LICENSING REPORT ON SPENT FUEL STORAGE RACKS FOR THE VIRGIL C. SUMMER NUCLEAR STATION

NRC DOCKET NO. 50-395

SOUTH CAROLINA ELECTRIC AND GAS COMPANY
COLUMBIA, SOUTH CAROLINA 29218

DECEMBER 1983

REVISION I APRIL 9, 1984

5. THERMAL-HYDRAULIC CONSIDERATIONS

A central objective in the design of the high-density fuel rack is to ensure adequate cooling of the fuel assembly cladding. In the following, a brief synopsis of the design basis, the method of analysis, and computed results are given. Similar analysis has been used in previous licensing reports on high density spent fuel racks for Fermi II (Docket 50-341), Quad Cities I and II (Dockets 50-254 and 50-265), Rancho Seco (Docket 50-312), Grand Gulf Unit 1 (Docket 50-416), and Oyster Creek (Docket 50-219).

5.1 Decay Heat Calculations for the Spent Fuel

This report section covers requirement III.1.5(2) of the NRC "OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications" issued on April 14, 1978. This requirement states that calculations for the amount of thermal energy removed by the spent fuel cooling system shall be made in accordance with Branch Technical Position APCSB 9-2 "Residual Decay Energy for Light Water Reactors for Long Term Cooling"[1]. The calculations contained herein have been made in accordance with this requirement.

5.1.1 Basis

The V.C. Summer Nuclear Station reactor is rated at 2775 Megawatt-Thermal (MWT). The core contains 157 fuel assemblies. Thus, the average operating power per fuel assembly, P_o, is 17.675 MW. The fuel assemblies are assumed to be removed from the reactor after a maximum of 4.5 years of cumulative operating time. The fuel discharge can be made in one of the following two modes:

(i) Normal discharge - Mode (i)

(ii) Full Core discharge - Mode (ii)

As shown in Table 1.1, the anticipated fuel batch size for normal discharge may vary from 68 to 72. Therefore, for analysis purposes, we assume the batch size to be 72 fuel assemblies. The fuel transfer begins after 144 hours of cool-off time in the reactor (time after shut down). It is assumed that the time period of discharge of this batch is 72 hours. (One assembly transferred to the pool per hour). The cooling system consists of two seismic category I spent fuel cooling circuits. The bulk temperature analysis assumes that one cooling train (out of two) is unavailable for cooling the pool water.

Mode (ii) corresponds to a full core discharge (157 assemblies). Full core off-load condition implies that the reactor core has no remaining fuel. It is assumed that the total time period for the discharge of one full core is 52 hours (after 144 hours of shut down time in the reactor). The discharge rate to the pool is assumed to be continuous and uniform. The bulk temperature analysis assumes two spent fuel pool coolers working in parallel.

Since the decay heat load is a monotonically increasing function of the cumulative reactor operating time, t_0, we assume that every fuel assembly discharged has had the maximum postulated t_0 of 4.5 years.

The water inventory in the reactor cavity cooled by the RHR heat exchanger exchanges heat with the fuel pool water mass through the refueling canal. This important source of heat removal is also neglected in the analysis. Thus, the results obtained for both modes (i) and (ii) are highly conservative.

In the following, all relevant performance data for the spent fuel pool heat exchangers is given.

a. Spent Fuel Pool Heat Exchanger:

Type	Tube and shell
Quantity	2
Performance data	
o Heat transferred	14.02×10^6 Btu/hr
Tube Side	
o Fluid flow	1,800 gpm
o Pool water inlet temperature	135°F
o Outlet temperature	119.2°F
Shell Side	
o Fluid flow	1800 gpm
o Coolant inlet temperature	105°F
o Outlet temperature	120.8°F
o Fouling factor	0.0005

The above data enables complete characterization of the thermal performance of the fuel pool heat exchanger.

5.1.2 Model Description

Reference[1] is utilized to compute the heat dissipation requirements in the pool. The total decay power consists of "fission products decay" and "heavy element decay". Total decay power P for a fuel assembly is given as a linear function of P_o and an exponential function of t_o and t_s.

i.e.: $P = P_o\ f(t_o, t_s)$

where

P = linear function of P_o

P_O=average operating power per fuel assembly

t_O=cumulative exposure time of the fuel assembly in the reactor

t_s=Time elapsed since reactor shutdown

The uncertainty factor K, which occurs in the functional relationship f (t_O, t_s) is set equal to 0.1 for $t_s > 10^7$ sec in the interest of conservatism. Furthermore, the operating power P_O is taken equal to the rated power, even though the reactor may be operating at less than its rated power during most of the period of exposure of the batch of fuel assemblies. Finally, the computations and results reported here are based on the discharge taking place when the inventory of fuel in the pool will be at its maximum resulting in an upper bound on the computed decay heat rate.

Having determined the heat dissipation rate, the next task is to evaluate the time-temperature history of the pool water. Table 5.1.1 identifies the loading cases examined. The pool bulk temperature time history is determined using the first law of thermodynamics (conservation of energy).

A number of simplifying assumptions are made which render the analysis conservative. The principal ones are:

1. The cooling water temperature in the fuel pool cooler is based on the maximum postulated values given in the FSAR.[2]

2. The heat exchangers are assumed to have maximum fouling. Thus, the temperature effectiveness, s, for the heat exchangers utilized in the analysis are the lowest postulated values: S= 0.526 for

fuel pool coolers, S is calculated from heat exchanger technical data sheets.No heat loss is assumed to take place through the concrete floor.

4. No credit is taken for the improvement in the film coefficients of the heat exchangers as the operating temperature rises. Thus, the film coefficient used in the computations are lower bounds.

5. No credit is taken for evaporation of the pool water.

6. No credit is taken for heat loss to pool walls and pool floor slab.

The basic energy conservation relationship for the pool heat exchanger system yields:

$$C_t \frac{dt}{d\tau} = Q_1 - Q_2 - Q_3 \qquad (5.1.2)$$

where

C_t: Thermal capacitance of stored water in the pool.

t: Temperature of pool water at time, τ

Q_1: Heat generation rate due to stored fuel assemblies in the pool. Q_1 is a known function of time, τ from the preceding section.

Q_2: Heat removed in the fuel pool cooler.

Q_3: Heat removed in the RHR heat exchanger (Q_3=0 if RHR is not used).

The pool has total water inventory of 38162 cubic feet when all racks are in place in the pool and every storage location is occupied.

5.1.3 Decay Heat Calculation Results:

The calculations were performed for the pool disregarding the additional thermal capacity and cooling system available in the transfer channel, and the reactor cavity.

For a specified coolant inlet temperature and flow rate, the quantities Q_2 and Q_3 are shown to be linear function of t in a recent paper by Singh (3). As stated earlier, Q_1, is an exponential function of τ. Thus Equation (5.1.2) can be integrated to determine t directly as a function of τ. The results are plotted in Figures (5.1.1) to (5.1.2). The results show that the pool water never approaches the boiling point under the most adverse conditions. These figures also give Q_1 as a function of τ. Four plots are generated for each case. The first and third plots for each case shows temperature and power generation respectively for a period extending from $\tau = 0 \rightarrow \tau = 2\tau_n$ where τ_n is the total time of fuel transfer. The second and fourth plots show the same quantities (i.e. temperature and power generation respectively) over a long period. The long-term plots are produced to indicate the required operating time for the heat exchangers. Summarized results are given in Table 5.1.2. It is noted that the maximum pool bulk temperature corresponds to the normal mode discharge; this value is 140°F. This is significantly lower than the initial plant design basis of 150°F.

