

# System cooling design for the water-cooled IBM Enterprise System/9000 processors

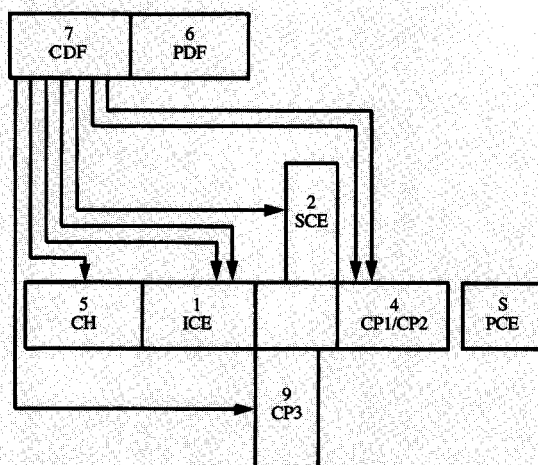
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The high operating speed and corresponding high chip heat fluxes in the IBM Enterprise System/9000™ water-cooled mainframe processors are made possible by improvements in component- and system-level cooling. The heart of the closed-loop water-cooling system is a coolant distribution frame (CDF) common to all water-cooled processors. The CDF provides a controlled water temperature of 21.7°C to the central electronic complex (CEC) at water flow rates up to 245 liters per minute (lpm) and rejects heat loads of up to 63 kW for the largest processor. The water flow provides cooling to multichip thermal conduction modules (TCMs), to power supplies, and to air-to-water heat exchangers that provide preconditioned air to channel and memory cards. As many as 121 chips are mounted on a TCM glass-ceramic substrate, with chip powers reaching 27 W or a heat flux of 64 W/cm<sup>2</sup>. A separable cold plate was

developed to cool these modules. The power supplies with high heat densities are primarily cooled by water which flows through a unique separable cold plate designed for ease of serviceability of the power supply. Although water cooling is utilized for components with high heat fluxes, air cooling is employed for elements of the system with lower power densities. For cards cooled by forced air, careful trade-off studies among acoustical power, chip reliability, and high availability were required. The acoustic noise emissions of all the fans and blowers were determined, and a system model was constructed to measure the noise radiated from each frame in the system. The data were used to design top covers and other components to ensure that the system could meet its thermal/acoustical requirements. A closed-loop frame in which all the heat was rejected to water was developed to meet these requirements.

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**Figure 1**

System water flow distribution loops among ES/9000 frames. (For clarity, only supply loops are shown.)

**Table 1** Comparisons of IBM water-cooled processors.

|                                            | 308X   | ES/3090 | ES/9000 |
|--------------------------------------------|--------|---------|---------|
| Total heat load (air/water) (kW)           | 8.2/31 | 18/35   | 12.5/63 |
| Pump size (kW)                             | 1.1    | 2.2     | 5.2     |
| System water flow rate (lpm)               | 80     | 161     | 245     |
| System water temperature (°C)              | 24.0   | 22.9    | 21.7    |
| Number of air-moving devices               | 13     | 22      | 43      |
| System air-flow rate (m <sup>3</sup> /min) | 49     | 108     | 136     |

## Introduction

Since the introduction more than ten years ago of the first IBM processors using water-cooled thermal conduction modules (TCMs)—the 308X family [1]—demands for more memory capacity, faster logic, and improved diagnostics have resulted in an increase in total system power. Heat fluxes at the chip and module level continue to increase at an almost exponential rate [2]. All elements within the system have been affected by the increased system power: logic circuits within the multichip TCM, power supplies, power distribution, and the air-cooled modules mounted on channel and memory cards. Table 1 shows some of these trends for the largest single-image processors—two processors for the 308X family and three for the Enterprise System/3090™ (ES/3090™) and Enterprise System/9000™ (ES/9000™) families.

Such developments continue to challenge the heat transfer designers of the devices and systems that maintain and control the functional temperatures of the various electronic elements and at the same time guarantee the thermal reliability of the electronics and of the cooling subsystems. A most important recent aspect is the overall availability of the system within its cooling environment. An increasing number of industry applications now require fail-safe operation. Cooling system maintenance and system operation must proceed concurrently. System operation must therefore be insensitive to environmental and component failures. These demands continue to require development and implementation of the most advanced and novel heat-transfer system elements, components, and designs. Air cooling will continue to be used, with an increasingly difficult trade-off between the air-flow rate required to maintain desired component temperatures and the limitations imposed by the system requirement for low acoustic noise levels [3].

## Water cooling

### • Water-cooling system design

A large percentage (approximately 80%) of the heat generated within the frames of the ES/9000 processor is removed by a closed-loop water-cooling system; the remainder is transferred into the room environment by forced or natural air convection. Water is circulated to the frames and returned to the coolant distribution frame (CDF), where heat from the system is rejected to customer-supplied chilled water via a shell and tube heat exchanger. Figure 1 illustrates the flow distribution between the CDF and the water-cooled intercommunication element (ICE), system control element (SCE), central processor (CP), and channel (CH) frames. The power distribution frame (PDF) and processor controller (PCE) frame are air-cooled. The system water is controlled to a temperature of  $21.7^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$  via a chilled-water control valve located in the CDF.

