an expression may be written that permits immediate calculation of the evaporator steaming rate.

$$W_{se} = \frac{Q_r}{H_{seo} - H_{fw} + PCBD\,(H_{sat} - H_{fw})} .$$

This will readily converge to the correct value of W_{se} and thus the steam generator heat loads are:

$$Q_e = W_{se} \; (H_{seo} - H_{fw}) \; + PCBD \; W_{se} \; (H_{sat} - H_{fw})$$

$$Q_s = Q_r - Q_e .$$

Combination of equations 1, 3 and 5 yields

$$T_{nsi} = T_{se} + \frac{Q_r - Q_s \, e^{-\frac{U_e A_e}{W_{n,s} Cp_n}}}{W_{n,s} \, Cp_n \, (1 - e^{-\frac{U_e A_e}{W_{n,s} \, Cp_n}})}$$

For equal flow rates in the IHX, equation 12 reduces to

$$T_{nsi} = T_{nro} - \frac{Q_r}{U_x A_x}$$

for the limiting case when $W_{n,s} = W_{n,p}$.

Therefore, the transcendental equation for the sodium flow rate is:

$$W_nCp_n\left(T_{nro} - T_{se} - \frac{Q_r}{U_xA_x}\right) = \frac{Q_r - Q_s\, e^{-\frac{U_eA_e}{W_nCp_n}}}{\left(1 - e^{-\frac{U_eA_e}{W_nCp_n}}\right)}$$

T_{se} is given as a function of the evaporator steaming rate and the heat transfer coefficients U_e and U_x are defined by equations 2 and 13 as being dependent upon the sodium flow rate and the evaporator heat load Q_e. The computer solves the sodium flow rate from the above equation by iteration.

Next, the sodium temperatures in the secondary and primary loops are computed from the appropriate equations as follows:

$$T_{nei} = T_{se} + \frac{}{W_nCp_n\left(1-e^{-\frac{U_eA_e}{W_nCp_n}}\right)}$$

$$T_{neo} = T_{nei} - \frac{Q_e}{W_nCp_n}$$

$$T_{nsi} = T_{nro} - \frac{Q_r}{U_xA_x}$$

$$T_{nri} = T_{nro} - \frac{Q_r}{W_nCp_n}$$

Finally, the superheater steam flow is determined by combining equations 6 and 7 to yield:

$$W_{ss} = \frac{Q_s}{C_{71}}\ \frac{1}{\left(T_{nsi} - \frac{C_{72}}{C_{71}}\right) - \left(T_{nei} - T_{se}\right) e^{-\frac{U_sA_s}{W_nCp_n}\left(1 - \frac{W_nCp_n}{W_sCp_s}\right)}}$$

$$\text{where } Cp_s = \frac{Q_s}{\frac{Q_s}{C_{71}} + \left(\frac{C_{72}}{C_{71}} - T_{se}\right) W_{ss}} . \qquad \text{(Equation 6)}$$

and U_s is defined by equation 8 as a function of the known sodium flow rate and the superheater steam flow.

Following the calculation of the steam temperature at the superheater outlet from:

$$T_{sso} = T_{se} + \frac{Q_s}{W_{ss}Cp_s}$$

the solution to this problem is now complete.

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3. Operating with controlled reactor sodium inlet temperature

The first part of the approach to the solution of this problem is identical to that discussed under the previous method of operation, however, the relationship for T_{nsi} valid for equal flow rates in the IHX is no longer applicable and a different expression for T_{nsi} must be found to determine the secondary sodium flow rate.

To circumvent the apparent difficulty, the primary sodium flow rate and the reactor sodium inlet temperature are computed first. Assuming a linear relationship of the form:

$$T_{nri} = Cf_1 + Cf_2 \frac{W_{n,p}}{W_{n,pN}}$$

and combining this expression with Equation 10, it may be readily verified that:

$$T_{nri}^2 - (T_{nro} + Cf_1)\, T_{nri} + Cf_1\, T_{nro} + \frac{Cf_2\, Q_r}{W_{n,pN}} = 0$$

and

$$W_{n,p}^2 - \left(\frac{T_{nro} - Cf_1}{Cf_2}\right) W_{n,pN}\; W_{n,p} + \frac{W_{n,pN}\, Q_r}{Cp_n\, Cf_2} = 0$$

being quadratic equations in T_{nri} and $W_{n,p}$ respectively and thus readily solved, for any arbitraty value of Q_r. For other than linear functions between T_{nri} and $W_{n,p}$, used by the protective system, these two quantities may be found by solving this arbitrary relationship simultaneously with Equation 10 by an iterative procedure.

The question remains as to what the exact value of the primary sodium flow rate might be under normal full load operating conditions. This may be found from the quadratic expression of $W_{n,p}$. Remembering that at full load

$$\frac{W_{n,p}}{W_{n,pN}} = 1$$

and replacing Q_r by the design value of the full load reactor power RNP, which must be given as imput data in megawatts, it is easily seen that

$$W_{n,pN} = \frac{RNP\ 1.137610^6}{Cp_n(T_{nro} - Cf_1 - Cf_2)}$$

and $W_{n,pN}$ is thus computed from available input data. It is now possible to derive a transcendental expression relating the superheater sodium inlet temperature to the secondary sodium flow rate by combining equations 10, 11 and 12 as follows:

$$T_{nsi} = T_{nro} - \frac{\frac{Q_r}{W_{n,s}Cp_n}\left(\frac{W_{n,s}}{W_{n,p}} - 1\right)}{1 - e^{\frac{U_xA_x}{W_{n,p}Cp_n}\left(1 - \frac{W_{n,p}}{W_{n,s}}\right)}}$$

This expression combined with the relation derived earlier:

$$T_{nsi} = T_{se} + \frac{Q_r - Q_e\, e^{-\frac{U_eA_e}{W_{n,s}Cp_n}}}{W_{n,s}Cp_n\left(1 - e^{-\frac{U_eA_e}{W_{n,s}Cp_n}}\right)}$$

gives a single transcendental equation in $W_{n,s}$ only, which affords calculation of the secondary sodium flow rate as all the remaining quantities in this equation are known or have been determined.

It may be seen that the flow rates can be expressed only in transcendental equations. Therefore iterative procedures must be used in all cases when the solution of flow rates is required.

The remainder of this problem is now readily calculated from the appropriate equations as follows:

$$T_{nei} = T_{se} + \frac{Q_e}{W_nCp_n\left(1 - e^{-\frac{U_eA_e}{W_{n,s}Cp_n}}\right)}$$ Equation 1 and 3

$$T_{neo} = T_{nei} - \frac{Q_e}{W_{n,s}Cp_n}$$ Equation 1

$$T_{nsi} = T_{neo} + \frac{Q_r}{W_{n,s}Cp_n}$$ Equation 11

$$T_{nri} = T_{nro} - \frac{Q_r}{W_{n,p}Cp_n}$$ Equation 10

and finally:

$$W_{ss} = \frac{Q_s}{C_{71}} \frac{1}{\left(T_{nsi} - \frac{C_{72}}{C_{71}}\right) - \left(T_{nei} - T_{se}\right) e^{\frac{U_sA_s}{W_{n,s}Cp_n}\left(1 - \frac{W_nCp_n}{W_{ss}Cp_s}\right)}}$$

where $$Cp_s = \frac{Q_s}{\frac{Q_s}{C_{71}} + \left(\frac{C_{72}}{C_{71}} - T_{se}\right) W_{ss}},$$

and U_s is defined by Equation 8.

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With

$$T_{sso} = T_{se} + \frac{Q_s}{W_{ss}Cp_s}$$

The solution to this problem has been completed.

Appendix C

Values of equation constants for cases studied

A_e = 3680 ft^2
A_s = 2150 ft^2
A_x = 5770 ft^2
T_{nro} = 945°F
Cp_n = 0.307 Btu/°F-lb
C_{71} = 0.5717
C_{72} = 257.6
X_1 = 0.0518
Y_1 = 0.1439
Z_1 = 14.10^{-4} (fouled
9.10^{-4} (clean)
X_2 = 0.0559
Y_2 = 6.35
Z_2 = 19.10^{-4} (fouled)
9.10^{-4} (clean)
X_3 = 3.56
Y_3 = 0.076
Z_3 = $2.146.10^{-4}$
PCBD = 0.02

Constant steam temperature program

$T_{sso} = 835^\circ F$

Balanced flow rate program

$Cf_1 = 0$

$Cf_2 = 0$

$RNP = 0$

$H_{sao} = 1416.4$ Btu/lb

Controlled reactor ΔT program

$Cf_1 = 560^\circ F$

$Cf_2 = 50^\circ F$

$RNP = 254$ MW

$H_{sao} = 1416.4$ Btu/lb.

Constant Reactor ΔT program

$Cf_1 = 607^\circ F$

$Cf_2 = 0$

$RNP = 0$

$H_{sao} = 1416.4$ Btu/lb

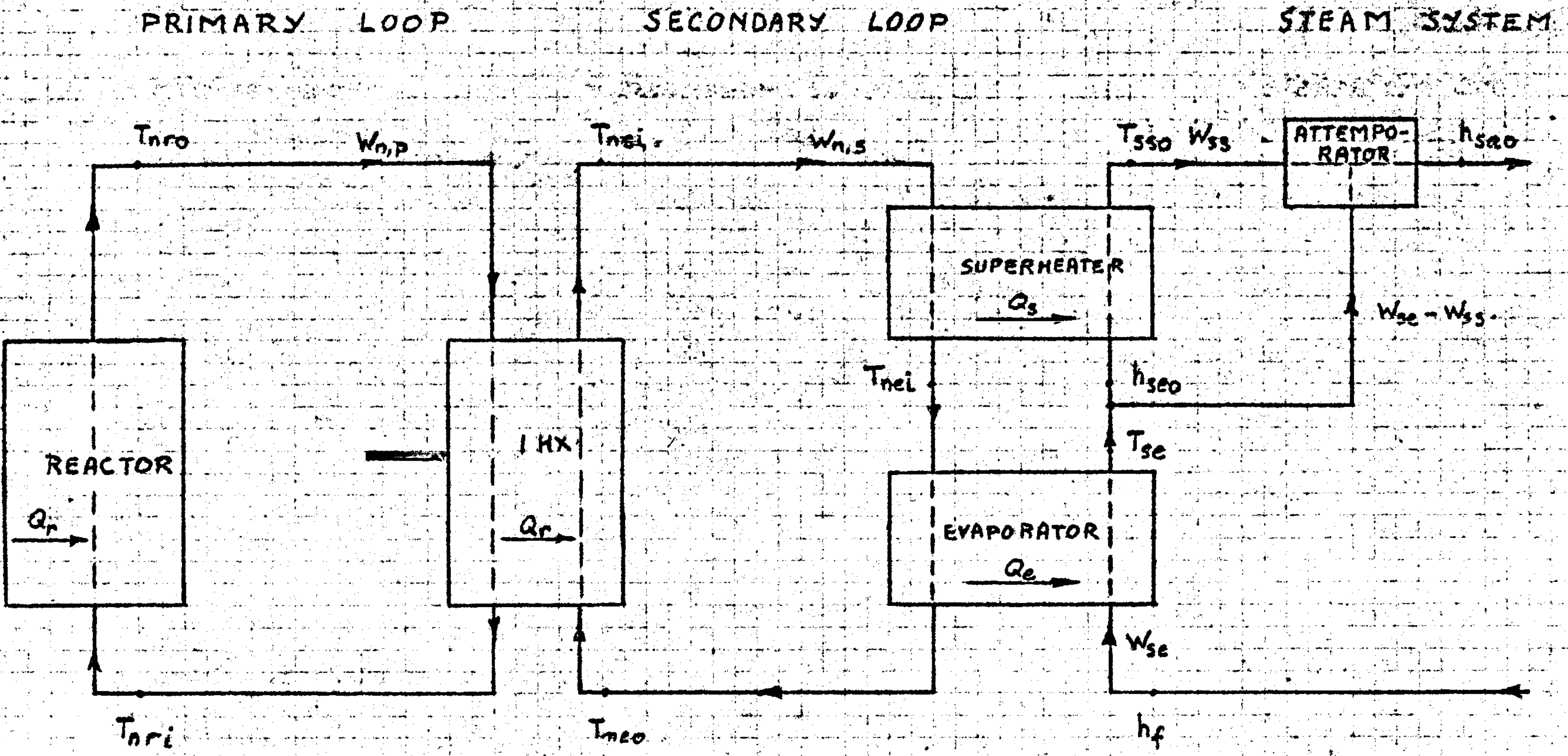

FIG 1. Sodium Heat transfer System. HNPF.

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CHECKED BY:
DATE: MAY 18 '59

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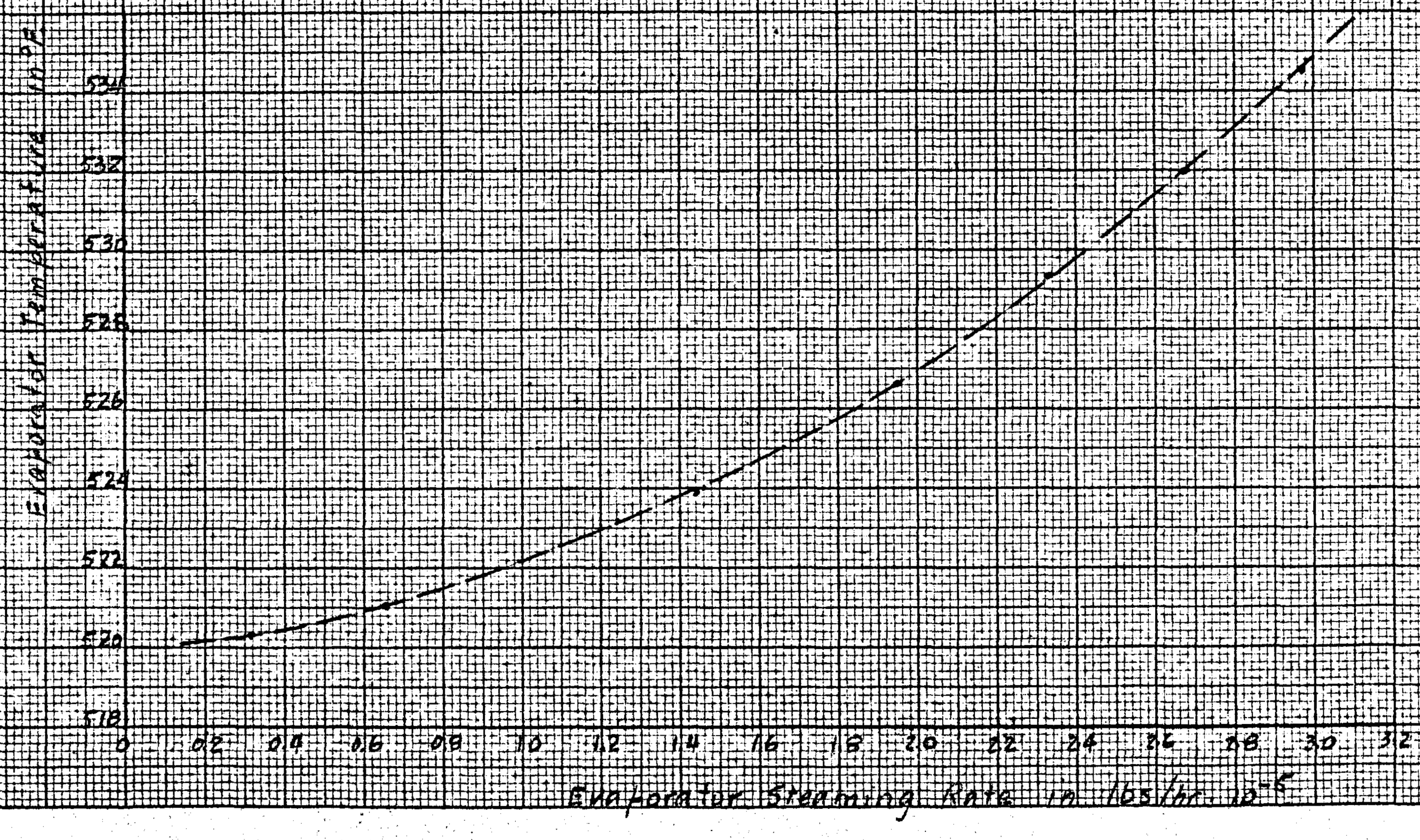
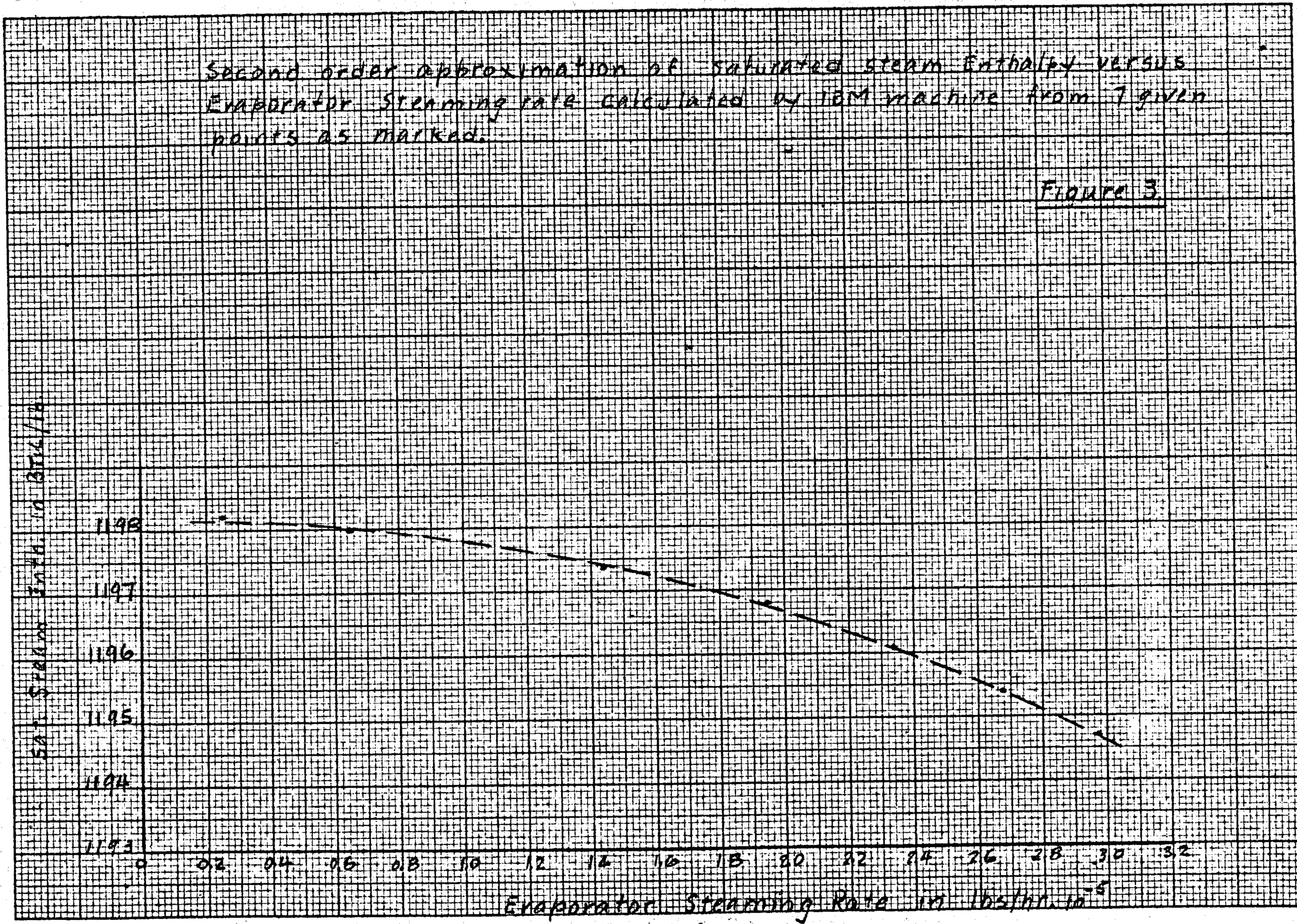
REPORT NO. 4093
MODEL NO.

Second order approximation of Evaporator temperature versus steaming rate calculated by IBM machine from 7 given points as marked.

Figure 2





Second order approximation of saturated steam Enthalpy versus Evaporator Steaming rate calculated by IBM machine from 7 given points as marked.

Figure 3.

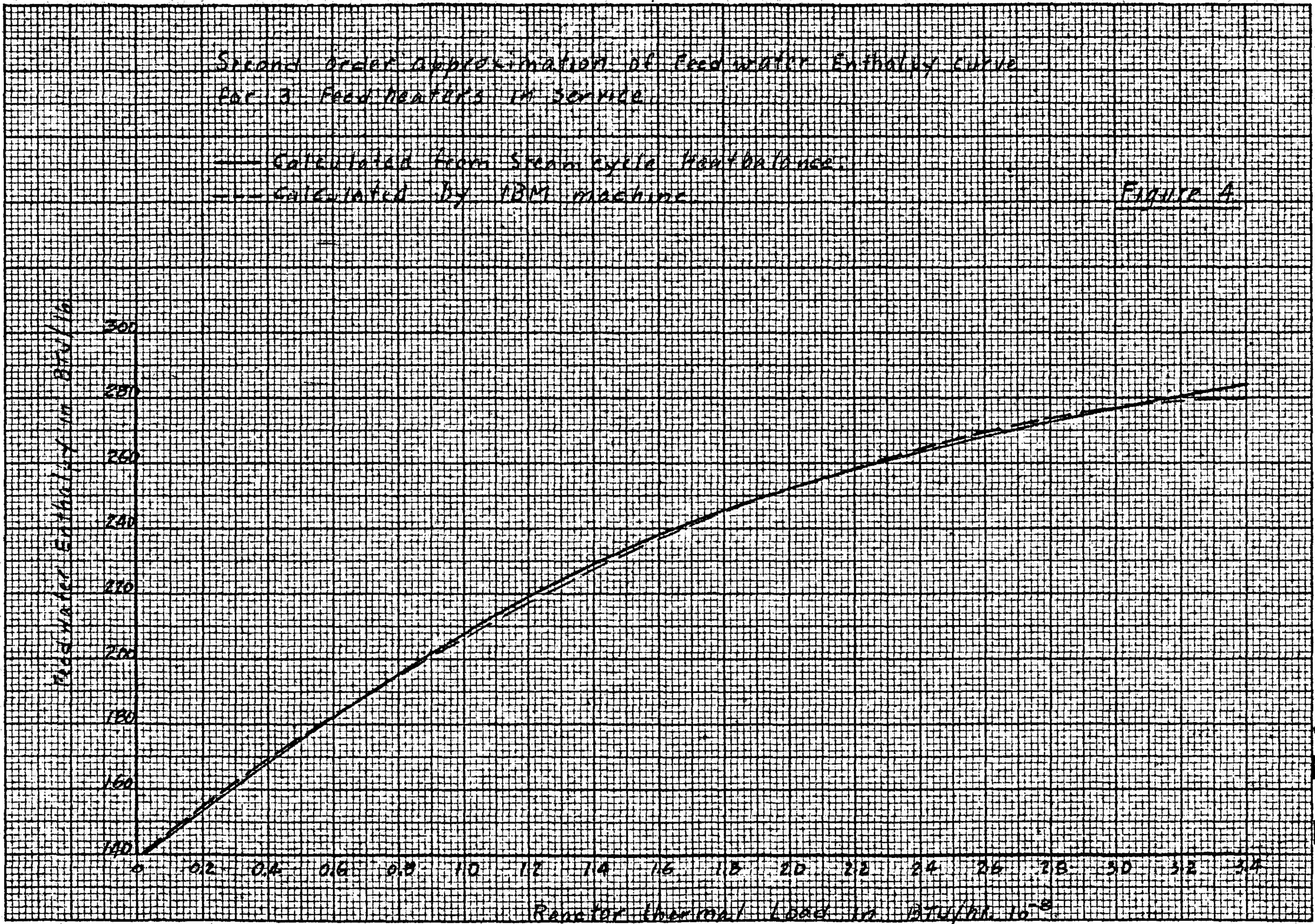
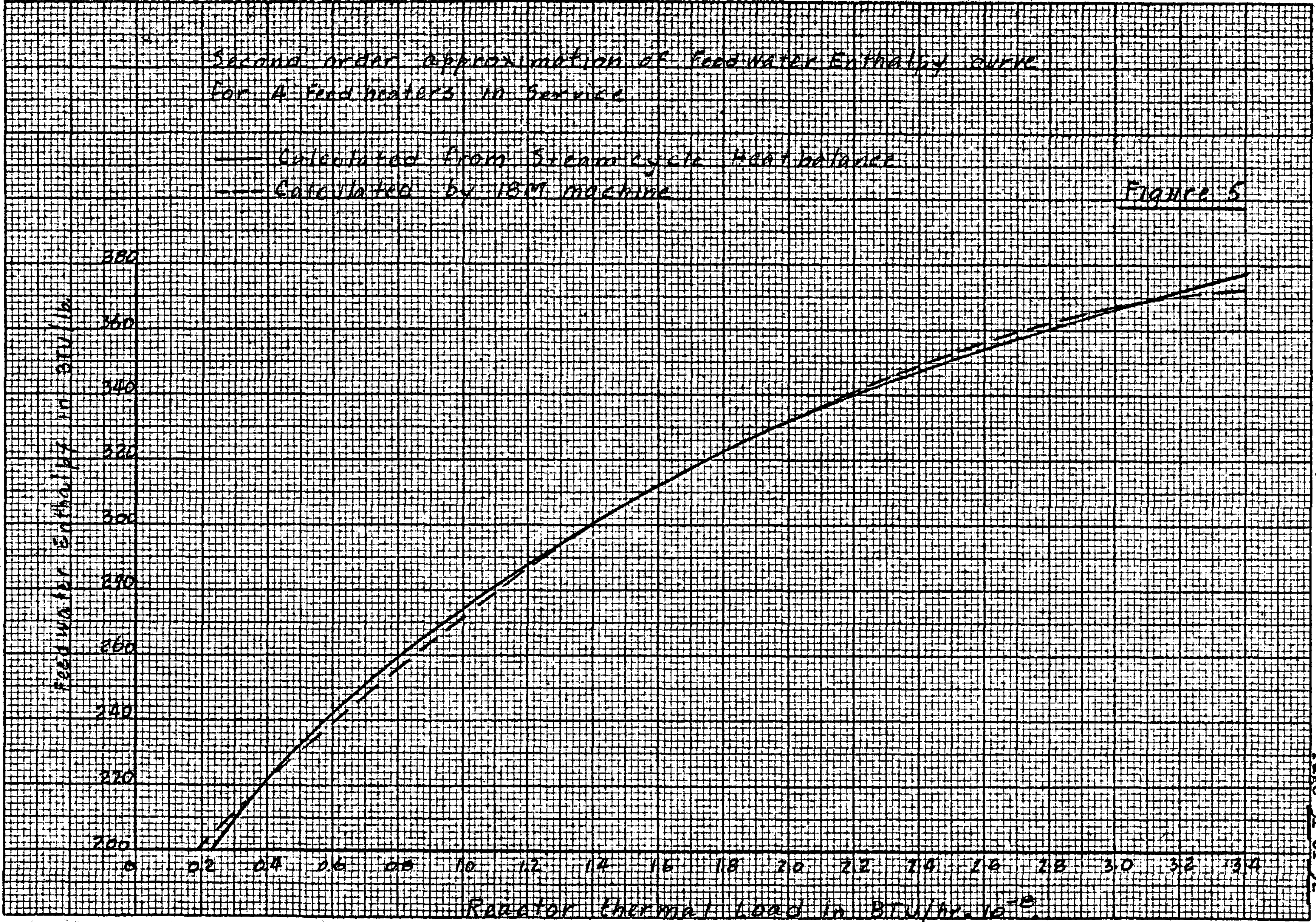


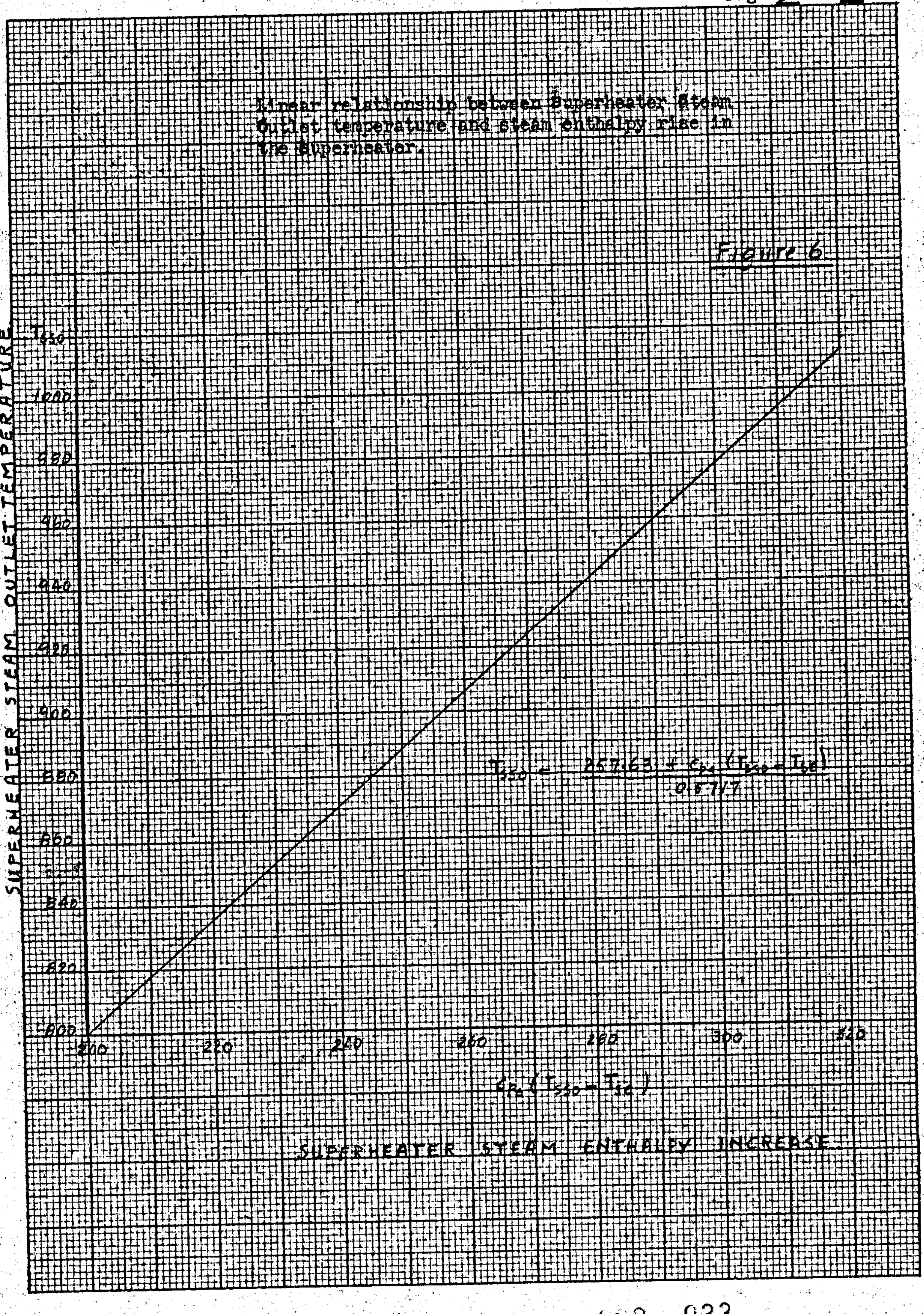
Figure 4

Second order approximation of Feedwater Enthalpy curve for 3 Feed heaters in Service.



Second order approximation of Feedwater Enthalpy curve for 4 Feed heaters in Service

Figure 5

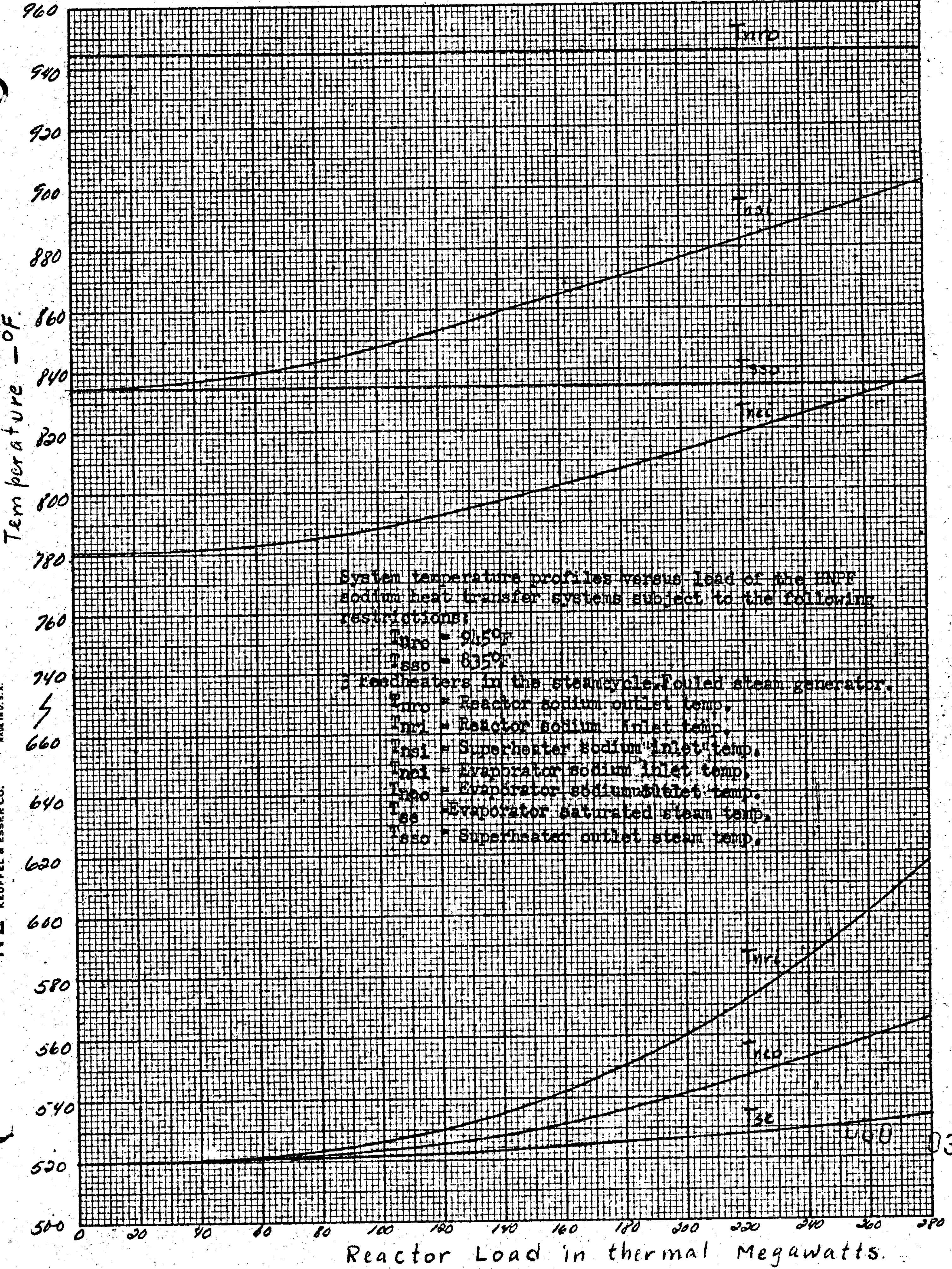


Linear relationship between Superheater Steam Outlet temperature and steam enthalpy rise in the Superheater.

