General Electric Advanced Technology Manual

Chapter 2.2

Core Heat Balance

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Learning Objectives

1. Explain what the core heat balance is used for.

2. List the three methods that can be used to obtain core thermal power.

3. List the parameters used in a heat balance calculation and indicate the most critical parameter.

2.2.1 Introduction

The thermal power of the reactor core is determined by a heat balance on the nuclear boiler using operating data.   Under steady state conditions, the nuclear boiler heat output is obtained as the difference between the total heat removed from the boiler system minus the total heat added in the flow streams returning to the boiler.

A core heat balance in the power range, greater than or equal to 10% power, is made to ensure that the core is operated at all times within licensed thermal limitations and/or fuel warranty requirements.   The results of heat balance calculations also provide input to additional core calculations (i.e., CPR & LHGR).

2.2.2 Methods of Calculation

Four methods of calculating the energy output of the core by heat balance are used:

-   Short Form Method - used when a fast estimate is needed and a high degree of accuracy is not essential.

-   Long Form Method - considers all heat losses and additions.

-   Process Computer - Normal calculational method.

-   Off-line Computer

Either the manual long form method or the off-line computer method is required when the process computer is unavailable.   This instruction covers the manual method long form and is addressed in NRC "Inspection and Enforcement Manual" chapter (IMC), 61706B.

The core thermal power is obtained by writing an energy balance on a system composed of the reactor vessel, recirculation loop piping, and cleanup demineralizer piping.   Flows entering the system are the reactor feedwater flow and the control rod drive system flow.

The only flow assumed to be leaving the system is the primary steam flow.   Non-flow power losses are the radioactive power loss and the net power transferred across the boundary of the cleanup demineralizer loop.

Figure 2.2-1 is a schematic diagram of the energy inputs and outputs to be evaluated. Mathematically, the heat balance equation is derived as follows:

The heat outputs from the system include:

Main Steam = m_{MS} x h_{MS} (equation A)

Cleanup System = m_{CU} x $(h_{in} - h_{out})$ (equation B)

$\qquad$ Where: $m_{CU} = m_{CU(A)} + m_{CU(B)}$

Fixed Losses = Q_{FL} (equation C)

The heat inputs to the system include:

Feedwater = m_{FW} x h_{FW} (equation D)

CRD Hydraulic = m_{RD} x h_{RD} (equation E)

Recirculation Pumps = Q_P (equation F)

Core Power = Q_C (equation G)

Since the measurement of main steam flow is normally much less accurate than the measurement of feedwater flow, and since this is a closed system, let:

m_{MS} $= m_{FW}$ + m_{RD} (equation H)

Substituting Equation H into Equation A:

Main Steam = h_{MS} x $(m_{FW}$ + $m_{RD})$ (equation I)

The total heat outputs are therefore:

Outputs = $K[h_{MS} (m_{FW} + m_{RD}) + m_{CU} (h_{in} - h_{out})] + Q_{FL}$ (equation J)

The total heat inputs are therefore:

Heat Inputs = $K[(m_{FW}$ x $h_{FW}) + (m_{RD}$ x $h_{RD})] + Q_P + Q_C$ (equation K)

Since the heat inputs must equal the heat outputs, equation J is set to equation K:

$K[(m_{FW}$ x $h_{FW}) + (m_{RD}$ x $h_{RD})] + Q_P + Q_C = K[h_{MS} (m_{FW} + m_{RD}) + m_{CU} (h_{in} - h_{out})] + Q_{FL}$

(equation L)

Solving Equation L for Core Power:

$$Q_C = K [h_{MS} (m_{FW} + m_{RD}) + m_{CU} (h_{in} - h_{out}) - m_{FW}h_{FW} - m_{RD}h_{RD}] + Q_{FL} - Q_P \qquad \text{(equation M)}$$