The various water-cooled components in the processor are hydraulically connected to form a maximum of seven parallel coolant flow loops. Most of the heat generated by the multichip modules and power supplies in the processor is removed by conduction to water-cooled cold plates. In addition, air-to-water heat exchangers are used in some areas to cool the air provided to channel and memory cards.

The primary components contributing to the water heat load for the system can be divided into three categories. These are listed in Table 2 along with the percentage of heat to air and water for a nominal environment ( $22.5^{\circ}\text{C}$  and an elevation of 152 m).

For a uniprocessor system, the maximum heat load to water is typically 37 kW, while for a triadic system (three processors), the heat load to water is 63 kW.

- *Water-cooled components*

### TCM/TCM cold plate

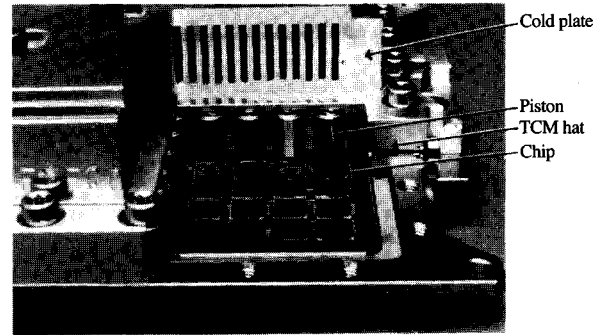
**TCM** The TCM design employed in the water-cooled ES/9000 system uses the reliable piston-type design employed in previous IBM water-cooled mainframes [4]. **Table 3** shows a comparison of the TCM designs employed in IBM water-cooled mainframes over the past decade. (Although multichip modules of higher chip counts exist for each system, for brevity only the 100-chip version is compared. The 100-chip version is also used to compare  $R_{int}$ .  $R_{int}$  is the thermal resistance from a chip to a TCM "hat" surface, while  $R_{ext}$  is the thermal resistance from the hat to the cold-plate inlet water.)

The ES/9000 TCM, as shown in **Figure 2**, is a hermetically sealed module containing a square 12.7-cm multilayer glass-ceramic substrate designed to hold up to 121 semiconductor chips. The maximum chip power dissipation is 27 W. The spring-loaded pistons contacting each chip allow for possible variations in chip height, tilt, and location resulting from manufacturing tolerances. To attain the thermal performance objective for this TCM, a simple modification was made to the conventional piston design. A slight taper was added to each end of the piston [5]. This modification, along with a very large spherical crown on the piston face adjacent to the chip, significantly lowered the thermal resistance between chip and hat (see **Figure 2**). In the TCM design of the 308X and ES/3090 systems, the TCM was filled with helium gas to improve the thermal conductance from the chip to the piston and from the piston to the hat. The helium gas has a thermal conductivity approximately six times higher than that of air, and could be maintained within the TCM modules for their entire lifetime. However, because the glass-ceramic substrate material used in the ES/9000 TCMs is permeable to helium gas, a synthetic oil having a thermal conductivity 5% higher than that of helium gas is used.

**TCM cold plate** Heat is removed from the hat assembly by a separable water-cooled cold plate [6]. The cold plate shown in **Figure 3** is an internal finned structure constructed from high-conductivity tellurium copper; it is attached to the aluminum TCM hat with 13 screws. Heat transferred from the TCM hat assembly to the cold plate is improved by adding a thin film of oil when the cold plate is mounted on the TCM hat assembly. Adding this oil decreases the nominal interface thermal resistance from 0.0021°C/W to 0.0013°C/W and results in an average chip-junction temperature decrease of approximately 1°C.

The cold-plate thermal resistance is defined as

$$R_{cp} = \frac{\bar{T}_{cp} - T_{in}}{Q}, \quad (1)$$



**Figure 2**

Thermal conduction module with dual-tapered pistons.

**Table 2** Typical heat load distribution for the water-cooled ES/9000 processors.

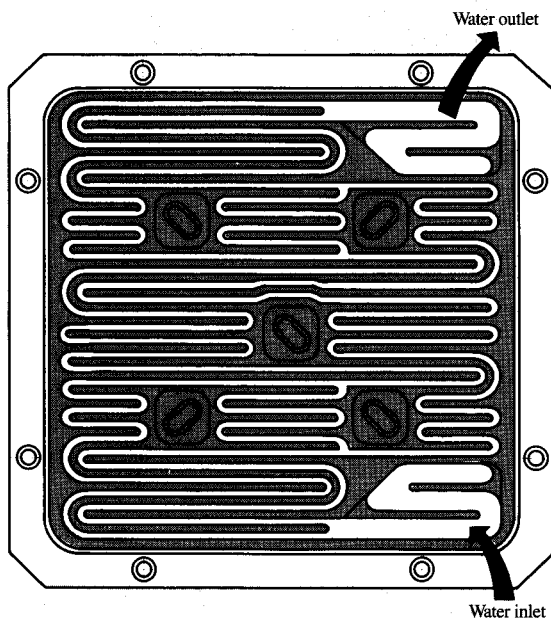
|                           | Heat load      |                  |
|---------------------------|----------------|------------------|
|                           | Percent to air | Percent to water |
| Closed-loop channel frame | 0              | 100              |
| TCM                       | 2              | 98               |
| Water-cooled power supply | 20             | 80               |