Figure 6

Figure 7a

TEMPERATURE PROFILES



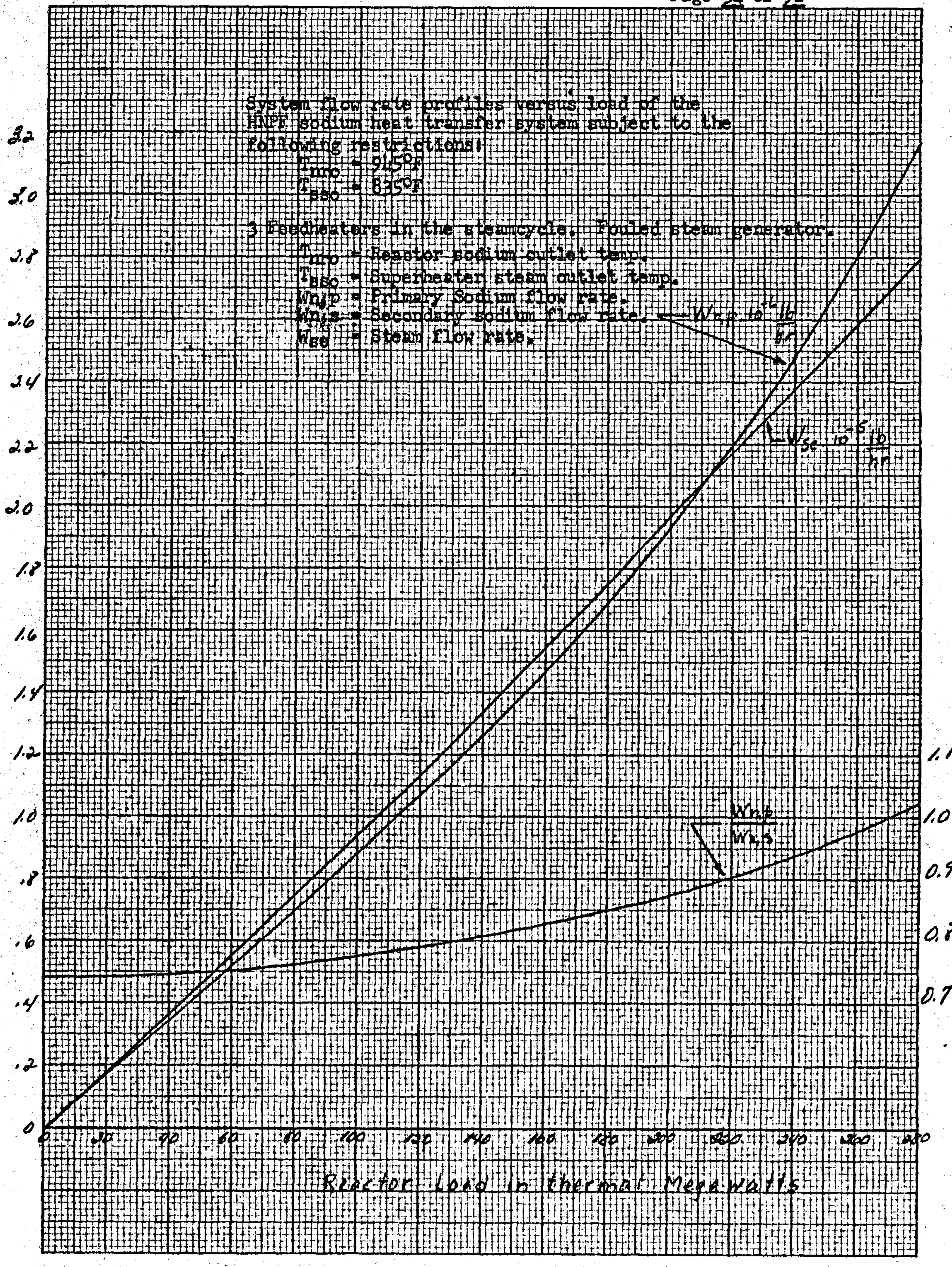
System temperature profiles versus load of the HNPF sodium heat transfer systems subject to the following restrictions:

T_{nro} = 945°F
T_{sso} = 835°F

3 Feedheaters in the steamcycle, Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium "Inlet" temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater outlet steam temp.

Figure 7b



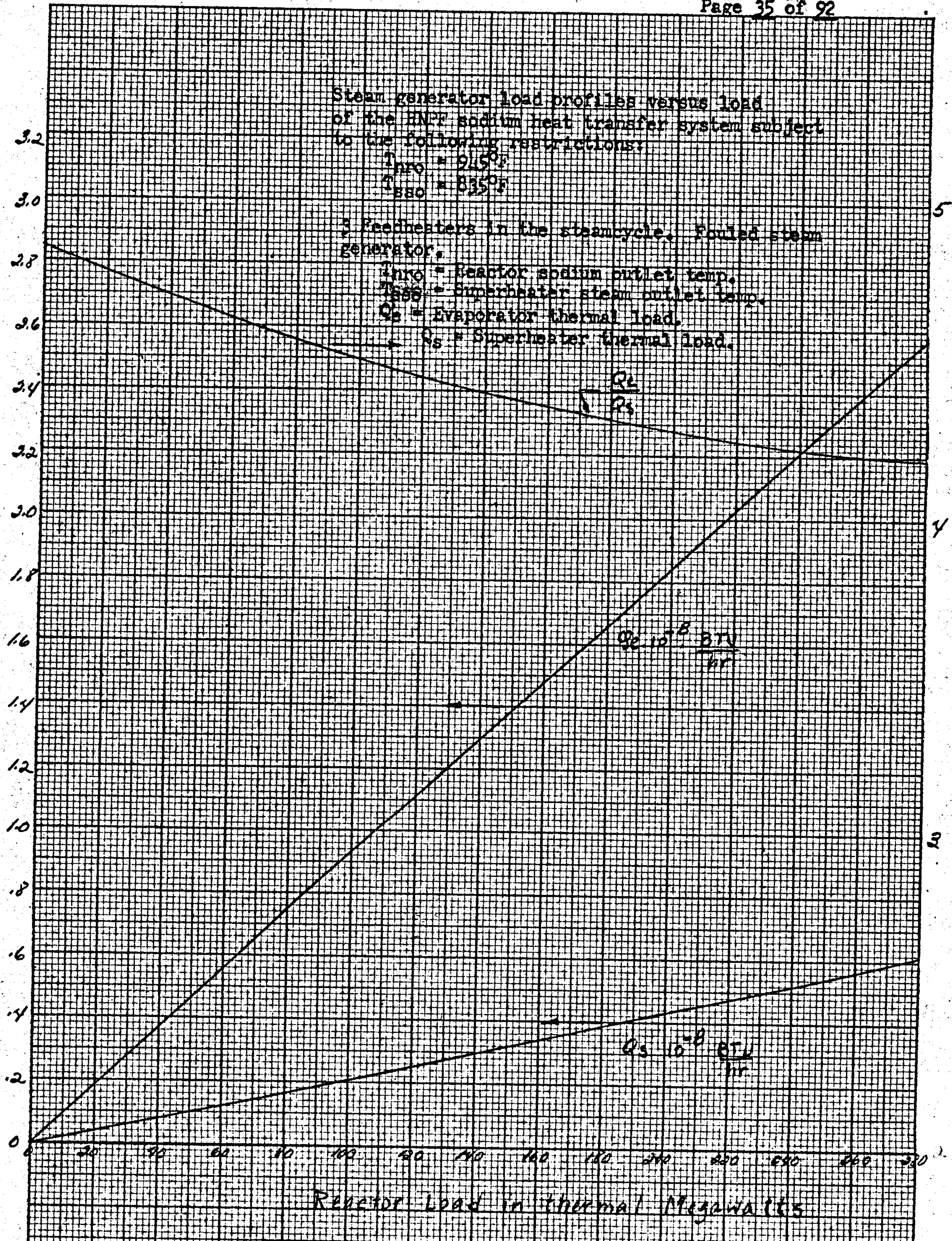
System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{sso} = 835°F

3 Feedheaters in the steamcycle. Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
$W_{n;p}$ = Primary Sodium flow rate.
$W_{n;s}$ = Secondary sodium flow rate.
W_{se} = Steam flow rate.

Figure 7c



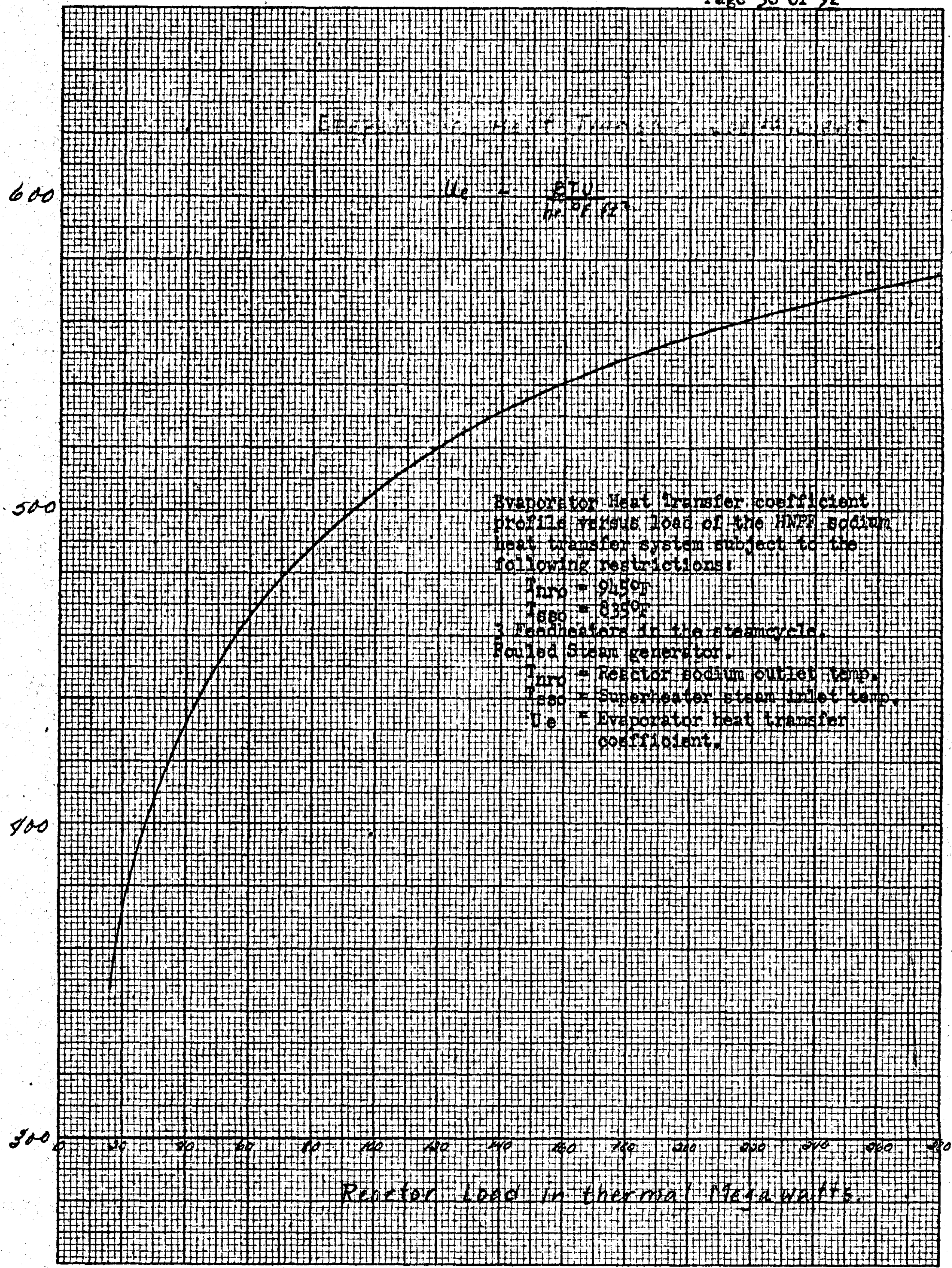
Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{hro} = 945°F
T_{sso} = 835°F

3 Feedheaters in the steamcycle. Fouled steam generator.

T_{hro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
Q_e = Evaporator thermal load.
Q_s = Superheater thermal load.

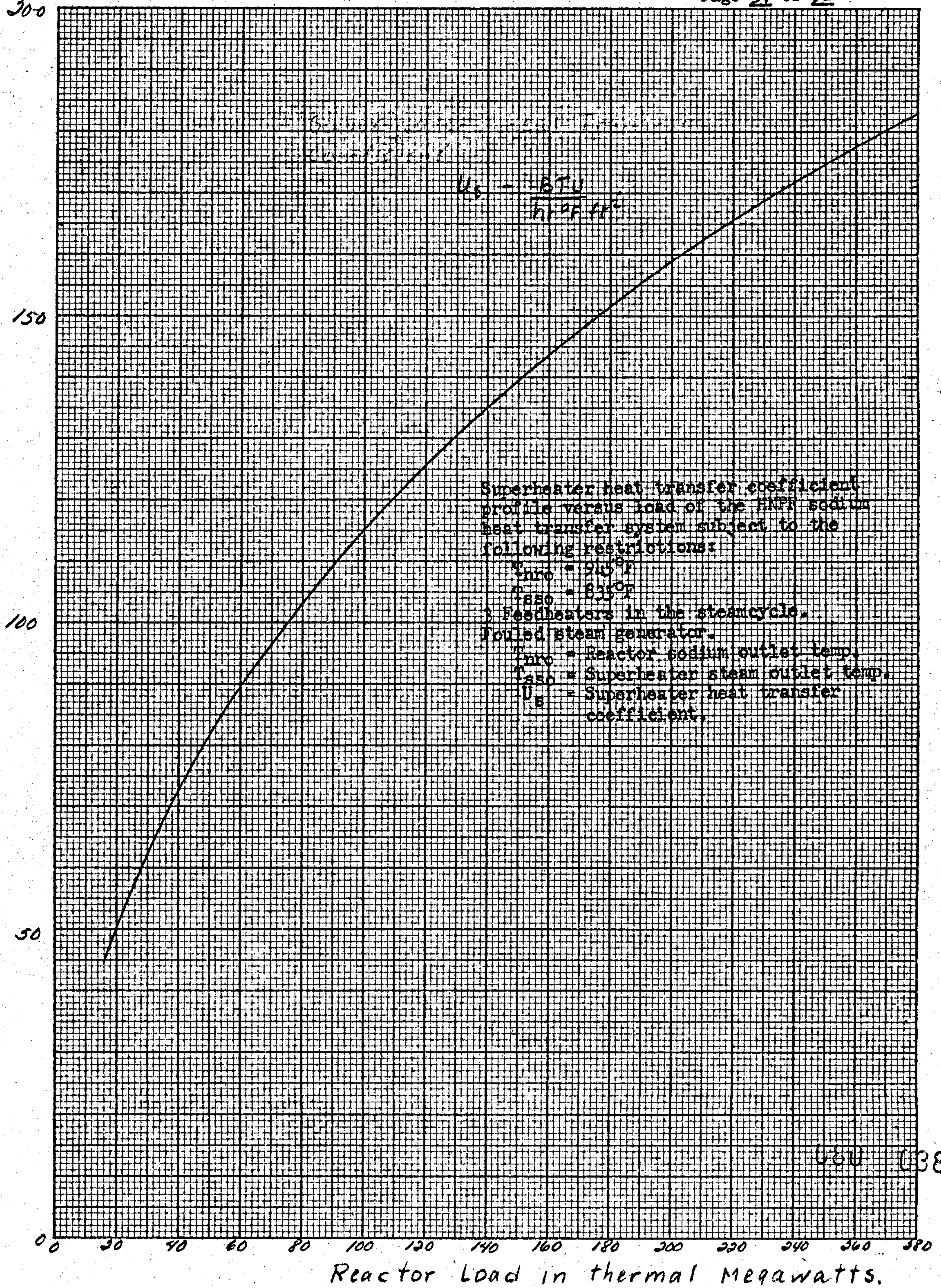
Figure 7d



Evaporator Heat Transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{sso} = 835°F
3 Feedheaters in the steamcycle.
Fouled Steam generator.
T_{nro} = Reactor sodium outlet temp.
T_{ssc} = Superheater steam inlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 7e



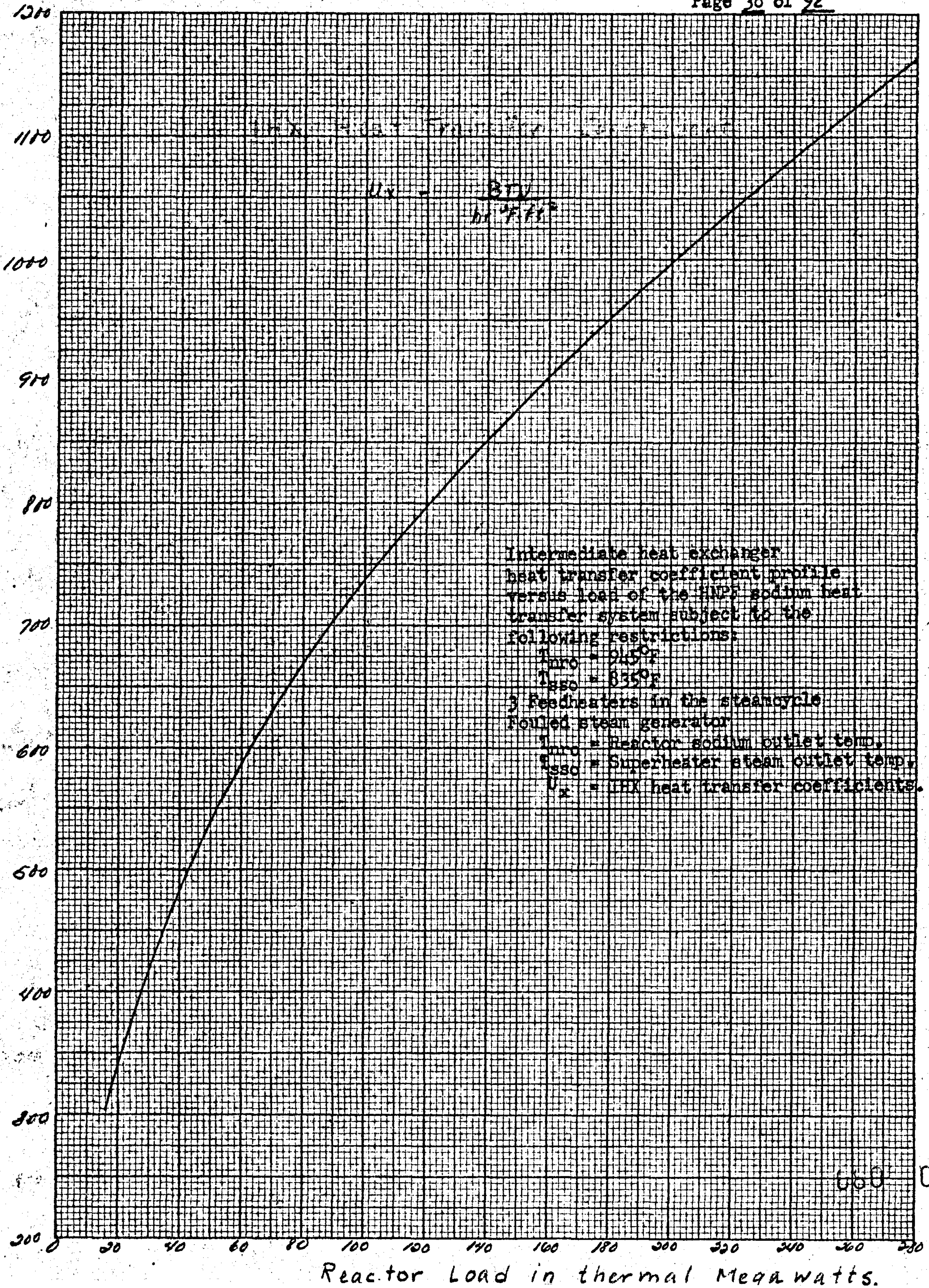
Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{sso} = 835°F

3 Feedheaters in the steamcycle.
Fouled steam generator.

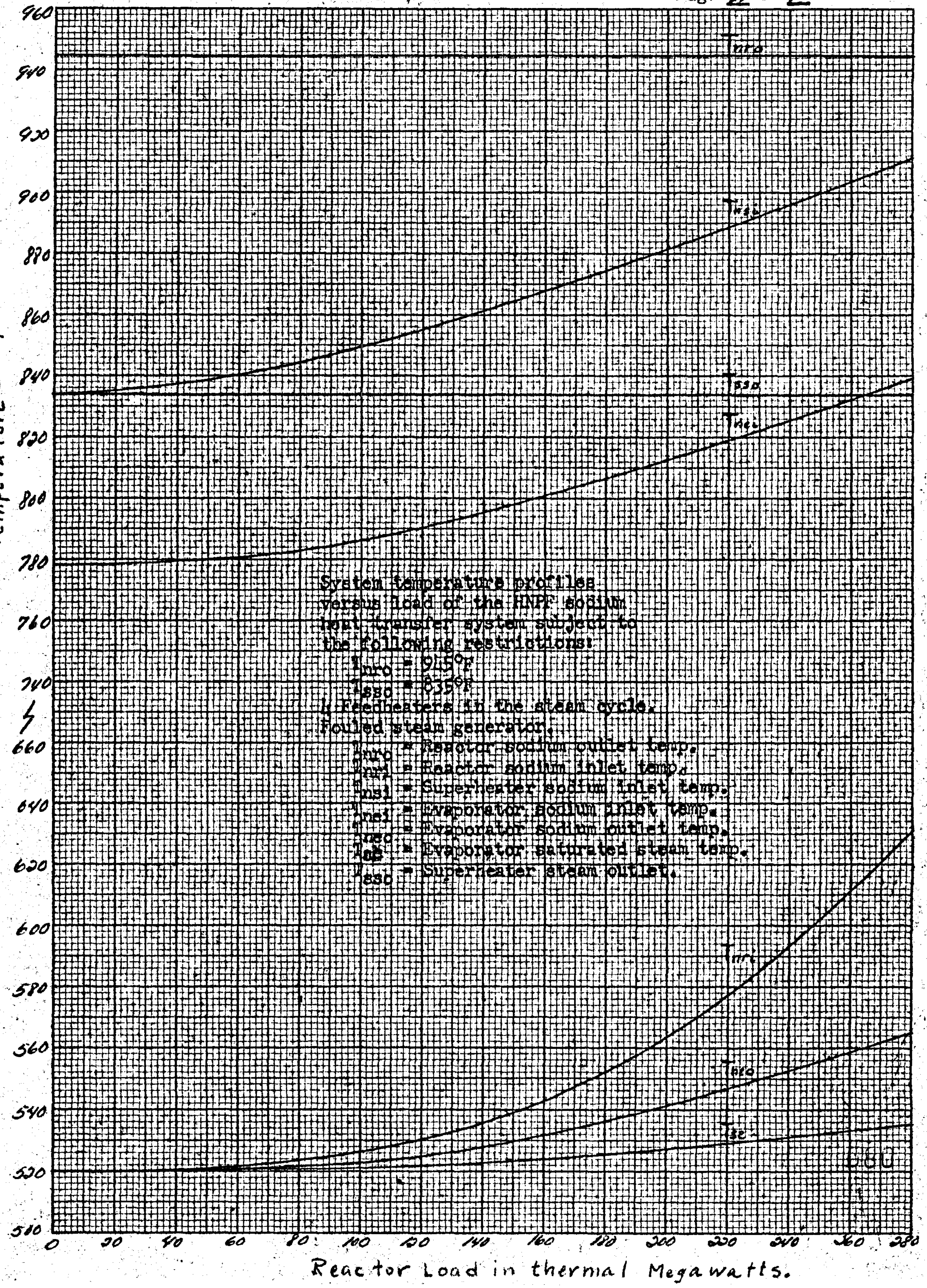
T_{nro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
U_s = Superheater heat transfer coefficient.

Figure 7f



Intermediate heat exchanger
heat transfer coefficient profile
versus load of the HNPF sodium heat
transfer system subject to the
following restrictions:
T_{nro} = 945°F
T_{sso} = 835°F
3 Feedheaters in the steamcycle
Fouled steam generator
T_{nro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
U_x = IHX heat transfer coefficients.

Figure 8a

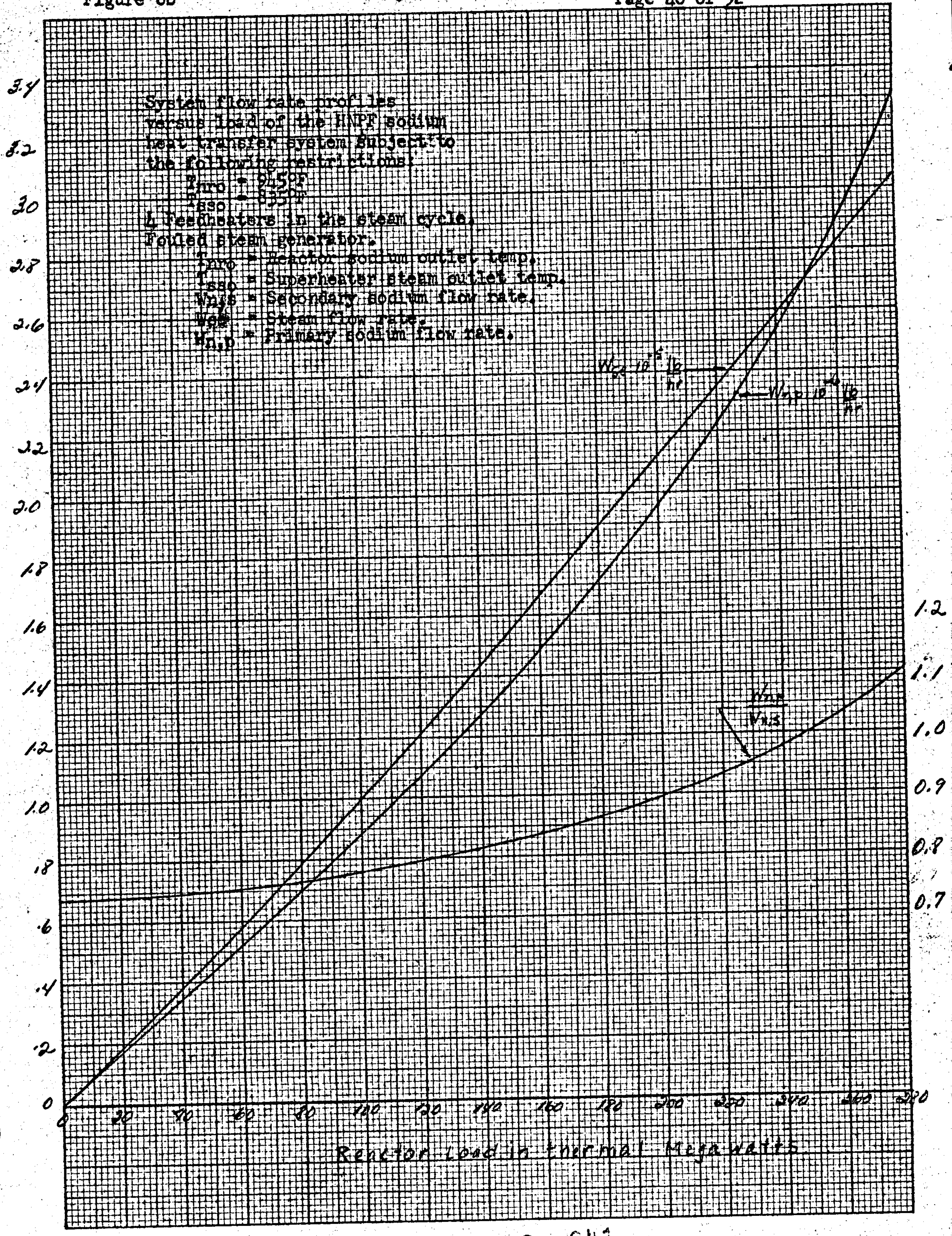


System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{sso} = 835°F
4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet.

Figure 8b

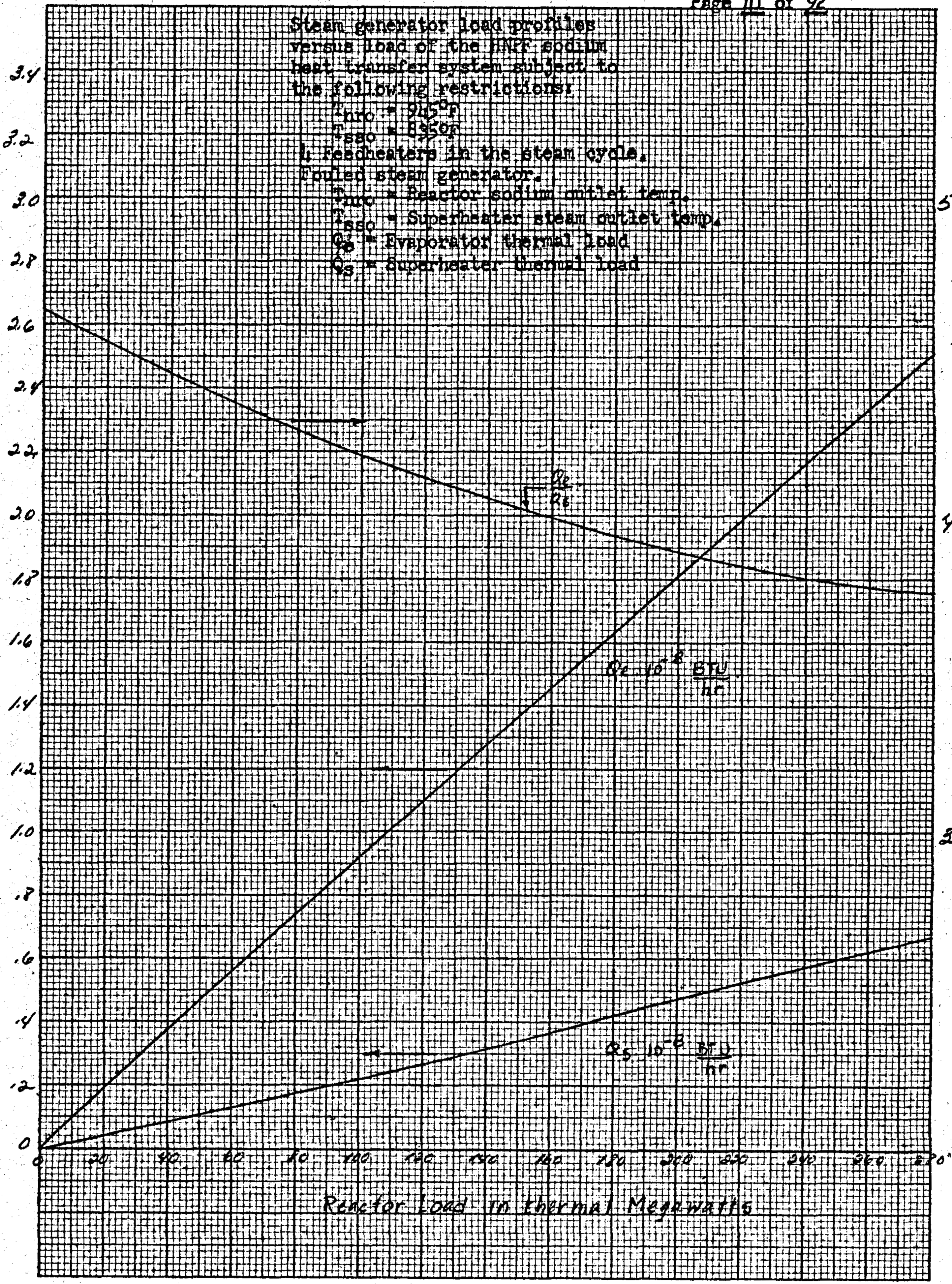


System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$
$T_{sso} = 835°F$

4 Feedheaters in the steam cycle.
Fouled steam generator.

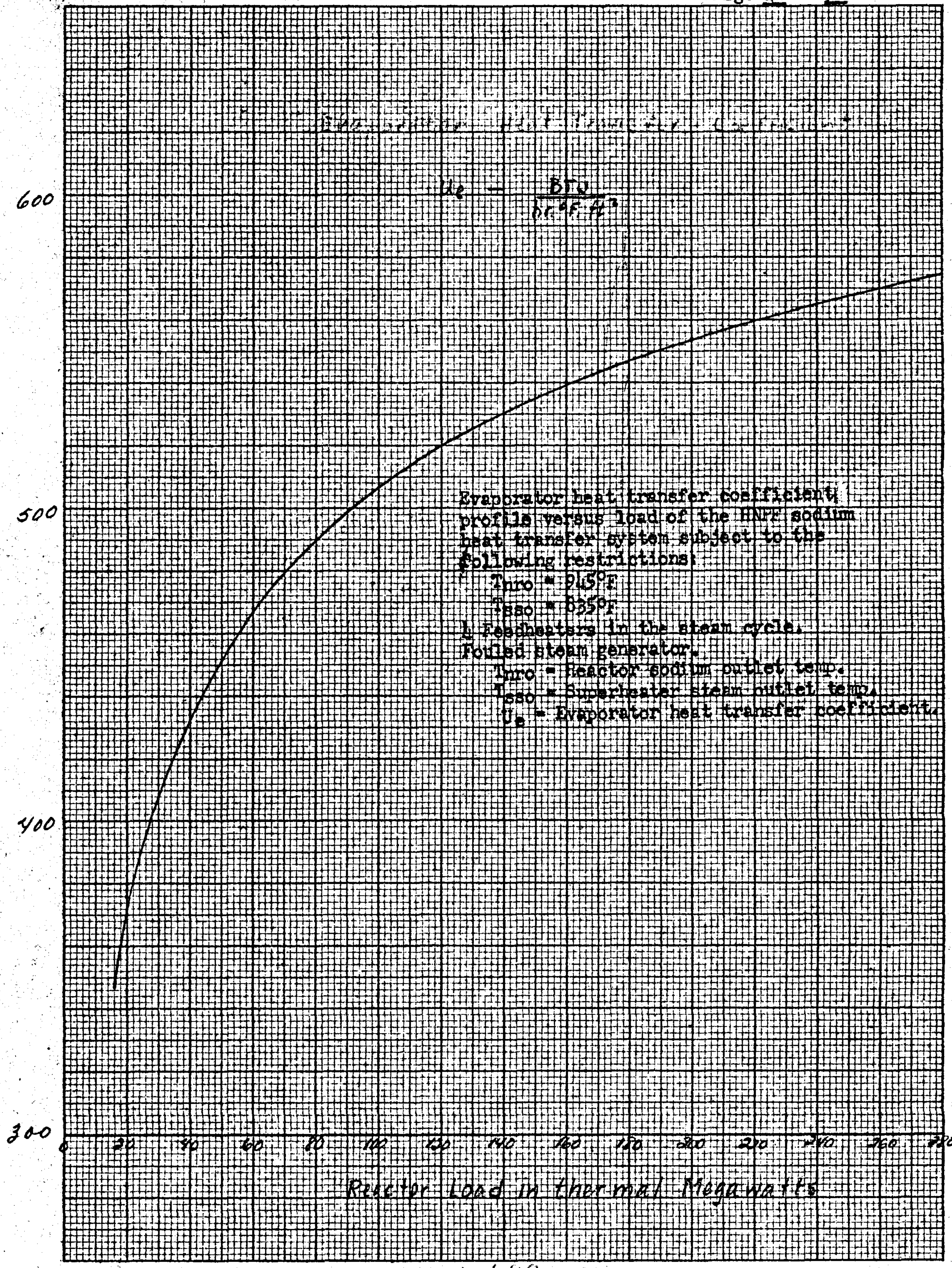
T_{nro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
$W_{n,s}$ = Secondary sodium flow rate.
W_{so} = Steam flow rate.
$W_{n,p}$ = Primary sodium flow rate.