Finally,computations are made to determine the time interval to boiling after all heat dissipation paths are lost. Computations are made for each case under the following two assumptions:

(i) All cooling sources lost at the instant pool bulk temperature reaches the maximum value.

TABLE 5.1.1

LIST OF CASES ANALYZED

Case No.	Condition	No. of fuel assemblies discharged N	No. of spent fuel pool HXS	No. of RHR's in-service	Total Time to transfer fuel into the pool t_h, hrs.	Cool off time before transfer begins, hrs.
1	Normal discharge	72	1	0	72	144
2	Full core discharge	157	2	0	52	144

TABLE 5.1.2

MAXIMUM POOL BULK TEMPERATURE t, COINCIDENT TOTAL POWER Q_1 and

COINCIDENT SPECIFIC POWER FOR THE HOTTEST ASSEMBLY

Case No.	No. of Assemblies	Time to transfer fuel into pool, hrs.	Maximum pool bulk temp.°F	Coincident time (since initiation of fuel transfer, hrs.	Coincident specific power q, BTU/sec.	$Q_1 \times 10^{-6}$ BTU/hour	Notes
1	72	72	140	83	45.055	16.383	Normal condition
2	157	52	139	58	47.111	31.332	Full core offload

TABLE 5.1.3

TIME (Hrs) TO BOILING AND BOILING VAPORIZATION RATE

FROM THE INSTANT ALL COOLING IS LOST

Case No.	CONDITION 1 Loss of Cooling at maximum pool bulk temperature		CONDITION 2 Loss of Cooling at maximum power discharge rate	
	Time (Hrs)	Vap. Rate lb./hr.	Time (Hrs)	Vap. Rate lb./hr.
1	10	16885	10	16691
2	5	32291	5	32033

(ii) All cooling paths lost at the instant the heat dissipation power reaches its maximum value in the pool.

Results are summarized in Table 5.1.3. Table 5.1.3 gives the bulk boiling vaporization rate for both cases at the instant the boiling commences. This rate will decrease with time due to reduced heat generation in the fuel.

The make-up water supply to the spent fuel pool is available from three discrete sources; namely the Demineralized Water Storage Tank (DWST) in the normal mode and the Refueling Water Supply Tank (RWST) or the Reactor Make-up Water Storage Tank (RMST) in the event of an emergency. The DWST pump is rated at 120 gpm and the RWST and RMST pumps are rated at 150 gpm (ref. Section 9.1.3.3 of the FSAR). These make-up rates are substantially in excess of the evaporation rates reported in the foregoing.

5.2 Thermal-Hydraulics Analyses for Spent Fuel Cooling

This report section covers requirement III.1.5(3) of the NRC "OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications" issued on April 14, 1978. Conservative methods have been used to calculate the maximum fuel cladding temperature as required therein. Also, it has been determined that nucleate boiling or voiding of coolant on the surface of the fuel rods does not occur.

5.2.1 Basis:

In order to determine an upper bound on the maximum fuel cladding temperature, a series of conservative assumptions are made. The most important assumptions are listed below:

a. As stated above, the fuel pool will contain spent fuel with varying "time-after-shutdown" (t_s). Since the heat emission fails off rapidly with increasing t_s, it is obviously conservative to assume that all fuel assemblies are fresh (t_s = 144 hours) and they all have had 4.5 years of operating time in the reactor. The heat emission rate of each fuel assembly is assumed to be equal.[2]

b. As shown in Figures 2.1 in Section 2, the modules occupy an irregular floor space in the pool. For purposes of the hydrothermal analysis, a circle circumscribing the actual rack floor space is drawn. It is further assumed that the cylinder with this circle as its base is packed with fuel assemblies at the nominal pitch of 10.405 inches (see Figure 5.2.1).

c. The downcomer space around the rack module group varies, as shown in Figure 5.2.1. The nominal downcomer gap available in the pool is assumed to be the total gap available around the idealized cylindrical rack; thus, the maximum resistance to downward flow is incorporated into the analysis.

d. No downcomer flow is assumed to exist between the rack modules.

5.2.2 Model Description

In this manner, a conservative idealized model for the rack assemblage is devised. The water flow is axisymmetric about the vertical axis of the circular rack assemblage, and thus, the

flow is two-dimensional (axisymmetric three-dimensional). Fig. 5.2.2 shows a typical "flow chimney" rendering of the thermal hydraulics model. The governing equation to characterize the flow field in the pool can now be written. The resulting integral equation can be solved for the lower plenum velocity field (in the radial direction) and axial velocity (in-cell velocity field), by using the method of collocation. It should be added that the hydrodynamic loss coefficients which enter into the formulation of the integral equation are also taken from well-recognized sources[4] and wherever discrepancies in reported values exist, the conservative values are consistently used. Reference [5] gives the details of mathematical analysis used in this solution process.

After the axial velocity field is evaluated, it is a straight-forward matter to compute the fuel assembly cladding temperature. The knowledge of the overall flow field enables pinpointing the storage location with the minimum axial flow (i.e. maximum water outlet temperature). This is called the most "choked" location. It is recognized that some storage locations, where rack module supports are located, have some additional hydraulic resis[illegible]t encountered in other cells. In order to find an upper [illegible] the temperature in such a cell, it is assumed that [illegible]ated at the most "choked" location. Knowing the gl[illegible] velocity field, the revised axial flow through this [illegible] can be calculated by solving the Bernoulli's eq[illegible]on [illegible] the flow circuit through this cell. Thus, an absolut[illegible] upper [illegible]ound on the water exit temperature and maximum fuel cladding temperature is obtained. It is believed that in view of the aforementioned assumptions, the temperatures calculated in this manner overestimate the temperature rise that will actually occur in the pool.

The maximum pool bulk temperature t is computed in Section 5.1.3

and reported in Table 5.1.2. The corresponding average power output from the hottest fuel assembly, q is also reported in that table. The maximum radial peaking factor is 1.55 for the V.C. Summer installation. Thus, it is conservative to assume that the maximum specific power of a fuel assembly is given by

$$q_A = q\ \alpha_r$$

where $\alpha_r = 1.55$

The maximum temperature rise of pool water in the most disadvantageously placed fuel assembly is given in Table 5.2.1 for all loading cases. Having determined the maximum "local" water temperature in the pool, it is now possible to determine the maximum fuel cladding temperature. It is conservatively assumed that the total peaking factor α_T is 2.32. Thus, a fuel rod can produce 2.32 times the average heat emission rate over a small length. The axial heat dissipation in a rod is known to reach a maximum in the central region, and taper off at its two extremities. For the sake of added conservatism it is assumed that the peak heat emission occurs at the top where the local water temperature also reaches its maximum. Furthermore, no credit is taken for axial conduction of heat along the rod. The highly conservative model thus constructed leads to simple algebraic equations which directly give the maximum local cladding temperature, t_c.