**Table 3** Comparison of TCMs utilized in IBM water-cooled processors.

| Parameters                                    | 3081  | ES/3090 | ES/9000 |
|-----------------------------------------------|-------|---------|---------|
| Chip size (cm)                                | 0.46  | 0.46    | 0.65    |
| Chip pitch (cm)                               | 0.85  | 0.85    | 1.08    |
| Substrate size (cm)                           | 9.0   | 12.7    | 12.7    |
| Number of chips                               | 100   | 100     | 100     |
| Maximum chip power (W)                        | 4     | 7       | 27      |
| Maximum module power (W)                      | 300   | 600     | 2000    |
| Maximum chip heat flux (W/cm <sup>2</sup> )   | 19    | 33      | 64      |
| Maximum module heat flux (W/cm <sup>2</sup> ) | 3.7   | 3.7     | 12.4    |
| Nominal $R_{int}$ per chip (°C/W)             | 9.5   | 5.9     | 1.21    |
| Nominal $R_{ext}$ per cold plate (°C/W)       | 0.028 | 0.0184  | 0.00547 |

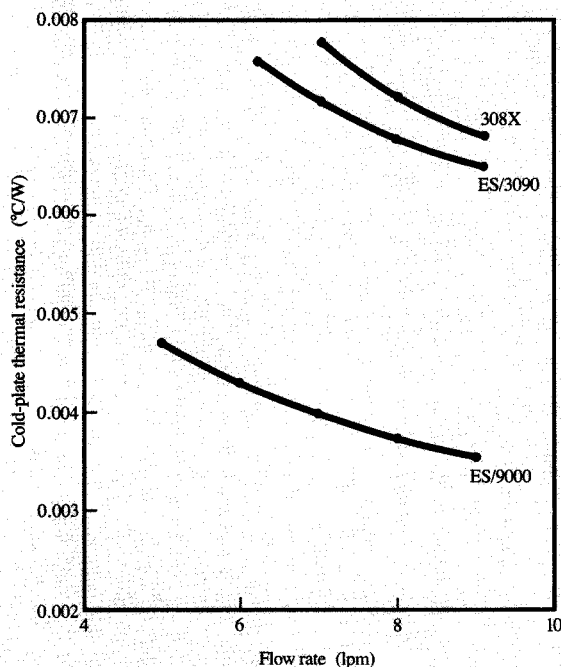
where  $\bar{T}_{cp}$  is the average temperature of the cold-plate surface adjacent to the TCM hat,  $T_{in}$  is the inlet water temperature, and  $Q$  is the heat dissipated. **Figure 4** shows the thermal resistance of the 308X, ES/3090, and ES/9000 TCM cold plates as a function of water flow rate. For the range of cold-plate flows within the ES/9000 system ( $7.57^{+1.37}_{-0.38}$  lpm), the thermal resistance of the cold plate is  $0.0039^{+0.0001}_{-0.0003}$  °C/W.

During the lifetime of the system, the cooling water forms light fouling deposits in the flow channels of the cold



**Figure 3**

TCM cold-plate internal flow configuration.



**Figure 4**

TCM cold-plate thermal resistance.

plate. Cold-plate samples from field-exposed ES/3090 systems used to determine the degree of fouling indicated that the fouling thermal resistance was small, of the order of  $0.00027^{\circ}\text{C/W}$ .

**TCM junction temperature** The maximum chip junction temperature can be calculated from the following equations describing the chip junction temperature and its associated variance [7]:

$$T_j = \Delta T_{j-c} + P_c R_{int} + P_m R_{ext} + T_w, \quad (2)$$

$$(\delta T_j)^2 = \left( \frac{\partial T_j}{\partial P_c} \delta P_c \right)^2 + \left( \frac{\partial T_j}{\partial P_m} \delta P_m \right)^2 + \left( \frac{\partial T_j}{\partial R_{int}} \delta R_{int} \right)^2 + \left( \frac{\partial T_j}{\partial R_{ext}} \delta R_{ext} \right)^2 + \left( \frac{\partial T_j}{\partial T_w} \delta T_w \right)^2, \quad (3)$$

where  $T_j$  is the junction temperature of the chip;  $\Delta T_{j-c}$  is the temperature drop from the junction to the chip;  $T_w$  is the inlet water temperature,  $P_c$  and  $P_m$  are the chip and module powers, respectively; the  $R$ s are thermal resistances; and  $\delta$  is the standard deviation of each parameter. Using values of  $P_c = 20.7 \text{ W} \pm 6.3 \text{ W}$ ,  $P_m = 1700 \text{ W} \pm 300 \text{ W}$ ,  $R_{int} = 1.21^{\circ}\text{C/W}^{+0.45}_{-0.20}$ ,  $R_{ext} = 0.00547^{\circ}\text{C/W}^{+0.0014}_{-0.0010}$ , and  $T_w = 21.7^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ , this analysis results in a maximum chip junction temperature of  $71.5^{\circ}\text{C}$  (only positive deviations for  $R_{int}$  and  $R_{ext}$  were used in this analysis in order to calculate a maximum temperature).