Combining all terms and rearranging yields the equation representing total Core Thermal Power:

$$Q = K[m_{.FW} (h_{MS} - h_{FW}) + m_{.RD} (h_{MS} - h_{RD}) + m_{CU} (h_{in} - h_{out})] + Q_{FL} - Q_P \qquad \text{(equation N)}$$

Where:

Q_c = Core thermal power (MWt)

K = 2.93 x 10-7 MWt-hr/BTU

m_{FW} = Feedwater Flow (lbs/hr)

m_{RD} = Control rod drive flow (lbs/hr)

m_{CU} = Clean-up System flow (lbs/hr)

h_{MS} = Enthalpy of main steam (BTUlb)

h_{FW} = Enthalpy of feedwater (BTU/lb)

h_{RD} = Enthalpy of control rod drive flow (BTU/lb)

h_{in} = Enthalpy of inlet flow to cleanup system (BTU/lb)

h_{out} = Enthalpy of return flow from cleanup system (BTU/lb)

Q_{FL} = Fixed Losses (MW) = 0.6 MW

Q_P = Recirculation pump work (7.6 MW)

For the case in which an estimate of this value is desired rapidly, the curves of Figure 2.2-2 may be used.   These curves are based upon a simplification of equation N of the form:

$$Q_c = K [m_{FW} (h_{MS} - h_{FW})] \quad + \quad \text{Constant} \qquad \text{(equation 0)}$$

The above constant is composed of all the small heat input and output terms that complete the thermal energy balance.   It is defined as:

$$\text{Constant} = K [m_{RD} (h_{MS} - h_{RD}) + m_{CU} (h_{in} - h_{out}) + Q_{FL} - Q_P \qquad \text{(equation P)}$$

2.2.3 Heat Balance Calculation Problem

Table 2.2-1 includes a practice problem for performing a core heat balance.   Using the values on form TI 1.1 of the table and the attached steam tables, calculate the core thermal power.

2.2.3.1 Assumptions

Core thermal power is equal to or greater than 329 MWt (10% power)

Reactor Water Cleanup system flow is directed back to the reactor.

Exponents - powers of 10 are compensated for in the formula derivations or are specifically indicated.

Assume atmospheric pressure is 15 psia.

Check results against the nomograph.

2.2.4 Licensed Power Level

The following is the text of an internal NRC letter from Mr. E. L. Jordon (Director, Office of I&E, August 22, 1980) to the Branch Chiefs of Reactor Operations in each Region. The letter provides guidance to inspectors for determining licensee compliance with Licensed Power limits.   This guidance is still in effect today.   A copy of the letter can be found in the Document Control System:

Dating back to at least 1974, there have been many lengthy "discussions" regarding the exact meaning of "full, steady-state licensed power level" (and similarly worded power limits).   We do not believe the real safety benefits that might be derived from an NRC-wide agreement would be worth the further expenditure of manpower in meetings, etc, which would be required to achieve a consensus.

We do realize that some common uniform basis for enforcing maximum licensed power is needed by I&E inspectors.   Therefore, until and unless an NRC-wide position is put for-ward and agreed upon (and as stated, I&E does not propose to initiate proceedings to that end), I&E will use the following guidance:

The average power level over any eight hour shift should not exceed the "full steady-state licensed power level" (and similarly worded terms).   The exact eight hour periods defined as "shifts" are up to the plant, but should not be varied from day to day (the easiest defini-tion is a normal shift manned by a particular "crew").   It is permissible to briefly exceed the "full, steady-state licensed power level" by as much as 2% for periods as long as 15 minutes.   In no case should 102% power be exceeded, buy lesser power "excursions" for longer periods should be allowed, with the above as guidance (i.e., 1% excess for 30 minutes, 1/2% for one hour, etc., should be allowed).   There are no limits on the number of times these "excursions" may occur, or the time interval that must separate such "excursions", except note that the above requirement regarding the eight hour average

power will prevent abuse of this allowance.   The above is considered to be within the licensing basis and, therefore, acceptable to us, and it is also fair to the utilities and their ratepayers.