5.2.3 Results:

Table 5.2.1 gives the maximum local cladding temperature, t_c, at the instant the pool bulk temperature has attained its maximum value. It is quite possible, however, that the peak cladding temperature occurs at the instant of maximum value of q_A, i.e., at the instant when the fuel assembly is first placed in a storage location. Table 5.2.2 gives the

maximum local cladding temperature at $\tau = 0$. It is to be noted that there are wide margins to local boiling in all cases. The local boiling temperature near the top of the fuel cladding is 240°F. Furthermore, the cladding temperature must be somewhat higher than the boiling temperature to initiate and sustain nucleate boiling. The above considerations indicate that a comfortable margin against the initiation of localized boiling exists in all cases.

TABLE 5.2.1

MAXIMUM LOCAL POOL WATER TEMPERATURE AND LOCAL FUEL

CLADDING TEMPERATURE
AT INSTANCE OF MAXIMUM POOL BULK TEMPERATURE

Case No.	Max. Local Pool Water Temperature °F	Maximum Coincident Local Cladding Temperature °F	Case Identified
1	170	196	72 Assemblies Cooling Mode B
2	170	197	157 Assemblies Cooling Mode A

* Cooling Mode A means 2 spent fuel pool coolers (SFPHX).

Cooling Mode B means only 1 SFPHX in operation.

TABLE 5.2.2

POOL AND MAXIMUM CLADDING TEMPERATURE AT THE INSTANCE FUEL ASSEMBLY TRANSFER BEGINS

Case No.	Cladding Temp. °F	Coincident Pool Temp, °F	
		Bulk	Local
1	180	115	149
2	175	110	144

REFERENCES TO SECTION 5

1. NUREG 0800 U.S. Nuclear Regulatory Commission, Standard Review Plan, Branch Technical Position, ASB 9-2, Rev. 2, July 1981.

2. FSAR, V.C. Summer Nuclear Station.

3. Journal of Heat Transfer, Transactions of the ASME August,1981, Vol. 103, "Some Fundmental Relationships for Tubular Heat Exchanger Thermal Performance," K.P. Singh.

4. General Electric Corporation, R&D Data Books, "Heat Transfer and Fluid Flow, " 1974 and updates.

5. 4th National Congress of the ASME, "A Method for Computing the Maximum Water Temperature in a Fuel Pool Containing Spent Nuclear Fuel", paper 83-NE-7, Portland, Oregon (June 1983).

PEAK VALUE = 140°F AT 83 HRS.