**TCM thermal protection** The primary role of thermal protection for the TCM is to prevent mechanical damage. The TCM is a sealed vessel filled with oil, and any cooling hardware failure that interferes with the removal of heat will result in internal pressures that could become high enough to crack the substrate. To prevent such a failure, the temperature of a single chip within each TCM is continually monitored by the power thermal control system using an on-chip temperature-sensing (OCTS) scheme [8]. The temperature range of all other chips on the module, the module average chip temperature, and the average temperature of the oil within the module are inferred from this single chip-temperature measurement.

The power thermal control system shuts the system down if the predetermined OCTS temperature limit is exceeded. Compared with prior IBM systems in which a substrate-mounted thermistor was used, OCTS offers an accurate and direct reading of chip temperature as well as a rapid response to any thermal transients. This system does not protect against any localized cooling anomalies in the TCM, but instead protects against problems that affect the entire array of chips in the TCM, such as degradation in water flow through the TCM cold plate.

Localized cooling problems are detected in the TCM manufacturing process. Following the completion of the

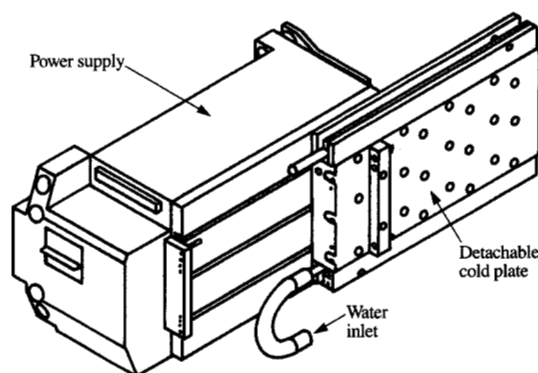
assembly of the TCM, each TCM is plugged into a tester which powers it to the same level as that in an actual system. Then, by utilizing the OCTS scheme in which a single diode on logic and array chips is monitored to measure temperature, the TCM assembly process is assessed. Temperature criteria for each chip are specified, and if any fall outside the criteria, the TCM is disassembled, examined, and rebuilt.

#### Power supplies

A key element in designing the ES/9000 system for high availability was the philosophy used in the design of the power supplies. To maximize system availability, power supplies are operated in a parallel-output, current-sharing arrangement of  $N$  supplies to satisfy the load requirements with a redundant supply ( $N + 1$ ) in each group of supplies. A fault occurring in any power supply of a group does not affect the power output rating of the group. Each supply can be removed from operation and replaced without affecting the operation of other members of the group. The cooling design for the water-cooled supplies permitted maintenance of the power supplies concurrently with system operation. To permit concurrent maintenance of the power supplies, a separable cold-plate design was implemented (see Figure 5). The power-supply cold plates are connected to structural members within the system frames. Each supply can be detached from the cold plate with a special camming tool which releases spring-loaded mechanisms that, when activated, force the power supply against the cold plate, creating a good thermal interface. Once the spring force is released, the supply can be removed from the frame.

To minimize pump size and still maintain component functional temperature limits, groups of two and three power supplies are plumbed in series. Each power supply is equipped with a thermal sensor, but only one sensor from each group in a flow loop will return a signal to the power thermal control system, where an interrupt is created if a malfunction occurs.

Laboratory and system tests were performed to thermally evaluate and characterize the power supplies. Because the supplies are geometrically similar, the supply with the highest heat dissipation was thermally profiled. The single voltage-level power supply chosen for analysis and test was the 3.6 V/500 A. The total heat dissipation of this supply is 733 W, with approximately 80% of the heat conducted through the cold plate to the water. In the laboratory, tests were run to determine the component temperatures and their sensitivities to conditions of water flow rate, water temperature, ambient air temperatures, cold-plate interface, and power-input voltages. Any component with a temperature near its maximum allowable temperature limit was identified as a critical component. The thermal performances of the critical components at



**Figure 5**

Water-cooled power supply with cold plate.

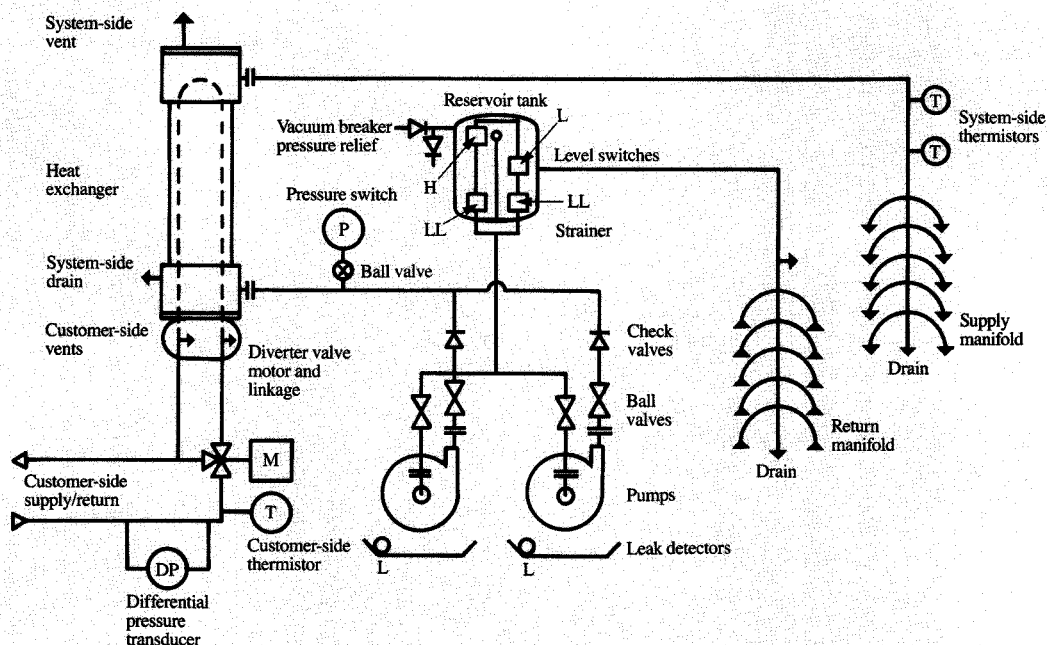
**Table 4** Thermal comparisons of critical power-supply components.

