USE OF AN INTEGRATED CONTAINMENT AND ULTIMATE HEAT SINK (UHS) RESPONSE APPROACH TO EVALUATE NUCLEAR POWER PLANT MODIFICATIONS

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ABSTRACT

Detailed containment and Ultimate Heat Sink (UHS) performance evaluations often are required to support major plant modifications, such as power uprates and steam generator replacements. These UHS and containment pressure and temperature response evaluations are interrelated. Not only is the containment heat load to the UHS a factor in these evaluations, but other heat loads, such as those from the spent fuel pool, may change as a result of the plant modification and impact containment or UHS response. Our experience is that if an integrated containment/UHS response model is developed prior to the feasibility evaluations for such plant modifications, significant savings in engineering hours can be achieved. This paper presents an overview of such a front-end engineering tool that has been developed and used to support engineering evaluations.

Rigorous calculations have been performed to support the design of the containment and the UHS for all nuclear plants. This work, requiring thousands of engineering hours, has been reviewed in detail by the U.S. Nuclear Regulatory Commission (USNRC) during the licensing of the plant. These evaluations have established the performance requirements for containment systems and the containment equipment qualification envelope and have served as a basis for technical specifications and plant operating procedures.

During the subsequent operation of the plant, numerous re-evaluations and sensitivity studies are performed on the interrelated analyses to assess plant operating procedures, plant degradation, revised limits on plant operation, and changes to the licensing basis of the plant. For a major plant modification, re-evaluating the entire system of interrelated containment and UHS performance analyses becomes a repetitive, cumbersome and jobhour intensive task. In today's operating plant environment, nearly all plant modifications are driven by increasingly tight schedules and reduced budgets. A plant-specific computer model, coupling the containment response directly to the performance of the UHS and auxiliary heat loads, increases the quality and consistency of the engineering evaluation for a major plant modification. Additionally, the studies can be performed in much less time and for considerably less cost than the original evaluations. Further, the integrated approach allows the engineering team and management to assess the sensitivity of proposed changes and to enhance the credibility of any associated licensing submittal.

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1. INTRODUCTION

The Ultimate Heat Sink (UHS) of a nuclear power plant is a complex cooling water system which serves the plant during a variety of both normal and emergency operating scenarios. As set forth by the USNRC in Regulatory Guide 1.27 (Reference 1), the UHS must be designed to:

- dissipate the heat of a design-basis accident of one unit plus the heat of a safe shutdown and cooldown of all other units it serves
- provide a thirty-day supply of cooling water at or below the design-basis temperature for all safety-related equipment
- be capable of performing under the meteorological conditions leading to the worst cooling performance and the conditions leading to the highest water loss

The containment for a nuclear power plant has several emergency safety features which operate during a Loss of Cooling Accident (LOCA) or Main Steam Line Break (MSLB). These systems provide core and containment cooling and pressure suppression. The performance of these systems, which include the containment air coolers, core injection, containment sprays and residual heat removal heat exchangers, is interdependent with the performance of the UHS. This interdependency can be different for each accident and can change during the course of an assumed accident.

The technical analyses performed in the design phase of the containment and the UHS for a nuclear plant and the subsequent detailed review by the USNRC during the licensing phase have helped to establish containment system performance requirements, containment equipment qualification envelopes, bases for technical specifications, and plant operating procedures. These analyses, done during the design and initial licensing phases of the plant, were typically performed separately from one another with conservative simplifying assumptions made concerning their areas of interdependency. For example, the containment pressure/temperature was calculated with certain heat exchanger performance and cooling water temperatures assumed. The heat exchanger performance was calculated using assumed heat rejection rates from the containment and assumed cooling water temperatures. Additionally, the UHS performance was calculated based on an assumed heat rejection rate from the plant. Changes to any of these systems required an iterative process of calculation and evaluation of impact on the other systems.

Over time, as a plant matures, age-related changes in the plant performance, revised limits on plant operation, and changes to the licensing basis of the plant necessitate the re-evaluation of these analyses. For a major plant modification, re-evaluating the entire system of interrelated containment and UHS performance analyses can become a repetitive, cumbersome and jobhour intensive task.

