FM TRANSMITTER COOLING TECHNOLOGIES AND TRADEOFFS

GARY LIEBISCH
Nautel
Bangor, Maine

ABSTRACT

As authorized HD Radio™ digital injection levels increase, the overall AC to RF efficiency of the typical FM broadcast transmitter is compromised. At the same time, the options for, and use of, high power hybrid solutions (both tube and solid state) have increased significantly since the HD Radio technology rollout began. This presents a challenge to both the manufacturer and the broadcaster to utilize the most efficient cooling techniques available. While FM broadcast transmitters have been traditionally air-cooled, liquid-cooled approaches have also been tried. This paper examines the relative advantages and disadvantages of air vs. water-cooling for high power HD Radio hybrid FM transmitters.

HD RADIO™ TRANSMITTER EFFICIENCY

One of the more significant operational costs faced by broadcasters has always been the cost of running the transmitter. This has been particularly true of high power stations. Over the past 20 to 30 years, advancements in both tube and solid state designs have resulted in steadily increasing reliability and efficiency, lowering the costs associated with both maintenance and power consumption. It was dismaying to some broadcasters, therefore, that with the introduction of HD Radio, efficiency would actually go DOWN, and their power bills would go UP, and quite often out of proportion to the incremental amount of RF actually radiated. To produce a digital signal at just 1% of the analog power, we were being told we could expect power bills that were 20-25% higher. This was due, of course, to the different amplifier classes, lossy combining methods, and additional cooling that these transmitter configurations required.

In the early years of the HD Radio technology rollout, most stations, particularly high power stations, deployed digital operation using either the very inefficient "high level combining" method, or the more efficient (at least in terms of power consumption) "space combining" method. Common amp, or "low level" systems were less common, simply because HD Radio transmitters were all solid state, and no single cabinet solutions of linear design above 10 kW were on the market. In fact due to de-rating factors, no common amp solutions were available above about 8 kW. Within a few years, Continental Electronics, whose core competency had been in high power tube designs, experimented with re-biasing tube transmitters to create common amp solutions beyond that 8 kW limit. They introduced solutions of 20 kW or more by redesigning their 30 and 35 kW models, and incorporating the Nautel M50 Exciter with adaptive pre-correction. The other tube transmitter manufacturers, Harris and BE, soon followed with similar modified models operating at class AB amplification. Cooling was a concern in all of these designs, since the lowered efficiency brought the tubes closer to maximum plate dissipation power and anode temperature. In some cases, different tubes were used as a workaround to the dissipation challenge.

It was clear from those developments that the market needed more common amp solutions in the 10 kW and up class. Nautel, whose core competency has always been solid state only, decided in 2006 to explore the manufacture of a single cabinet solution that would break the traditional 10 kW barrier. Further fueling the development was the talk that HD Radio injection levels might soon be raised. Those new levels, as high as -10 dBc, would make high and mid level combined approaches obsolete, and would further exacerbate the de-rating, efficiency, and cooling challenges for all transmitter manufacturers. Since Nautel was starting with a clean slate with respect to high power solutions, we were free to explore designs and architectures not tied to existing legacy product. And while the decision to produce a solid state solution was rather easy, the decision on whether it should be water-cooled or air-cooled was not so clear at the outset.

WATER-COOLED SOLUTIONS

While virtually all domestic US radio transmitters produced in the last 50 years have been air-cooled, it was not always that way. The infamous WLW 500 kW transmitter, built in the 1930's used 700 gallons per minute and an outdoor "pond" to cool its twenty high power PA and modulator tubes (See Figure 1).