|                    | Heat load<br>to water<br>(%) | Reliability<br>temperature<br>limit<br>(°C) | Measured<br>temperature<br>at nominal<br>conditions<br>(°C) |
|--------------------|------------------------------|---------------------------------------------|-------------------------------------------------------------|
| Power MOSFET       | 90                           | 100 (junction)                              | 81                                                          |
| Output transformer | 87                           | 130 (winding)                               | 102                                                         |
| Output rectifier   | 81                           | 125 (junction)                              | 120                                                         |
| Bulk capacitor     | 39                           | 85 (case)                                   | 65                                                          |

nominal conditions are compared to the target reliability temperatures in Table 4. Similar comparisons were made between functional temperature limits and worst-case temperatures on the basis of projections from the sensitivity studies described above. To experimentally verify the thermal performance of the power supplies, thermal tests were performed in the system for nominal and worst-case conditions which included disabling of redundant power supplies.

#### • Hydrodynamic modeling

Many variables were considered in the early design stages of development of the water-cooling system, including space available for water-cooling hardware, flow required for each component, cooling hardware cost, parallel vs. serial flow or combinations thereof, and component selection to attain reliability requirements. Key to the development of the water-cooling system was the creation of a hydrodynamic model.



**Figure 6**

Schematic of coolant distribution frame.

Estimates of many component flow characteristics not yet determined were made early in the development cycle on the basis of analysis or knowledge from prior system designs. A major objective was to design a system with a minimum pump size that still provided the desired flow for each component. Large network models were developed connecting and characterizing fluidic elements—hoses, manifolds, piping, cold plates, heat exchangers, valves, etc. that were used within the system. The models were created using the Advanced Statistical Analysis Program (ASTAP) [9]. ASTAP is an electrical network analysis program; it was used to analyze flows and pressures throughout the water-cooled system.

For components such as pipes, bends, or T-connections where loss coefficients were known as a function of flow rate and component geometry, the loss coefficient was calculated and used to determine the component resistance used in the electrical analogy. For a pipe, the losses depend on the friction factor, the pipe length and diameter, and the flow rate. Bends, hose, contractions, expansions, and orifice models were created which calculated a flow- and geometry-dependent resistance for the ASTAP analysis in a manner similar to the pipe model.

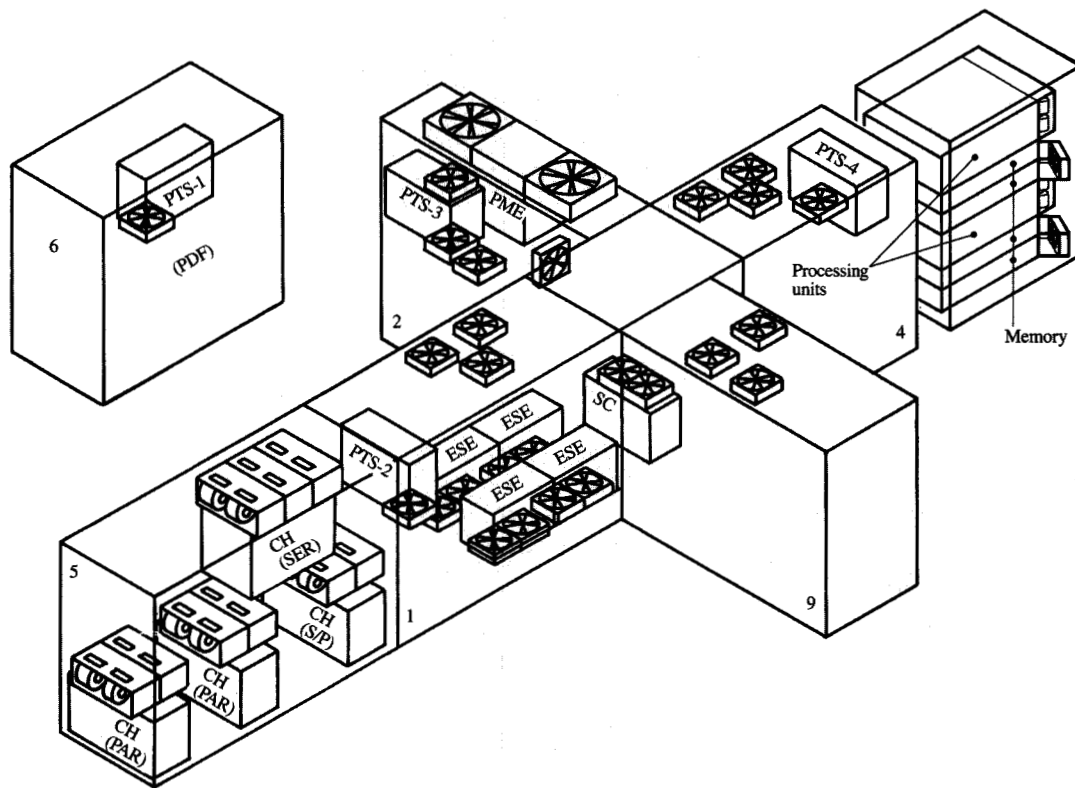
T-connections were modeled as a combination of voltage sources and resistances.