This paper details the development of a plant-specific computer code, COPATTA-CT, which couples the containment response directly to the performance of the UHS and auxiliary heat loads. The Bechtel Standard Computer Code for containment analysis, COPATTA (Reference 2), is integrated with a UHS performance model, including the effects of mechanical draft cooling towers, to assess proposed changes such as the engineering feasibility of a steam generator replacement. COPATTA-CT, like COPATTA, prepares a history of pressure and temperature in the containment atmosphere from the moment of the accident up to any specified later time. COPATTA-CT, unlike COPATTA, also has the capability of modelling a dual cooling train with cooling towers.

2. COPATTA, A CONTAINMENT ANALYSIS CODE

The COPATTA (Containment Pressure and Temperature Transient Analysis) Code is a pressurized water type nuclear reactor plant design and analysis tool and is documented in Topical Report BN-TOP-3 (Reference 3). It provides capability for calculating the pressure and temperature within the reactor containment building as functions of time following the release of water and/or steam to the containment due to a pipe rupture. The code provides for consideration of the effects of reactor system blowdown, decay power energy release, metal-water reaction energy release, sensible heat release from the reactor system piping, and engineered safeguards including air coolers, containment sprays and reactor core safety injection. COPATTA uses the implicit finite difference method to calculate the heat absorbed by the containment structure and equipment. Examples of problems solved by COPATTA include:

- Loss of Coolant Accident (LOCA)
- Main Steam Line Break (MSLB) in containment
- any high energy line break (HELB) in a single compartment, and
- assessment of equipment thermal responses during accidents for the purpose of equipment qualification

2.1 General COPATTA Model

COPATTA performs a stepwise iteration between thermodynamic statepoints based on the laws of conservation of mass and energy in calculating the transient containment response. A three region containment model is used which consists of the containment atmosphere (or vapor region), the sump (or liquid region), and the water contained in the reactor vessel. Mass and energy are transferred between the liquid and vapor regions by boiling, condensation, and liquid dropout from the containment atmosphere.

2.2 Thermodynamic Assumptions

The sump, vapor, and vessel regions are treated as open systems in a thermodynamic sense since mass flows across boundaries for all three regions. The first law of thermodynamics for such a system is:

$$\frac{dU}{dt} = \sum_j \frac{dQ_j}{dt} + \sum_i h_i \frac{dm_i}{dt}$$

where:
U is the internal energy of the system (Btu)
Q is the heat energy transferred to the system (Btu)
h is the enthalpy of the mass entering or leaving the system (Btu/lbm)
m is the mass entering or leaving the system (lbm)
t is time (hr)

This equation is integrated for each region from the start of the transient to any later specified time, yielding the thermodynamic conditions from which the state point properties of pressure and temperature can be determined. The following assumptions are inherent in COPATTA:

- At the break, the discharge flow flashes into a steam portion that is added to the atmosphere and a liquid portion that is added to the sump. The water portion is at the saturation temperature corresponding to the total containment pressure, while the steam portion mixes with the containment atmosphere.
- Each region is assumed homogeneous, but a temperature difference can exist between regions.
- Any moisture condensed in the vapor region during a time increment is assumed to fall immediately to the sump.
- Mass and energy are transferred as steam from the liquid regions (sump and reactor vessel) to the atmosphere by boiling if the containment pressure is less than the saturation pressure corresponding to the liquid temperature.
- The sump region contains no water at the beginning of the transient.

2.3 Atmosphere and Sump Regions

Typically, the containment system is assumed to be initially at normal operating conditions with water vapor and air occupying the entire free volume of the containment. During subsequent time increments, pipe break mass and energy is added to the containment. The transient pressure and temperature calculations are made by considering the mass, volume, and energy equations for water, steam, and air in the atmosphere and sump regions. These equations are solved iteratively for the vapor and sump temperatures after each time increment until a specified convergence criterion is met. The total containment pressure is computed from the sum of the partial pressures of steam and air at the containment atmosphere temperature.