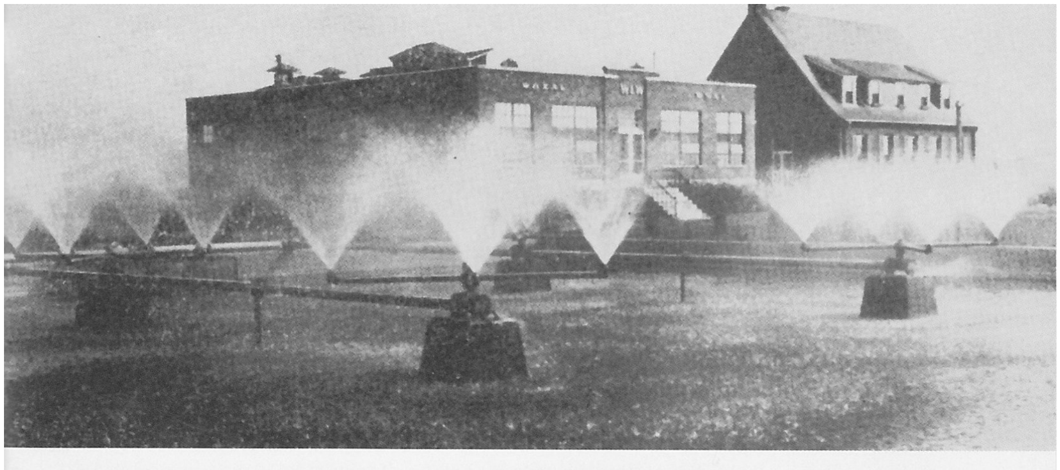

Fig 1 "The Fountain"-- Cooling spray pond at 500 kW WLW (1932)

Even at 50 kW, early transmission plants utilized water cooling, and their outside cooling pools outlasted the transmitters. For shortwave and medium wave transmitters internationally at 100 kW and higher, water cooling has continued to be widely used. In the TV transmitter market, water-cooled klystrons, and more recently, IOT tubes for analog and digital UHF have been in common everyday use.

So the inclination of the design team at Nautel was to take on water-cooling to achieve a new, highest power FM transmitter. It was to be in the 40 kW class to allow for de-rating for digital, and still have enough analog TPO capability to address a majority of installations in the 20 and 30 kW range.

The challenges of removing heat in a tube vs. a solid state transmitter are somewhat different. In a tube transmitter, the goal is to keep the plate structure at a reliable operating temperature to avoid failure of the ceramic and metal seals. In a solid state transmitter, we are concerned with keeping the heat source (FET) junction temperatures within their range. And unlike the tube, which is a single component, the solid state transmitter will have potentially over one hundred of these junction temperatures to maintain. In general for silicon devices and other electronic components, including modern electronic cooling fans, MTBF can improve significantly for every 10 deg C reduction in operating temperature.

THE PHYSICS OF HEAT TRANSFER

The Specific Heat and Mass Density properties of air and water tell us that water can transfer more heat with considerably less flow volume. The formula is:

$$\text{Temp rise of media} = \frac{\text{Power(W)}}{\text{(Specific Heat x Mass Density x Flow Volume)}}$$

This formula tells us that air must flow about 3000 times faster, in terms of volume, than water to remove the same amount of heat (due to the relative mass densities of water and air).

Another factor is the surface area of the respective heat sinks. The formula here is:

$$Q = H \times A \times \Delta t$$

where Q = heat removed (watts), H = Heat transfer coefficient (heat per square meter), A= surface area in square meters, and Δt = rise in temperature of media. Here again, water has the advantage of a much higher Heat Transfer Coefficient, so the surface area required for a water-cooled heat sink can be much smaller.

The heat from a cooled semiconductor, whether by water or air, must still traverse a path through solid materials before it reaches the cooling medium. That path comprises an equivalent Thermal (not electrical) Resistance Circuit, consisting of a resistance from device junction to its own case, commonly called the device's R_θ (*R theta*) then from case to the heat sink, called the thermal interface, the 'spreading' resistance of the heat sink, and finally from heat sink to the cooling medium (air or water). Figure 2 illustrates these thermal resistance components. The heat flow, in equation form, is represented by:

$$T_J = P(R_{JC} + R_{CS} + R_{SPREAD} + R_{SA}) + T_A$$

Where:
T_J = Junction temperature
P = Power dissipated by device (in watts)
R_{JC} = Heat resistance, junction to case, or Rθ
R_{CS}= Heat resistance, thermal interface
R_{SPREAD} = Spreading resistance
R_{SA} = heat resistance, sink to air or cooling medium
T_A = Design maximum air or water temp.

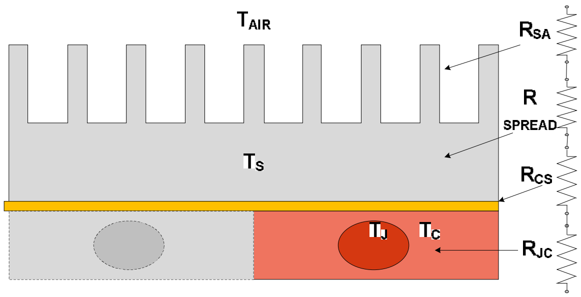

Fig. 2 Thermal Resistance (Air)

This equation tells us that the junction temperature is a function of the device dissipated power multiplied by the sum of the thermal resistances (expressed in °C/W), and added to the outside air or water to arrive at a resulting T_J junction temperature.