2.2.5   100% Power Exceeded Examples

Core thermal power for nuclear power plants is controlled on the basis of a licensed thermal power rating. Nuclear instruments and plant calorimetrics are used to monitor reactor power. The accuracy of the calorimetric power determination (heat balance)is sensitive to several measurements, but is most affected by feedwater flow measurement accuracy. Thus, an accurate determination of core thermal power hinges on the accurate knowledge of feedwater flow.

Two nonconservative errors in feedwater flow measurement led to power in excess of the licensed thermal power limit at FitzPatrick.   The feedwater flow transmitters were replaced on October 3, 1988, but were not calibrated properly.   The calibration was completed on November 14, 1989.   When more accurate transmitters were placed in service on January 29, 1990, the power level was found to exceed the licensed limit. Power was immediately reduced.   Flow element vendor input errors have since been identified and corrected.

Operation in excess of the thermal power limit occurred at Oyster Creek on May 11, 1990 and again on August 1, 1990.   The first event occurred because of a miscalculation in the plant heat balance equation.   The second event, August 1, 1990, was a result of feedwater flow calibration calculation which was approximately 2% in the nonconservative direction.

Operation in excess of the thermal power limit occurred at Cooper Nuclear Station from 1980 to April 1994, at those times when the reactor was operated at full power.   The actual reactor power was approximately 2400 MWt while the calculated power level was 2381 MWt.   This was attributed to the licensee not compensating for an error in the calibration of the pressure transmitters used for feedwater flowrate determination.

On July 16, 1993, a NRC Resident Inspector reviewed WNP-2 procedure for Manual Core Heat Balance.   The procedure was found to be inadequate in that it directed data to be taken form total Reactor Water Cleanup flow by using computer data points which did not reflect the actual flow through the bypassed RWCU demineralizers.   This error allowed a nonconservative value for the calculation of core thermal power.

The common link in all of these cases is that there was no indication of a problem until an independent means of measurement or calculation was employed. The existing feedwater flow measurement instrumentation, for most BWR plants, consists of a differential pressure transmitter providing an output proportional to the differential

pressure across the flow nozzle. Resistance thermometers (or thermocouples) measure the feedwater temperature. Typically, these outputs are supplied to the plant computer where the density and enthalpy are calculated with the aid of synthesized ASME steam tables.   Thermal power is then calculated by the plant computer.

Operation experiences in the United States, Japan, and Germany have shown that venturi flow measurement accuracy is susceptible to degradation. The principle source of degradation is fouling with corrosion deposits, which adhere preferentially to the nozzle throats of the venturi tubes. The corrosion deposit fouling causes an increase in the differential pressure measured for a given volumetric flow and results in erroneously high feedwater flow readings. When the overestimates of feedwater flow are used to calibrate the nuclear instruments, these calibrations result in operating with the actual core thermal power below the intended level. Various studies have shown that fouling recurs during each operating cycle and can contribute up to 2 to 3 percent reduction in thermal power, $$$$.

In the August 26, 1999 issue of Nucleonics Week an article stated "GE PROPOSES BWR UPRATES OF 1% BASED ON GENERIC APPROACH".   The article stated that in mid August, General Electric (GE) submitted a proposal to the NRC that would allow BWR owners to proceed with 1 % uprates by reducing conservatism in calculating reactor power.

GE wants to take advantage of the awaited NRC approval of a similar generic uprate for PWRs based on uncertainty reductions stemming from use of a new feedwater measurement technology.

The NRC approved an exemption to allow Texas Utilities to reduce the error assumption calculated into its heat balance from 2% to 1% at its two Comanche Peak PWRs, and the utility followed with a request for a power uprate.

The Caldon Leading Edge Flow Meter (LEFM) is currently the only such instrument approved by the NRC but ABB Combustion Engineering may soon introduce the Crossflow, its own feedwater flow measuring device and is closely following GE's generic proposal.