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{hro} = 945°F
T_{sso} = 835°F
4 Feedheaters in the steam cycle.
Fouled steam generator.
T_{hro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
Q_e = Evaporator thermal load
Q_s = Superheater thermal load

Figure 8d



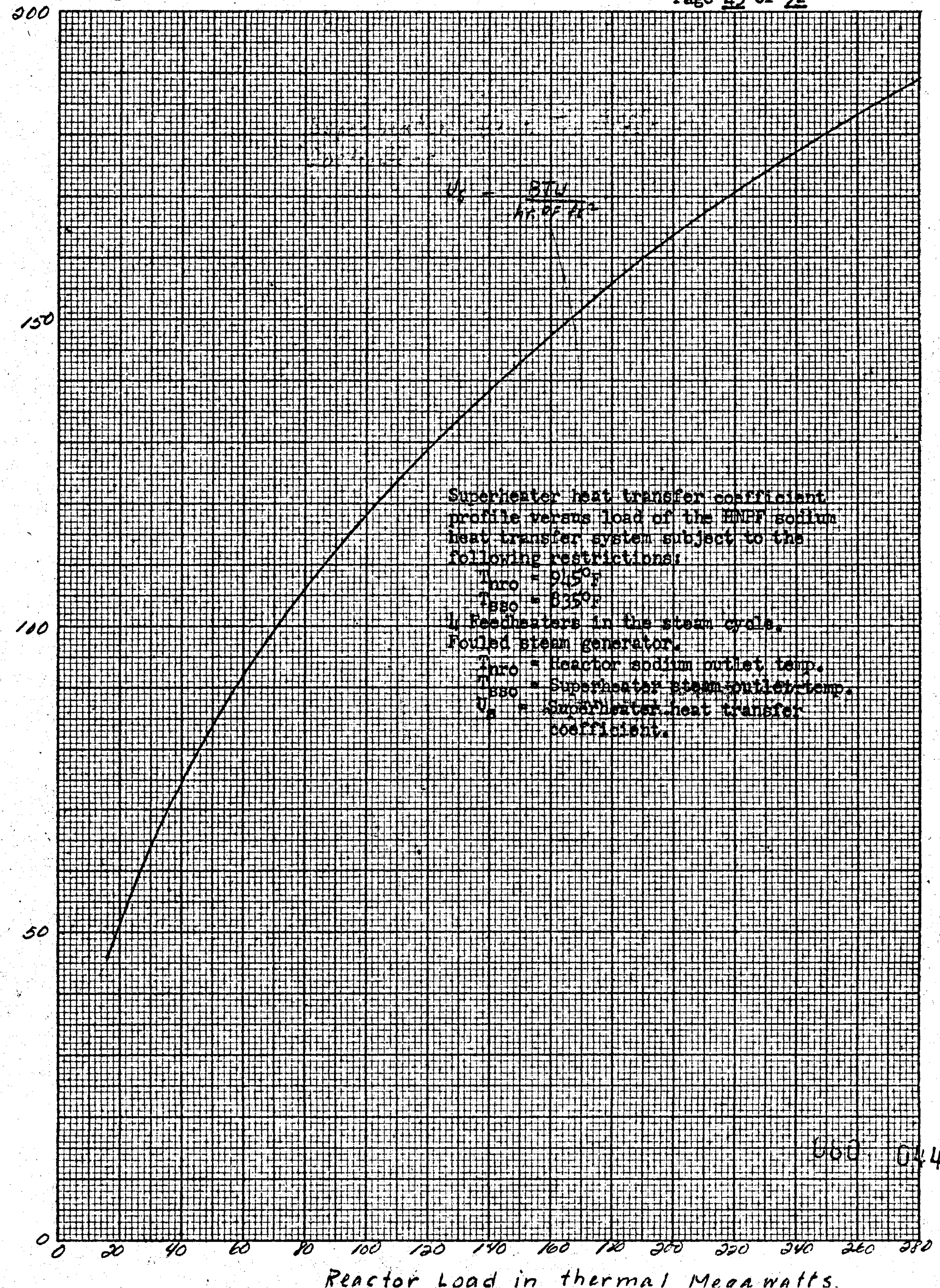
Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{hro} = 945°F
T_{sso} = 835°F

4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{hro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 8e



Superheater heat transfer coefficient profile versus load of the ENPF sodium heat transfer system subject to the following restrictions:

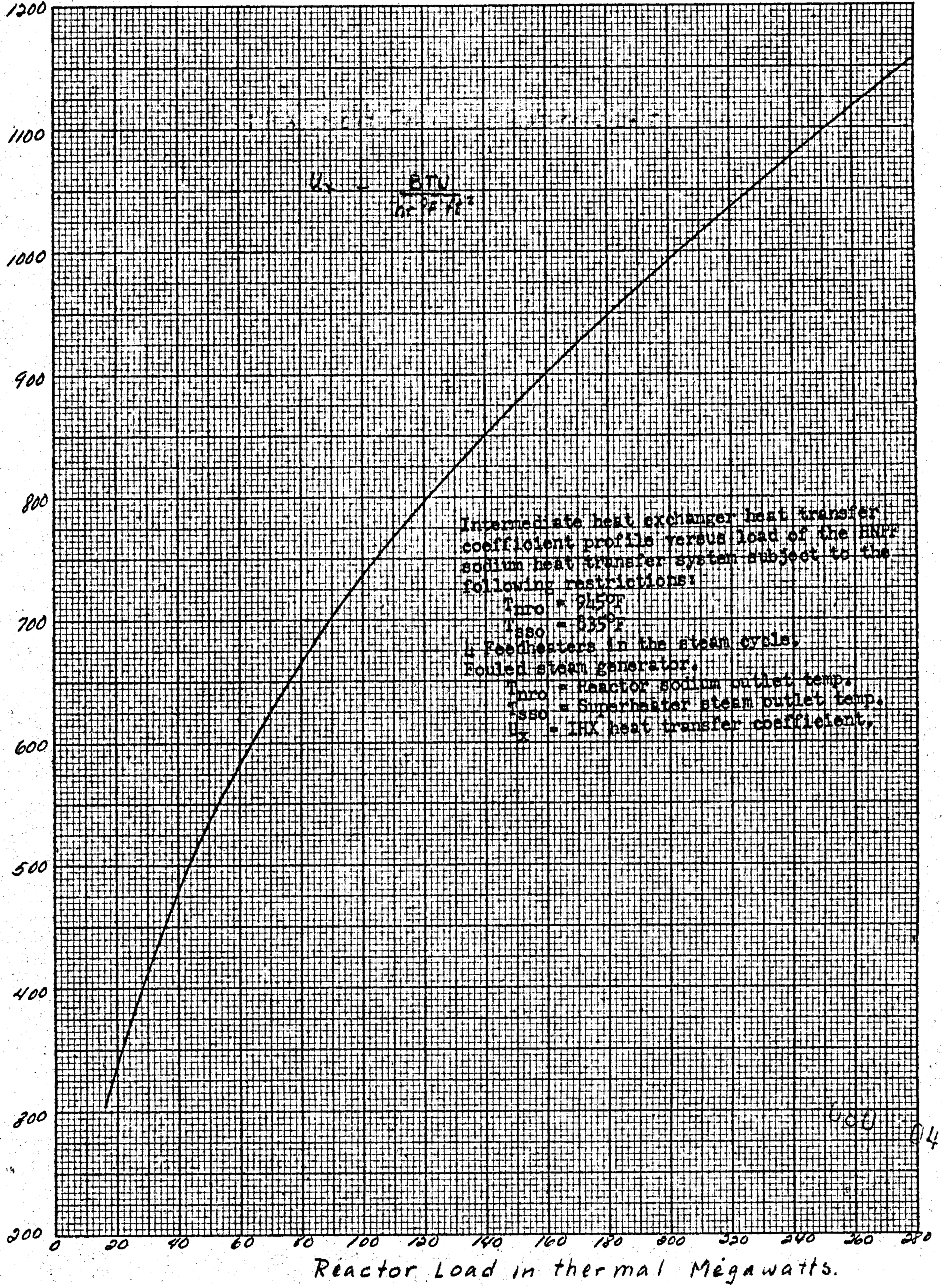
T_{hro} = 945°F
T_{sso} = 835°F

4 Feedheaters in the steam cycle.

Fouled steam generator.

T_{hro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
U_s = Superheater heat transfer coefficient.

Figure 8f



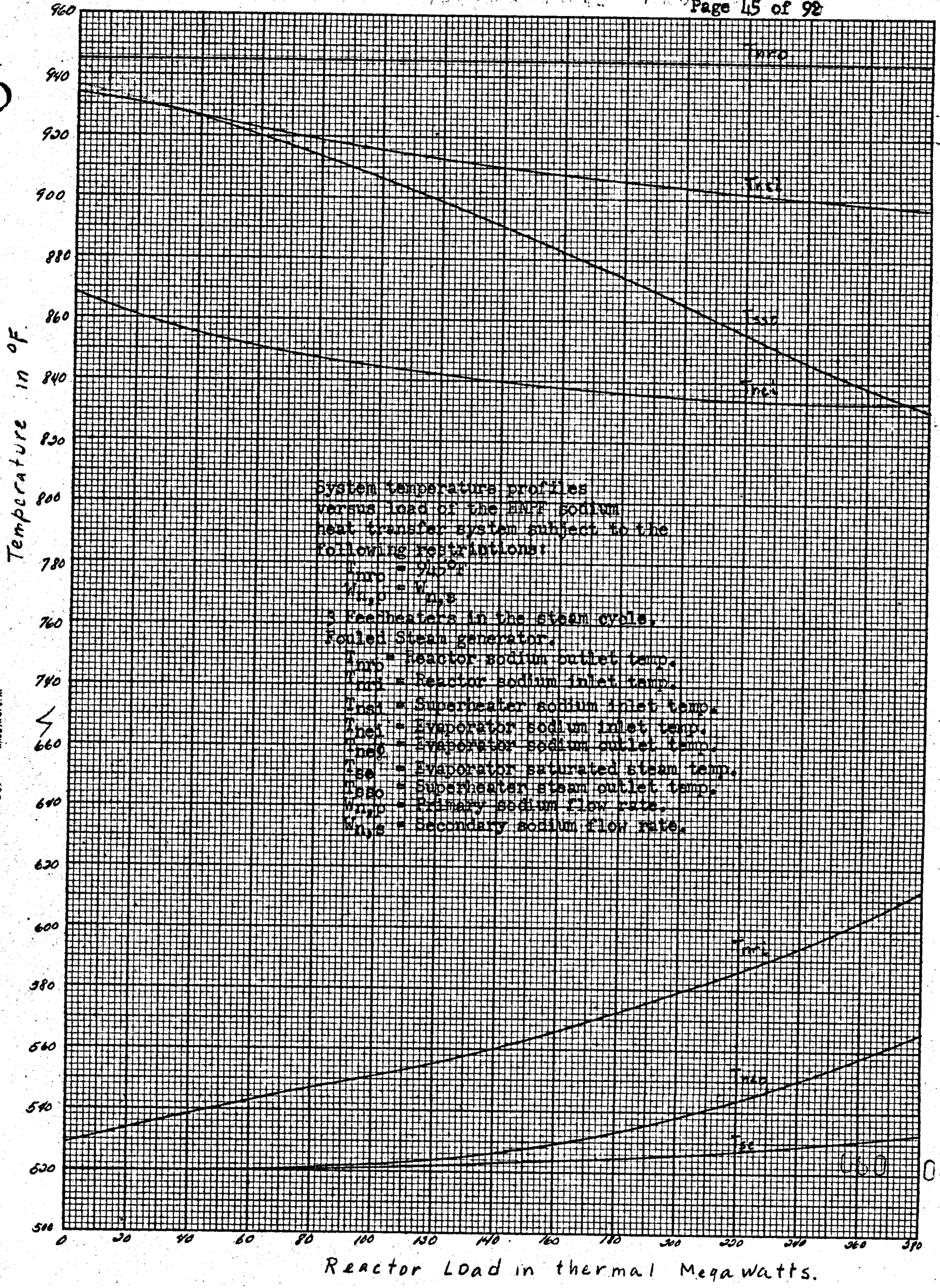
Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{sso} = 835°F

4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{sso} = Superheater steam outlet temp.
U_x = IHX heat transfer coefficient.

Figure 9a



System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrintions:

T_{nro} = 945°F
$W_{n,p}$ = $W_{n,s}$

3 Feedheaters in the steam cycle.
Fouled Steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.

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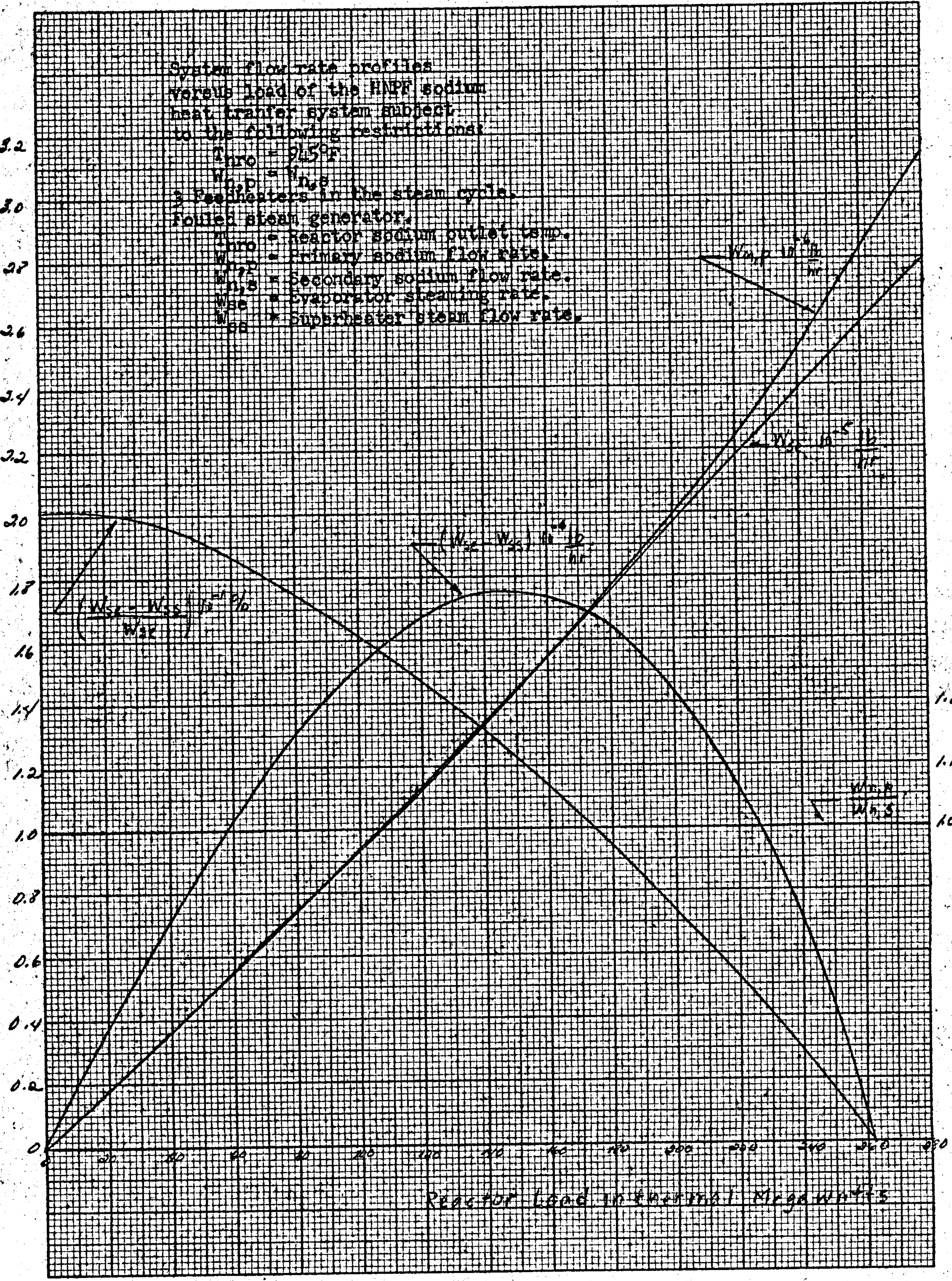
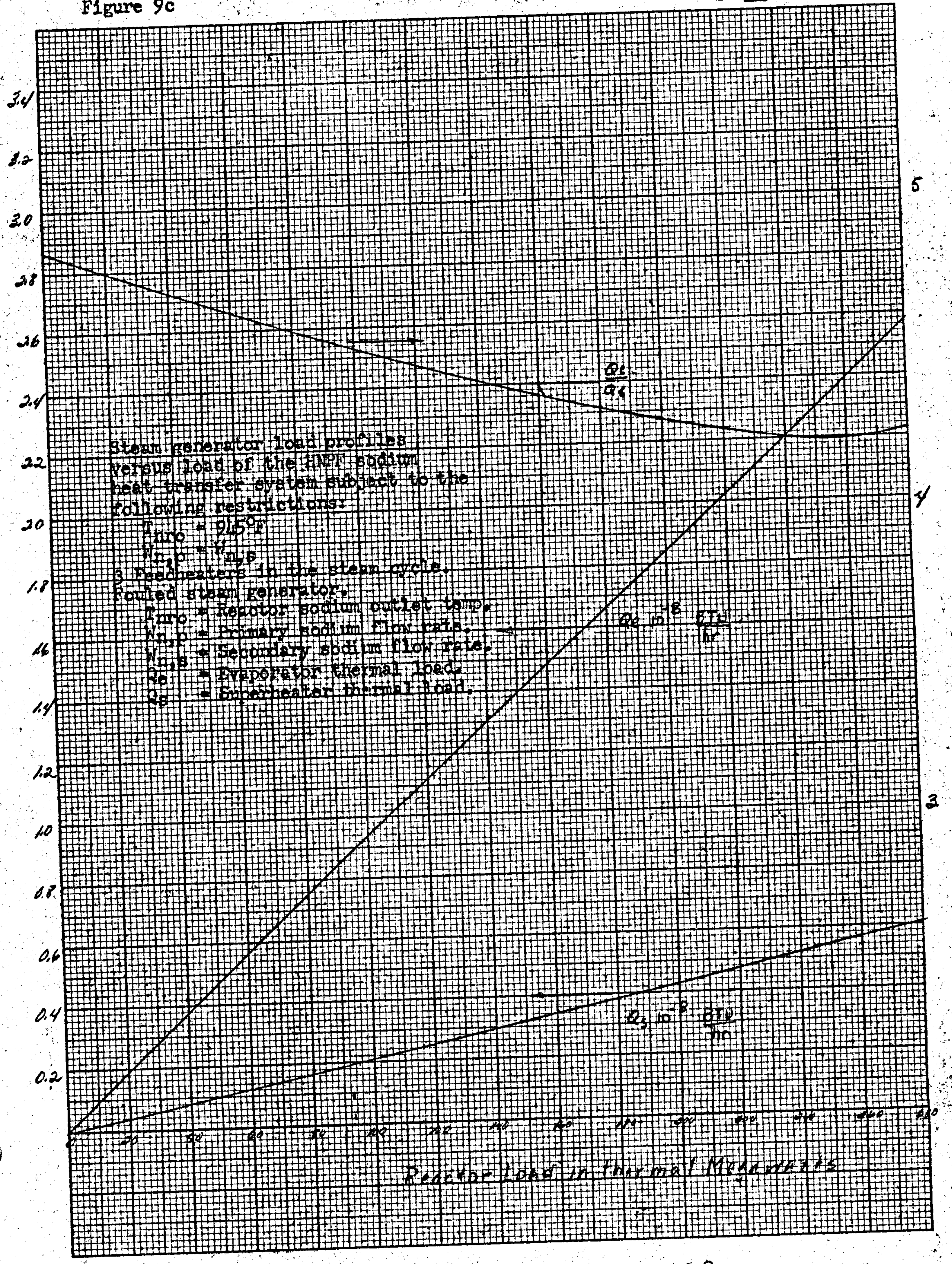
Figure 9b



System flow rate profiles
versus load of the HNPF sodium
heat tranfer system subject
to the following restrictions:
$T_{hro} = 945°F$
$W_{n,p} = W_{n,s}$
3 Feedheaters in the steam cycle.
Fouled steam generator.
T_{hro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
W_{se} = Evaporator steaming rate.
W_{ss} = Superheater steam flow rate.

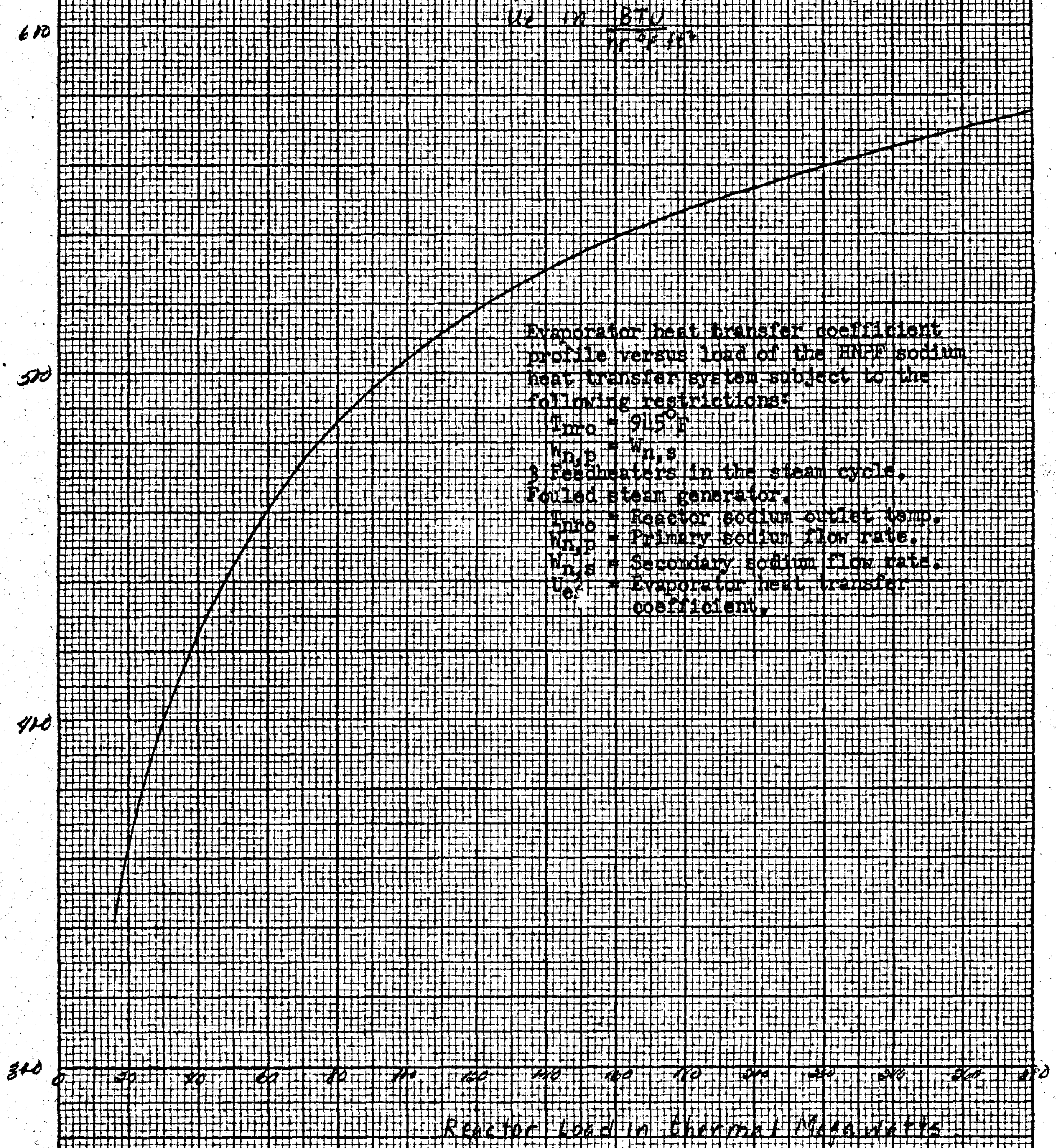
Figure 9c



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 915°F
$W_{n,p} = W_{n,s}$
3 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
Q_e = Evaporator thermal load.
Q_s = Superheater thermal load.

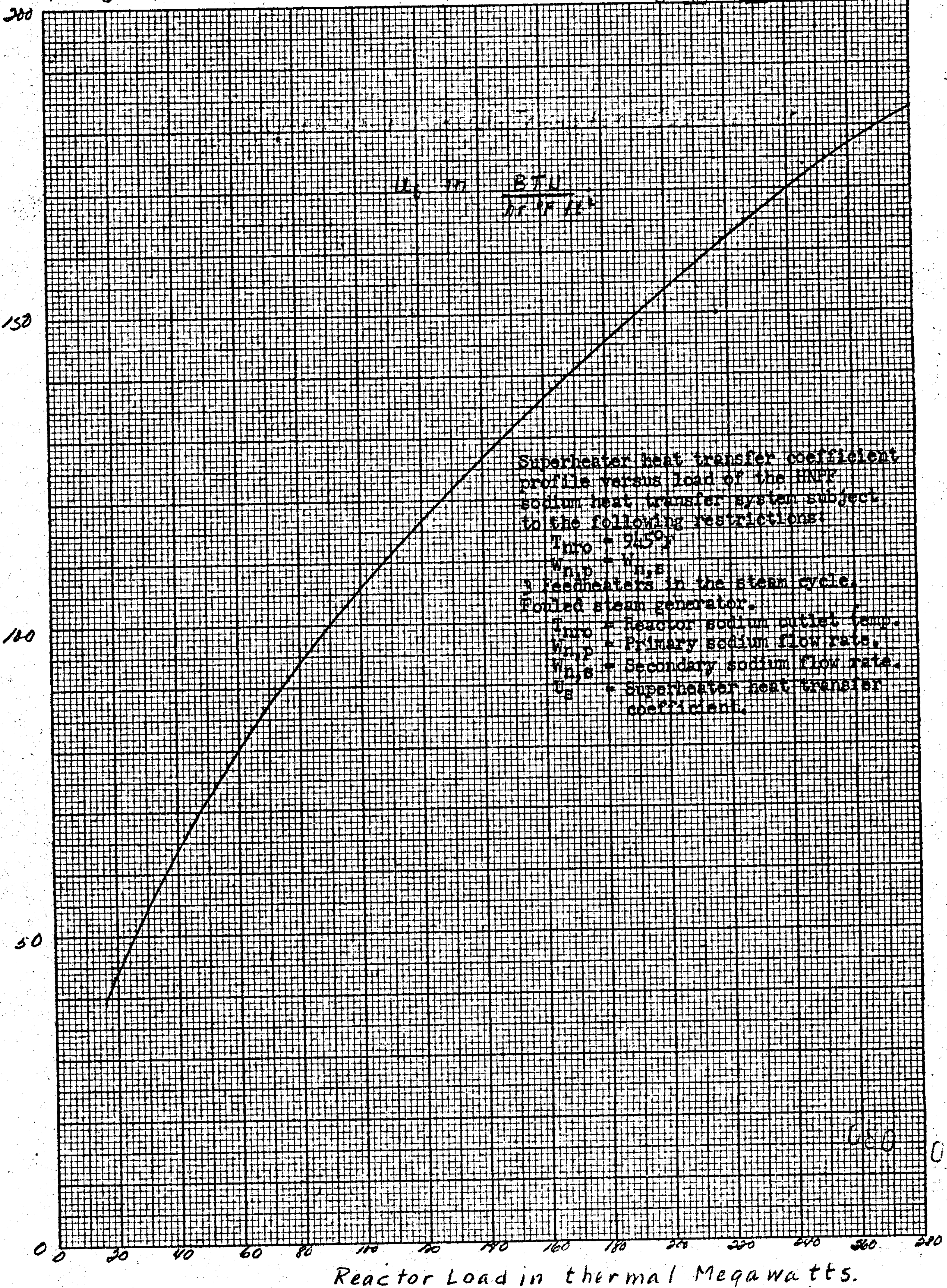
Figure 9d



Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 915°F
$W_{n,p}$ = $W_{n,s}$
3 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
U_{e} = Evaporator heat transfer coefficient.

Figure 9e



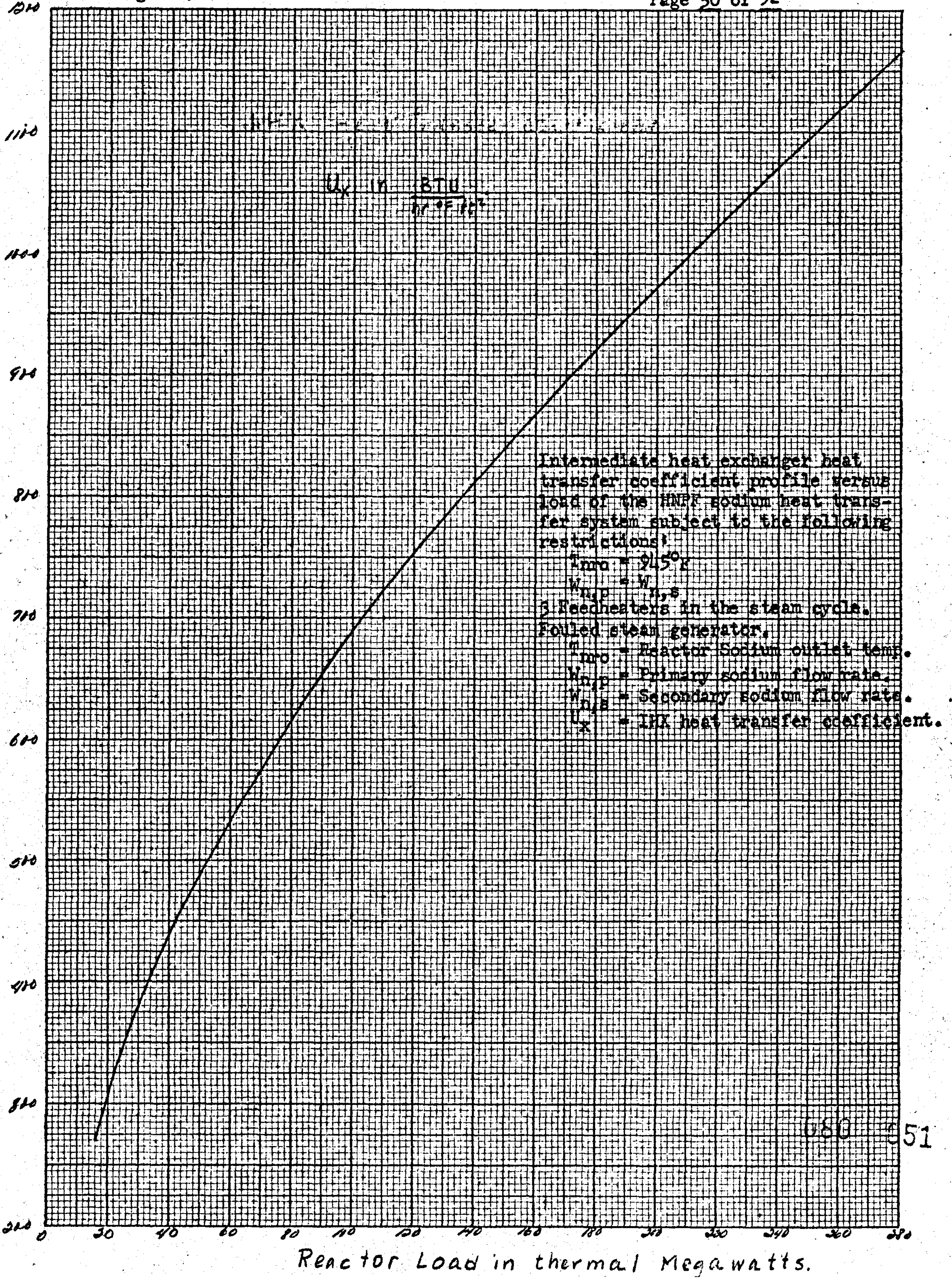
Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{hro} = 945°F
$W_{n,p}$ = $W_{n,s}$

3 feedheaters in the steam cycle.
Fouled steam generator.