2.4 Reactor Vessel Region

For the evaluation of a postulated loss of coolant accident, the rates of mass and energy released to the containment are typically supplied by the reactor manufacturer. Data is provided for the initial blowdown and reflooding phases, up to the time when the reactor vessel is in pressure equilibrium with the containment. At that point, usually a mass and energy balance is initiated for the reactor vessel. The reactor vessel region is modelled to include the effects of decay heat, metal-water reaction, transfer of sensible heat from the reactor coolant system metal, and ECCS operation. If the vessel water internal energy is less than saturation at the containment total pressure, no steam is transferred from the reactor vessel to the containment atmosphere. If it is greater than saturation, water is boiled off to the containment until the vessel water internal energy is reduced to saturation conditions.

3. PDAP AND UHSSIM, THE MECHANICAL DRAFT COOLING TOWER CODES

The computer codes PDAP and UHSSIM, written by William E. Dunn of the University of Illinois, together model the performance of the mechanical draft cooling tower. The Performance Data Analysis Program (PDAP) calculates the cooling tower performance characteristic, KaV/L, based on the design data from the manufacturer. The Ultimate Heat Sink Simulation Program (UHSSIM) calculates the evaporative water loss, basin inventory, and basin temperature for a given set of meteorological data, heat loads, and cooling tower performance data. The rate of heat addition to the basin is the difference between the plant heat load and the rate of heat rejection by the tower, determined using a model of cooling tower operation. The rate of evaporation is also determined from the cooling tower model, and the assumption of no make-up water is employed. The solids content of the basin is found from the basin mass and the initial condition based on a simple conservation of solids principle.

4. COPATTA-CT, THE INTEGRATED CODE

In the creation of COPATTA-CT, the cooling tower code modules were incorporated into the existing version of COPATTA. These modules consist of the program UHSSIM and its supporting functions and subroutines. A schematic of a typical COPATTA-CT model is shown in Figure 1. This figure shows the COPATTA three region model (sump, vessel, and containment atmosphere). In COPATTA, safety injection (SI) is added directly to the vessel region. Additionally, containment sprays and air coolers can be modelled. The source of the SI and the spray water initially is from the Refuelling Water Storage Tank (RWST). At recirculation, the pumps are realigned such that water is drawn from the sump region. Depending upon plant design, the SI and/or the sprays are cooled by the primary heat exchanger. Auxiliary heat loads, including those from the containment air coolers, can be modelled as being cooled by the intermediate loop or by the secondary heat exchanger loop. The UHS cooling tower model in COPATTA-CT evaluates the resulting UHS response based on the transient plant emergency heat load.

A separate program, PDAP, is run prior to running COPATTA-CT. PDAP uses as-built information on the mechanical draft cooling towers and design meteorological conditions to calculate the cooling tower performance characteristic, KaV/L. The cooling tower performance characteristic, KaV/L, is part of the input required by COPATTA-CT.

The UHSSIM portion of COPATTA-CT calculates the time dependent evaporative losses, basin inventory, and basin temperatures given the tower performance characteristic, meteorological data, and the COPATTA-CT calculated heat load. The UHSSIM calculations are performed every fifty COPATTA-CT calculational timesteps since the tower water temperature changes slowly compared to the containment temperature. The cooling water to the secondary heat exchangers has a temperature equal to that of the tower basin. Hence, heat exchanger calculations are done explicitly, eliminating the need to iterate on basin temperature and the calculated heat load.

The enhanced features of COPATTA-CT are:

- two independent cooling trains
- the option for a cooling tower Ultimate Heat Sink (UHS) on each cooling train. The cooling tower code modules are based on UHSSIM and its supporting functions and subroutines. The basic calculational algorithm of

COPATTA is not changed. Critical variables and algorithms in the UHSSIM related modules are retained in their original form.

- the air cooler coolant temperature can be one of three options: (1) a constant value, (2) the UHS cold water (return) temperature, or (3) the intermediate loop coolant temperature
- meteorological data is input for use in cooling tower calculations
- the option for cooling tower makeup water can be chosen such that the amount of water in the tower basin remains at a constant level (i.e. at its originally specified value). The makeup water is assumed to be added at a constant temperature as specified by the user.