On May 3, 2000, the NRC approved a rule change amending 10CFR50 Appendix K to permit power increases based on improvements in accuracy of the instrumentation used to measure thermal power. These power increases, referred to as "Appendix K Uprates"' are relatively small increases on the 1% to 1.7% range, depending on the demonstrated instrument accuracy.

It is anticipated that licensees will make use of the new measurement instruments such as the LEFM mass flow and temperature measurements by directly substituting the new

information in the plant computer. The plant computer would then calculate enthalpy and thermal power as it does now. In order to maintain control of thermal power at 100 percent power, a real-time display of thermal power, as calculated using the new technology, will be available in the main control room for the reactor operator's use. The operators would then use the new display to maintain reactor power at or below the licensed thermal power limit. A validity indication will also be present to alert the operators of the condition of the new instruments.

Described below are three ultrasonic technologies used in the measurement of volumetric flow in a pipe:

- Chordal Transit Time system (LEFM) consisting of arrays of ultrasonic transducers housed in fixtures in a pipe so as to form parallel, precisely defined acoustic paths. The times of flight of pulses of ultrasonic energy traveling along these paths are measured to determine the volumetric flow and the velocity of sound of the flowing fluid. A numerical integration method is used to determine the volumetric flow rate directly from the meter's four path velocities without the need for a pipe area measurement.

- Externally Mounted Transit Time systems consisting of ultrasonic transducers mounted on the exterior of the pipe so as to form one or more diagonal and diametral acoustic paths. The times of flight of pulses traveling between pairs of transducers are measured to determine the axial fluid velocity projected onto the acoustic path (In some designs, the fluid sound velocity is also measured.). With knowledge of the shape of the axial velocity profile, the mean fluid velocity can be inferred from the axial fluid velocity measurement. The volumetric flow is then calculated as the product of the mean axial velocity and the pipe cross sectional area.

- Cross Correlation systems(Canadian General Electric) consisting of two pairs of ultrasonic transducers mounted so as to form two parallel diametral paths, perpendicular to the axis of the pipe, and separated by a known axial distance. One transducer in each path continuously transmits ultrasound to the opposite transducer on that path. The received signal for the upstream path is subjected to an adjustable time delay, then cross correlated with the downstream signal. A characteristic fluid velocity is calculated from the quotient of the distance between acoustic paths and the time delay at which maximum correlation is achieved. The mean axial velocity is inferred from this characteristic fluid velocity. The volumetric flow is then calculated as the product of the mean axial velocity and the pipe cross sectional area.

2.2.6   Summary

The thermal power of the reactor core is determined by a heat balance on the nuclear boiler using operating data.   Under steady state conditions, the nuclear boiler heat output is obtained as the difference between the total heat removed from the boiler system minus the total heat added in the flow streams returning to the boiler.

A core heat balance in the power range, greater than or equal to 10% power, is made to ensure that the core is operated at all times within licensed thermal limitations and/or fuel warranty requirements.   The results of heat balance calculations also provide input to additional core calculations (i.e., CPR & APLHGR).

Either the manual long form method or the off-line computer method is required when the process computer is unavailable.

Table 2.2-1   TI 1.1 Core Heat Balance

	Parameter	Panel	Instrument No.	Units	Reading
(1)	m_{FW}	9-5	FR-3-78	10^6lb/hr	13.3
(2)	m_{RD}	9-5	FI-85-11A	gpm	80
(3)	$m_{CU(A)}$	9-4	FI-69-35	gpm	135
(4)	$m_{CU(B)}$	9-4	FI-69-60	gpm	0.0
(5)	T_{FW}	9-6	TI-3-48	^{o}F	375
(6)	$T_{CU(in)}$	9-4	TI-69-6	^{o}F	526
(7)	$T_{CU(out)}$	9-4	TI-69-6	^{o}F	430
(8)	T_{RD}		Spec. Meas.	^{o}F	85
(9)	P_R	9-5	PR-3-53	psig	1010
(10)	P_{RD}	9-5	PI-85-13A	psig	1335
(11)	$Q_{Loop\ A}$	9-4	EI-96-14A	MW	3.75
(12)	$Q_{Loop\ B}$	9-4	EI-96-14B	MW	3.75