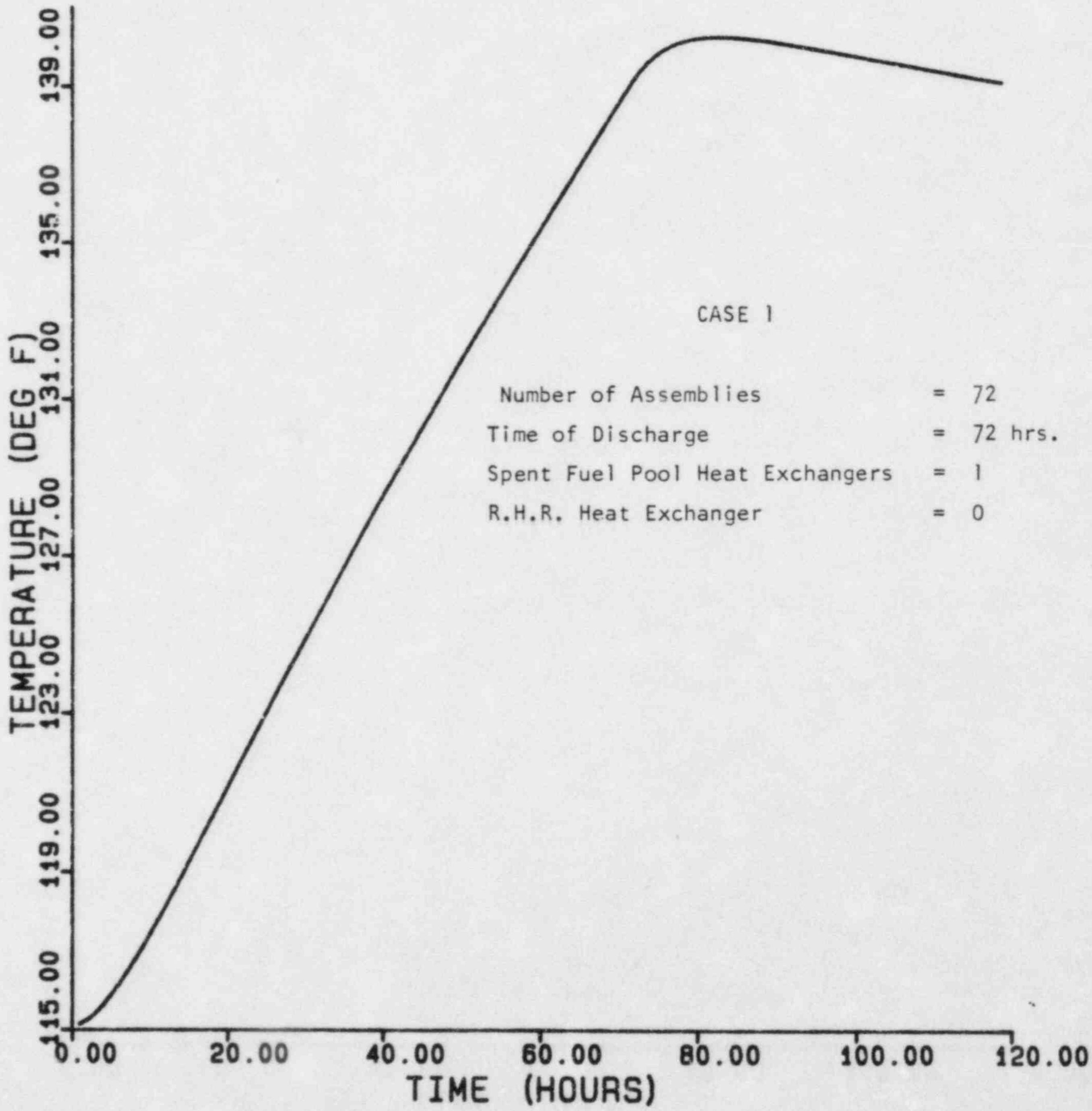

FIG. 5.1.1(a) POOL BULK TEMPERATURE; NORMAL DISCHARGE

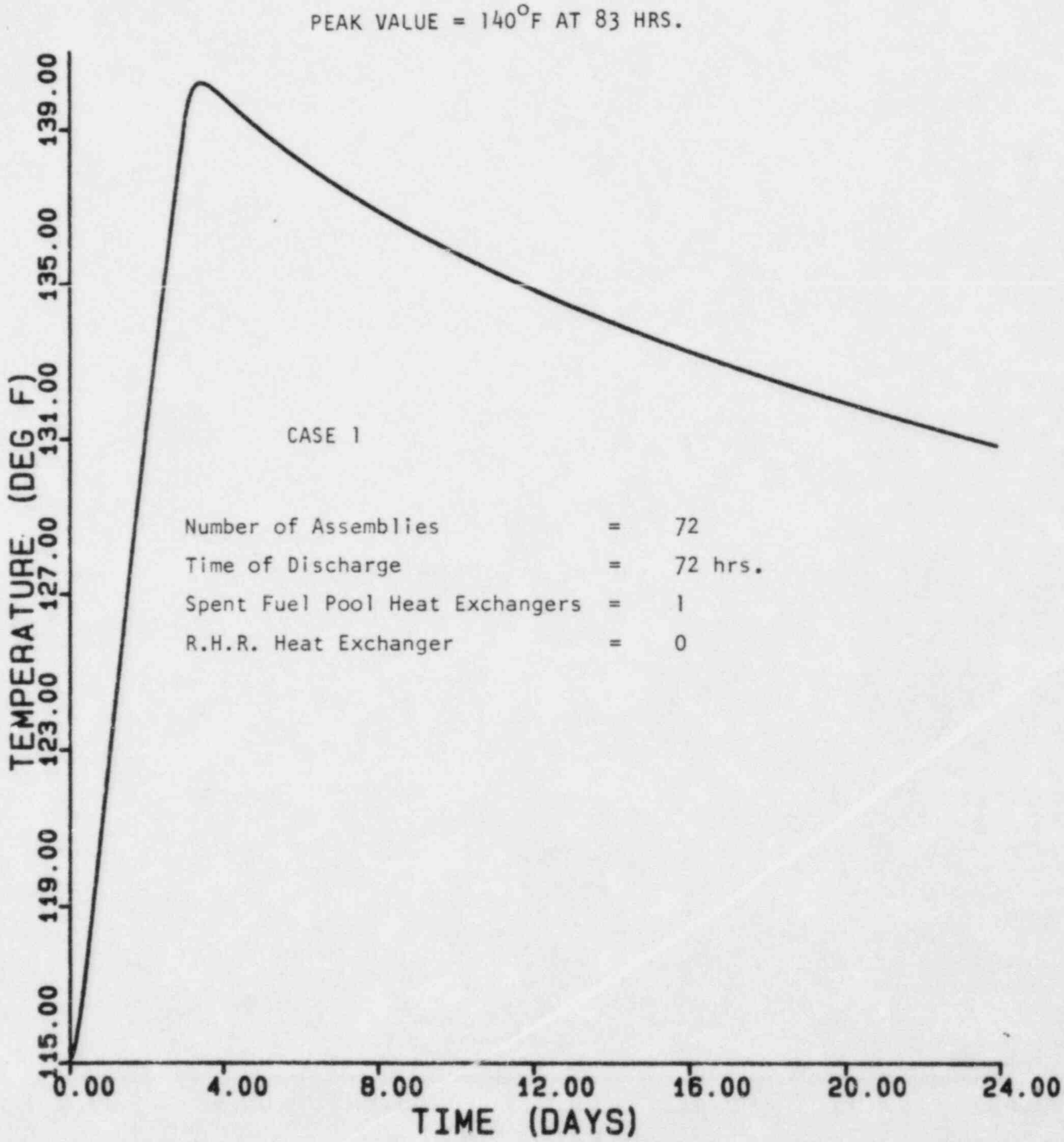

FIG. 5.1.1(b) POOL BULK TEMPERATURE; NORMAL DISCHARGE