If two trains of engineered safeguards features are modelled, the following simplifying assumptions are made:

- the heat exchanger configuration and heat exchanger types are identical for each train.
- two cooling towers are specified and the basin temperature is assumed to be the same for both trains. (If one train is used, one cooling tower must be specified.)
- the configuration of the air cooler component cooling water piping is identical for each cooling loop.

To facilitate the interpretation and documentation of results, the COPATTA-CT program uses input from a single input file and produces four output files: (1) the normal output file with word descriptions of the output parameters, (2) a file containing containment, sump, and reactor vessel data. This file is suitable for use by a post-processor for constructing tables or plots, (3) a file containing primary and secondary heat exchanger data, and (4) a file containing the UHS tower results. The integrated code is PC-based and runs under the WINDOWS™ environment.

Figure 2 shows a sample family of curves illustrating the type of results that can be obtained using COPATTA-CT. The particular study involved engineering support for a steam generator replacement and a fuel cycle change. In Figure 2, the long term containment pressure and temperature responses are shown. These curves are used for evaluation of containment design and assessment of equipment qualification. The third figure shows the calculated transient heat load of the secondary heat exchanger loop. The shape of the curve is characterized by the initiation of the containment air coolers at 35 seconds and the subsequent start of SI/spray recirculation at 3050 seconds. The temperatures associated with these heat loads were used to evaluate thermal stresses in the intermediate and secondary cooling water systems. The last curve shows the actual heatup of the UHS cooling tower basin. The basin temperature remains approximately constant until the significant increase in heat load associated with the start of recirculation. This curve also shows that in the long-term, the basin temperature is driven by the daily cyclic change in wet bulb temperature.

The COPATTA-CT model used to generate the responses shown in Figure 2 has also been utilized to assess UHS cooling tower basin inventory and makeup capability. The approach eliminates unnecessary conservatism because the model integrates the containment response with the performance of the heat exchangers, containment air coolers, and the UHS cooling tower. The use of the integrated approach has also resulted in at least a 50 percent savings in both the cost and schedule required to perform the associated engineering. This same technology has been successfully applied for plants with a cooling pond, a spray pond and for plants with a time-varying bay temperature as a UHS.

5. CONCLUSION

This paper presents an overview of how a front-end engineering tool which couples the containment response directly to the performance of the UHS and auxiliary heat loads has been developed and used to support engineering evaluations. The plant-specific computer model, COPATTA-CT, has been found to significantly increase the quality and consistency of related engineering evaluations. Additionally, studies can be performed in much less time and for considerably less cost than the original evaluations. The integrated approach allows the engineering team and management to assess the sensitivity of proposed changes and to enhance the credibility of any associated licensing submittal.

6. REFERENCES

1. U.S. Nuclear Regulatory Commission Regulatory Guide 1.27, "Ultimate Heat Sink for Nuclear Power Plants," Revision 2, January 1976.

2. Bechtel Standard Computer Program COPATTA (MAP-175), "Containment Pressure and Temperature Transient Analysis Code," Version G1-14, November 1993.

3. Topical Report BN-TOP-3, "Performance and Sizing of Dry Pressure Containments," Revision 4, March 1983, Bechtel Power Corporation.