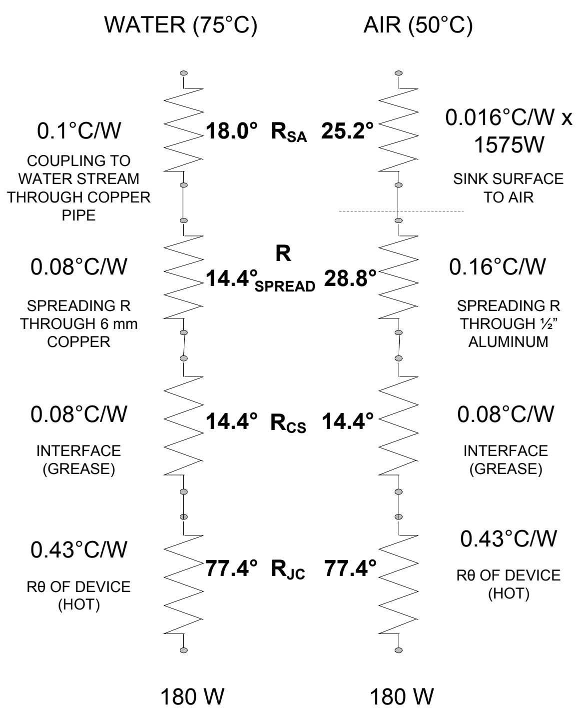

Fig. 3 Typical thermal resistance calculation through water and air

Figure 3 shows a typical calculation for a target junction temperature of 200°C. We can't really control R_{JC}, as that is a property provided by the device manufacturer. We can control the other terms of the equation, but only to the point of diminishing returns. Spreading Resistance occurs whenever heat flows through one or more solids involving a change in cross sectional area. There is a resistance associated with the spreading or constricting of heat flow. The last term R_{SA} can be manipulated with the number and surface area of the fin count on the heat sinks, but again, only to the point of diminishing returns. In solid state design, there is no "shortcut" to put the heat source in direct contact with the coolant, as there might be in a water-cooled tube. Both the water and air models can be tweaked to obtain the required <200°C junction temperature. Given this requirement to dissipate heat through these materials on its way to the cooling medium, leveraging lower junction temperature falls to the limited range controllable through heat sink design and/or air temperature for the air model, and to the control of water temperature (i.e. chilling) in the water model. In both cases, the working range is about 25 degrees.

While the typical air ambient design limit is 50°C, in actual practice the devices are subject to mixed ambient temperatures over their life. MTBF analysis shows us that an average ambient drop of 10°C can yield a 30% improvement in MTBF. To the extent that a user can control ambient air in an air cooled system, reduction of the average from 50°C to 40 or 30°C will yield an order of magnitude improvement in FET MTBF. In the case of liquid coolant, the user has less control. Extending MTBF will be more a function of the heat exchanger design. But water chilling can be employed to achieve similar gains.

It is worth noting that in both the water-cooled and air-cooled designs, the heat is ultimately transferred to air. It's just than in the water-cooled case it goes through one additional heat exchange step to get it outside. The air-cooled challenge, of course, is to get that 30 kW or more of heat outside the room.

HIGH POWER, WATER-COOLED SOLID STATE

Nautel thoroughly investigated the design and manufacture of a water-cooled 40 kW FM transmitter. Figure 4 is a conceptual design of the footprint. This drawing shows a cabinet markedly different from the end product, which was air. Note that the power modules are oriented horizontally and stacked vertically, while the opposite is the case in the final product. This allowed for vertically oriented manifold pipes at the corners, with RF cubes and water-cooled power supplies between them. This transmitter had a smaller footprint—unless you consider the footprint of the heat exchanger, which of course goes outside. The coolant would be propylene glycol mix. A single pump circulates the coolant to the outside heat exchanger in this single loop design. More complex systems are possible (but not contemplated here), having redundant pumps, or DUAL loop systems, where an inside loop circulates de-ionized water, and an outside loop circulates the glycol mix. In a dual loop system, an additional heat exchanger is added to transfer heat between the two loops. Figure 5 is a photo of the heat exchanger used on the Continental tube water-cooled system.