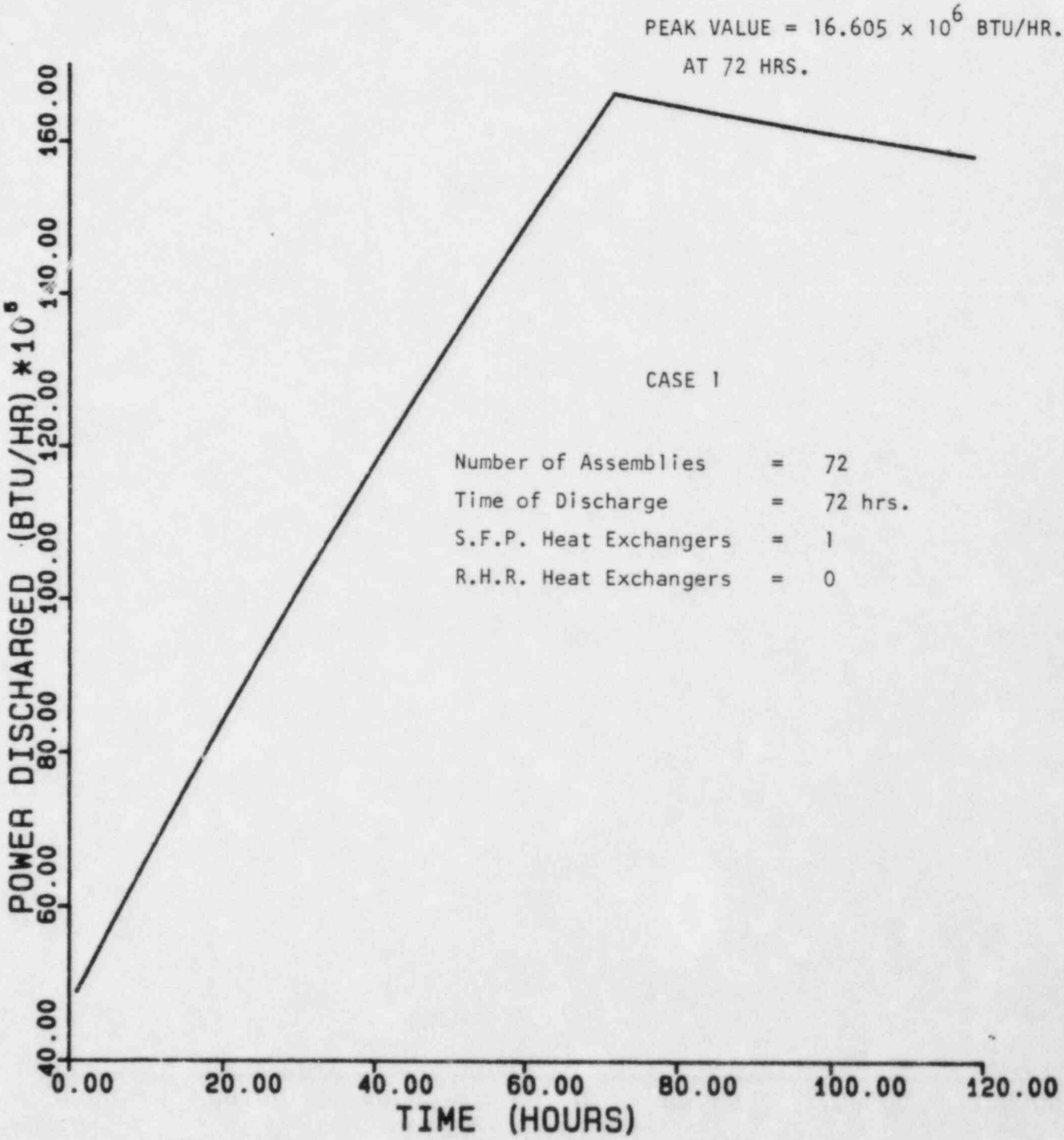

FIG. 5.1.1 (c) POWER DISCHARGE; NORMAL DISCHARGE

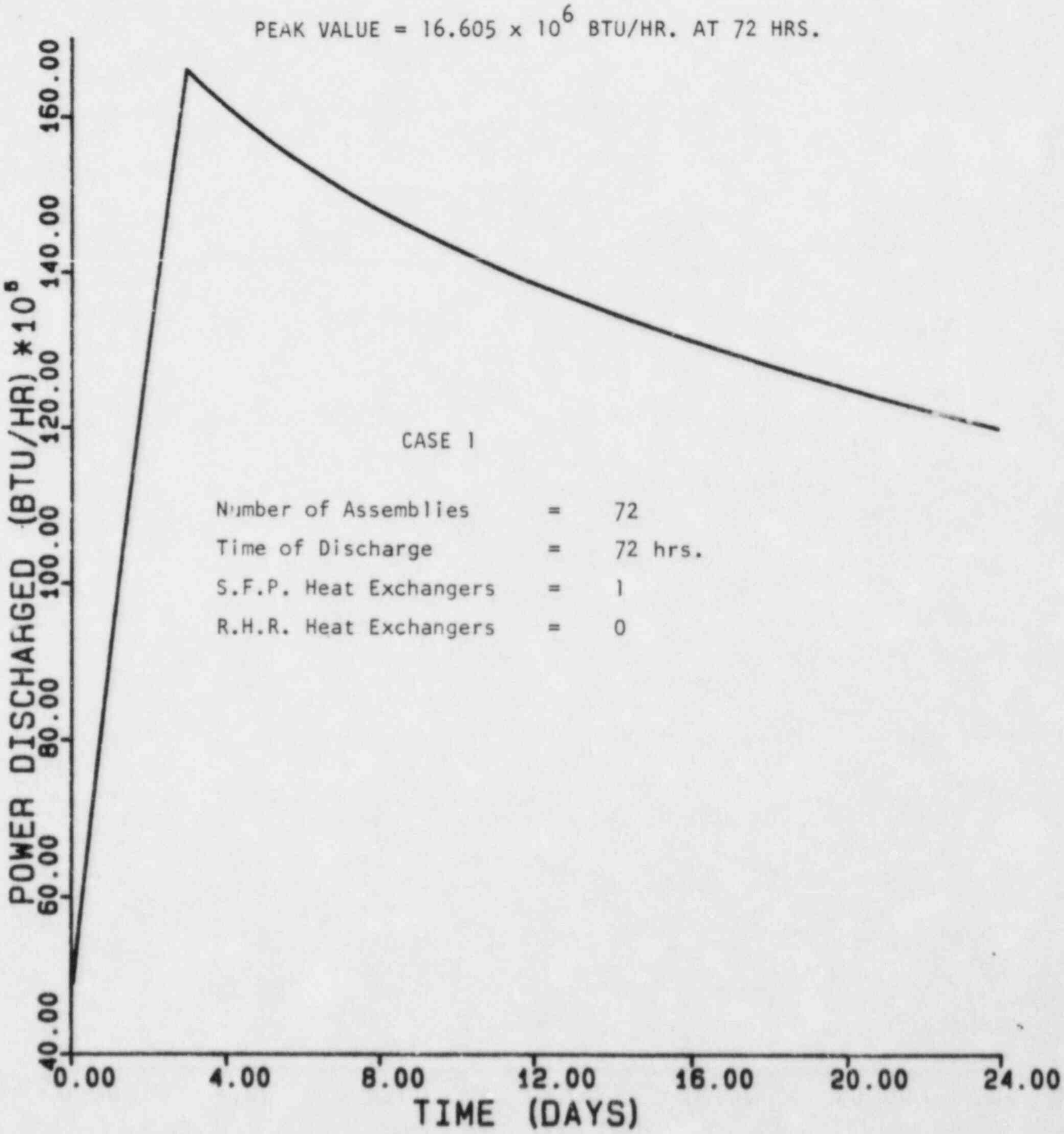

FIG. 5.1.1 (d) POWER DISCHARGE; NORMAL DISCHARGE