Data Taken _____

Initials

Table 2.2-2   TI 1.1 Core Heat Balance (Continued)

	Quantity	Data Used	Value (BTU/lb)
(13)	h_{MS}	(9)	_____
(14)	h_{FW}	(5) & (9)	_____
(15)	h_{in}	(6) & (9)	_____
(16)	h_{out}	(7) & (9)	_____
(17)	h_{RD}	(8) & (9)	_____

Note: Assume that atmospheric pressure equals 15 psia.

enthalpy (h):   A quantity associated with a thermodynamic system expressed as the internal energy of a system plus the product of the pressure and volume of the system.

thermodynamics: The science concerned with the relations between heat and mechanical energy or work, and the conversion of one into the other.

entropy: A measure of the amount of work unavailable for work during a natural process.

Table 2.2-3   TI 1.1 Core Heat Balance (Continued)

	Quantity	Data Used	Value (MWt)
(18)	Q_{FW}	(1) x (14) x .293	_____
(19)	Q_{RDin}	(2) x (17) x (1.47×10^{-4})	_____
(20)	Q_p	(11) + (12)	_____
(21)	Q_{Tin}	(18) + (19) + (20)	_____
(22)	Q_{MS}	(1) x (13) x .293	_____
(23)	Q_{RDout}	(2) x (13) x (1.47×10^{-4})	_____
(24)	Q_{CU}	[(3) + (4)] x [(15) - (16)] x (1.47×10^{-4})	_____
(25)	Q_{FL}	Special Measurement	0.6
(26)	Q_{Tout}	(22+23+24+25)	_____
(27)	Q_C	(26) - (21)	_____

Calculation Done By   _____

Table 2.2-4 Steam Tables

Properties of Superheated Steam and Compressed Water (Temperature and Pressure)

Press., psia	1000	1025	1050
Tsat	544.58	547.56	550.53
Sat Steam	1192.9	1191.95	1191.0
Sat. Water	542.55	546.35	550.15
540	536.69	536.65	536.60
530	524.12	524.09	524.05
520	511.79	511.77	511.74
510	499.69	499.68	499.66
450	430.55	430.57	430.58
440	419.45	419.47	419.49
430	408.46	408.48	408.50
420	397.55	397.58	397.60
410	386.72	386.75	386.77
400	375.96	375.99	376.02
390	365.27	365.31	365.34
380	354.65	354.69	354.72
370	344.08	344.12	344.16
360	333.57	333.61	333.65
100	70.63	70.70	70.76
90	60.69	60.70	60.83
80	50.76	50.83	50.89
70	40.82	40.89	40.96
60	30.88	30.95	31.02

Properties of saturated Steam and Water (Pressure)