T_{hro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
U_s = Superheater heat transfer coefficient.

Figure 9f

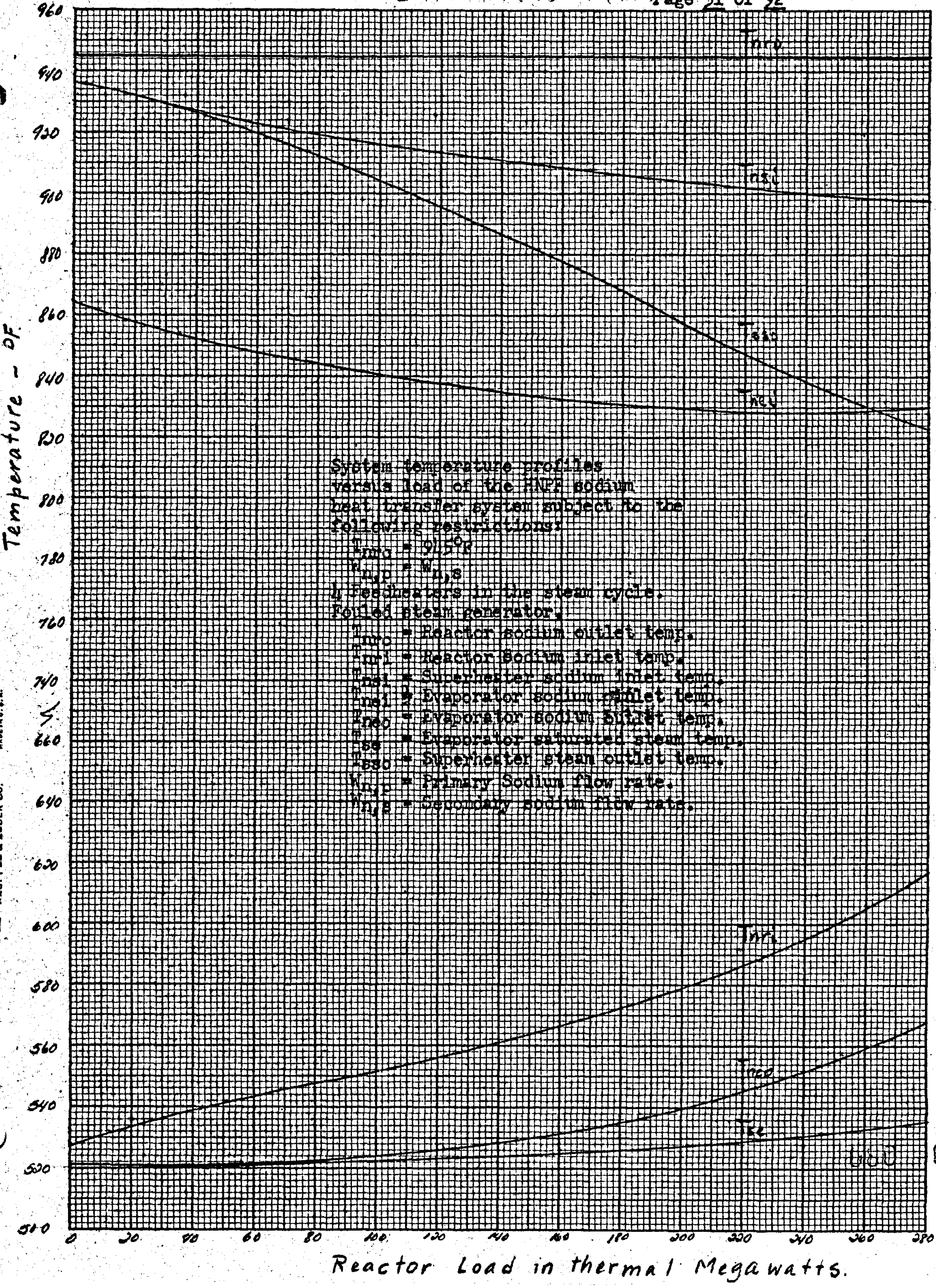


Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
$W_{n,p}$ = $W_{n,s}$
3 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor Sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
U_x = IHX heat transfer coefficient.

Figure 10a

TEMPERATURE PROF



System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
$W_{n,p}$ = $W_{n,s}$
4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor Sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.
$W_{n,p}$ = Primary Sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.

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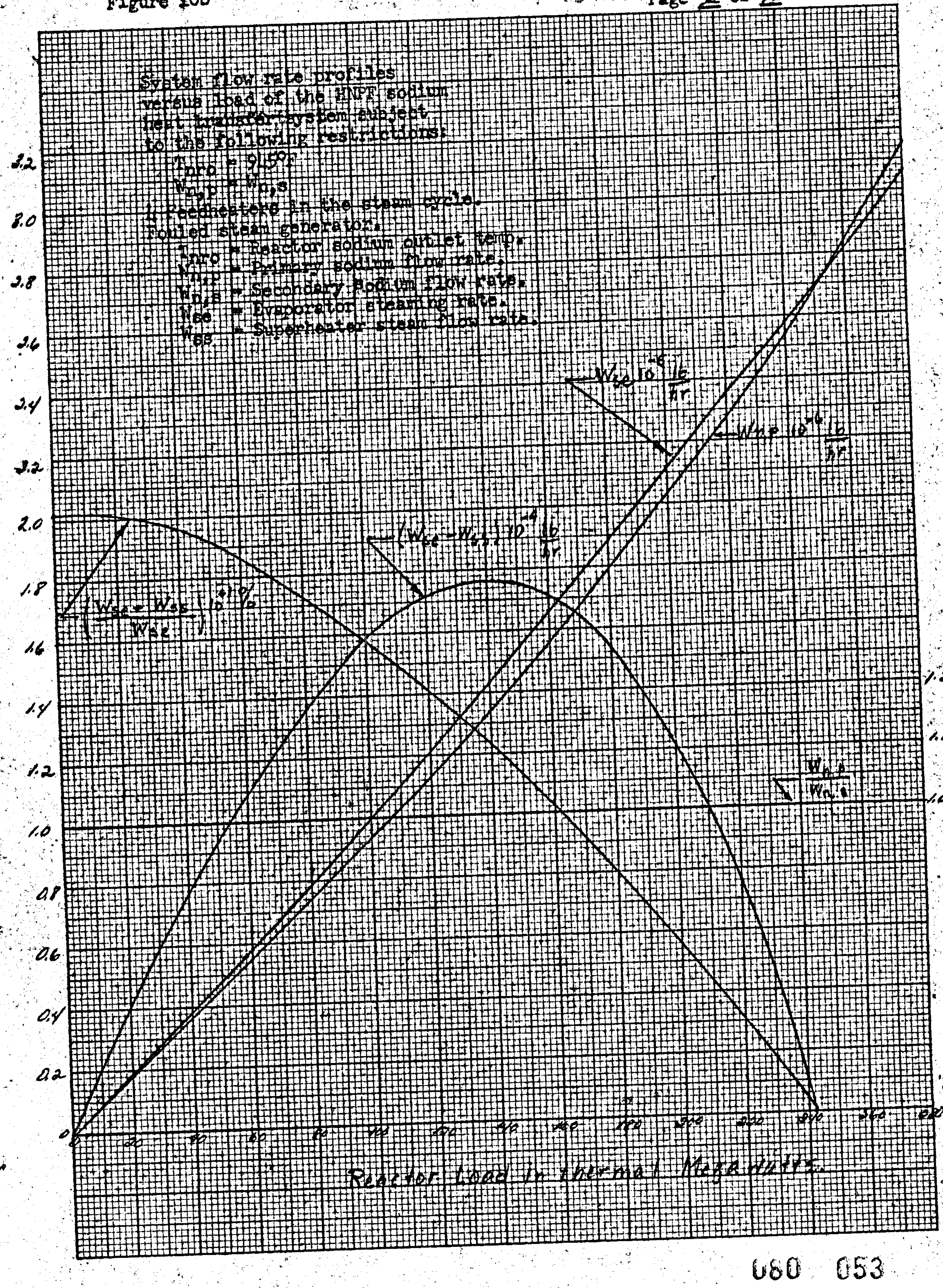
Figure 10b

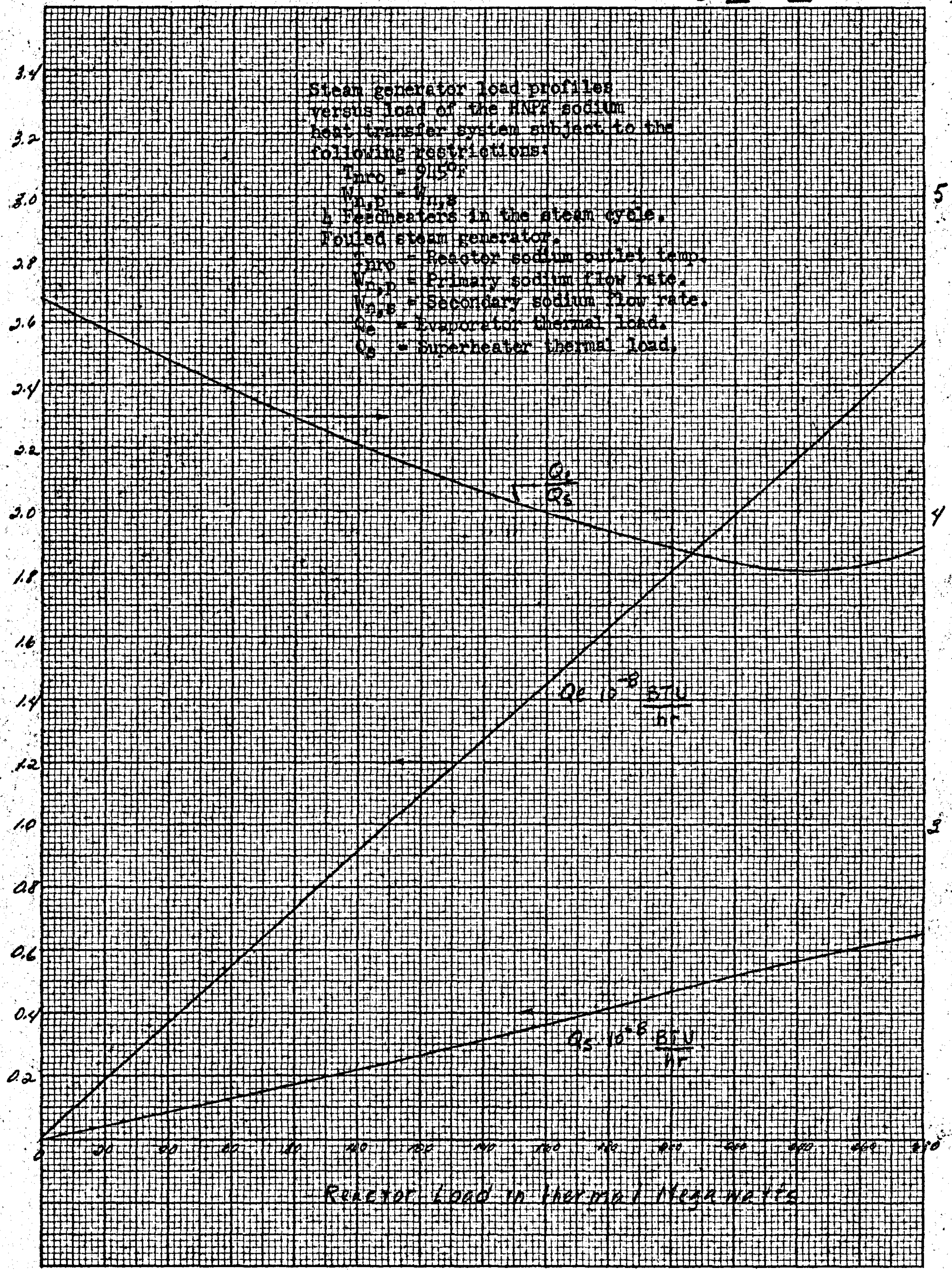


System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
$W_{n,p} = W_{n,s}$
4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
W_{se} = Evaporator steaming rate.
W_{ss} = Superheater steam flow rate.

Figure 10c



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$

$W_{n,p} = W_{n,s}$

4 Feedheaters in the steam cycle.

Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.

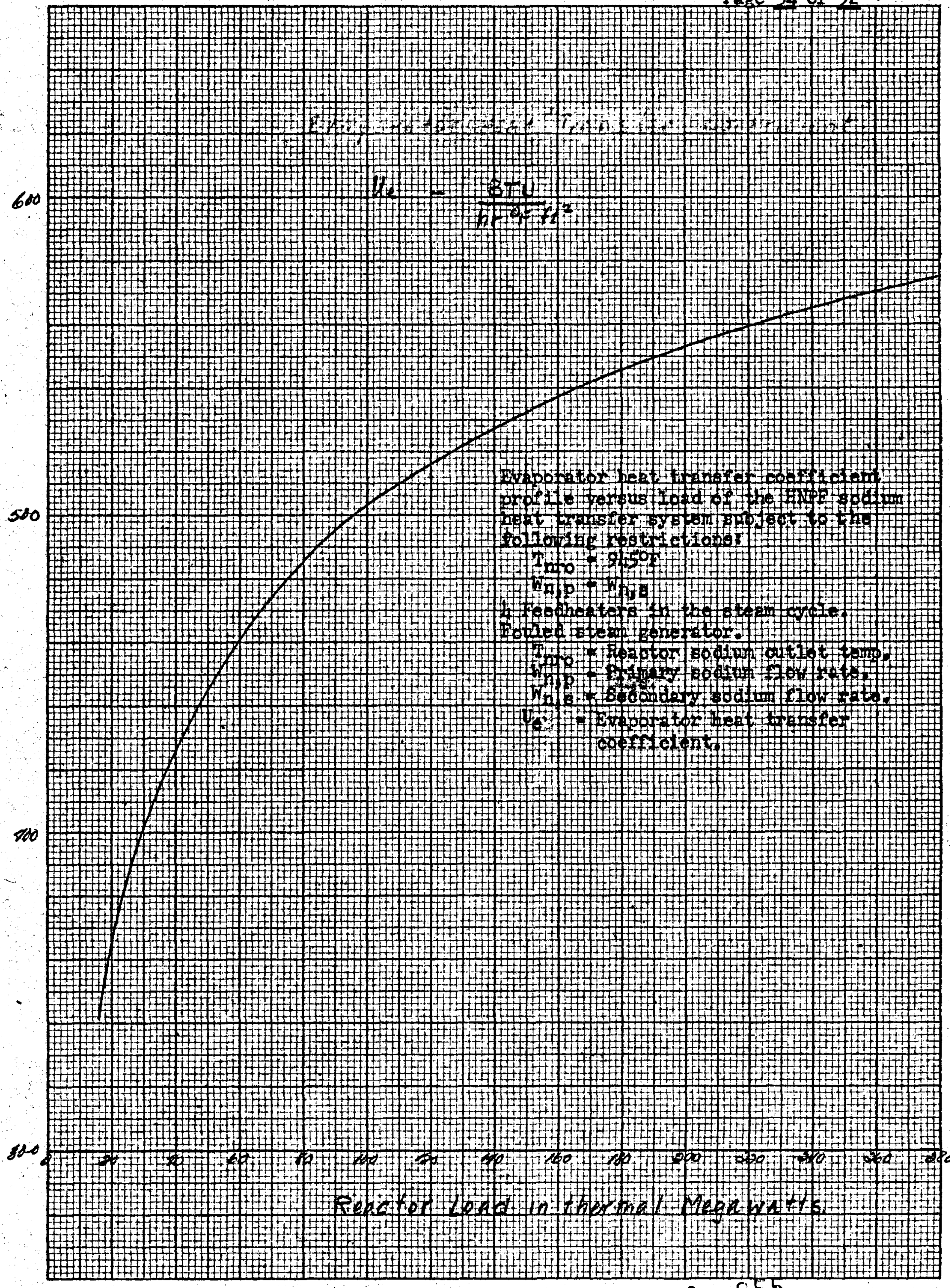
$W_{n,p}$ = Primary sodium flow rate.

$W_{n,s}$ = Secondary sodium flow rate.

Q_e = Evaporator thermal load.

Q_s = Superheater thermal load.

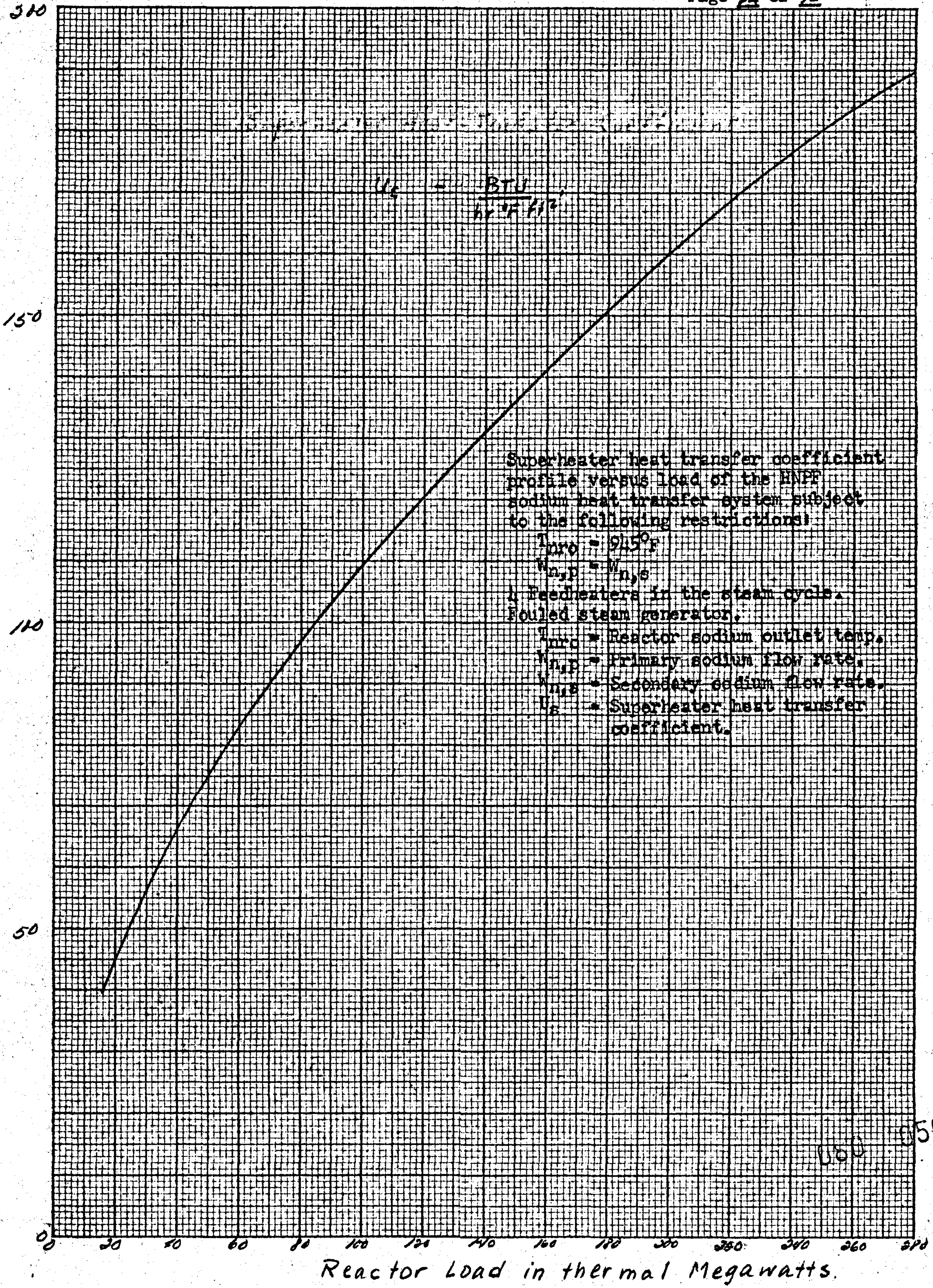
Figure 10d



Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
$W_{n,p} = W_{n,s}$
4 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
U_e = Evaporator heat transfer coefficient.

Figure 10e

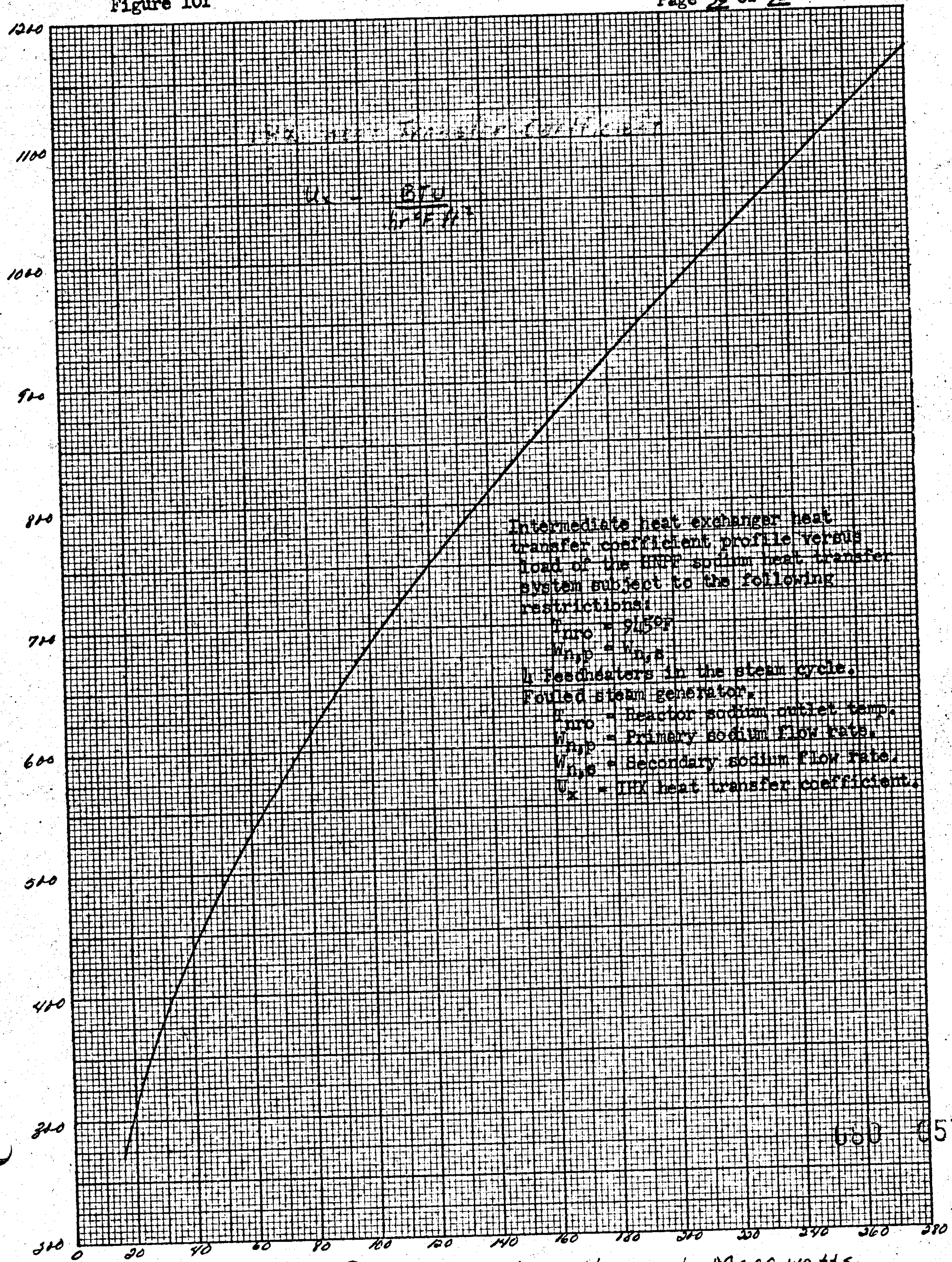


Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
$W_{n,p}$ = $W_{n,s}$
4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
U_s = Superheater heat transfer coefficient.

Figure 10f



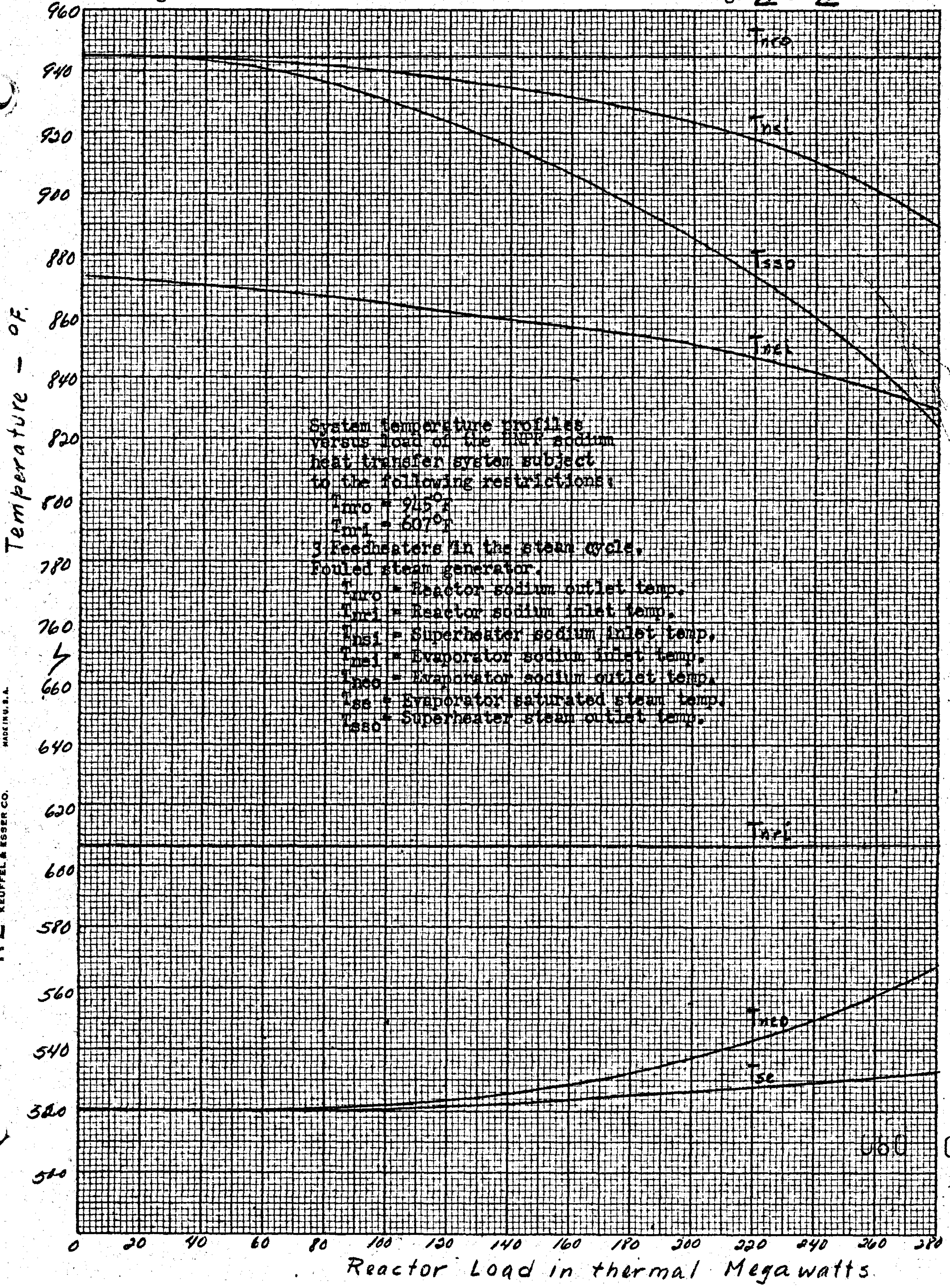
Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
$W_{n,p}$ = $W_{n,s}$

4 Feedheaters in the steam cycle.
Fouled steam generator.

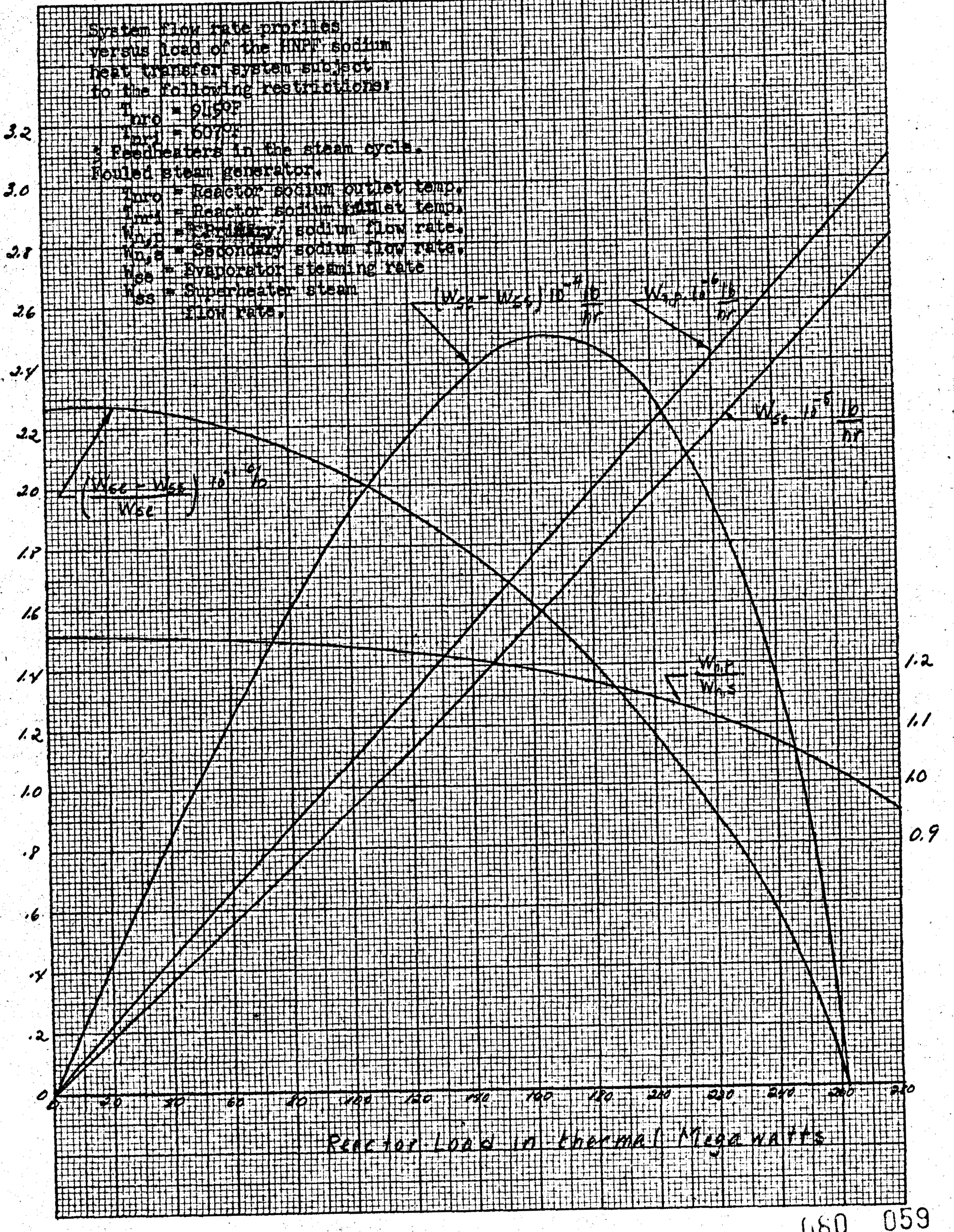
T_{nro} = Reactor sodium outlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
U_x = IHX heat transfer coefficient.

Figure 11a



System temperature profiles
versus load of the HNPF sodium
heat transfer system subject
to the following restrictions:
T_{nro} = 945°F
T_{nri} = 607°F
3 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.