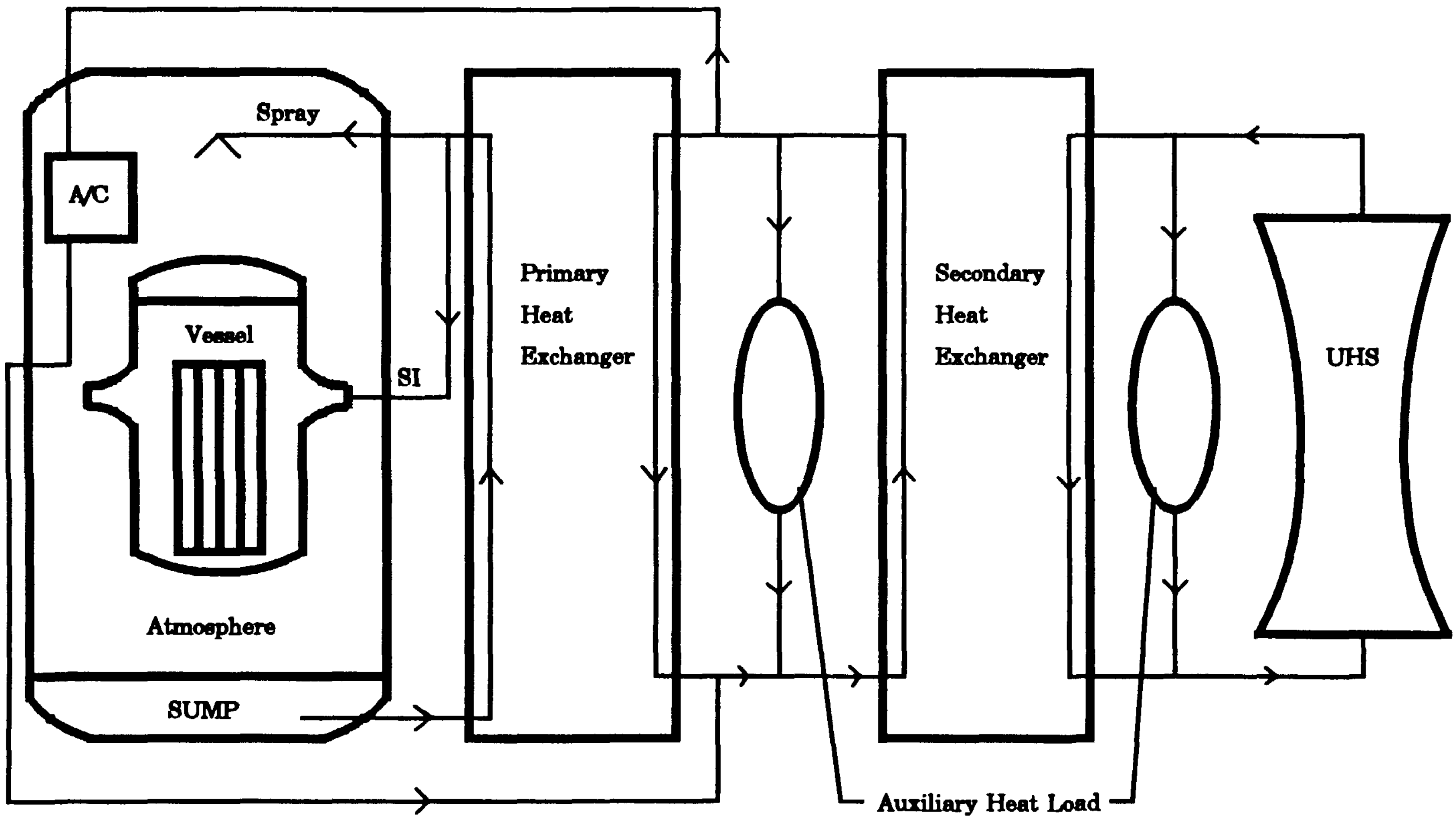


Figure 1: COPATTA-CT Model Schematic