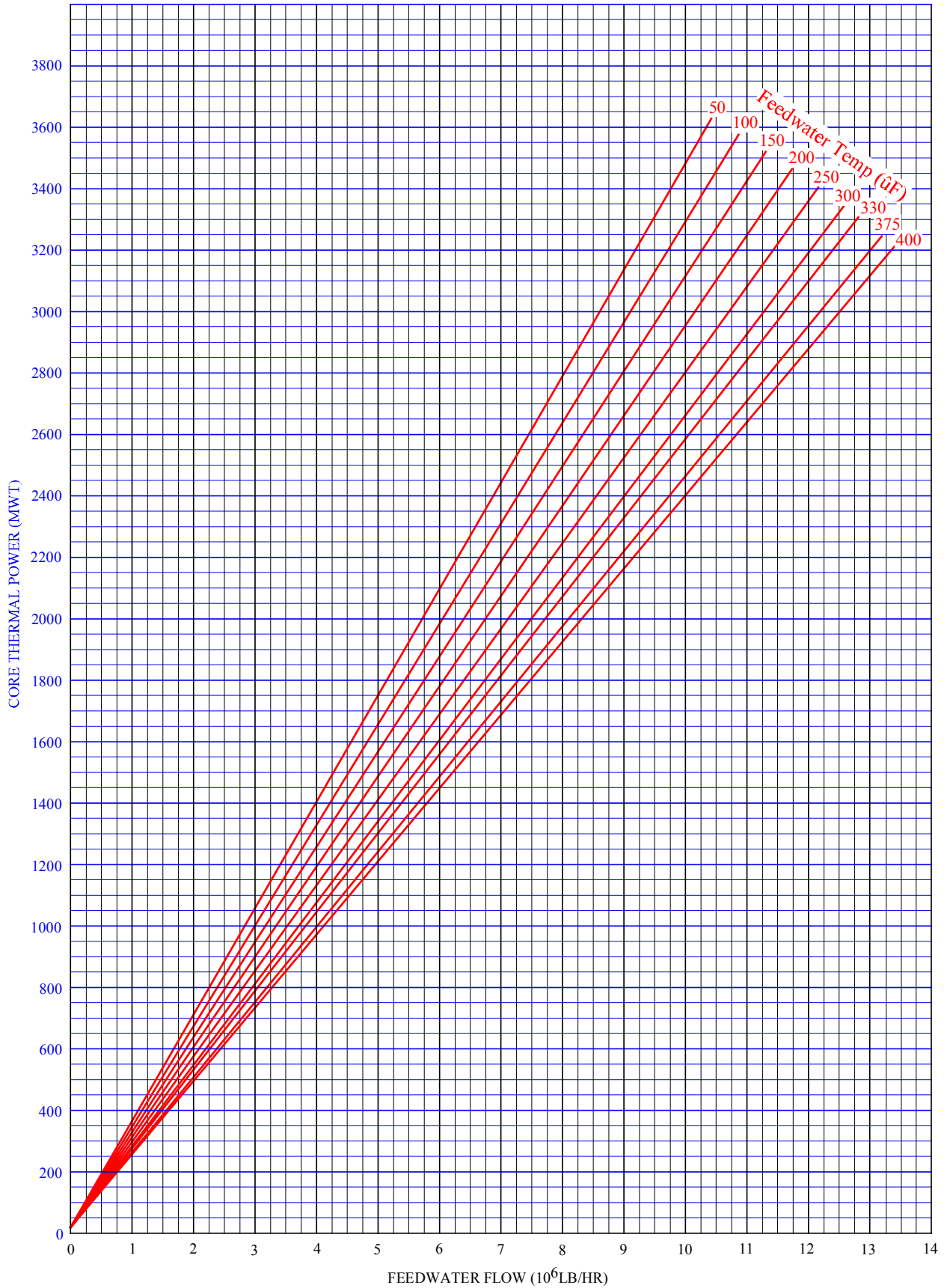| Pressure psia	Temperature °F	Enthalpy, Btu/lbm		
		h_f	h_{fg}	h_g
1050	550.53	550.1	640.9	1191.0
1040	549.36	548.6	642.8	1191.4
1030	548.18	547.1	644.7	1191.8
1020	546.99	545.6	646.6	1192.2
1010	545.79	544.1	648.5	1192.6
1000	544.48	542.6	650.4	1192.9
990	543.36	541.0	652.3	1193.3
980	542.14	539.5	654.2	1193.7
970	540.9	537.9	656.1	1194.0
960	539.65	536.3	658.0	1194.4