For each frame model, the impedance of each loop was determined and used to construct a mathematical representation of the total system model. This model was employed to determine the need for balancing orifices to ensure that each element received flow adequate for specific cooling requirements in a maximum-configuration triadic system. It was also necessary to ensure that the flow did not exceed the maximum allowable material erosion limit when the system was configured as a uniprocessor with minimum features present. Comparisons of the measured water flow rate of the system to the flow rate calculated by ASTAP showed agreement within 8%.

#### • Coolant distribution frame

The CDF is the heart of the cooling system for all water-cooled ES/9000 processors. Through a closed-loop system, it supplies the central electronic complex (CEC) with water at a nominal temperature of 21.7°C and flow rates between 150 and 245 lpm, depending upon processor model. Heat removed from the CEC is transferred to customer-supplied chilled water. This CDF was designed to reject 80% more heat and provide 50% higher system water flow rates than the ES/3090 CDF.

The primary flow and heat transfer components within the CDF are two centrifugal pumps driven by 5.2-kW



**Figure 7**

CEC layout showing air-cooled elements.

motors, a shell-and-tube exchanger, and a three-way diverter valve (see **Figure 6**). System water is circulated at a constant flow rate by one of the pumps. The temperature of the system water is controlled by the diverter valve, which regulates the amount of chilled-water flow through the heat exchanger. A microprocessor controls the motor which drives the diverter valve.

To satisfy customer demand for high system availability,

- Redundant pumps and critical sensors are included in the system.
- Pump switchover is performed automatically in the event of a pump failure.
- Many components are replaceable while the system is operating.

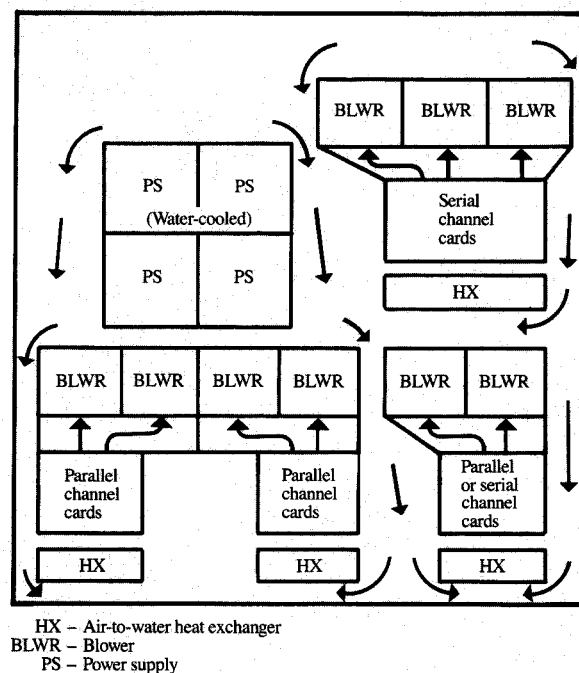
### Air cooling/acoustics

#### • Air-cooling system design

As shown in **Figure 7**, a great number of the system elements in the water-cooled ES/9000 system are air-

cooled because of their lower power densities and packaging configurations. The air-cooling system was designed to provide superior reliability, availability, and serviceability (RAS) characteristics in comparison to previous IBM mainframe products. A single air-moving device (AMD) failure for any functional element is detected but does not cause a critical interrupt for the system. In addition, most AMDs can be concurrently maintained to provide maximum system availability. The AMDs were designed and qualified for longer life expectancies than had previously been attained on any IBM mainframe system.

One significant new feature of the ES/9000 is a closed-loop frame design. The frame is termed "closed loop" because all heat is removed by the water-cooling system rather than having the heat exhausted into the computer room. A naphthalene sublimation technique was used to exploit the analogy between mass and heat transfer. Mass-transfer tests allowed analogous heat-transfer problems to be studied. This technique was used in a thermal/acoustical model of an ES/9000 system. The model allowed system-



**Figure 8**

Closed-loop channel frame.

level thermal characteristics to be studied well before a functional system was available.

#### *Closed-loop frame design*

During the early stages of development, it became evident that the noise emission of the system would greatly exceed the allowable limits if the design concepts of the ES/3090 were followed. From noise-emission data, prediction of the blower noise levels, and knowledge of the attainable noise attenuation through the use of typical side and top covers, it was determined that a closed-loop frame design would be required for the channel (Figure 7, frame 5).

The closed-loop design provided the unique challenge of removing all generated heat through air-to-water heat exchangers, as shown in Figure 8. From a heat exchanger, the cards received preconditioned air, which was forced across each card and then exhausted into the frame for recirculation. A total of 1500 W was transferred to the heat exchangers rather than being exhausted into the computer room. Aside from the acoustical advantage gained, insensitivity to computer room ambient temperature was achieved. Temperatures within this frame are largely unaffected by temperature variations outside the frame. Allowable variations of 16–32°C in computer room

temperature would result in only a 2.5°C variation in card inlet temperatures.