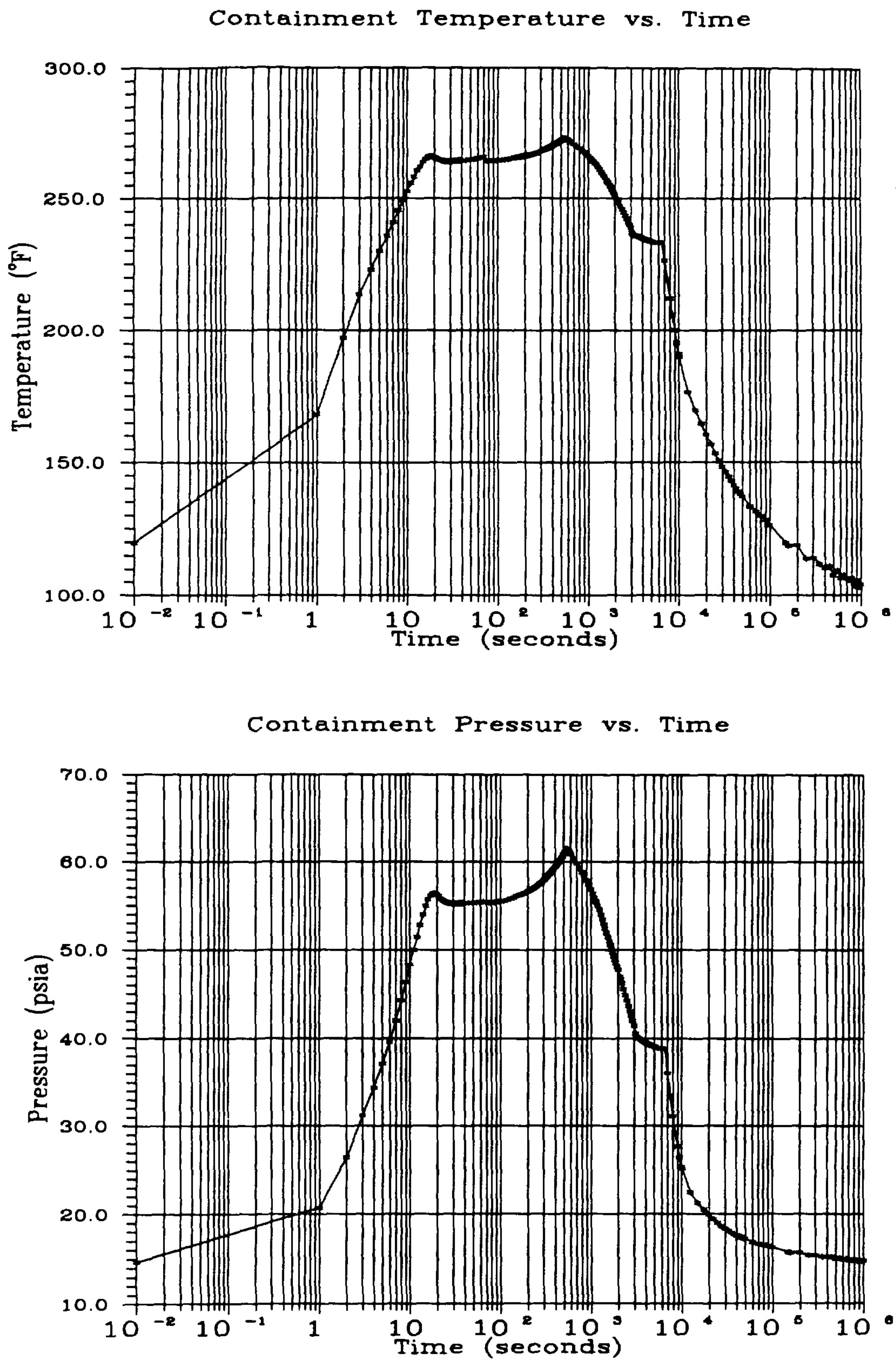
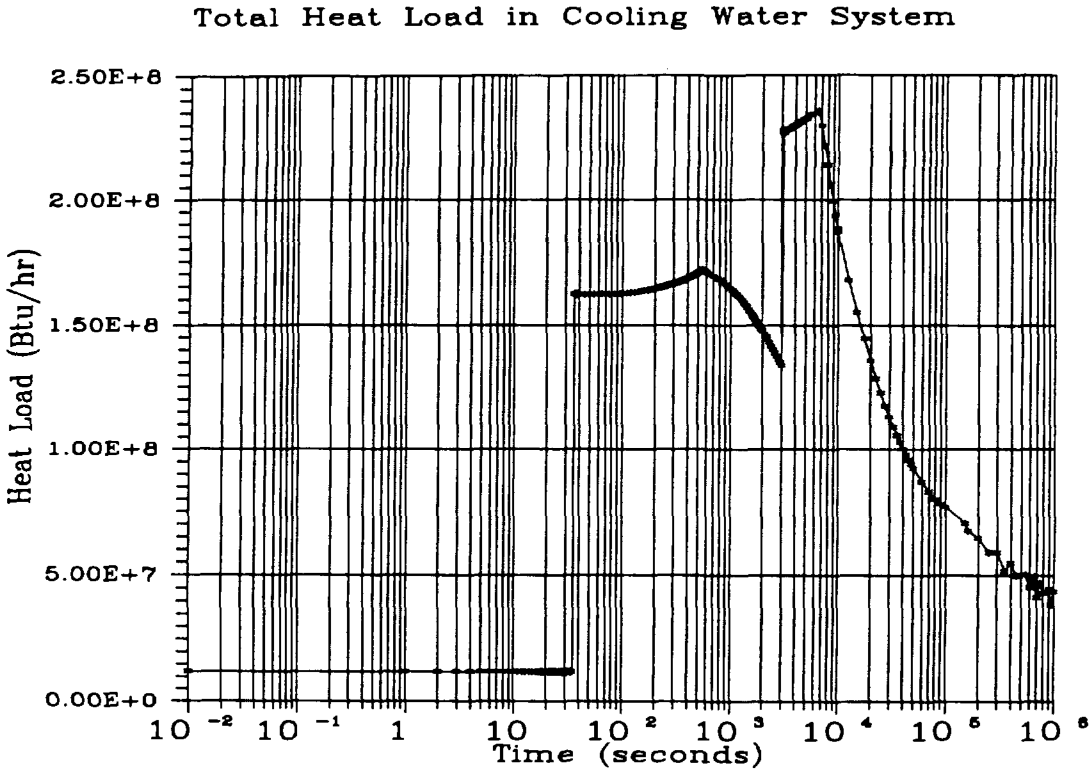