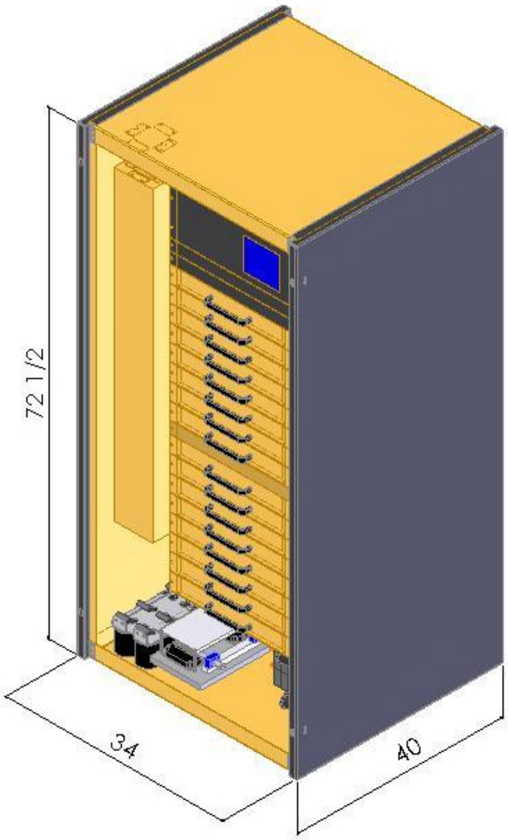

Fig. 4 – Concept Drawing of Water-cooled 40 kW Transmitter (Heat Exchanger not shown)

Fig. 5- Heat exchanger in Continental tube system (WNCI, Columbus, OH)

WATER VS. AIR DECISION MATRIX

While the design was solid and viable, customer feedback and buy-in was essential, as it would be for any new product introduction. In this case, we actively sought input on the use of water-cooling from those who would be called upon to install and maintain them.

Initial Cost

From a manufactured cost point of view, the water-cooled design would be slightly higher than the air-cooled design (about 10%). Slight advantage: Air.

Installation Cost & Time

When we expand the definition of initial cost to include installation of cooling infrastructure, we note that the water-cooled system will require plumbing, pump, and heat exchanger installation. In one site I visited, the heat exchanger was 50 ft away from the transmitter with all copper piping between them. While it may be argued that an air cooled system will similarly require HVAC installation, it is quite possible that such infrastructure may already exist in some installations, or may require only a modest upgrade. While most high-rise downtown office buildings are accustomed to additional HVAC, they may not be inclined to accepting the risks associated with possible fluid leaks without some significant, and perhaps costly, safeguards. HVAC improvements can be made independent of transmitter purchase and delivery, but the tight integration of a water-cooling system with the transmitter would almost always dictate that it be performed concurrent with transmitter installation, inevitably extending the installation lead time, and involving additional subcontractors. Furthermore, virtually every liquid cooled system would require some custom design to accommodate variations in building layout. An air-cooled design would remain a faster, lower cost installation in most cases. Advantage: Air-cooled.

Operating Cost

With respect to operating cost, and here I am primarily referring to cost of electricity, the advantage would have to go to water-cooled. The largest component of the savings would be the elimination of the large HVAC unit. A somewhat smaller component would be operating water pumps in place of the banks of fans. Keep in mind that the transmitter and other equipment will still have components that will need to be air-cooled (e.g.

power supplies, exciter, rack equipment, etc.). Advantage: Water-cooled.

Noise

Without the high volume of air passing across the heat sink fins, the room noise is reduced to the low hum of pumps, along with whatever small fans are required to cool components not in the liquid cooling path. Advantage: Water-cooled.

Redundancy

While both types of systems can be designed to be reliable, the water-cooled system is prone to single points of failure, unless additional steps are taken at additional cost for redundancy. The single points of failure are primarily pumps and potential for leaks. An air system with a single 3-phase blower has a similar single point of failure, however, the basis for comparison in our design is redundant cooling using many small DC operated fans, so one or a few failed fans is a minor issue. There is massive redundancy. Advantage: Air-cooled.

Hot pluggable modules

RF modules in an air-cooled design can easily be designed to be hot pluggable (blind-mated) without the need for a user to "make" or "break" a connection. Designing such an easy connect-disconnect for a water-cooled RF module would be quite expensive. Advantage: Air-cooled.

Maintenance

An air system will require periodic inspection, cleaning, and changing of air filters, which can generally be performed without on-air interruption. A liquid-cooled system will require additional monitoring—differential pressures, temperatures, water levels, and water purity. Trending of these parameters over time with appropriate record keeping is essential. Also to be considered is periodic flush and change of water, as well as inspection of the heat exchanger's coils, hoses, piping, and pumps. Some of this maintenance will require that the transmitter be off air. Advantage: Air-cooled.

Water and glycol availability is a major consideration, particularly at remote locations. While the systems are closed loop, there are times when periodic flushing will require the addition of significant amounts of fluid. Such times may occur unexpectedly in the case of a significant leak or contamination. One customer told me that while he has a water level detector, when he gets an alarm at any time of day or night, he makes an immediate trip to the site. It may only be an evaporation threshold reached, but it also MIGHT be a leak. If the system does not use pure water, due to potential for freezing in the heat exchanger, it will then be a water-glycol mix. On site storage of propylene glycol must be considered, and is subject to EPA regulation. Advantage: Air-cooled.