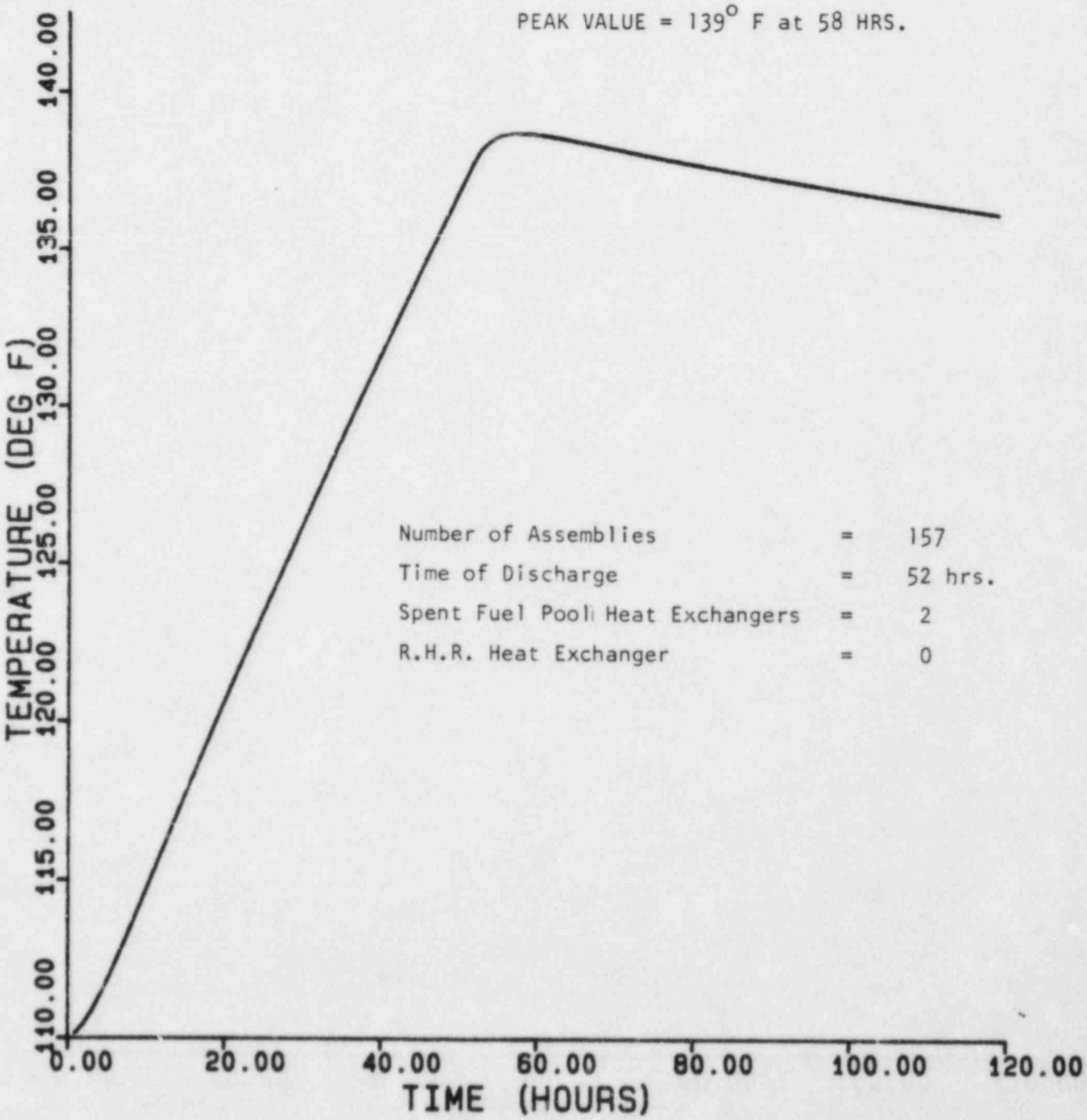

FIG. 5.1.2 (a) POOL BULK TEMPERATURE; FULL CORE DISCHARGE

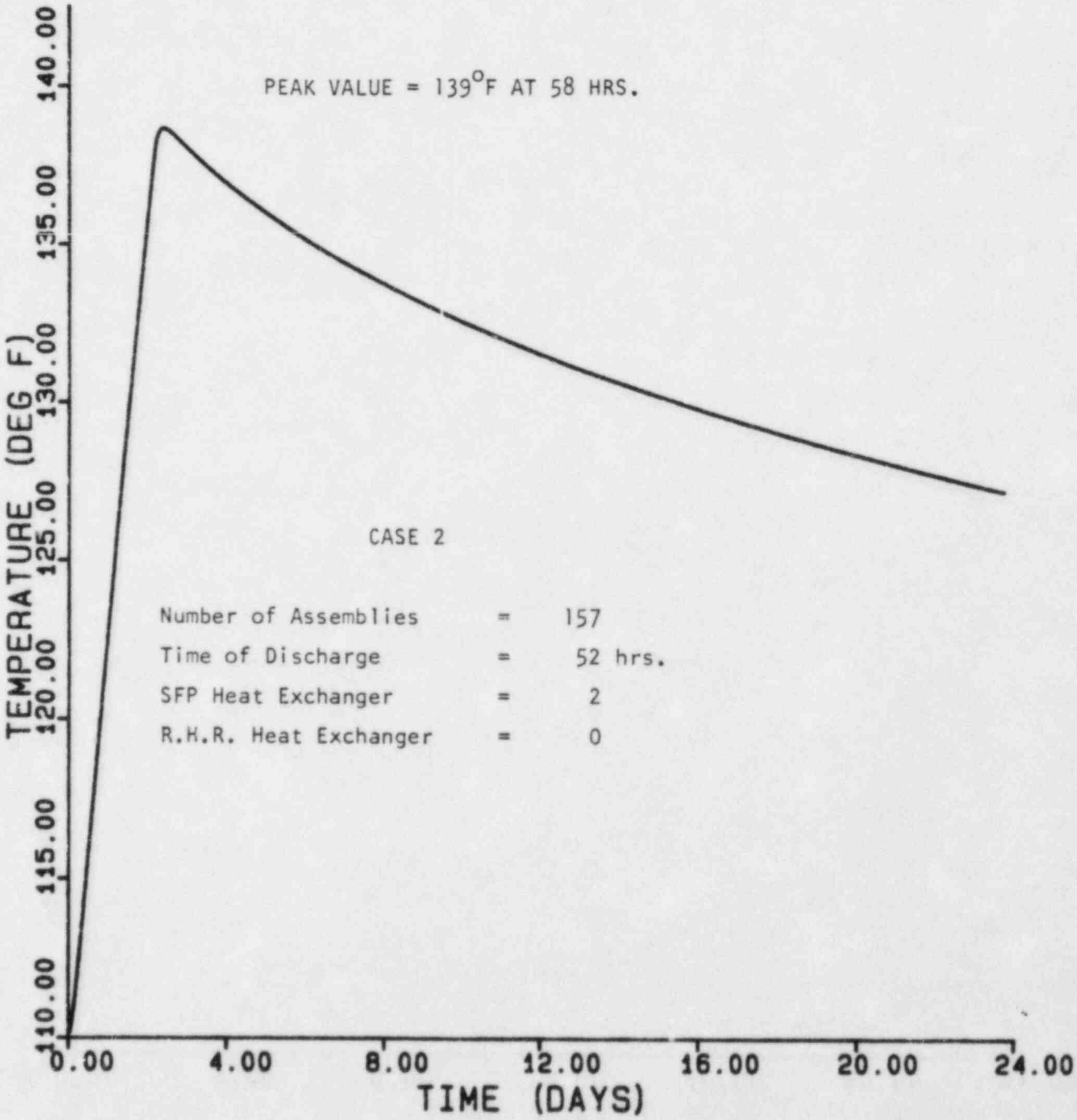

FIG. 5.1.2 (b) POOL BULK TEMPERATURE; FULL CORE DISCHARGE