#### *Naphthalene sublimation technique*

A new test method first used in the development of air cooling for the ES/9000 was the naphthalene sublimation technique [10]. This is an experimental technique employed to determine heat-transfer coefficients in convection flows. The basic characteristic of the technique is that the heat-transfer problem to be investigated is replaced by an analogous mass-transfer problem.

Dimensional analysis performed on the equations describing heat- and mass-transfer processes demonstrate that for any geometrically similar configuration and for similar boundary conditions, equations of the same form can be obtained [11]. The result is that a simple relationship exists between the Sherwood number describing the mass-transfer process and the Nusselt number describing the heat-transfer process. The boundary condition for the mass-transfer experiments corresponds to an isothermal surface for the analogous heat-transfer problem. For example, to determine the heat-transfer characteristics of the surface of a module mounted on a printed circuit card, a geometrically similar module is cast



of naphthalene. By installing this naphthalene module in the same air-flow environment and by measuring the weight loss for a predetermined length of time, the mass transferred can be related to the surface thermal characteristics of the actual electronic module. Sparrow et al. [12] described the application of this technique to blocklike arrays of electronic components.

The advantages of using the mass-transfer technique were threefold:

- Thermal test data were obtained long before any functional hardware was available.
- Mechanically similar, nonfunctional card or TCM board hardware could be used.
- Thermal testing cost could be substantially reduced.

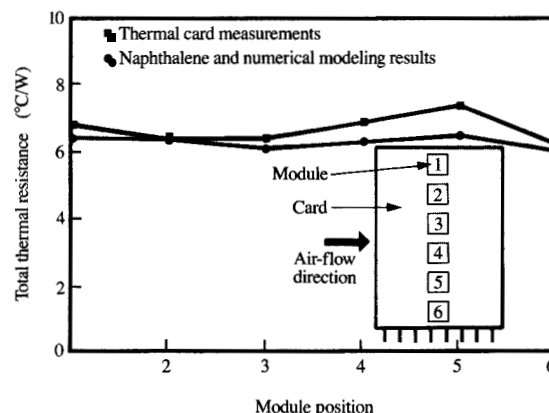
Naphthalene was employed in the mass-transfer experiments because of its properties. It sublimes at room temperature, has a low toxicity, and has excellent casting properties.

#### *Thermal/acoustical model (T/A model)*

In past mainframe system designs, identified thermal problems required design changes late in the development schedule. To avoid these problems and to implement and verify new thermal testing techniques, a mechanical thermal model of the system was constructed. This mechanical model was built to thermally duplicate the air-cooled and hydrodynamic elements within the system while at the same time providing an acoustical test vehicle. Experiments with new and more effective thermal designs were also possible.

Naphthalene mass transfer, AMD operating point, and ambient temperature measurements could all be determined using this model. To measure frame ambient temperatures, the T/A model was populated with resistive heaters to simulate all heat-generating elements in the system. A coolant distribution frame (CDF) was connected to the hydrodynamic flow loops to remove heat using the air-to-water heat exchangers and power-supply cold plates. The resistive heaters, AMDs, and CDF were all powered to simulate nominal machine air heat loads so that ambient air temperature measurements could be taken. This testing was most critical for the closed-loop channel frame because no fresh air enters the frame.

After the frame ambient tests had been completed, naphthalene testing was performed on cards. Card cages populated with mechanical models of most of the cards were mounted in the T/A model to perform naphthalene mass-transfer testing for each element. The mechanically correct electronic modules on the cards were then selectively removed and tested with naphthalene castings of similar geometry. In this manner profiles of convective heat transfer were developed by running tests in various



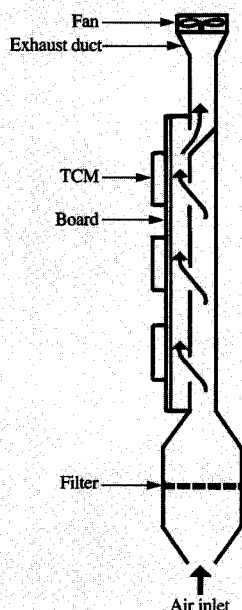
**Figure 9**

Comparison of thermal tests and mass-transfer/numerical tests.

module and card locations and under varying system conditions. Card-column-to-card-column variation and module position sensitivities were studied. These convective heat-transfer coefficients were then used as input to module, card, and board numerical thermal models.

As previously described, naphthalene testing was used to determine convective heat-transfer characteristics for the first time in an IBM mainframe system design. To determine the accuracy and potential limitations of this technique, printed circuit cards thermally and mechanically similar to the functional product cards in the system were constructed. Thermal chips in modules on these cards were powered to levels similar to those seen in a functional system, allowing chip-temperature measurements to be made using thermal diodes on the chips. Interactions between modules on the same cards, card heat-transfer effects, and card column variations were studied and were then compared with naphthalene mass-transfer testing and numerical modeling results under the same conditions (see **Figure 9**).