Figure 11b



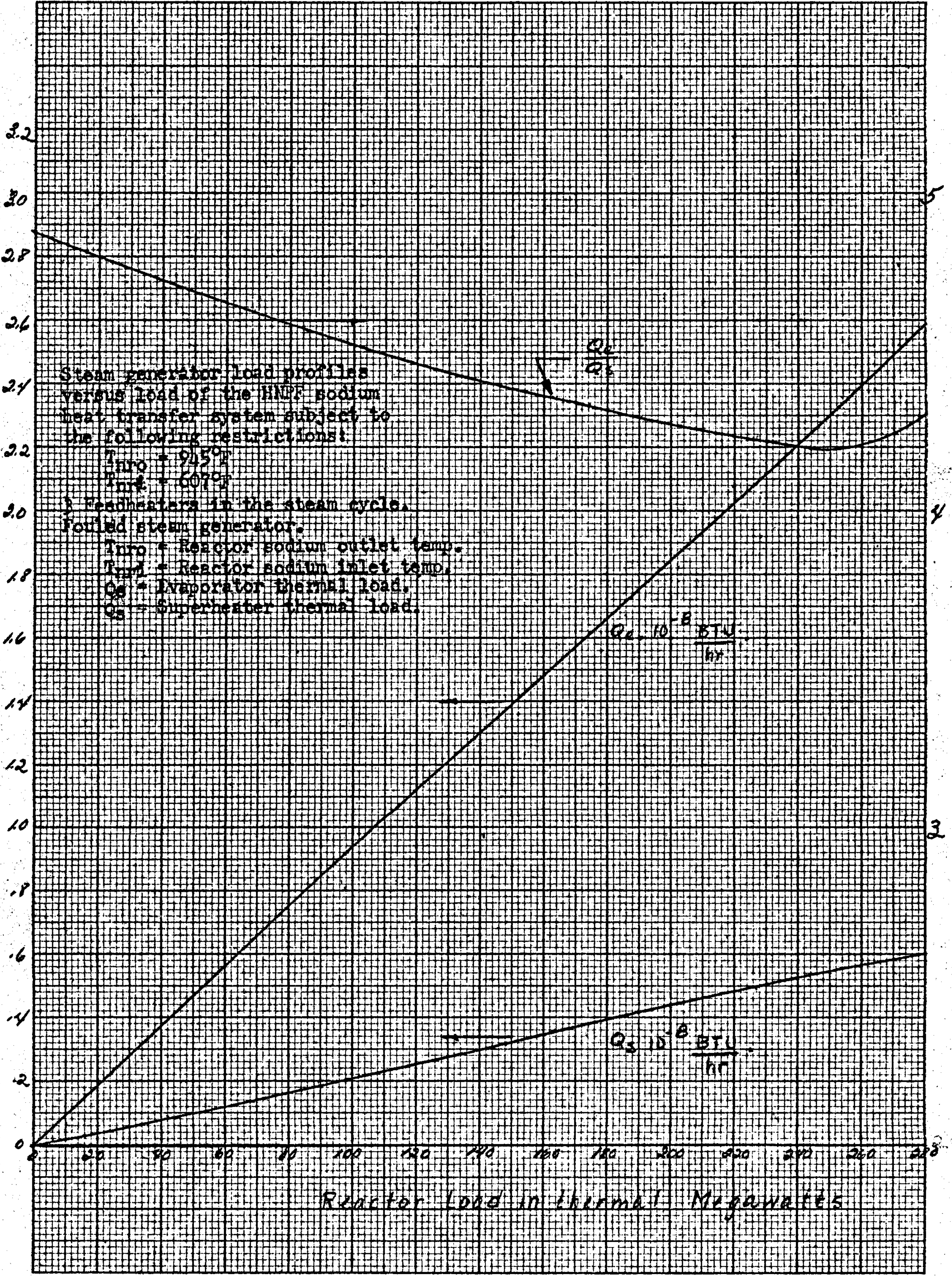
System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{nri} = 607°F

3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
W_{se} = Evaporator steaming rate
W_{ss} = Superheater steam flow rate.

Figure 11c [illegible] STEAM GENERATOR LOAD

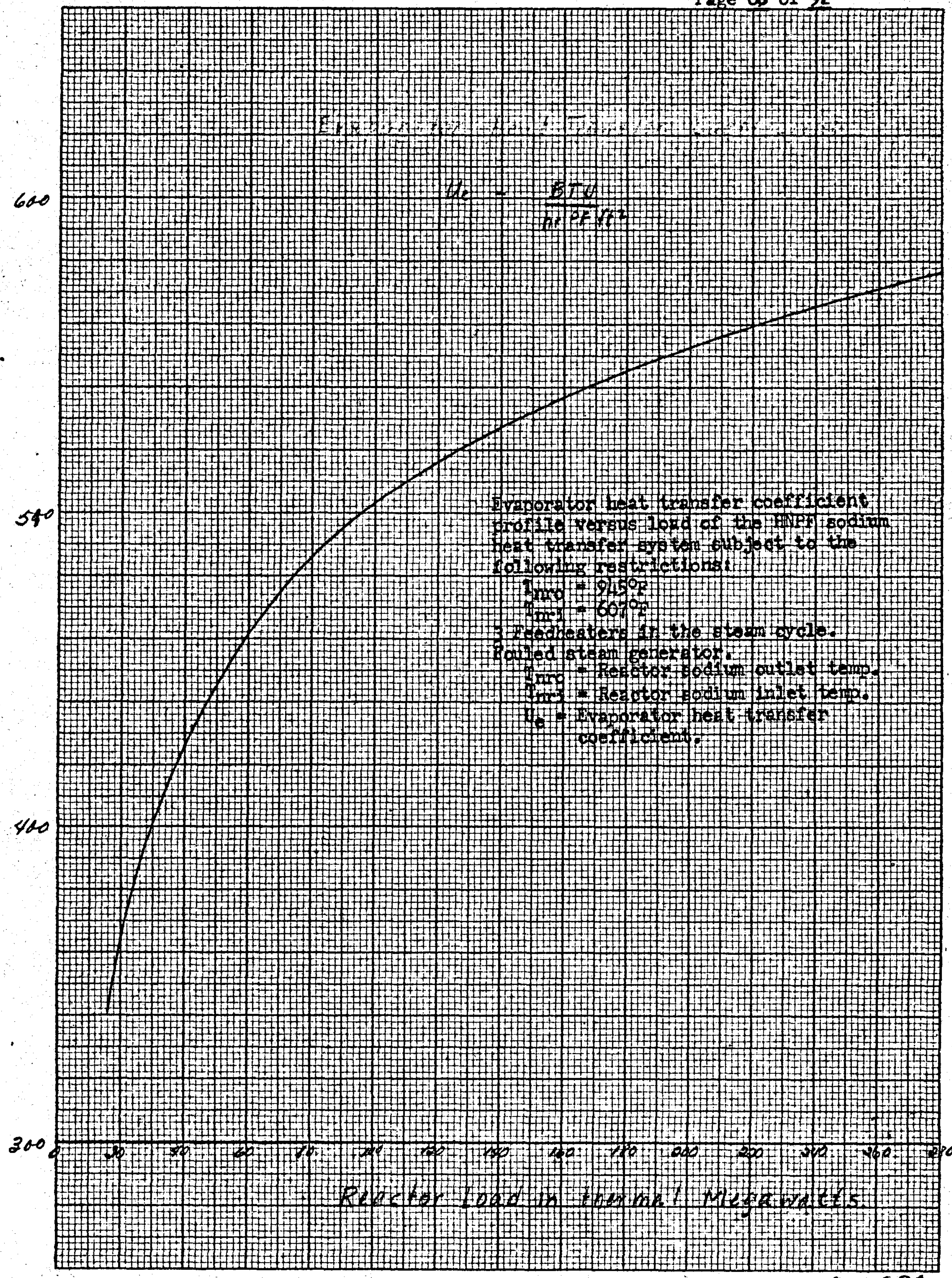


Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{nri} = 607°F

3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
Q_e = Evaporator thermal load.
Q_s = Superheater thermal load.



Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

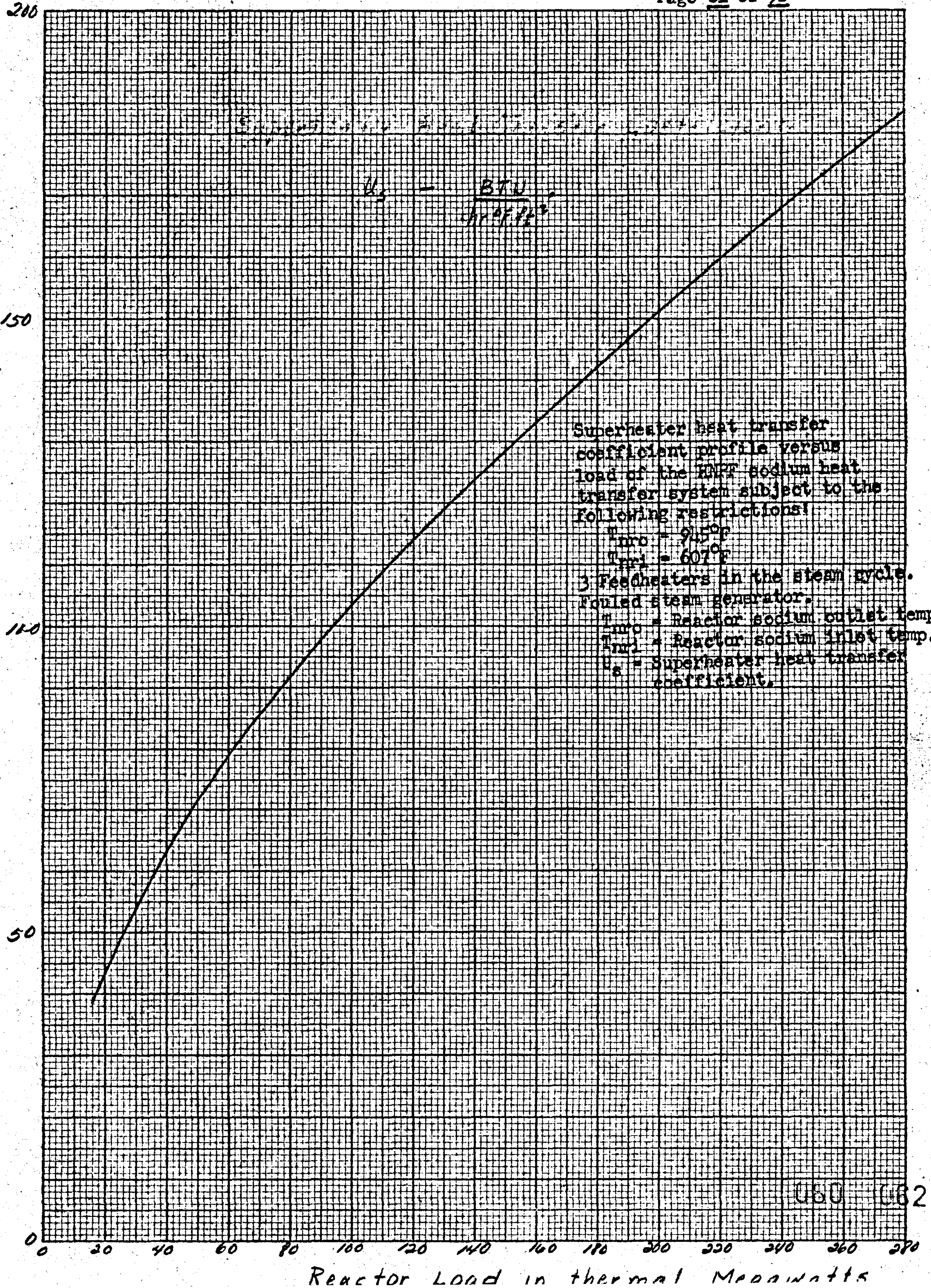
T_{nro} = 945°F
T_{nri} = 607°F

3 Feedheaters in the steam cycle.

Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 11e



Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions!

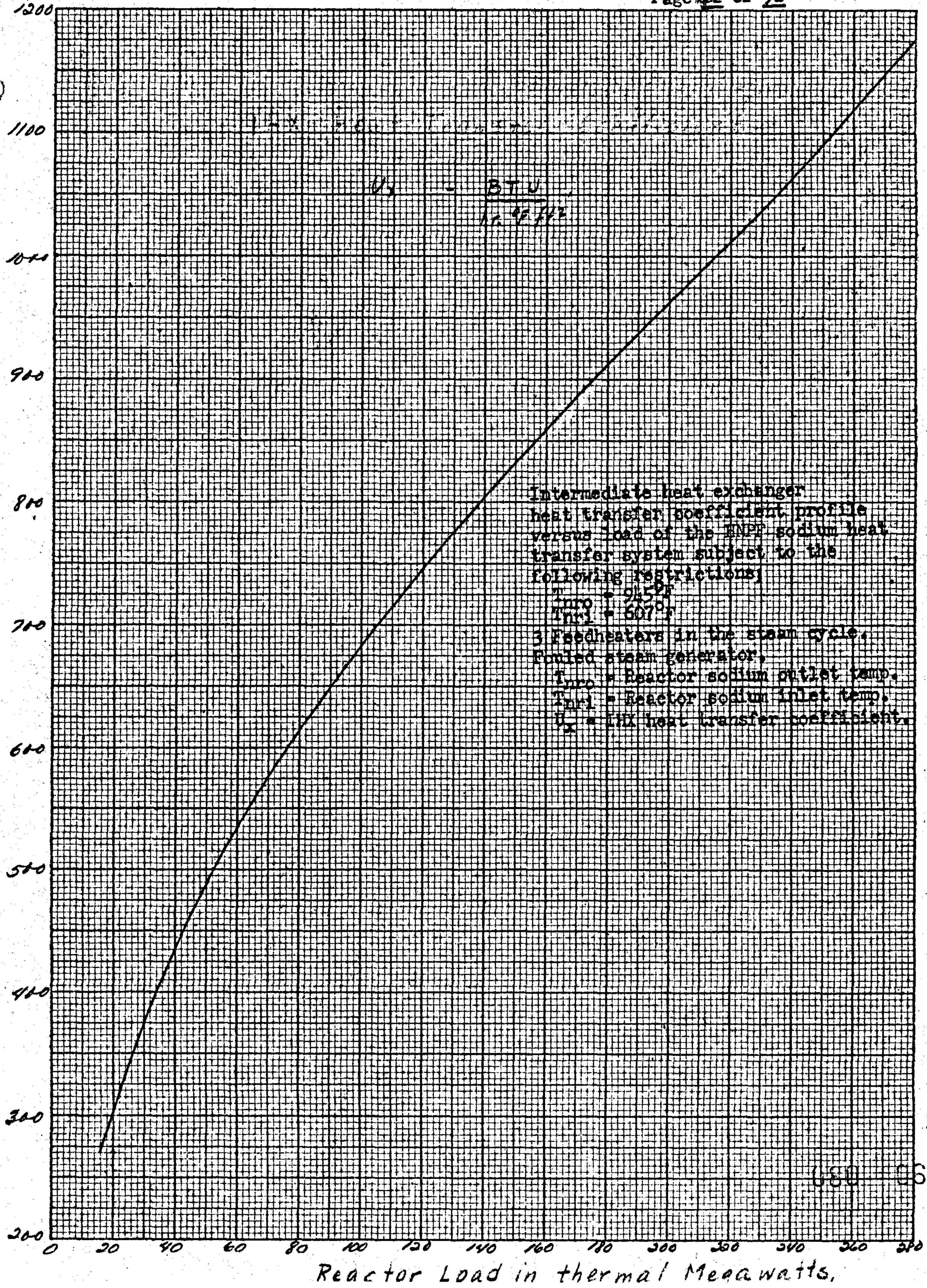
T_{nro} = 945°F
T_{nri} = 607°F

3 Feedheaters in the steam cycle.

Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_s = Superheater heat transfer coefficient.

Figure 11f



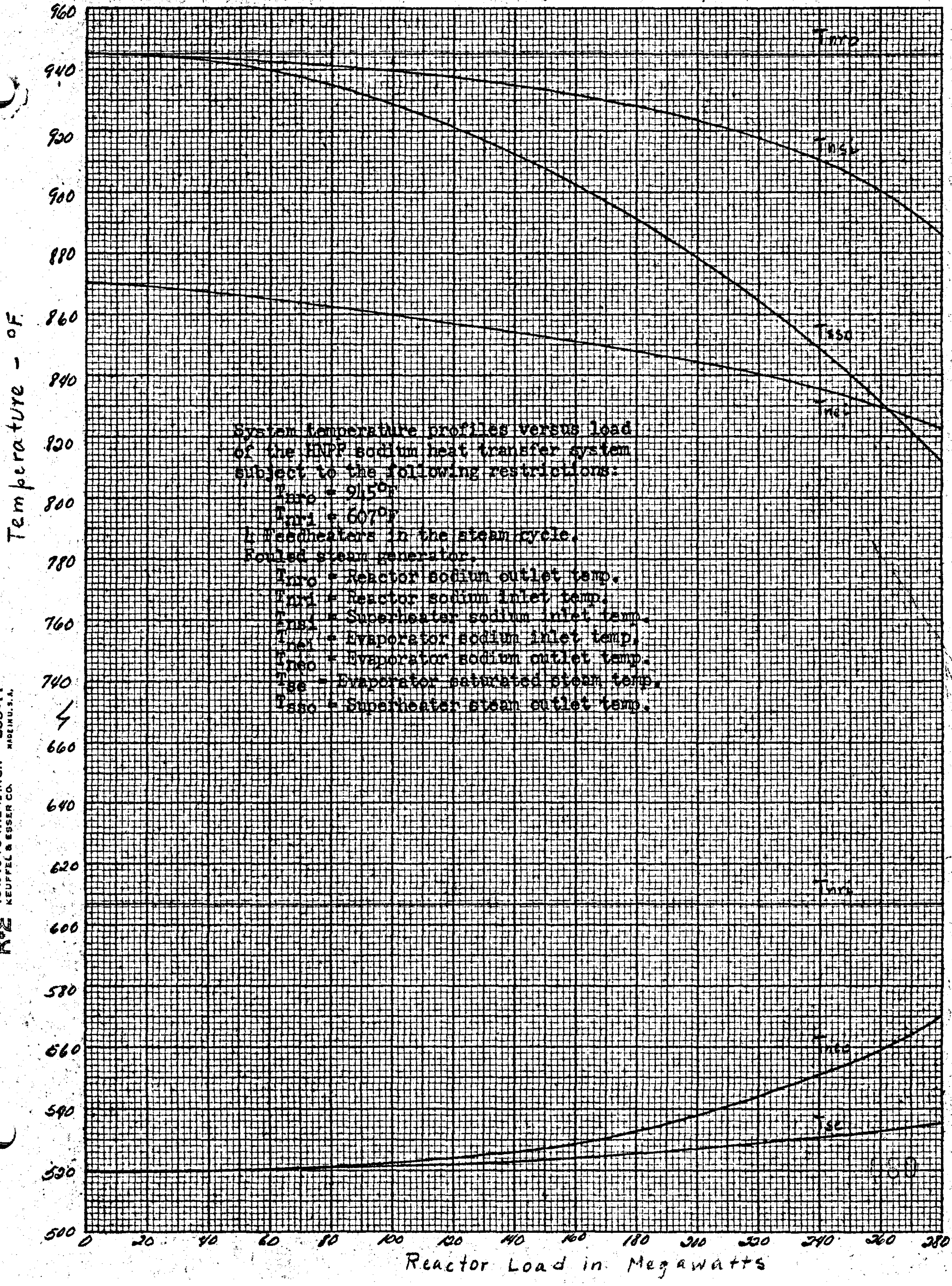
Intermediate heat exchanger heat transfer coefficient profile versus load of the ENPF sodium heat transfer system subject to the following restrictions;

T_{nro} = 945°F
T_{nri} = 607°F

3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_x = IHX heat transfer coefficient.

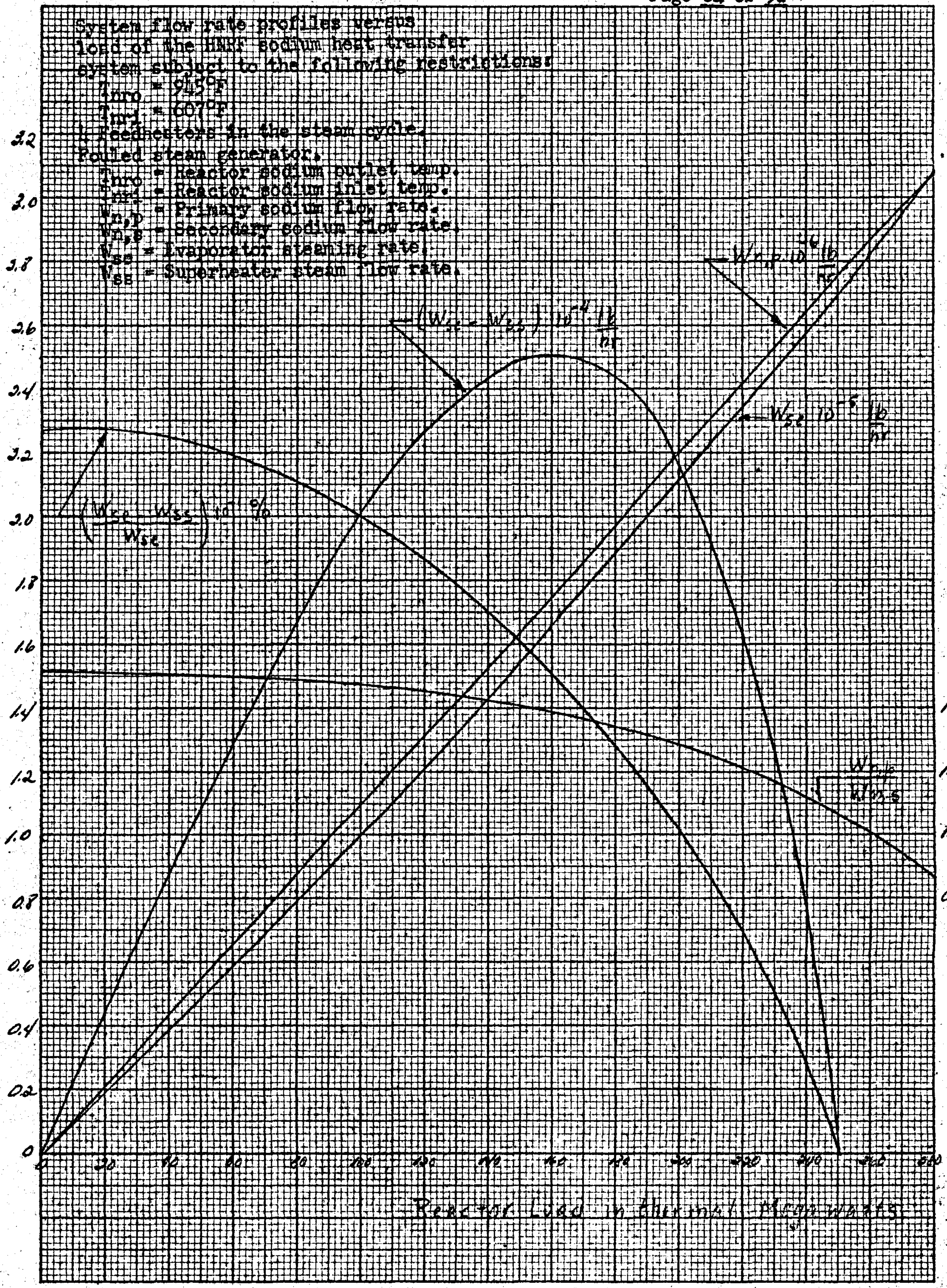
Figure 12a



System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{nri} = 607°F
4 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.

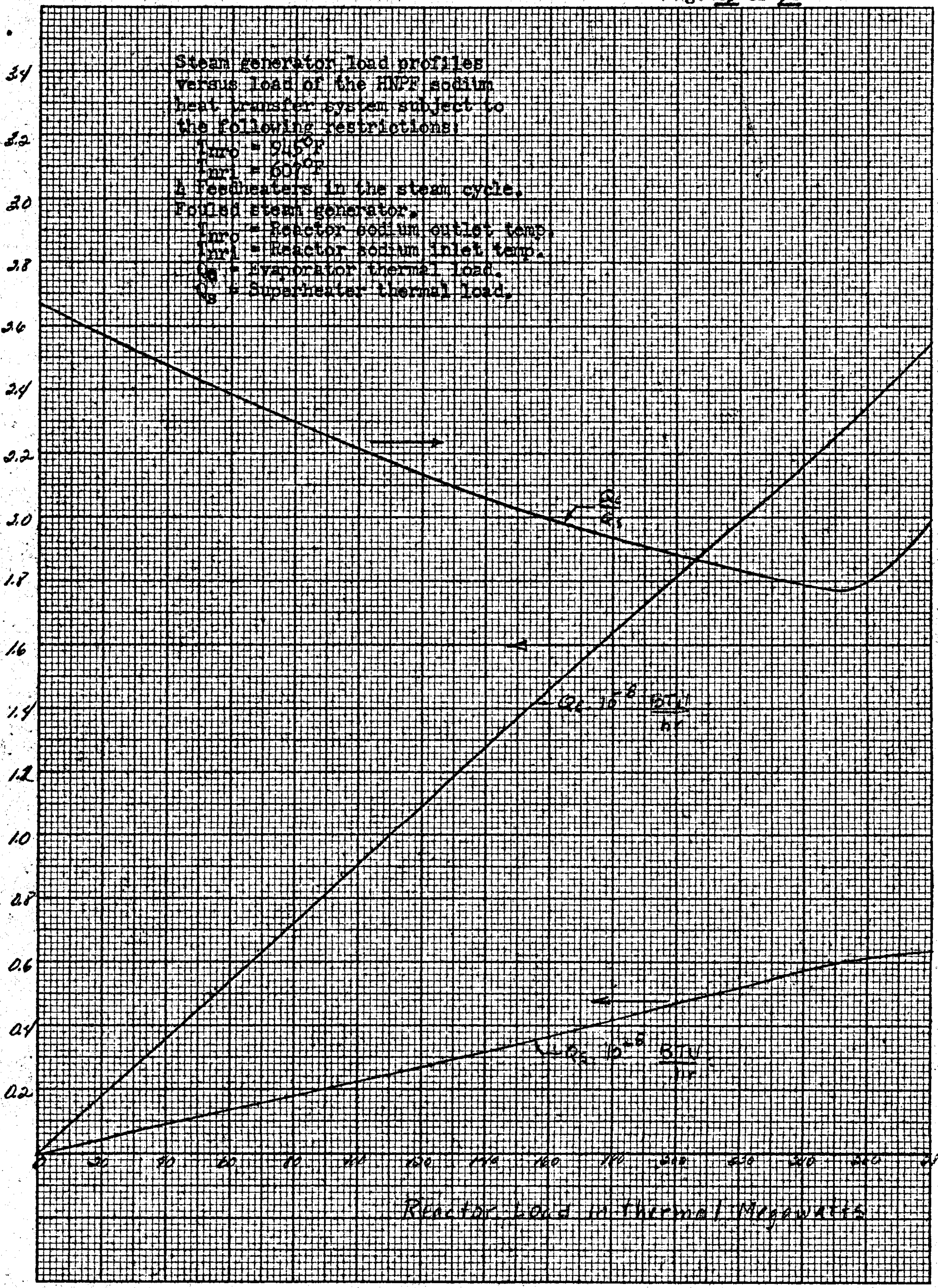
Figure 12b



System flow rate profiles versus load of the HNRF sodium heat transfer system subject to the following restrictions:

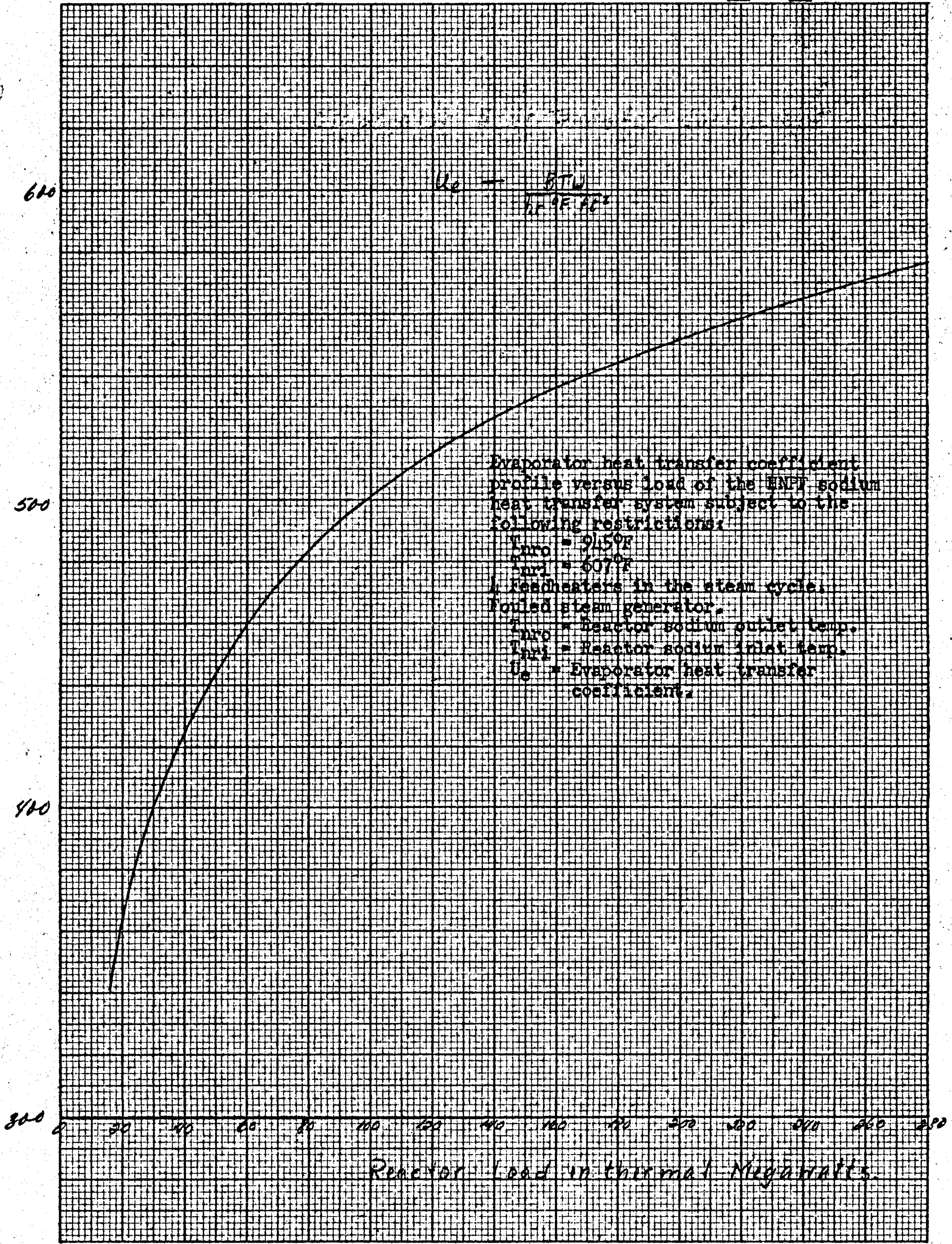
T_{nro} = 945°F
T_{nri} = 607°F
4 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
W_{se} = Evaporator steaming rate.
W_{ss} = Superheater steam flow rate.

Figure 12c



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

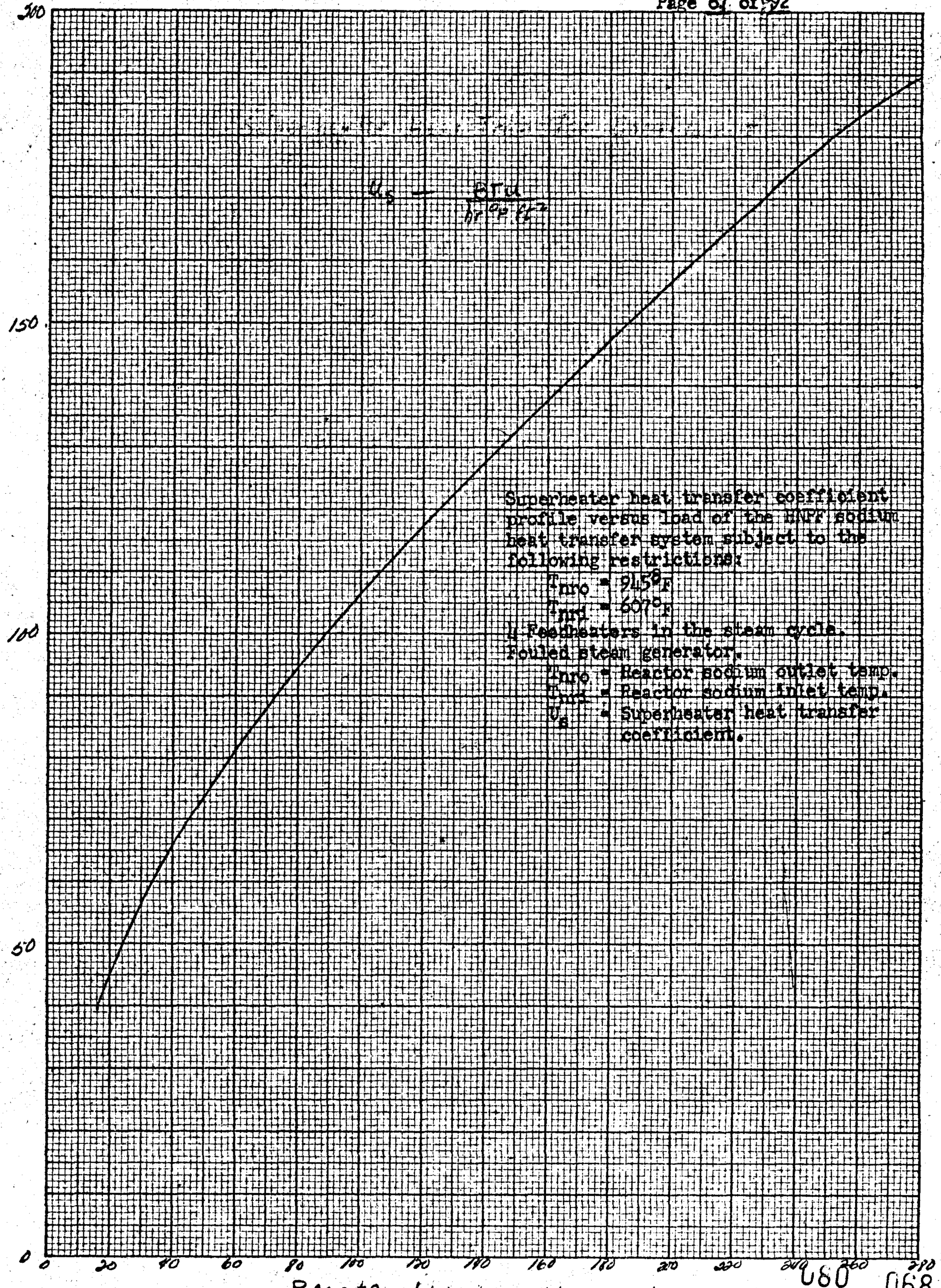
T_{nro} = 945°F
T_{nri} = 607°F
4 feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
Q_e = Evaporator thermal load.
Q_s = Superheater thermal load.



Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{nri} = 607°F
4 Feedheaters in the steam cycle.
Fouled steam generator.
T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 12e



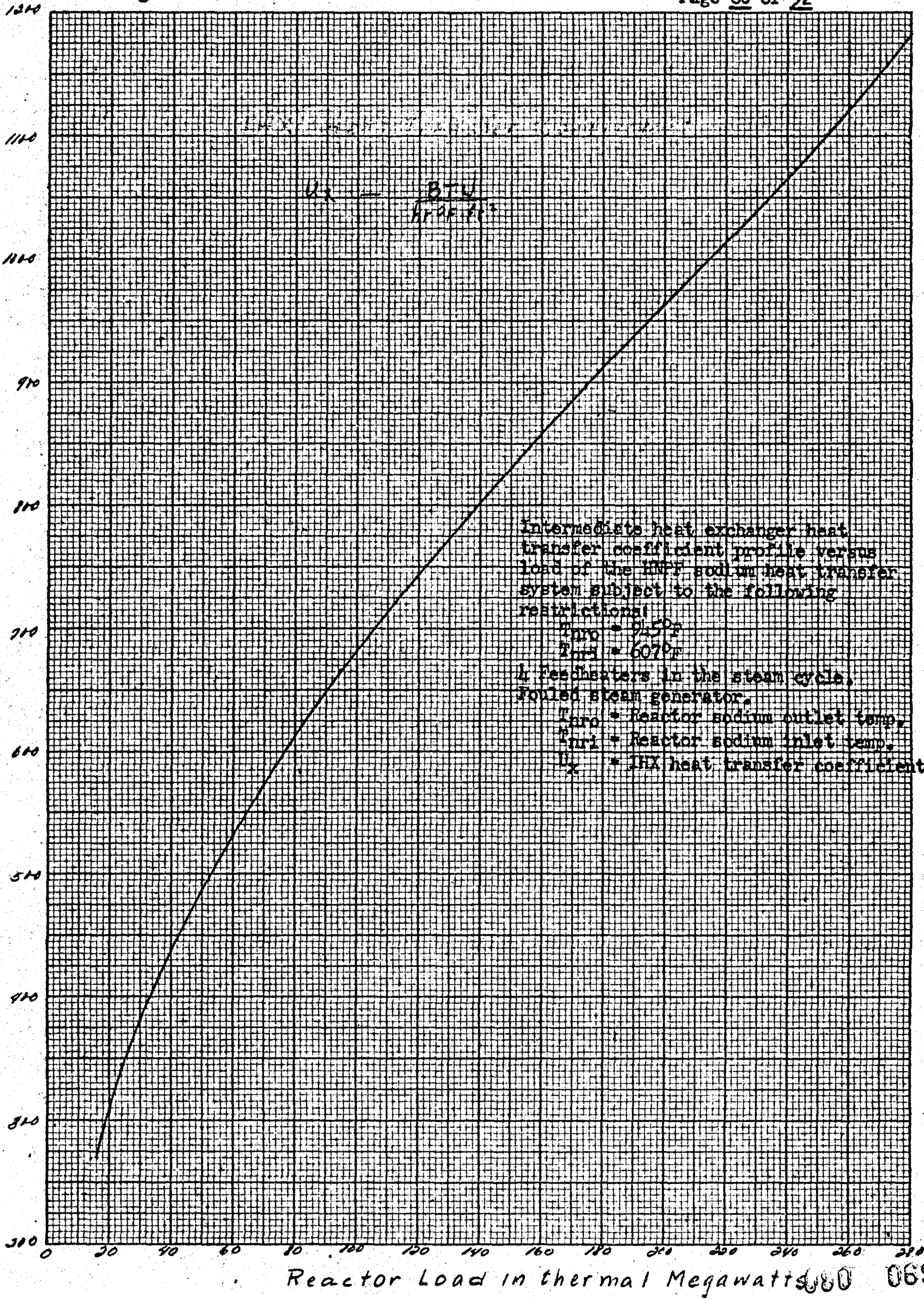
Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{nri} = 607°F

4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_s = Superheater heat transfer coefficient.

Figure 12f



Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

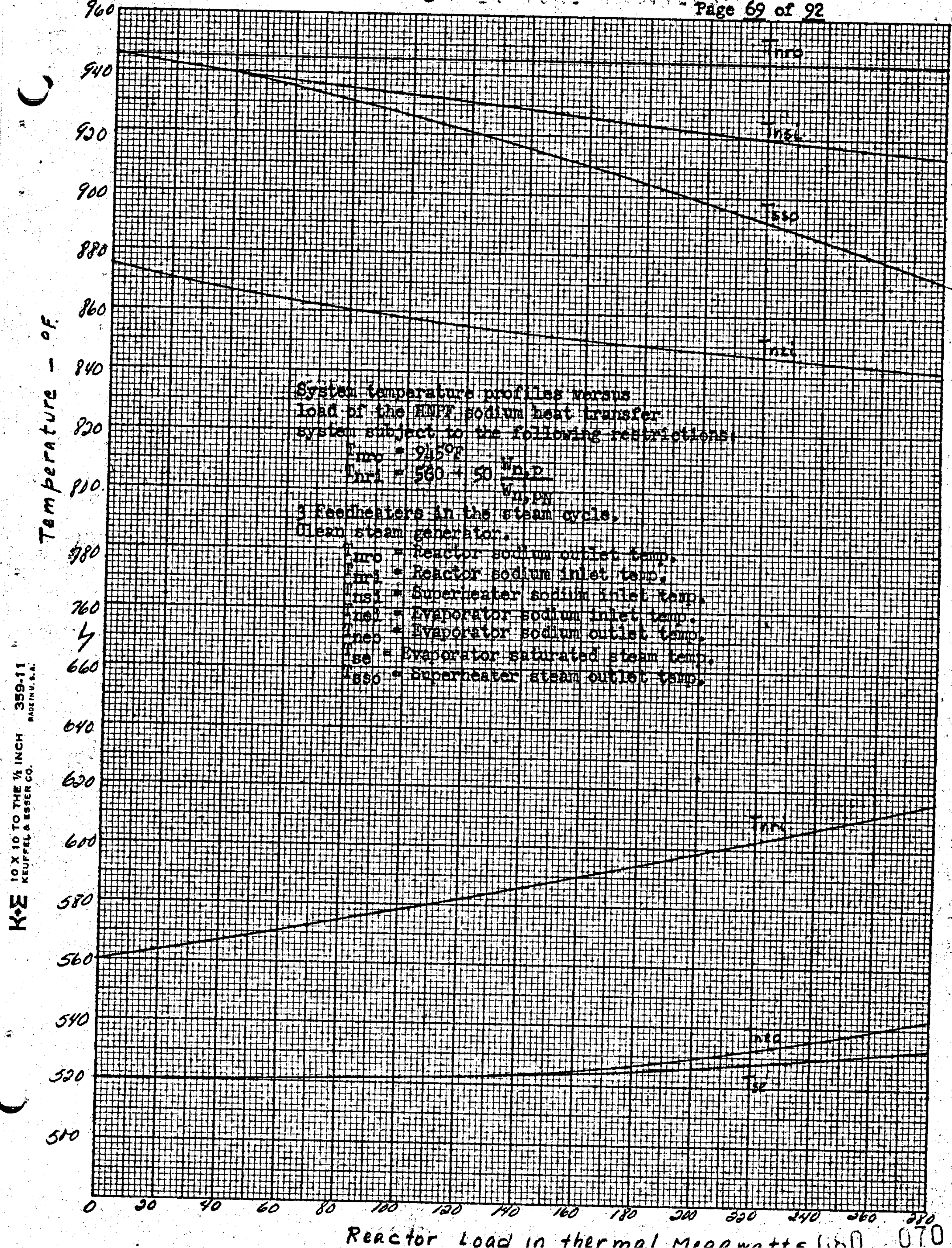
T_{hro} = 945°F
T_{hri} = 607°F

4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{hro} = Reactor sodium outlet temp.
T_{hri} = Reactor sodium inlet temp.
U_x = IHX heat transfer coefficient.

Figure 13a

TEMPERATURE PROFILES



System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F

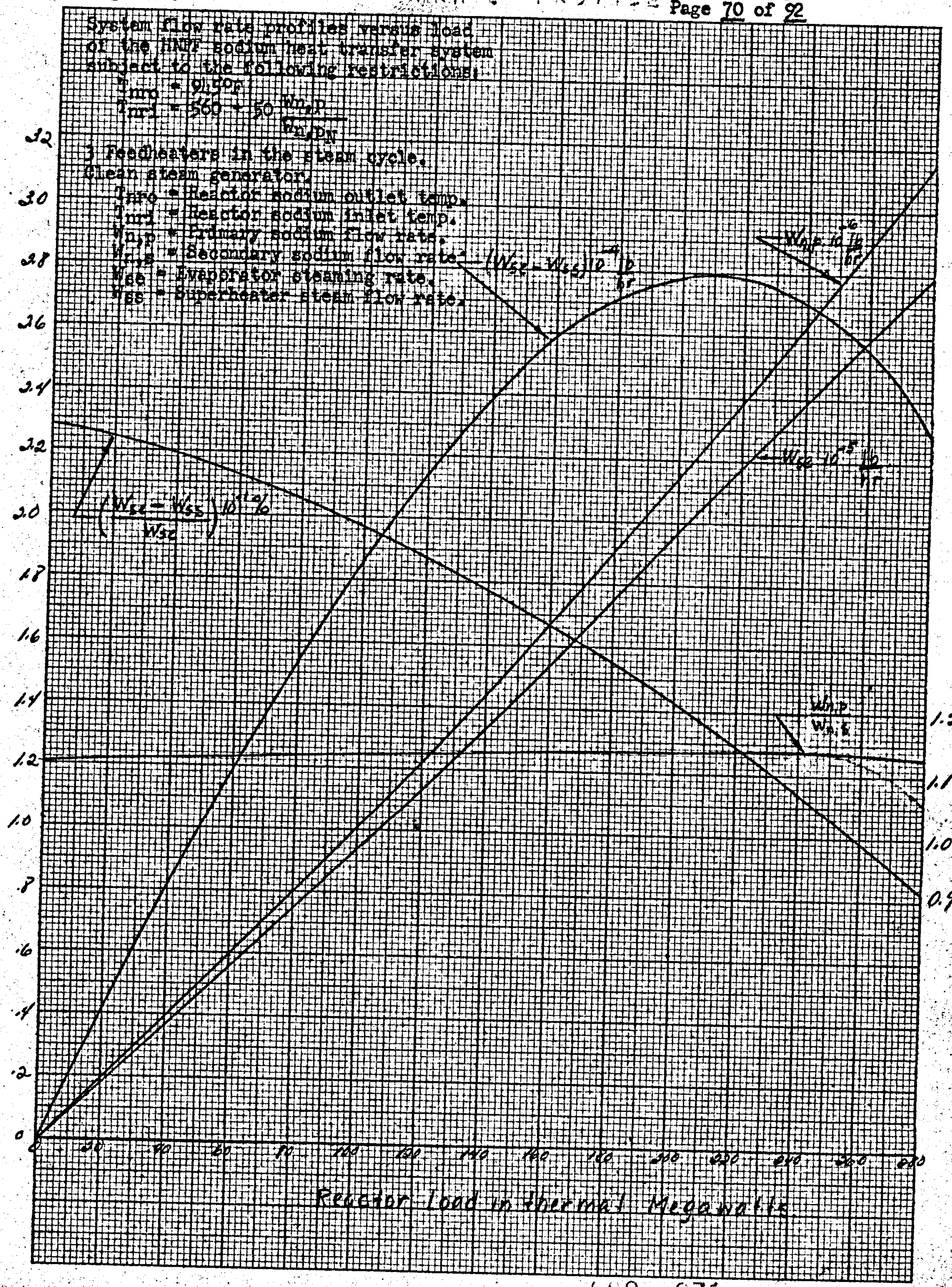
$T_{nri} = 560 + 50 \frac{W_{n,P}}{W_{n,PN}}$

3 Feedheaters in the steam cycle.
Clean steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.

Figure 13b

FLOW RATE PROFILE



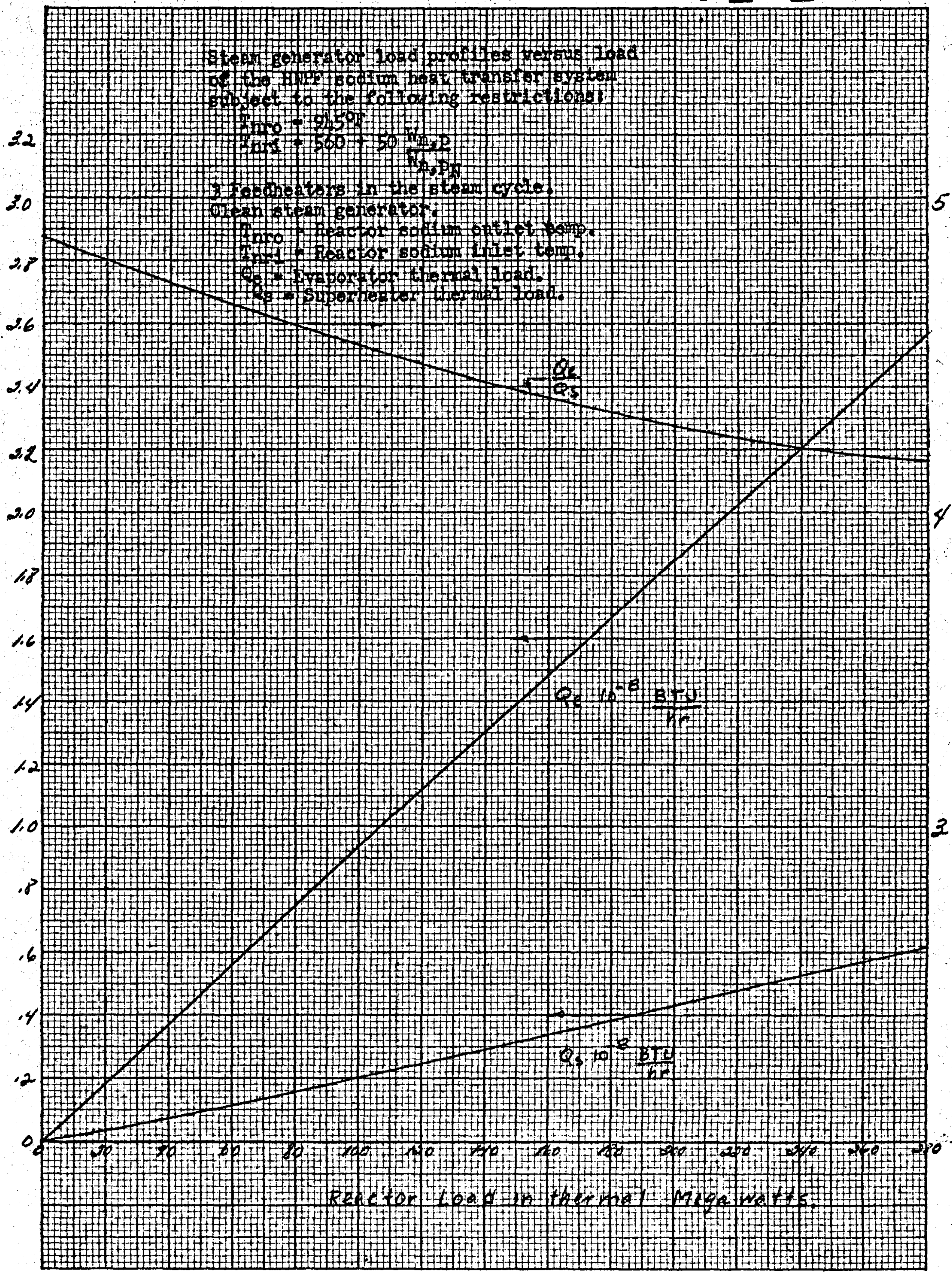
System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,pN}}$

3 Feedheaters in the steam cycle.
Clean steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
W_{se} = Evaporator steaming rate.
W_{ss} = Superheater steam flow rate.



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,P}}{W_{n,PN}}$

3 Feedheaters in the steam cycle.

Clean steam generator.

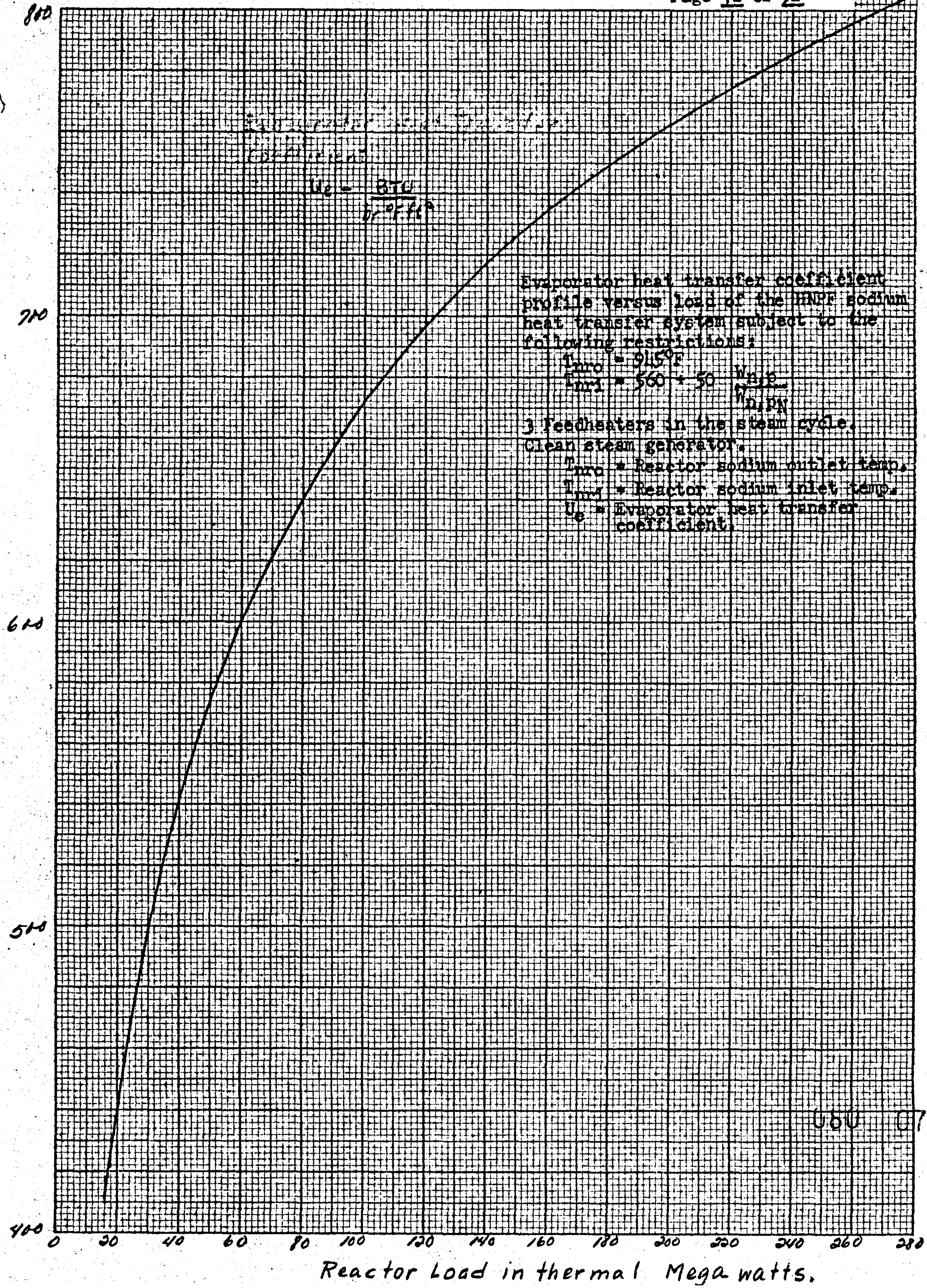
T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

Q_e = Evaporator thermal load.

Q_s = Superheater thermal load.

Figure 13d



Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 915^\circ F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,pN}}$

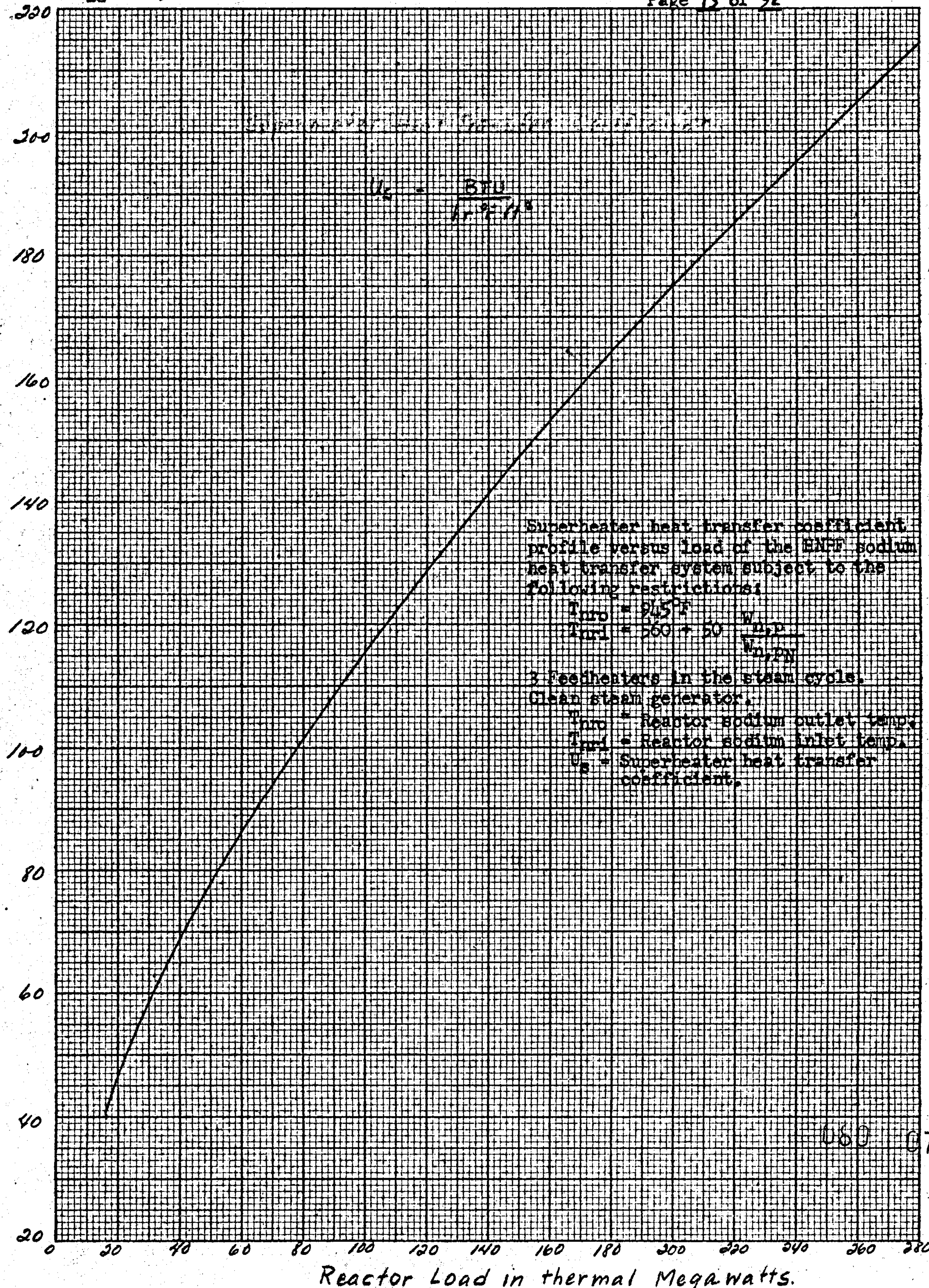
3 Feedheaters in the steam cycle.
Clean steam generator.

T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

U_e = Evaporator heat transfer coefficient.

Figure 13e



Superheater heat transfer coefficient profile versus load of the ENPF sodium heat transfer system subject to the following restrictions:

$T_{hro} = 945^\circ F$

$T_{hri} = 560 + 50 \frac{W_{n,P}}{W_{n,PN}}$

3 Feedheaters in the steam cycle.

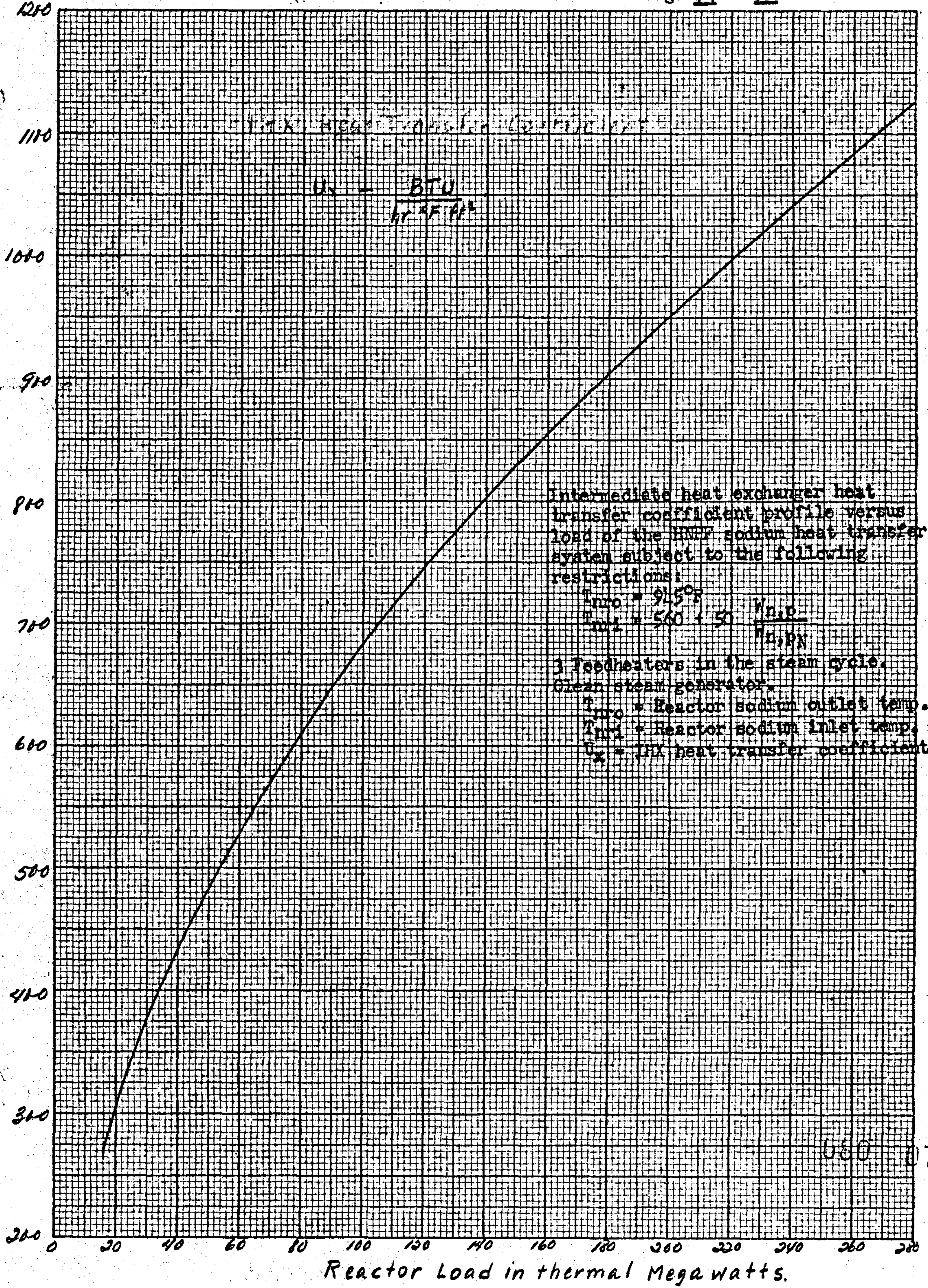
Clean steam generator.

T_{hro} = Reactor sodium outlet temp.

T_{hri} = Reactor sodium inlet temp.

U_s = Superheater heat transfer coefficient.

Figure 13f



Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

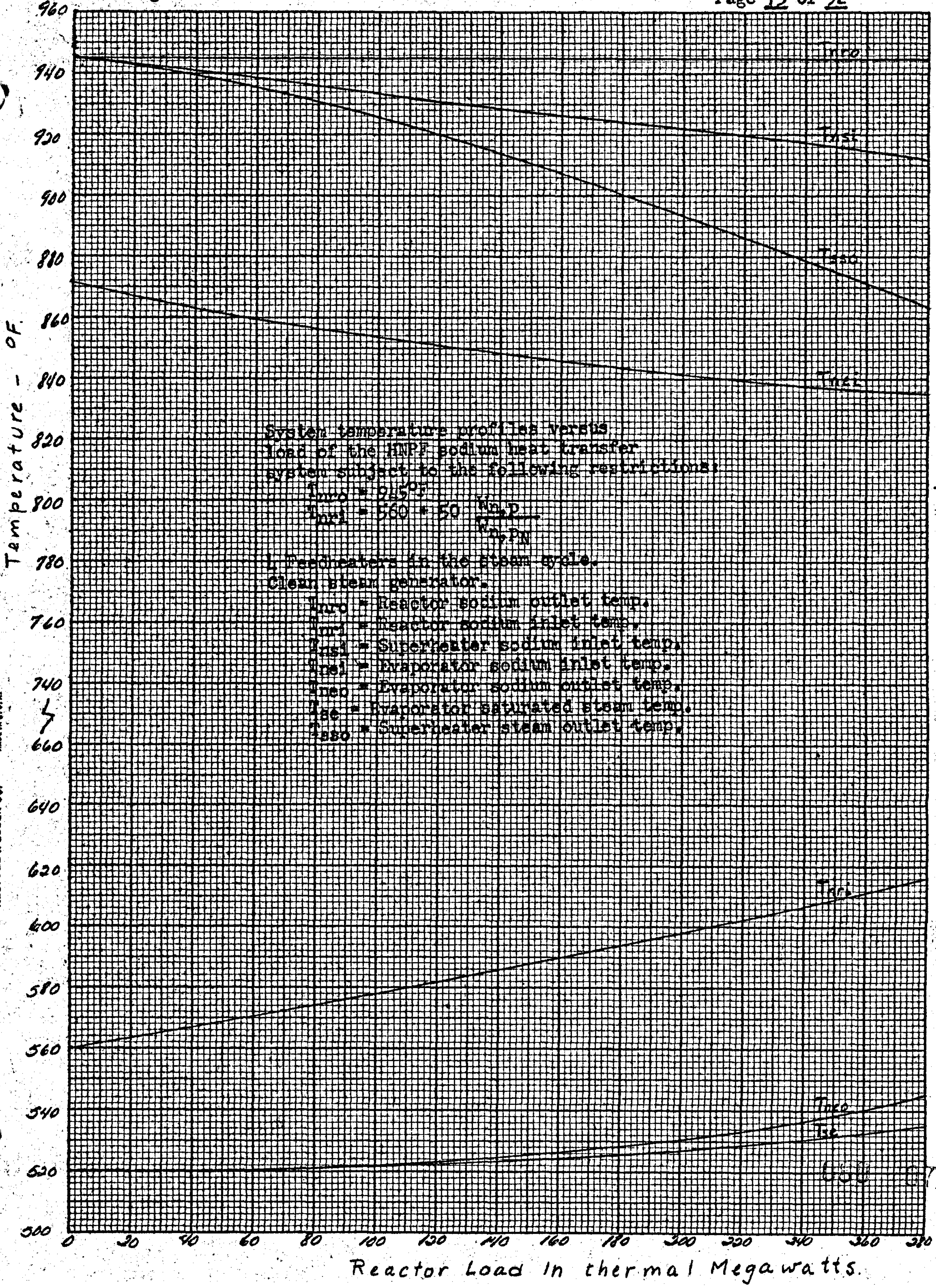
$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,pN}}$

3 Feedheaters in the steam cycle.
Clean steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_x = IHX heat transfer coefficient.