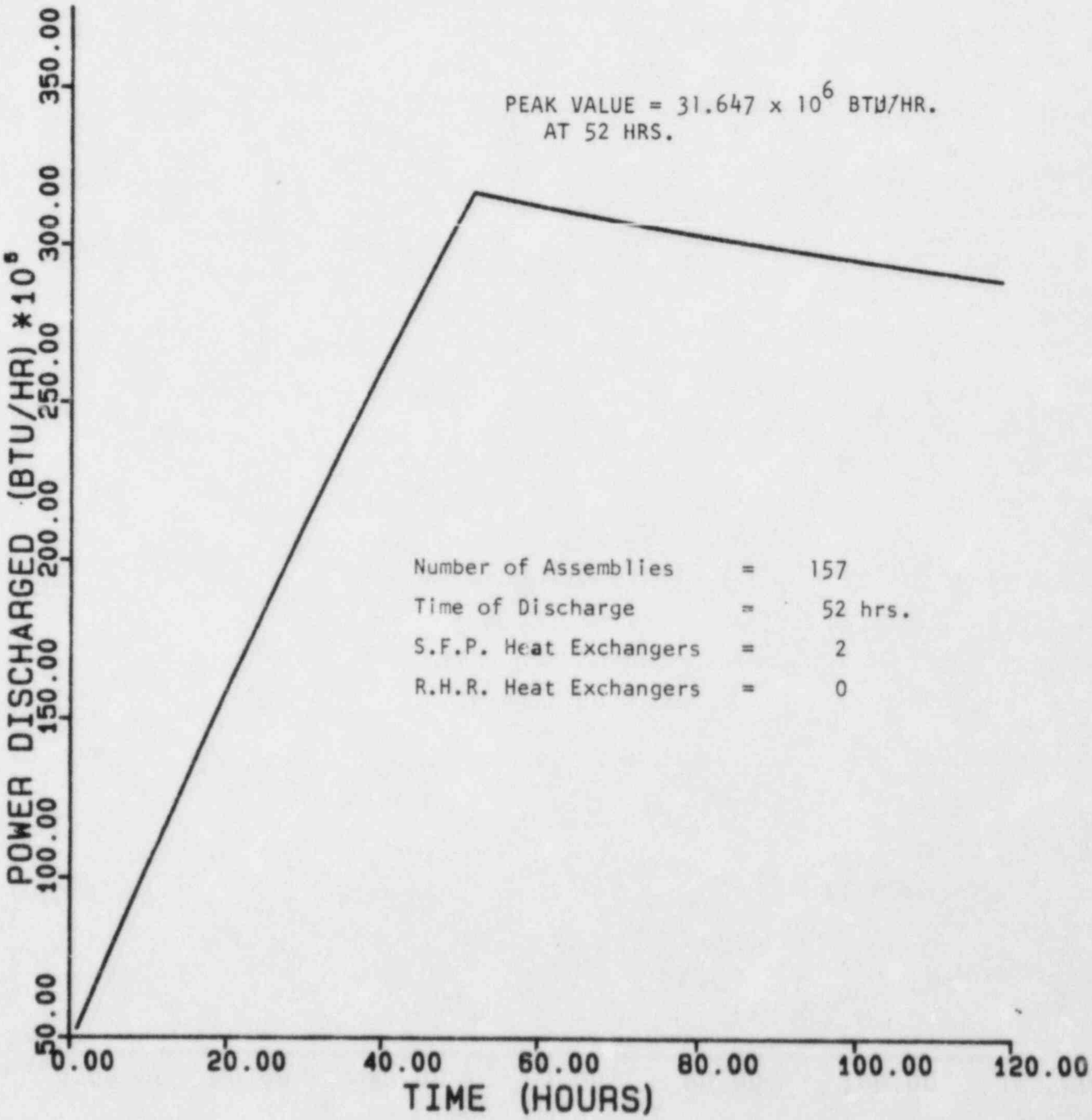

FIG. 5.1.2 (c) POWER DISCHARGE; FULL CORE DISCHARGE

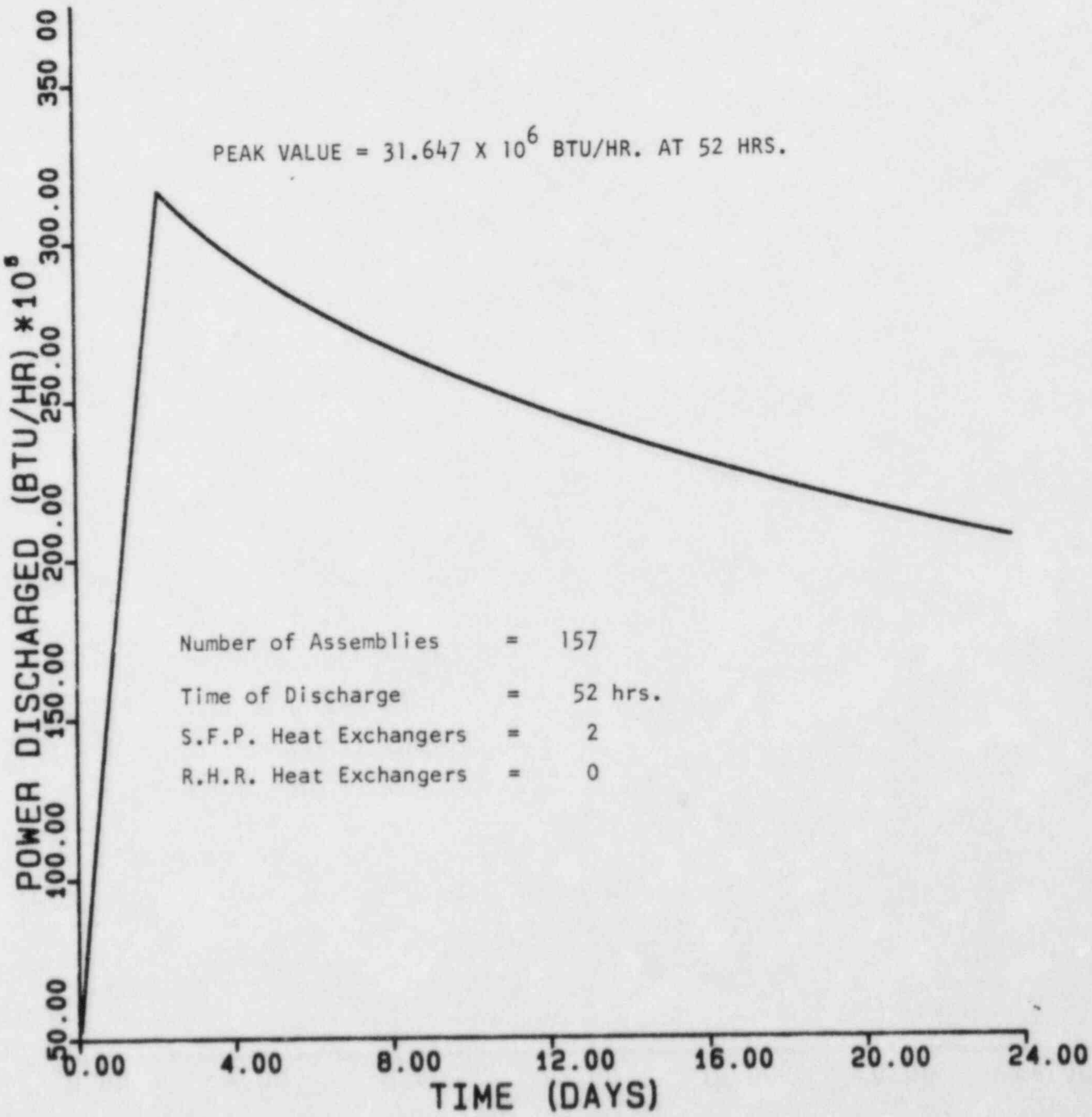

FIG. 5.1.2 (d) POWER DISCHARGE; FULL CORE DISCHARGE