Figure 2.2-1 Simplified Short Form Core Heat Balance
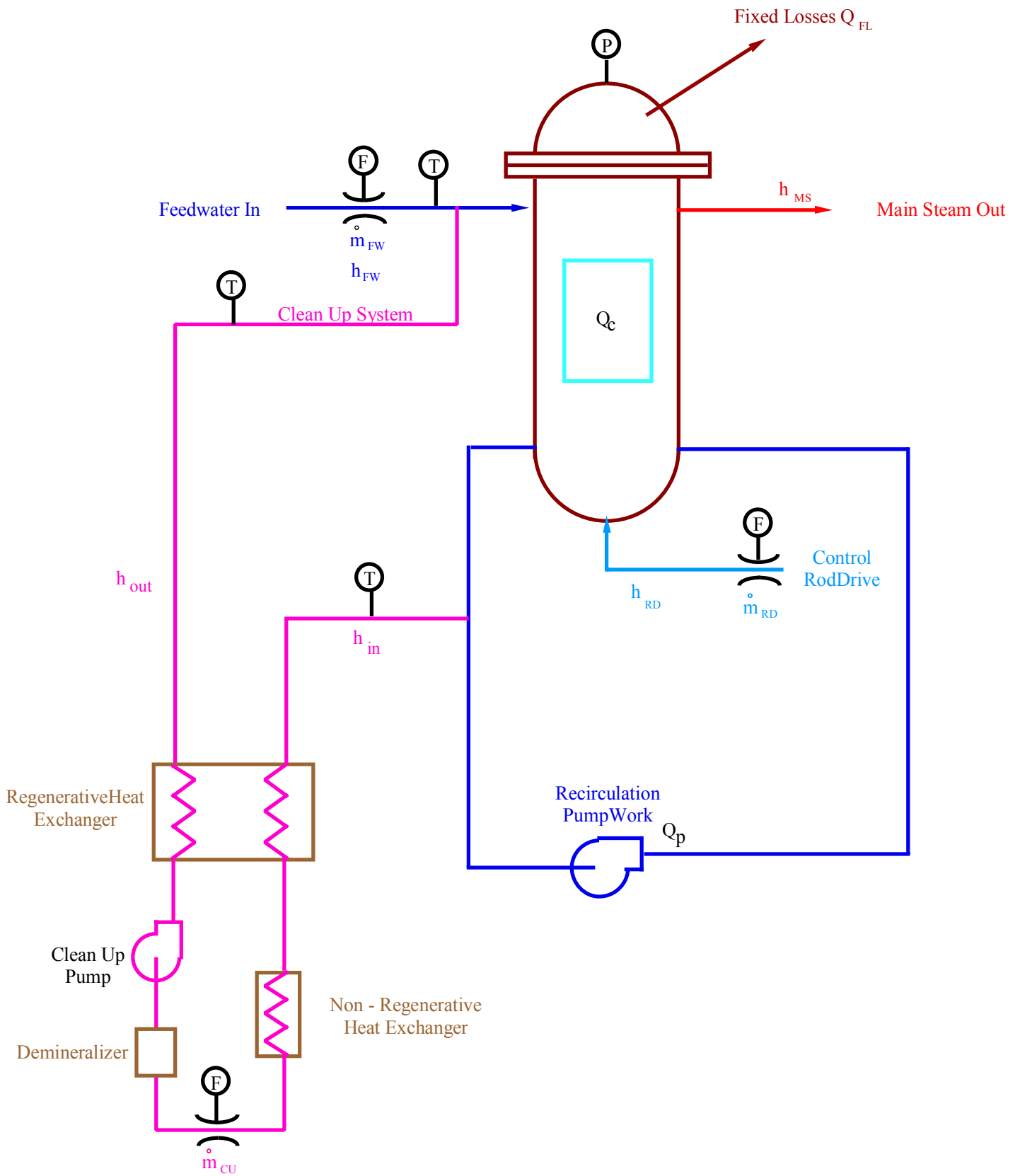
Figure 2.2-2 Simplified Core Heat Balance Diagram