Figure 14a TEMPERATURE PROFILES



System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F

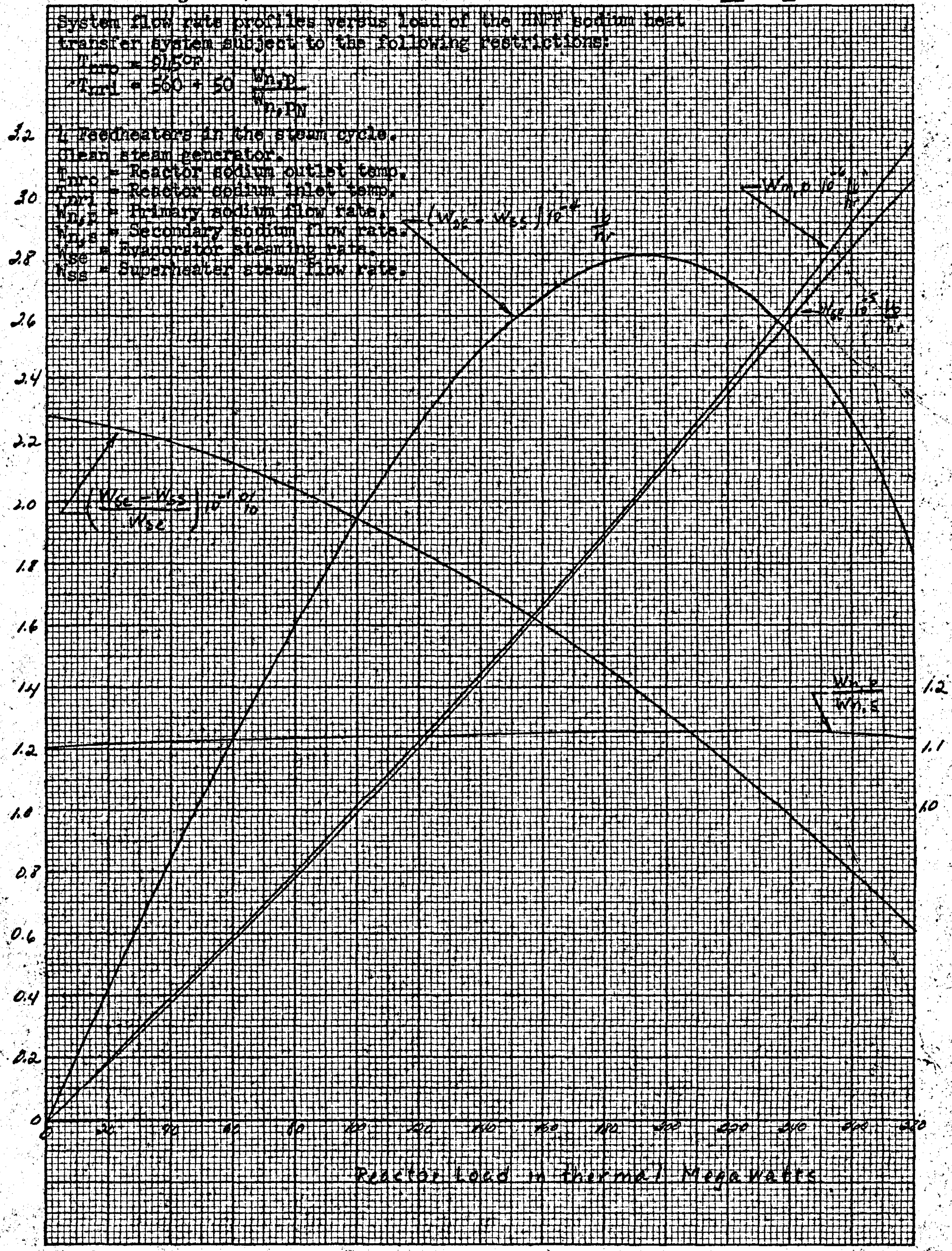
$T_{nri} = 560 + 50 \frac{W_{n,P}}{W_{n,PN}}$

4 Feedheaters in the steam cycle.

Clean steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.

Figure 14b



System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$

$T_{nri} = 560 + 50\ \frac{W_{n,p}}{W_{n,pN}}$

4 Feedheaters in the steam cycle.

Clean steam generator.

T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

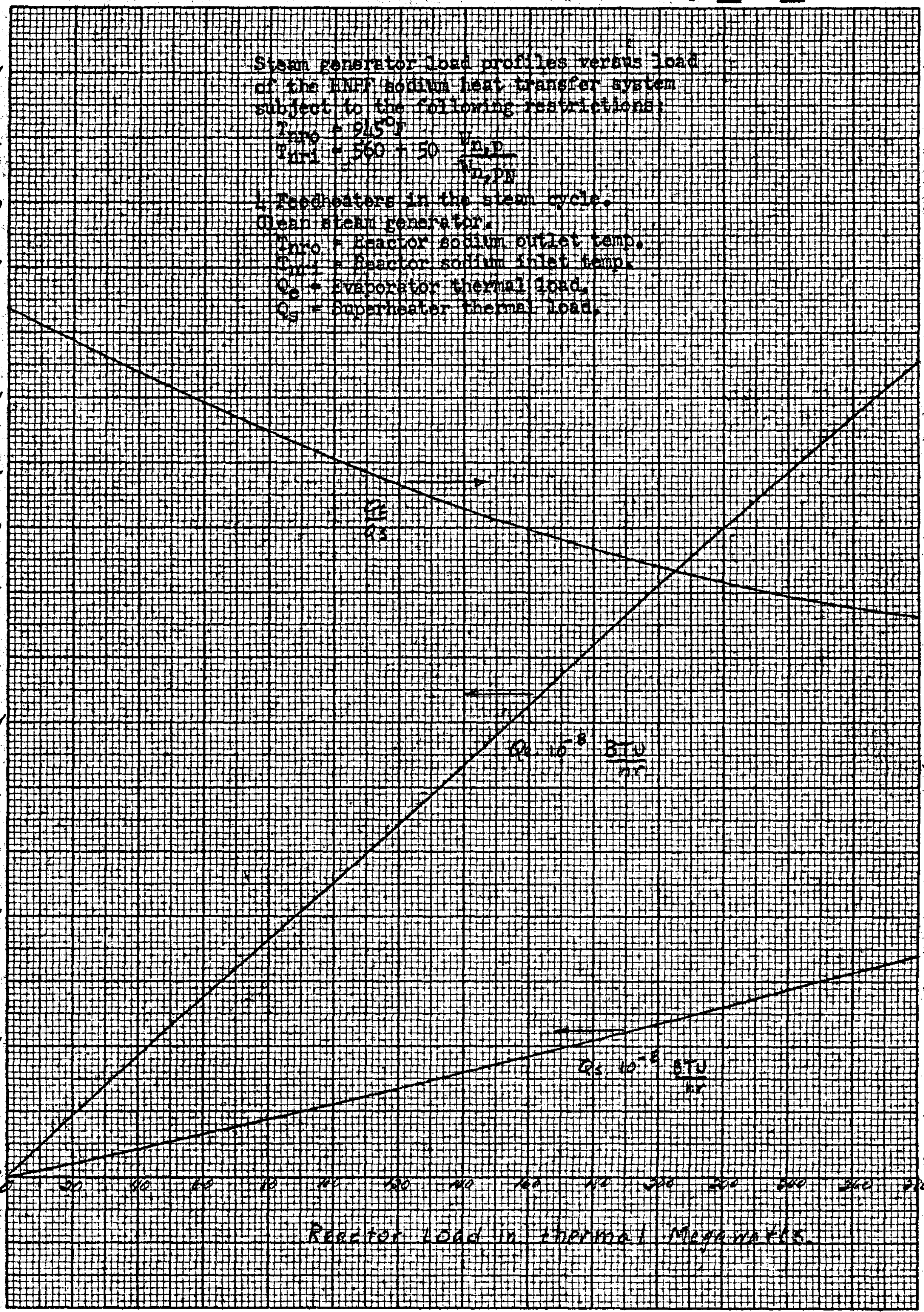
$W_{n,p}$ = Primary sodium flow rate.

$W_{n,s}$ = Secondary sodium flow rate.

W_{se} = Evaporator steaming rate.

W_{ss} = Superheater steam flow rate.

Figure 14c



Steam generator load profiles versus load of the ENFF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945^{\circ}F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,PN}}$

4 Feedheaters in the steam cycle.

Clean steam generator.

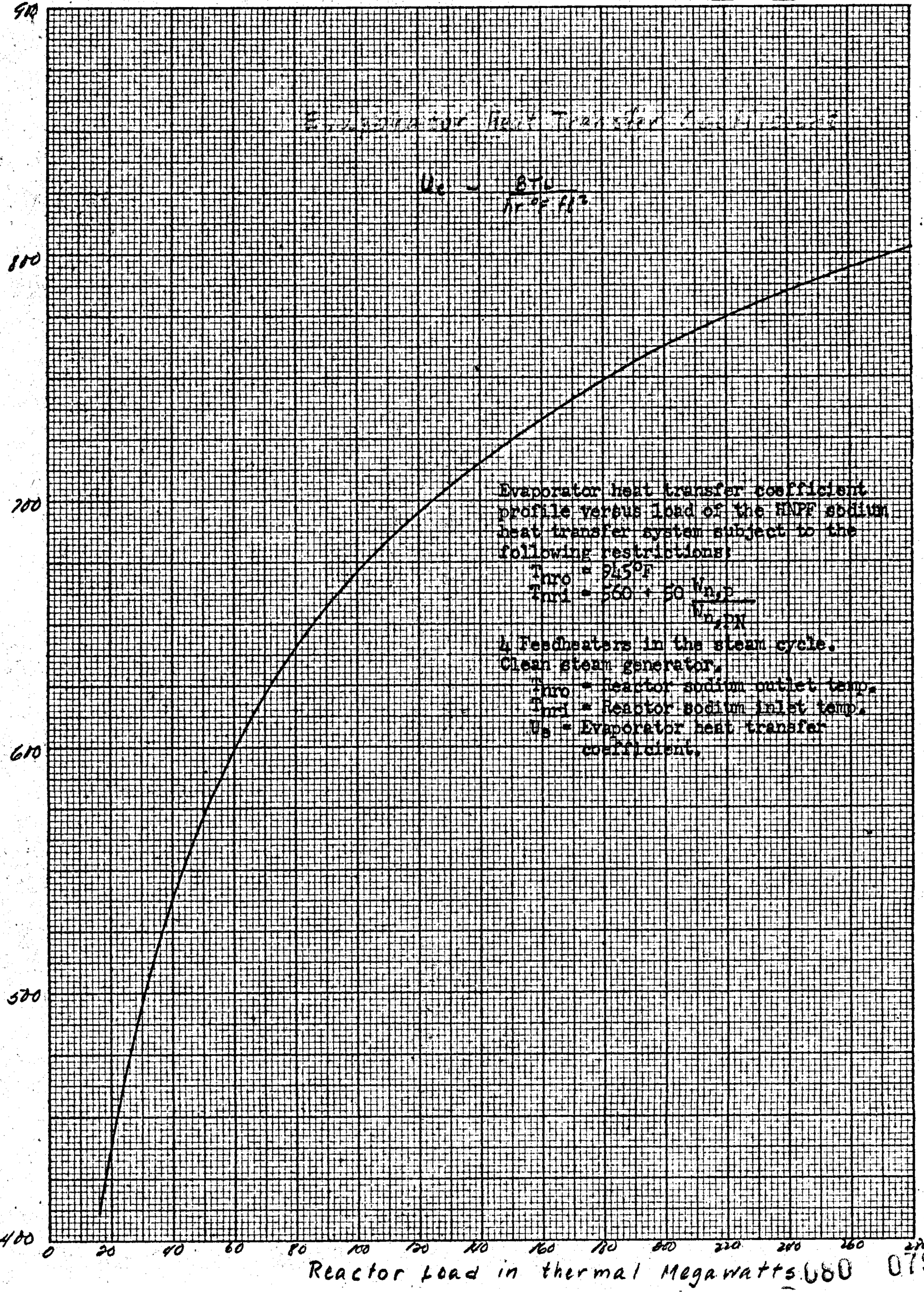
T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

Q_e = Evaporator thermal load.

Q_s = Superheater thermal load.

Figure 14d



Evaporator Heat Transfer Coefficient

$U_e = \frac{BTU}{hr\ °F\ ft^2}$

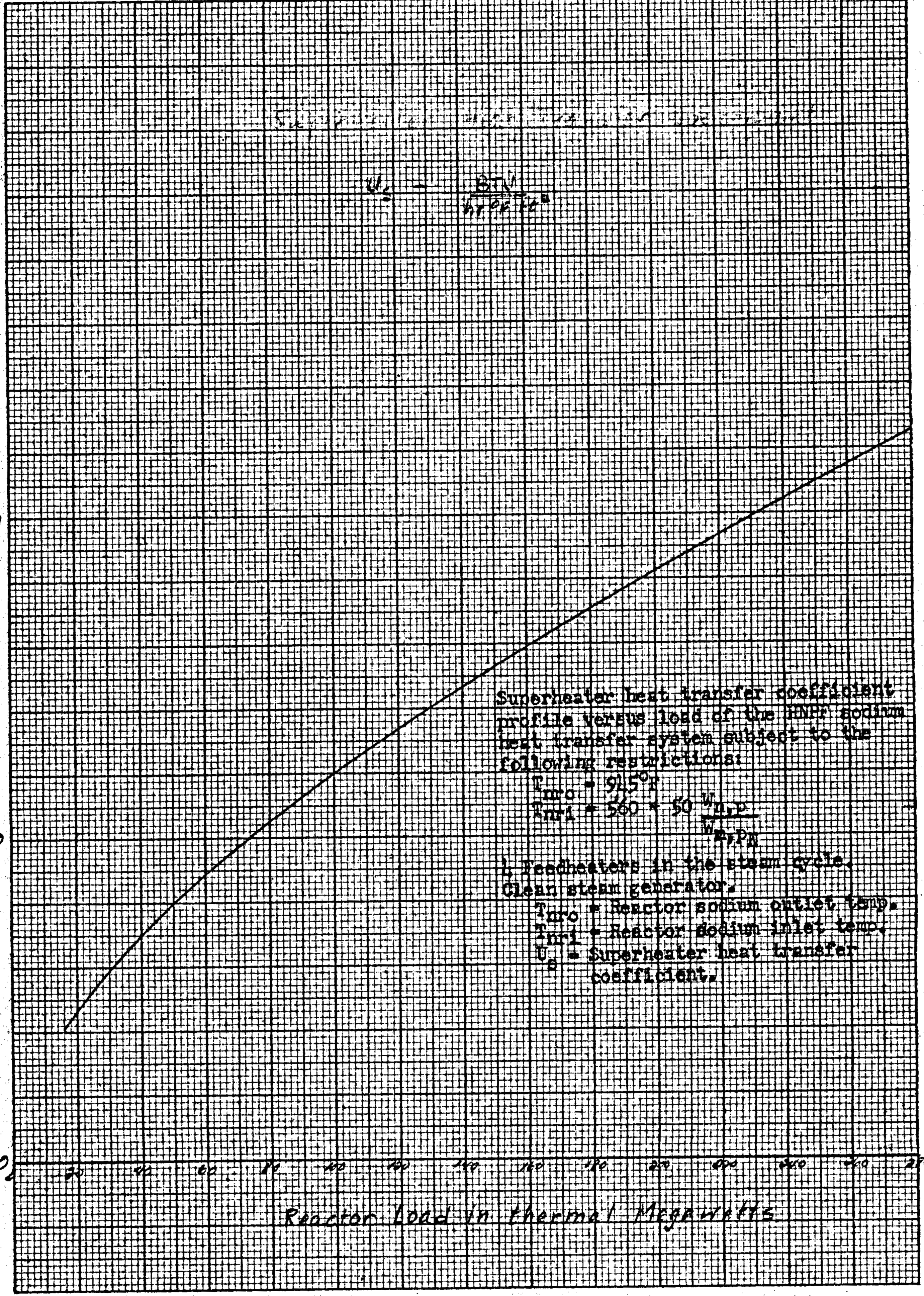
Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$
$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,PN}}$

4 Feedheaters in the steam cycle.
Clean steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 14e



Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

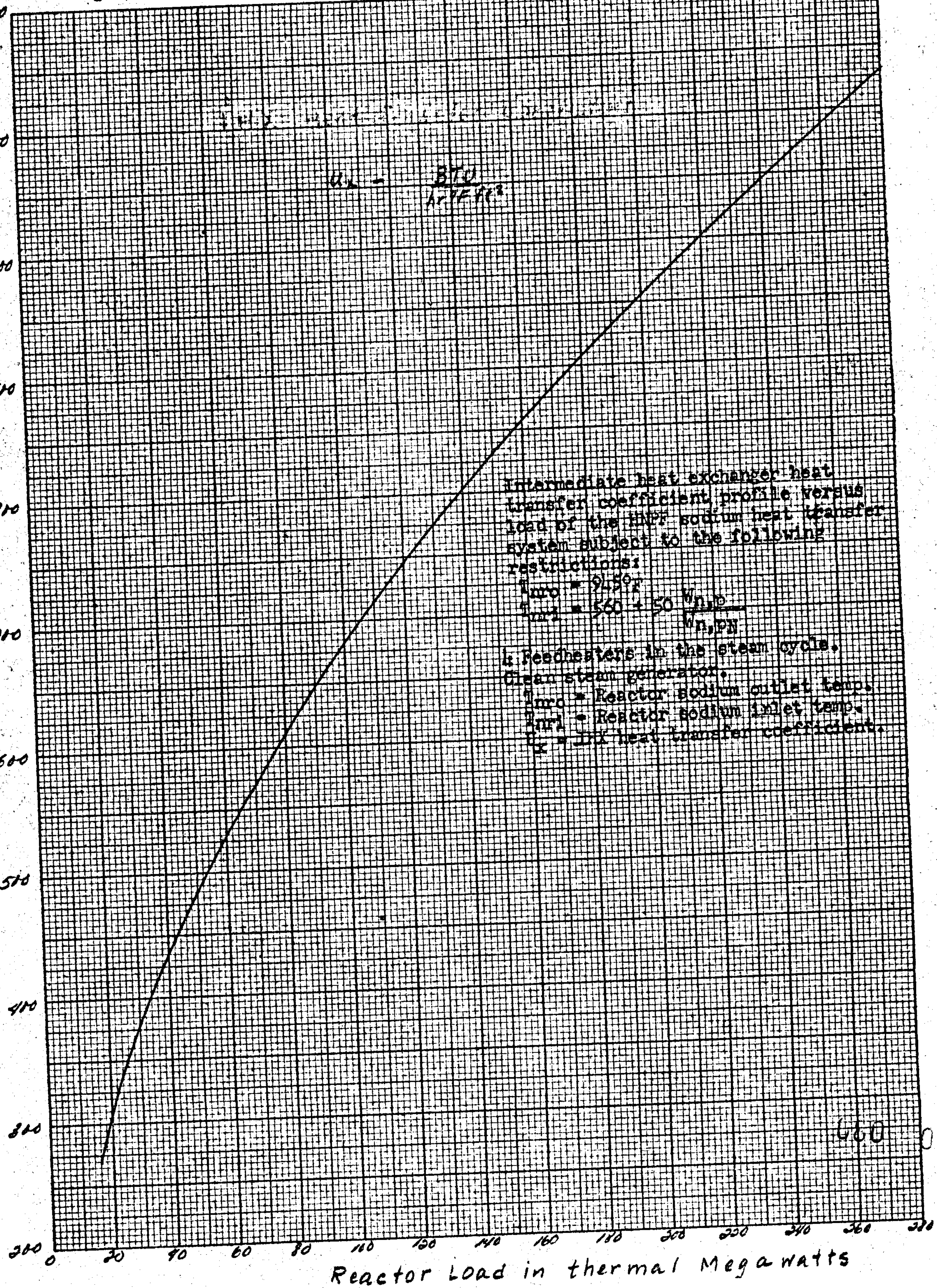
$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,P}}{W_{m,P_N}}$

4 Feedheaters in the steam cycle.
Clean steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_s = Superheater heat transfer coefficient.

Figure 14f



Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,PN}}$

4 Feedheaters in the steam cycle.

Clean steam generator.

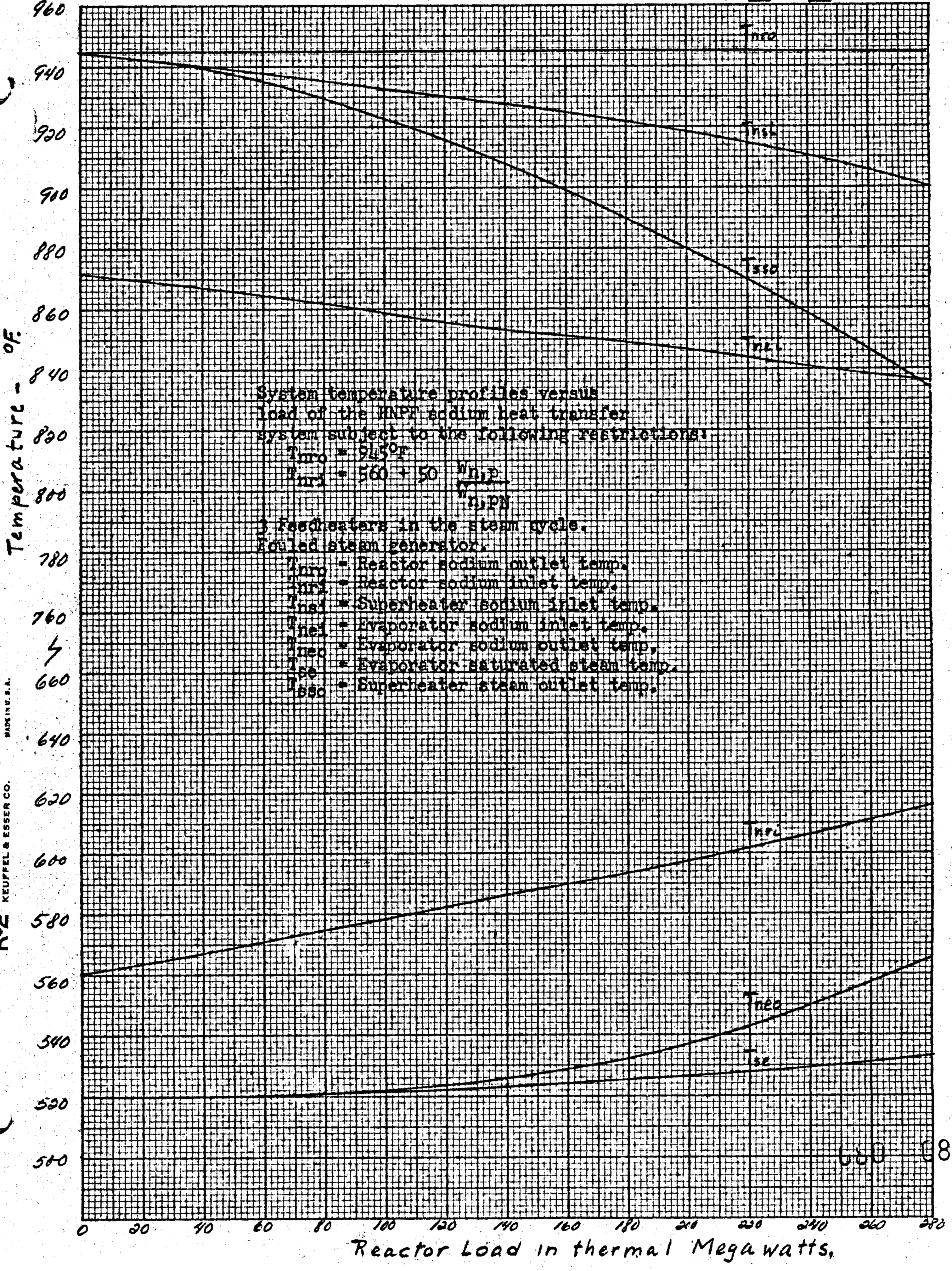
T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

U_x = IHX heat transfer coefficient.

Figure 15A

TEMPERATURE PROFILE



System temperature profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F

$$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,PN}}$$

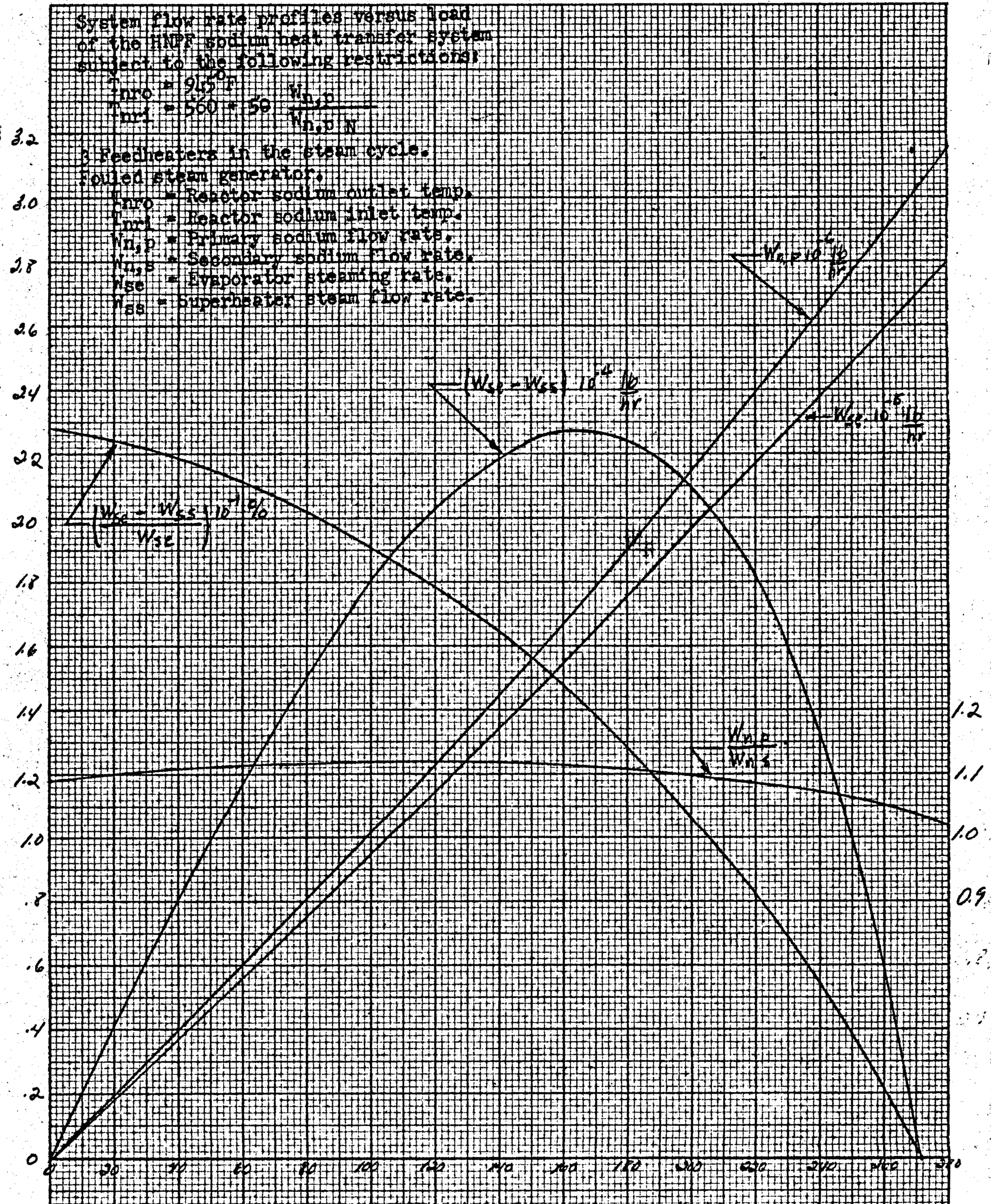
3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.

680 082

Figure 15b

FLOW RATE PROFILES



System flow rate profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945^{\circ}F$

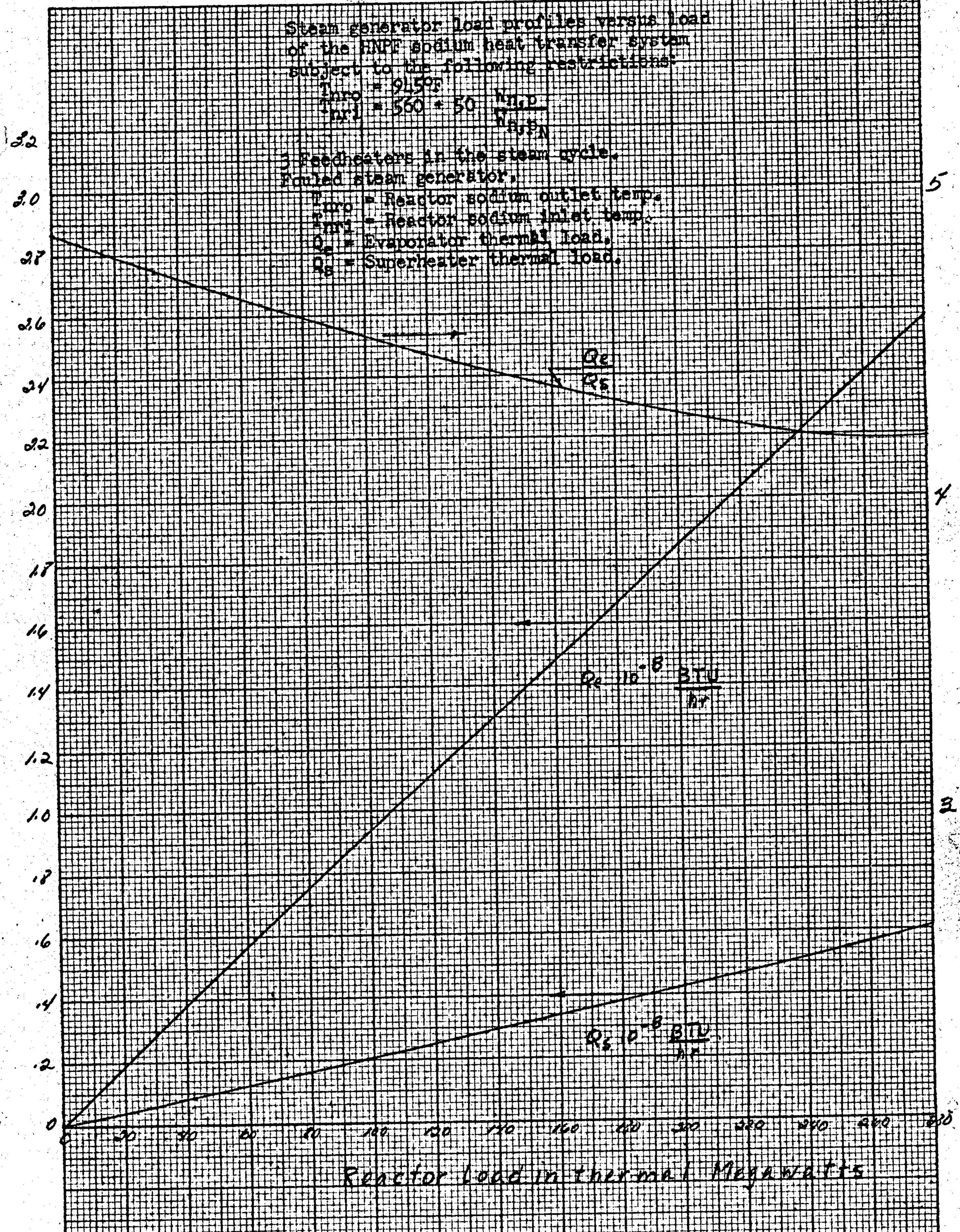
$T_{nri} = 560 + 59 \dfrac{W_{n,p}}{W_{n,p\,N}}$

3 Feedheaters in the steam cycle.

Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
$W_{n,p}$ = Primary sodium flow rate.
$W_{n,s}$ = Secondary sodium flow rate.
W_{se} = Evaporator steaming rate.
W_{ss} = superheater steam flow rate.

Figure 15c



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 915°F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,p_N}}$

3 Feedheaters in the steam cycle.

Fouled steam generator.

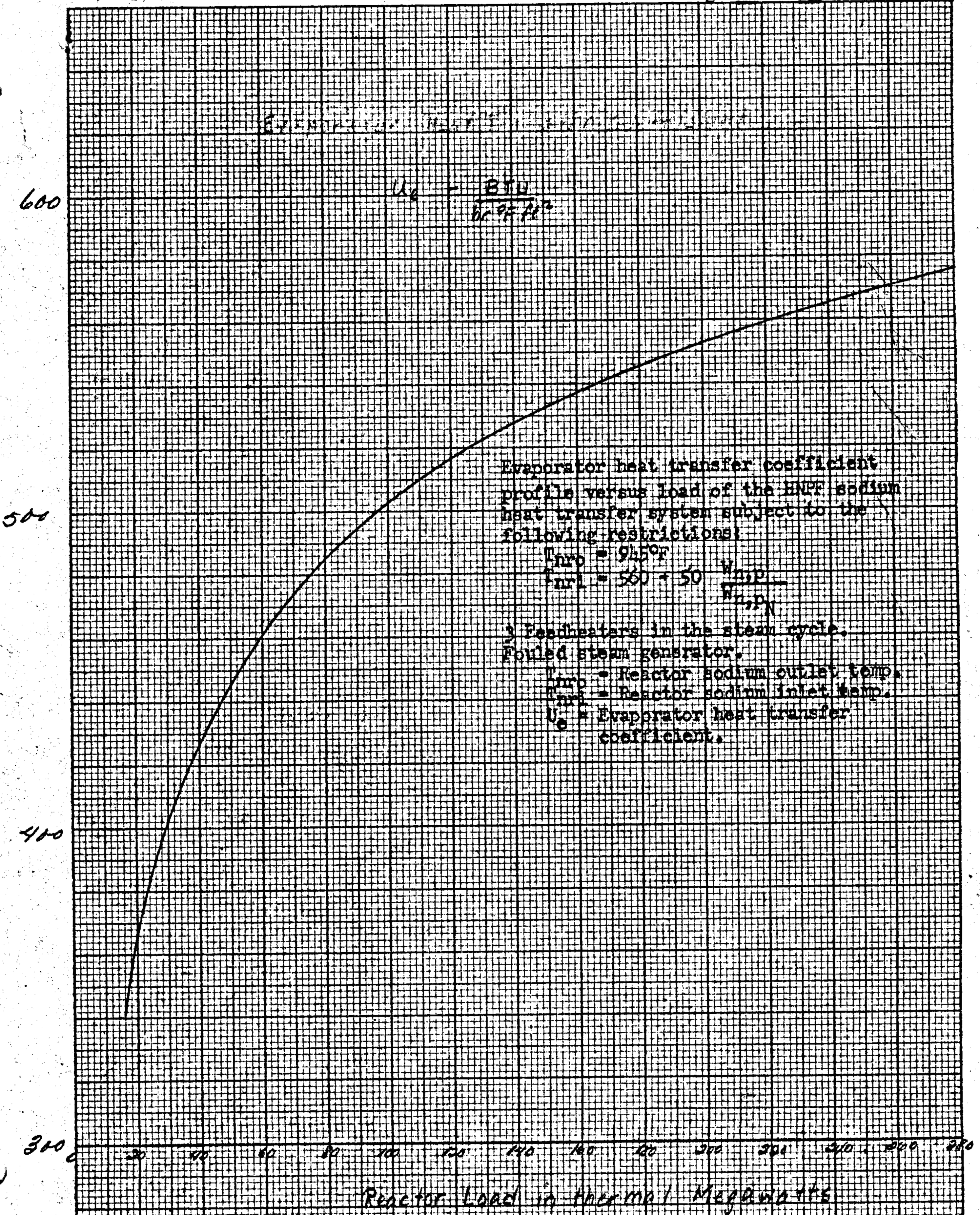
T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

Q_e = Evaporator thermal load.