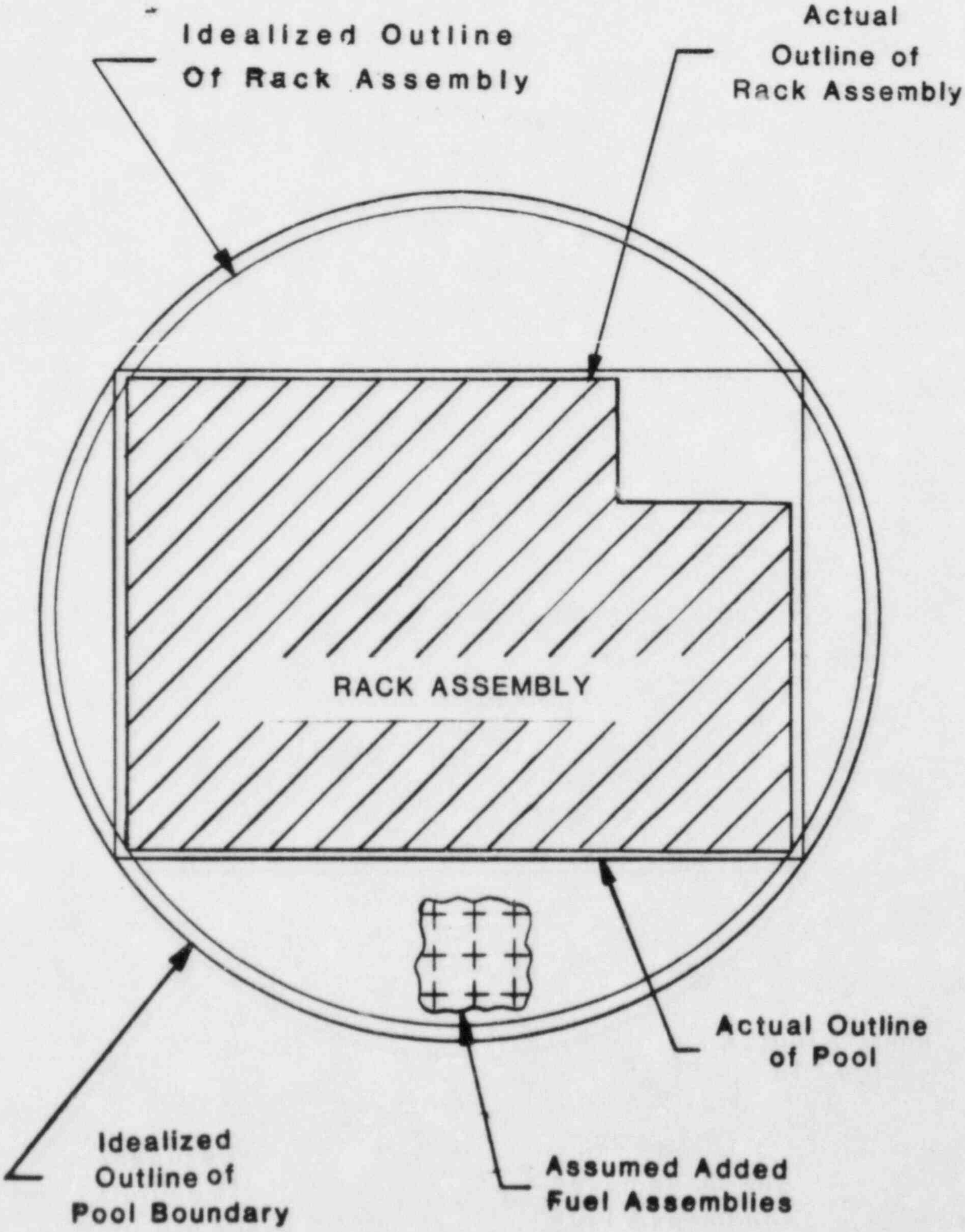

FIG. 5.2.1 IDEALIZATION OF RACK ASSEMBLY

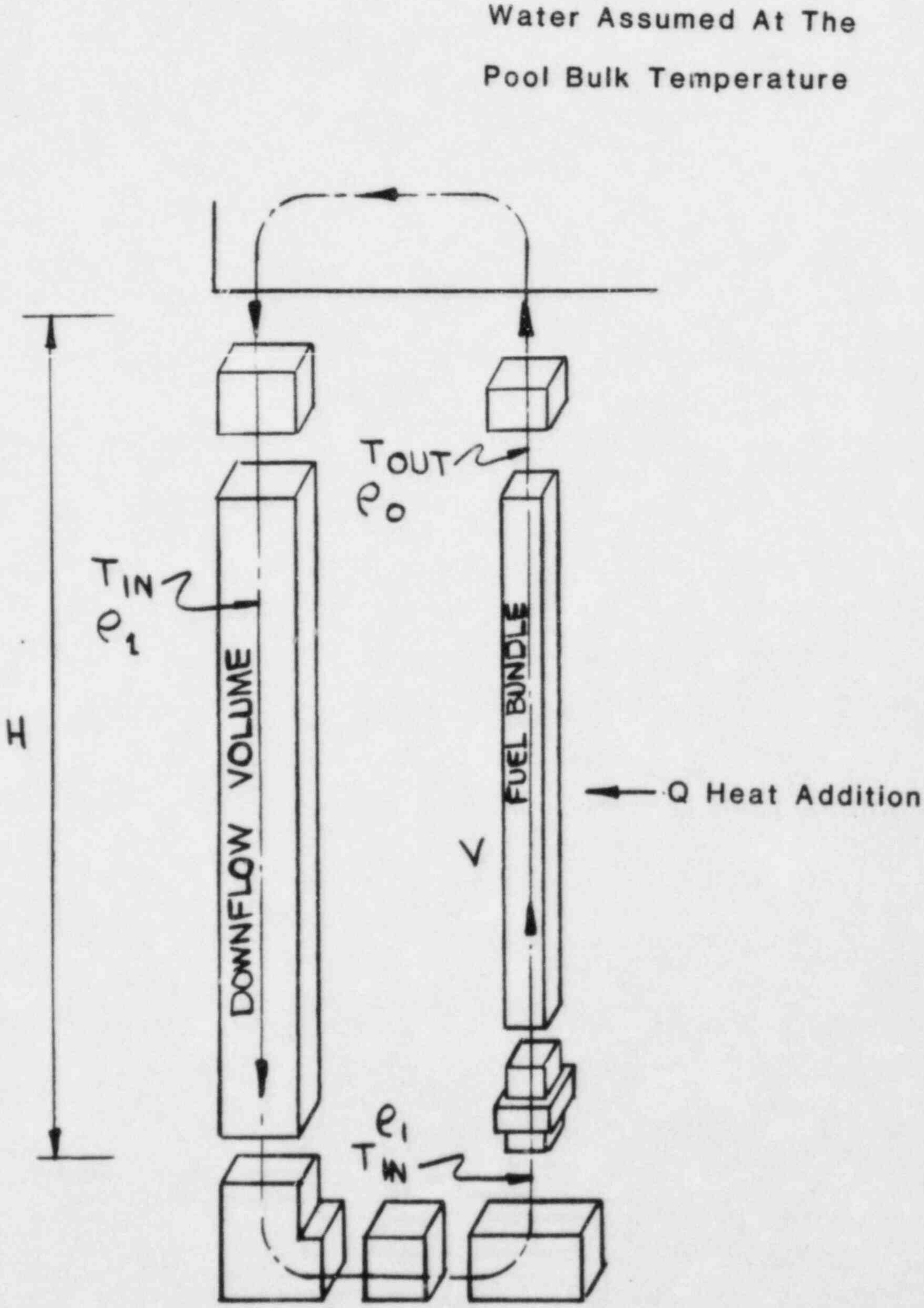

FIG. 5.2.2 THERMAL CHIMNEY FLOW MODEL