Figure 2: Sample COPATTA-CT Results



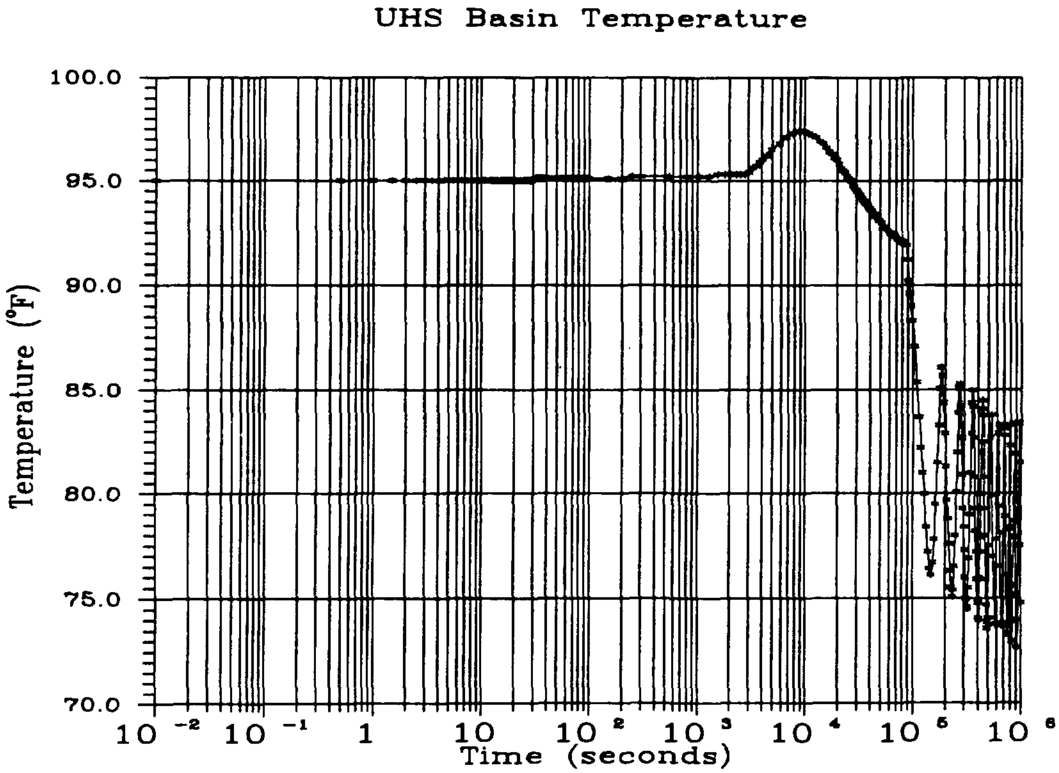


Figure 2: Sample COPATTA-CT Results, concluded