Q_s = Superheater thermal load.

Figure 15d



U_e - $\frac{Btu}{hr\,°F\,ft^2}$

Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

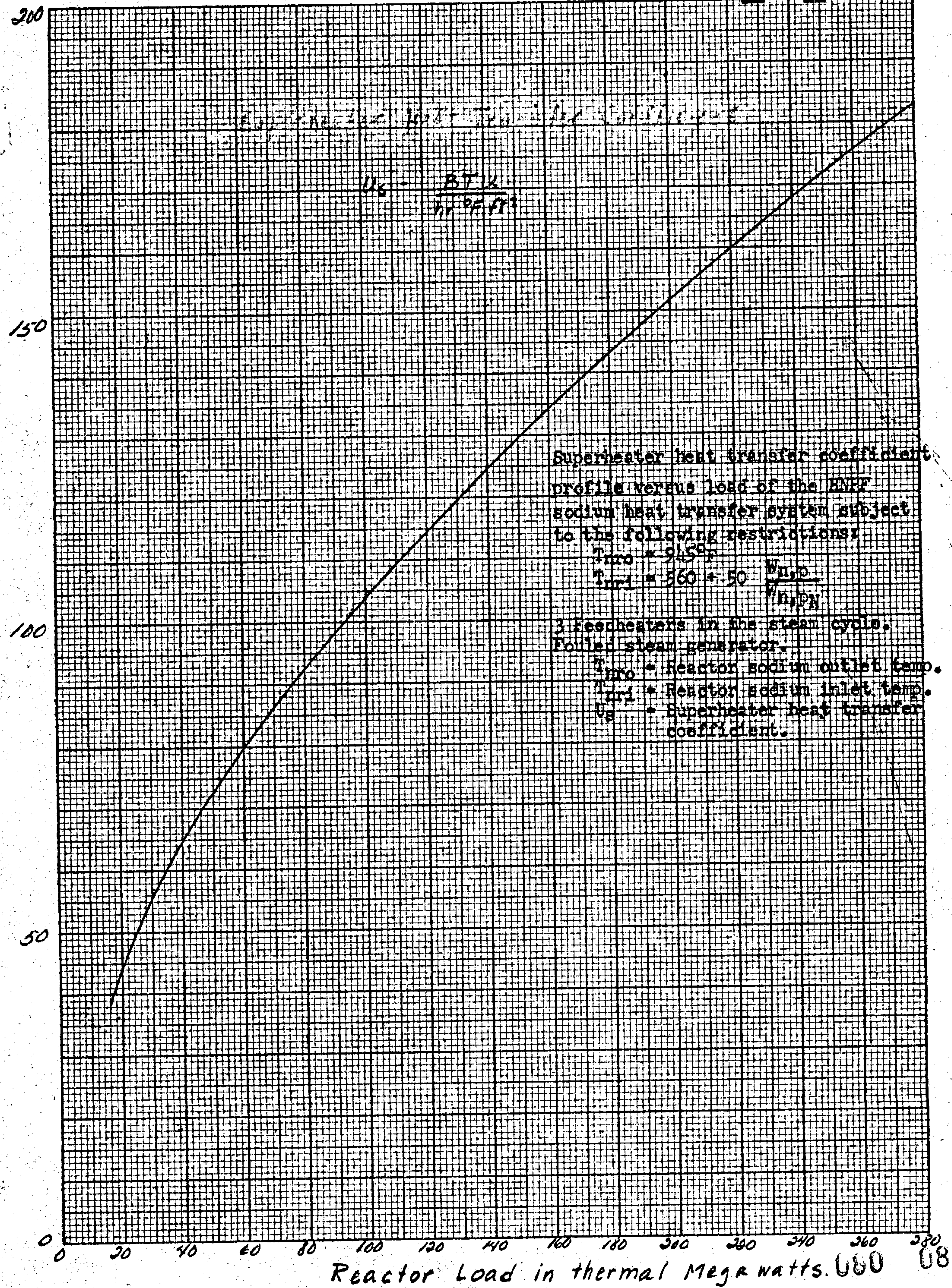
$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,p_N}}$

3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 15e

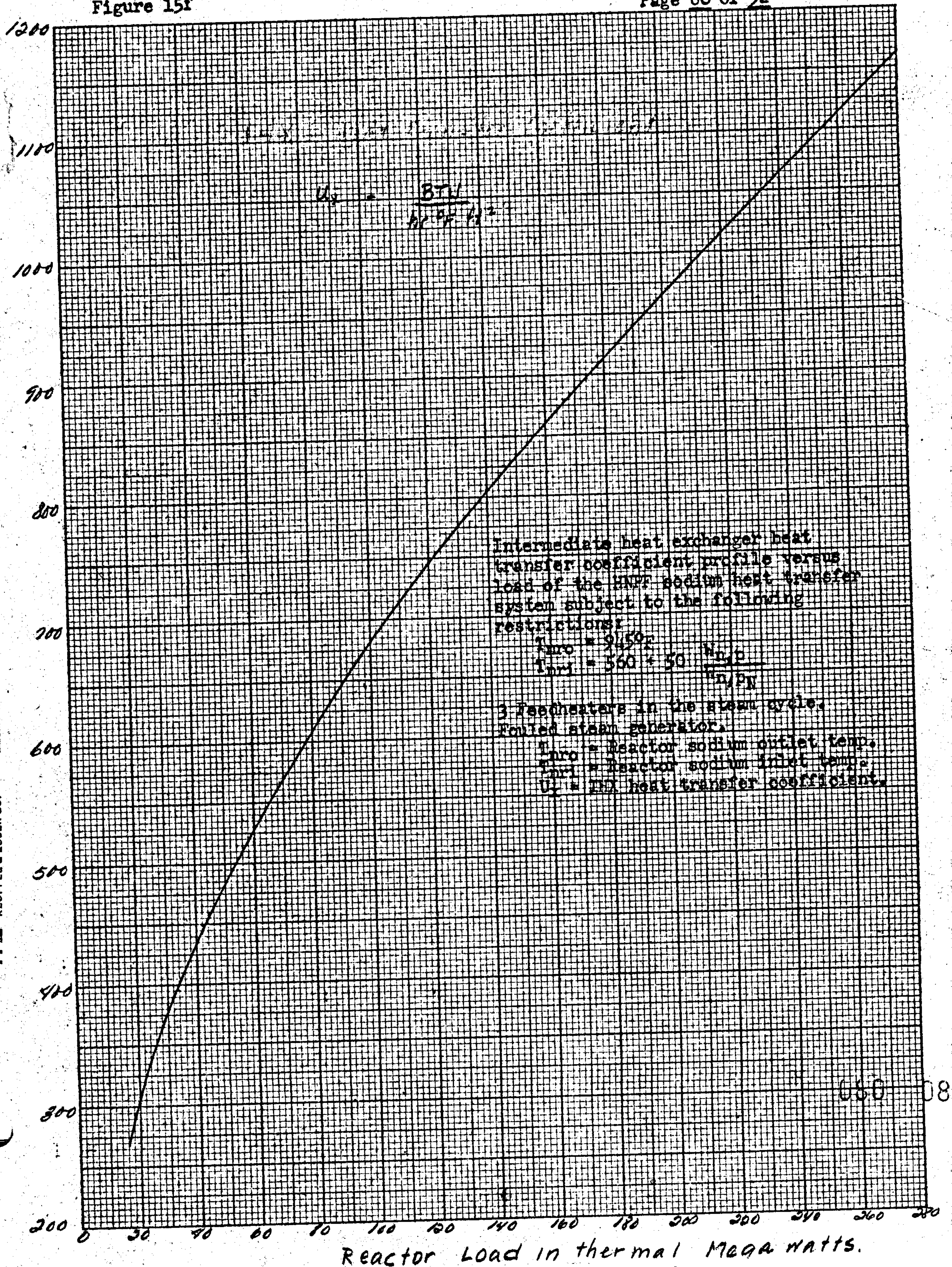


Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

T_{nro} = 945°F
T_{nri} = 560 + 50 $\frac{W_{n,p}}{W_{n,PN}}$

3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_s = Superheater heat transfer coefficient.



Intermediate heat exchanger heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

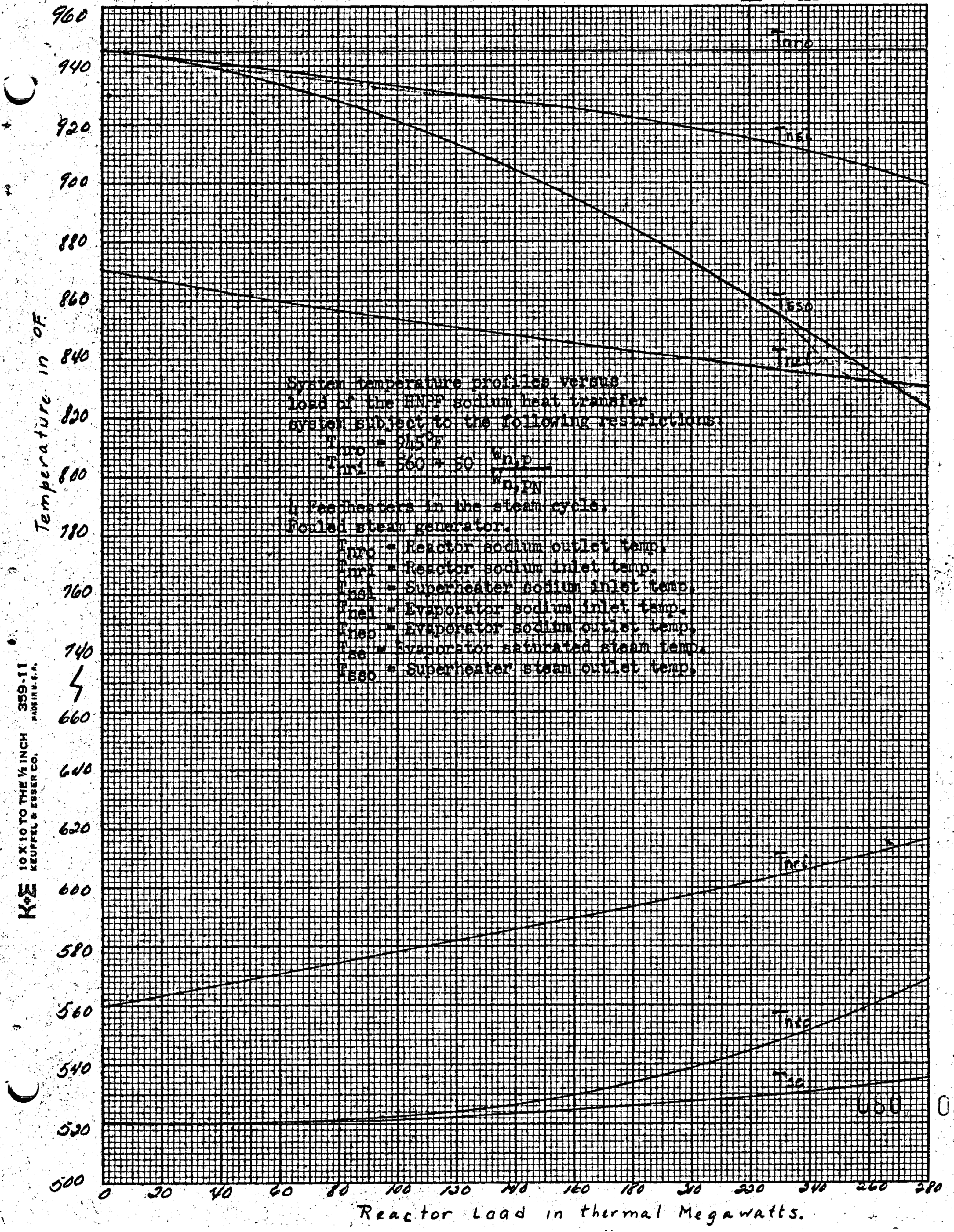
$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n/P}}{W_{n/P_N}}$

3 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_I = IHX heat transfer coefficient.

Figure 16a



System temperature profiles versus load of the ENPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{w_{n,p}}{w_{n,FN}}$

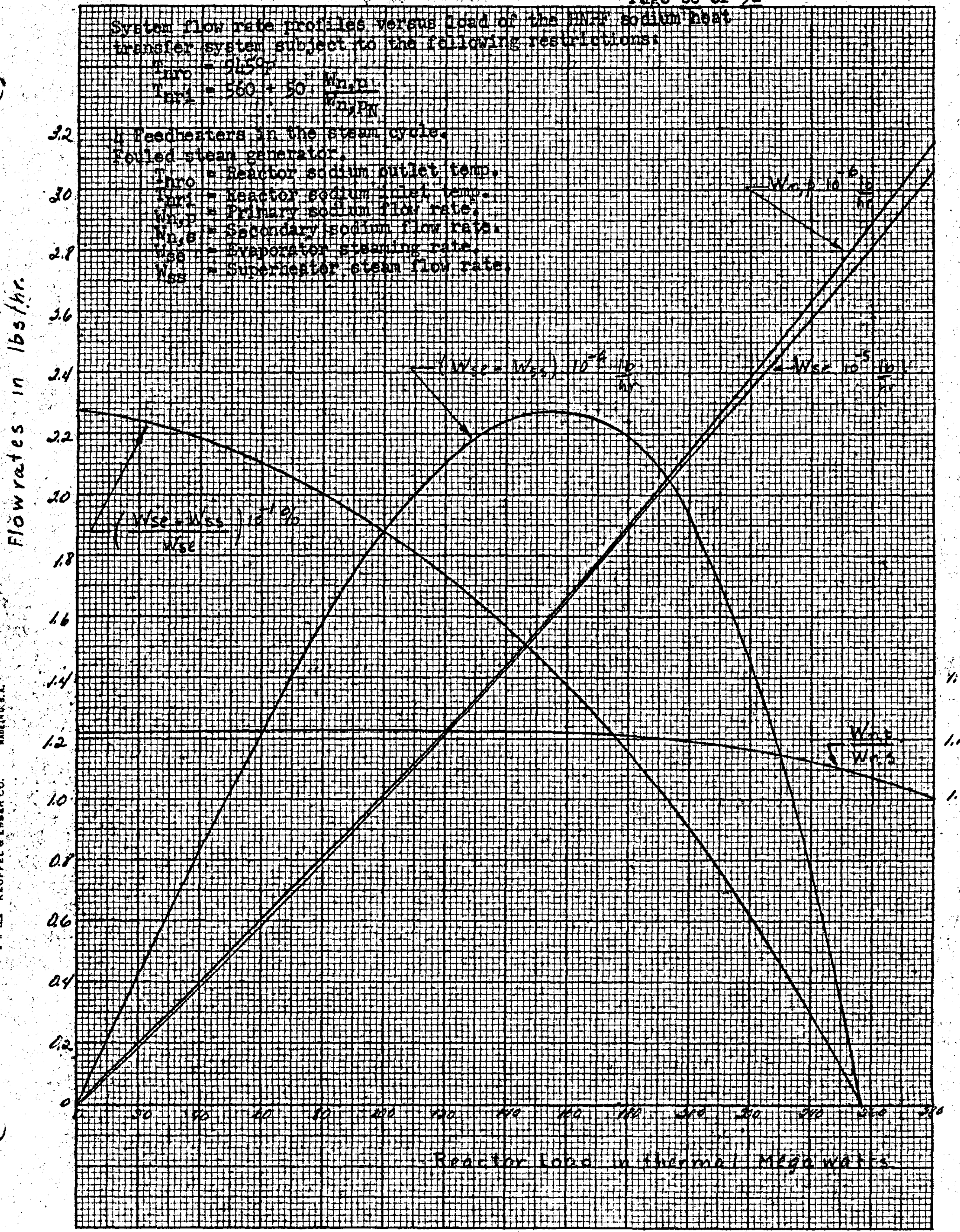
4 Feedheaters in the steam cycle.

Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
T_{nsi} = Superheater sodium inlet temp.
T_{nei} = Evaporator sodium inlet temp.
T_{neo} = Evaporator sodium outlet temp.
T_{se} = Evaporator saturated steam temp.
T_{sso} = Superheater steam outlet temp.

060 08

Figure 16b



System flow rate profiles versus load of the ENRF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,pN}}$

4 Feedheaters in the steam cycle.

Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

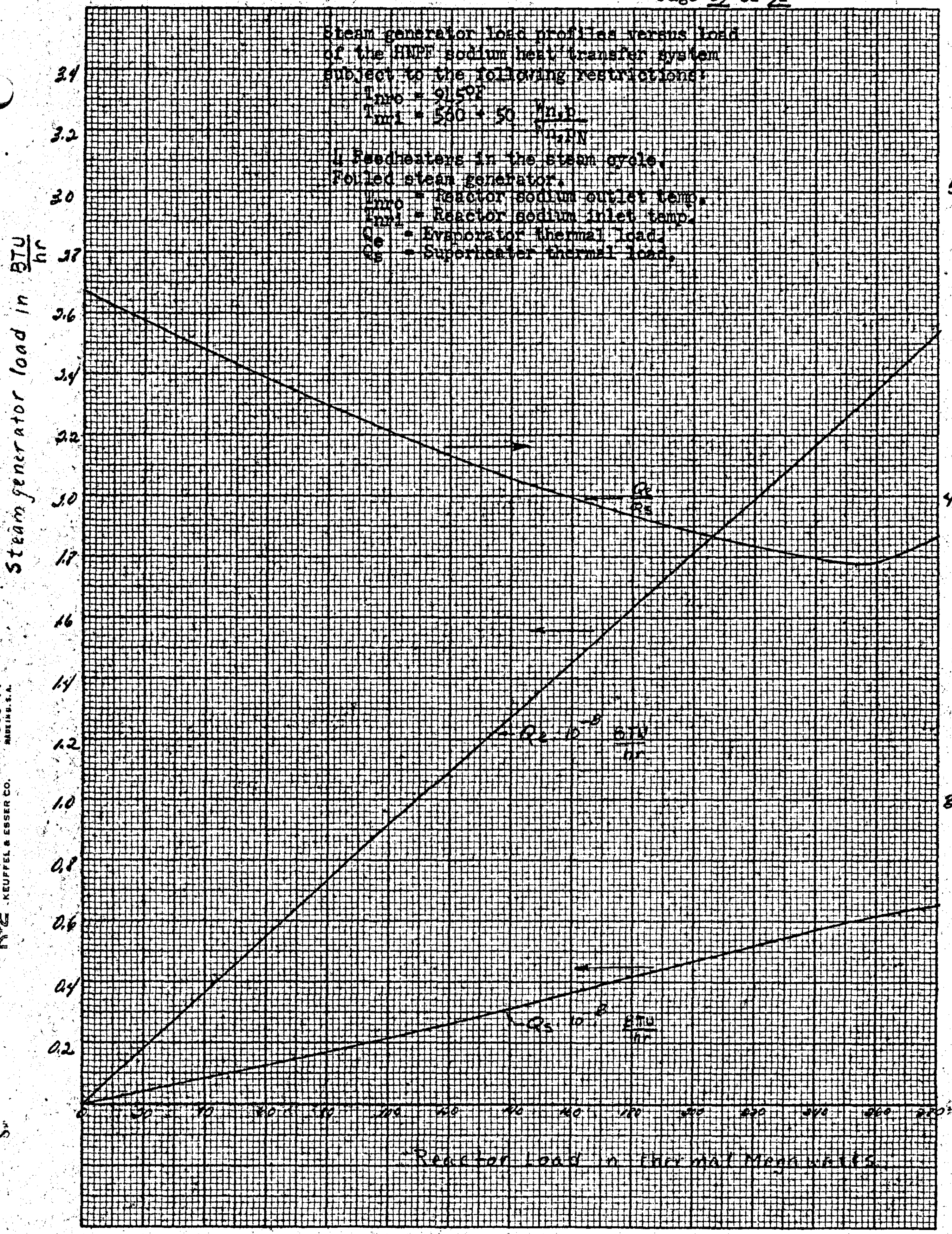
$W_{n,p}$ = Primary sodium flow rate.

$W_{n,s}$ = Secondary sodium flow rate.

W_{se} = Evaporator steaming rate.

W_{ss} = Superheater steam flow rate.

Figure 16c



Steam generator load profiles versus load of the HNPF sodium heat transfer system subject to the following restrictions:

$T_{nro} = 915°F$

$T_{nri} = 580 + 50 \frac{W_{n,p}}{W_{n,FN}}$

4 Feedheaters in the steam cycle.

Fouled steam generator.

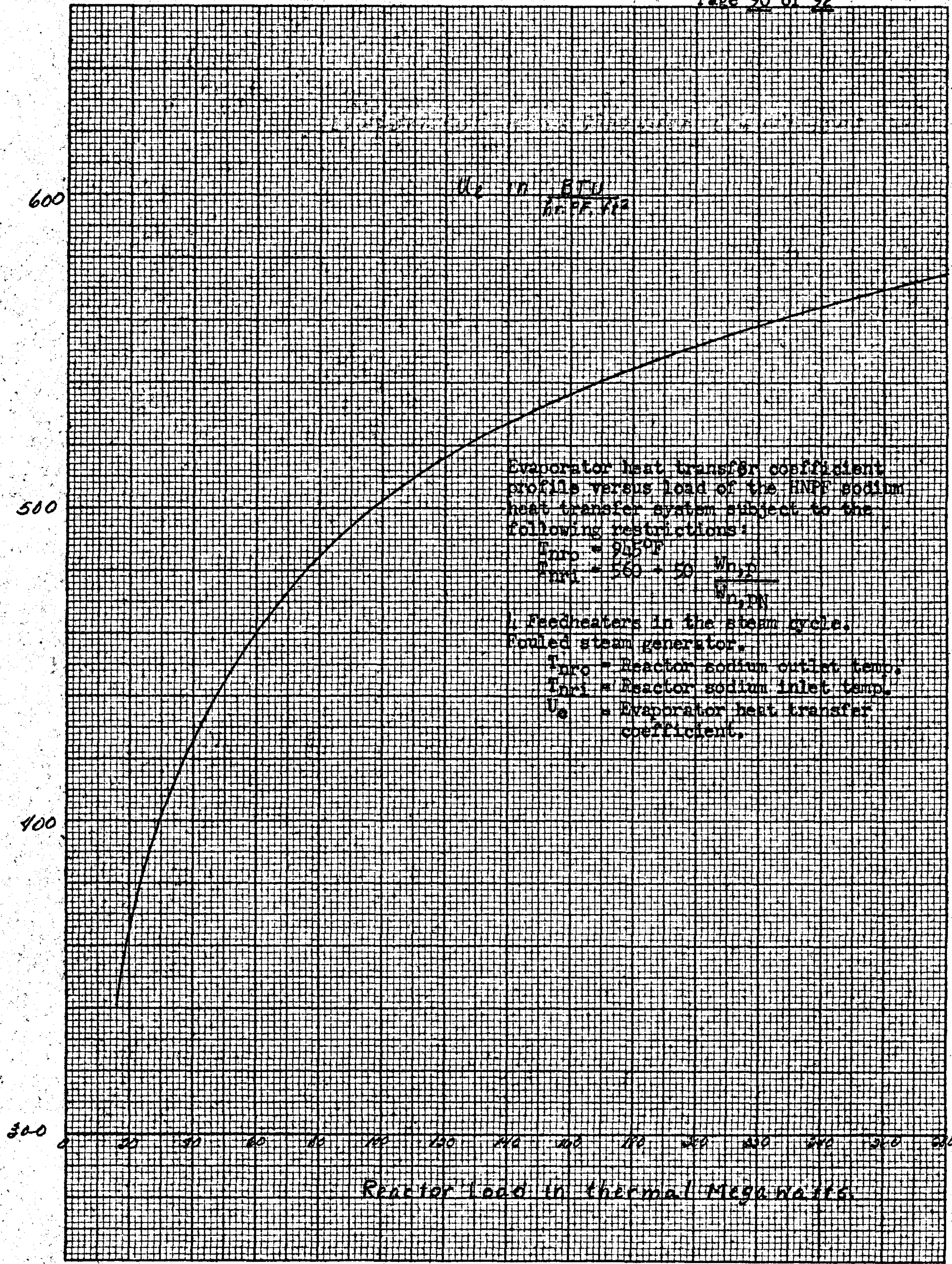
T_{nro} = Reactor sodium outlet temp.

T_{nri} = Reactor sodium inlet temp.

Q_e = Evaporator thermal load.

Q_s = Superheater thermal load.

Figure 16d



Evaporator heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

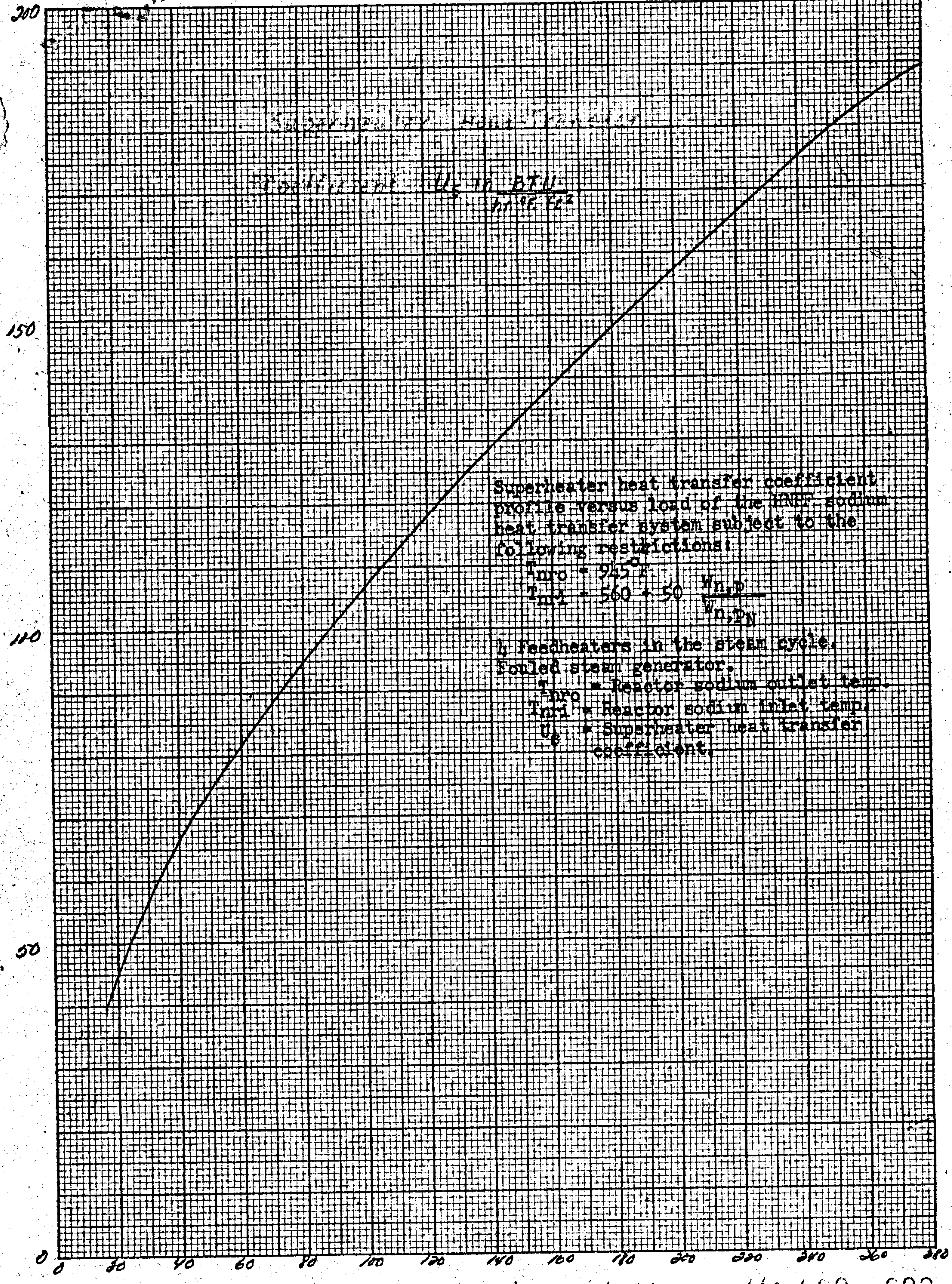
$T_{nro} = 945^{\circ}F$

$T_{nri} = 560 + 50 \frac{W_{n,p}}{W_{n,DN}}$

4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_e = Evaporator heat transfer coefficient.

Figure 16e



Superheater heat transfer coefficient profile versus load of the HNPF sodium heat transfer system subject to the following restrictions:

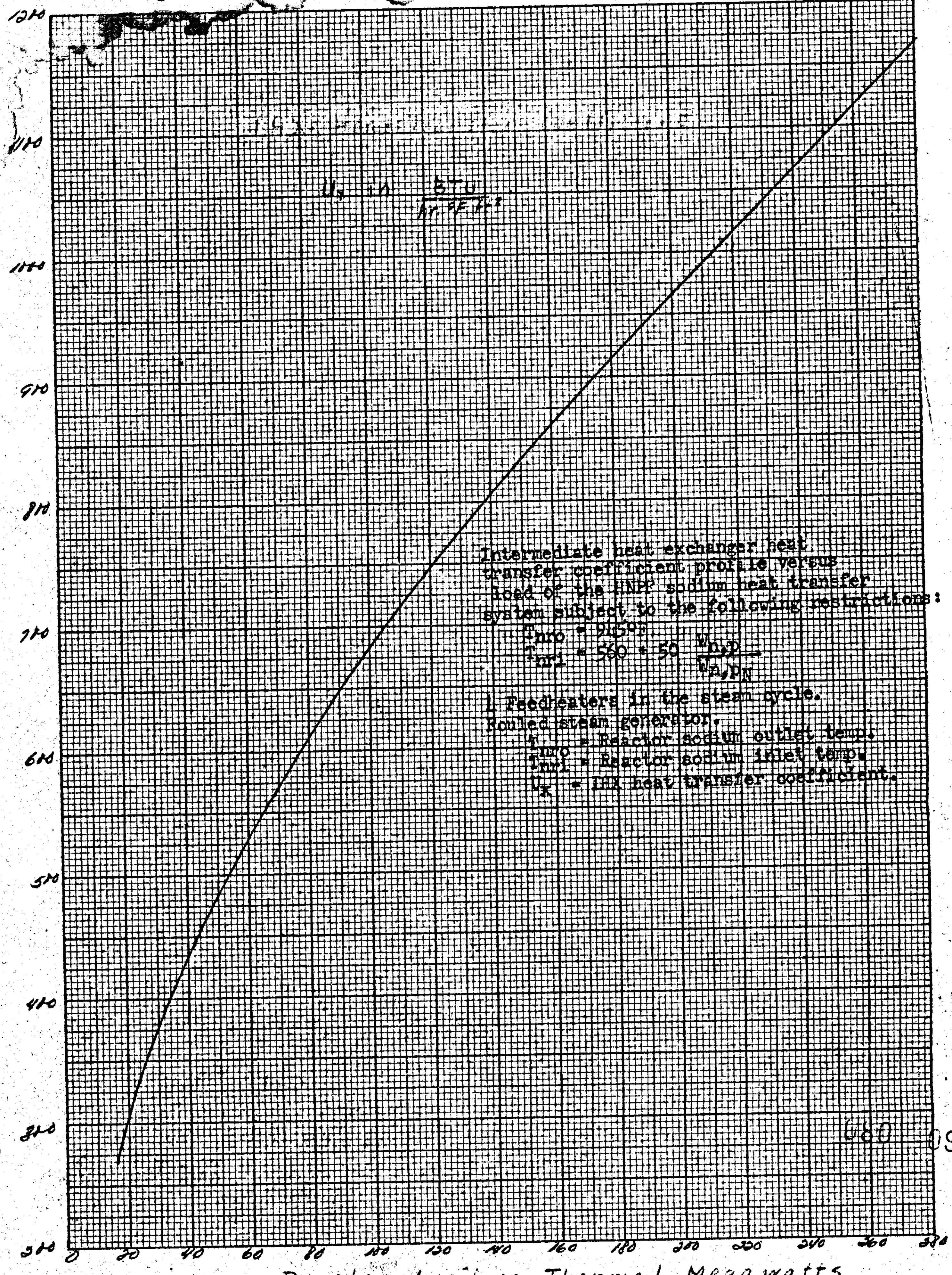
$T_{nro} = 945°F$

$T_{nri} = 560 + 50 \frac{W_{n,P}}{W_{n,P_N}}$

4 Feedheaters in the steam cycle.
Fouled steam generator.

T_{nro} = Reactor sodium outlet temp.
T_{nri} = Reactor sodium inlet temp.
U_6 = Superheater heat transfer coefficient.

Figure 16f



Intermediate heat exchanger heat
transfer coefficient profile versus
load of the HNPF sodium heat transfer
system subject to the following restrictions:

$T_{hro} = 950°F$

$T_{hri} = 560 + 50 \frac{W_{n,P}}{W_{n,PN}}$

1 Feedheaters in the steam cycle.
Rouled steam generator.

T_{hro} = Reactor sodium outlet temp.

T_{hri} = Reactor sodium inlet temp.

U_K = IHX heat transfer coefficient.