Additional mass-transfer tests were performed on the air-cooled TCM board shown in **Figure 10**. TCM boards were tested separately from the rest of the air-cooled components in the T/A model. A full-scale board model was created to determine the necessary air flow to meet the board cooling requirements. Naphthalene tests were then performed at the TCM sites on the board. By using the heat/mass-transfer analogy previously described, convective heat-transfer characteristics were determined. Through iterative naphthalene testing, an air-impingement scheme was found to provide the best thermal



**Figure 10**

Air-cooled TCM board.

performance. Impingement heat-transfer coefficients were more than twice those that could be achieved using a parallel-flow scheme. Representative results are shown in **Figure 11**.

#### • Acoustics

National, international, and European standards [13, 14] describe methods for the measurement and declaration of acoustical noise generated by computer and business equipment. Internal IBM standards set limits on the noise emission of IBM products which are intended to satisfy noise-level requirements in Germany [15] and Sweden [16], and to meet IBM marketing requirements. The ES/9000 processor was one of the first IBM machines designed to meet Swedish noise requirements.

The now-standard measure of noise emission, the A-weighted sound power level, was determined in the hemi-anechoic room in the Poughkeepsie Acoustics Laboratory, a room specifically designed for measurements on mainframe computers. It has a large low-noise air-conditioning system, a raised floor typical of those used in data processing installations, adequate power for testing large systems, and a chilled-water supply.

Thus, the main sources of noise in the frames were the AMDs (fans and blowers) used for air cooling and the water pumps in the CDF. The two essential elements of the acoustical design are control of the noise level of the fans and blowers themselves, and control of the noise along the path from the source to the listener. In the early design stages, we were guided by the acoustical design of the ES/3090 system and by a procedure for modeling sources and paths [17] which was very useful in selecting air-moving devices and the packaging needed to ensure that the acoustical requirements were met. The air-moving devices were measured using a special noise-measurement apparatus first developed by IBM and modified by the computer and business equipment industry to become an American National Standard [18].

The acoustical design was greatly simplified by the construction of a T/A model of the system. It was necessary to evaluate only Frames 1, 2, 3, and 5; the effect of adding Frames 4 and 9 could be determined by measurement on selected fans in Frame 1. An extensive series of tests on the model confirmed that the closed-loop design for Frame 5 would be necessary to meet the acoustical requirements, and that the noise-emission level of Frame 2 was satisfactory. The thermal/acoustical model evaluation also showed that the louvered top covers which were part of the original design did not provide adequate noise reduction. The main problem was that the back pressure on the TCM backboard cooling fans was higher than had been expected. Consequently, the fans had a higher noise-emission level than had been predicted. The top covers of the machine were redesigned to provide additional attenuation. A study was also made of the need for redundant fans for TCM backboard cooling and for cooling PTS gates. It was possible to eliminate redundant fans with a savings in cost, reduction in the noise-emission level, and no significant effect on reliability.

The declared noise-emission level [19] of the CEC which consists of Frames 1, 2, 3, 4, 5, and 9 is 7.8 bels, which just conforms to Swedish noise-emission limits [16] and the German Workplace Noise Law [15]. The noise emission of the other two major frames in the system, the CDF/PDF and the processor controller, was carefully considered, and measurements were made during the development cycle. The noise emission of these frames is well below European requirements; the declared noise-emission levels of the CDF/PDF and processor controller are 7.1 bels and 6.7 bels, respectively.

#### Summary

The water-cooled IBM ES/9000 cooling design is a significant enhancement over that of the ES/3090 machines. It plays an important part in enabling a fivefold improvement in packaging density, implementation of fiber optic channels, and a 25-times increase in memory

and bandwidth performance compared to the previously most powerful IBM ES/3090J models. In the ES/9000 processors, IBM has employed and initiated advances in the system cooling technologies. Some of the key elements are the following:

- A dual-tapered TCM piston design that provides enhanced performance compared to prior system designs, ease of manufacturability, and improved reliability.
- A synthetic oil added internal to the TCM and between the cold plate and TCM hat to further lower TCM chip temperatures, thereby improving reliability.
- A separable cold-plate design for the water-cooled power supplies that permits replacement of the supplies without interfering with the water system.
- A coolant distribution frame designed to reject 80% more heat and provide 50% higher water flow rate than the ES/3090 CDF.
- Many cooling components concurrently maintained to maximize system availability.
- A mass-transfer technique extensively employed to evaluate convective coefficients that permitted early optimization studies of the air-cooling system.
- A closed-loop frame design permitting German and Swedish noise-level requirements to be met.

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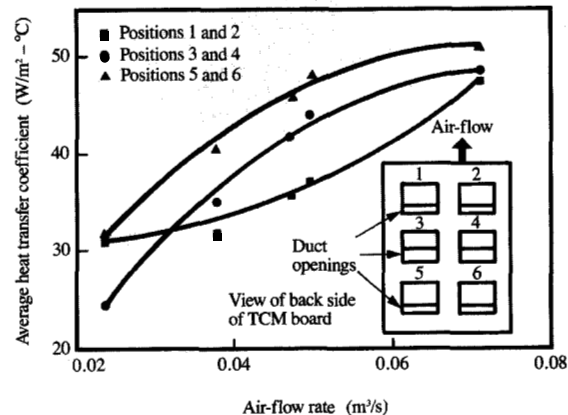


Figure 11

TCM backboard cooling convective results.

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