Environmental Contamination

Transmitters operating under harsh environmental conditions would benefit from liquid-cooled solutions. This goes beyond just the cleanliness of the transmitter building. Locations with corrosive industrial air, dust, and dirt can be maintained with conscientious attention to air filters, but may be better candidates for liquid cooling. Advantage: water-cooled.

Customer Resources and Training

While experienced television maintenance engineers may consider the installation and maintenance of a water-cooled system to be familiar territory, the lack of any widespread use of liquid cooling in radio, particularly in the domestic US, would mean engineers would encounter a steep learning curve upon introduction of the technology. The larger groups with staffed engineering departments may have some depth in resources, but from the experiences of the few who have been through it, it is not to be taken lightly. Beyond the large clusters, available engineering resources vary widely—some may have dedicated full time engineers, but more often stations are maintained by contractors with many stations, or by no engineer at all unless there is a problem. The improved reliability of transmitters over the past 20 years has allowed, for better or for worse, resources to be spread very thin. Can an engineer who "comes in cold" diagnose and maintain this potentially complex system? Are the savings reaped from lower building cooling costs worth the additional maintenance steps? The clear answer we received was "no". Advantage: Air-cooled.

Scalability

Once we redirected our efforts to the air-cooled design, one additional advantage became evident, and that is scalability. Since we did not propose to make a water-cooled transmitter at any power level other than 40 kW, a different architecture would have been used for 5 to 20 kW. With the air-cooled design, however, we were able to create power cubes that could be used from 40 kW all the way down to 5 kW. A similar scalability factor was achievable for power supplies. Instead of one large 64 kW supply, it was possible to source smaller 2 kW switched mode power supplies for even more redundancy. This, of course, lowered our cost for those cubes, allowing all models to benefit in cost and price. The customer benefit was not only lower cost, but commonality in spare parts where several transmitters are owned, and familiarity in operation of all transmitters in the family. (Advantage: Air-cooled)

	WATER	AIR
Initial cost		✓
Installation Cost and Time		✓
Operating Cost	✓	
Noise	✓	
Redundancy		✓
Hot Pluggable Modules		✓
Maintenance		✓
Environmental Contamination	✓	
Customer Resources and Training		✓
Scalability		✓

Fig. 6 – Water-Air Decision Matrix

THE FUTURE – LDMOS DEVICES

The FM broadcast transmission design is about to advance one step by the adoption of LDMOS devices. Nautel has already begun to integrate these devices into our product line. The LDMOS devices have thermal resistance benefits as a result of having a backside source that can be connected directly to the thermally and electrically conductive package flange, which in turn is directly mounted to the heat sink. Typical VMOS devices have the drain on the backside of the wafer and require attaching the die to an electrically isolating flange material which increases the effective thermal resistance of this device structure. The excellent thermal conductivity of the LDMOS packaged products allows them to achieve significantly higher power levels in a given package, especially the 50V technology with its inherently higher power density compared to the 28V version.

CONCLUSIONS

The broadcast industry has traditionally preferred air-cooling except where they cannot provide sufficient cooling capacity. It is only when "reaching" to some formerly unattainable level that water-cooling is considered as a means to that end. It seems that if 40 kW, or higher powers can be attained with air-cooling, the U.S. FM broadcaster prefers it. The market for 40+ kW power levels is small, so any manufacturer contemplating a product for that level would have to analyze the anticipated return on their investment, and compete with combined air-cooled systems that can achieve the same power.

REFERENCES

Seaho Song, Seri Lee, and Van Au, *Closed-Form Equation for Thermal Resistances with Constriction /Spreading Resistance Boundary Condition*, Bell-Northern Research Ltd, Ottawa, Ontario, Canada, Aavid Engineering, Inc., Laconia, NH.

AXCERA, LLC, *Tech Notes*, No. 11, August 2002.

50V RF LDMOS, An ideal RF Power technology for ISM, broadcast and commercial aerospace application, Freescale™ Semiconductor.

A Trip Through WLW, The Crosley Radio Corporation, 1935.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the invaluable assistance provided by **John Collier**, Senior Engineer, Nautel Ltd., Halifax, NS. Canada, in the preparation of this paper, as well as customer experience with water-cooled systems provided by the following:

Dale Bryan, Entercom, Gainesville, FL.

Greg Savoldi, Clear Channel Communications, Inc., WNCI, Columbus, OH.