Dramatic Power Savings using Depressed Collector IOT Transmitters in Digital and Analog Service

Andy Whiteside
Ai
10706 Beaver Dam Road
Cockeysville, MD 21030
andy.whiteside@acrodyne.com

Ray Kiesel
Ai
10706 Beaver Dam Road
Cockeysville, MD 21030
ray.kiesel@acrodyne.com

Jay Gamerman
Ai
10706 Beaver Dam Road
Cockeysville, MD 21030
jay.gamerman@acrodyne.com

ABSTRACT

The Second DTV Periodic Review resulted in the September 2004 FCC Report and Order that clarified the requirements for Broadcasters to complete their transitions to DTV transmission. It is now clear that stations are required to maximize transmitter power to fully protect coverage area and provide adequate signal strength for reception in the required coverage area. Failure to do so may lead to lost coverage and, potentially, lost revenue and lost opportunities.

The economic considerations of this R&O to the US Broadcaster are many and far reaching. Undoubtedly, one of those considerations will be the cost to operate the new full power transmission facility side-by-side with the existing analog facility for several years to come. In the past year or so, transmitters equipped with the multi-stage depressed collector IOT have been successfully installed in both analog and digital service. The savings realized by those broadcasters using this new equipment are significant, immediate and very likely to increase as power costs increase.

This paper will present a review of the features of the new transmitters using the water-cooled, depressed collector IOT. A brief description of the challenges presented by the new technology to the transmitter designer and how these challenges are overcome is included. Operating results from several fully operational analog and digital installations will show the benefits already available to those broadcasters.

BACKGROUND

In the past 2 years multi-stage depressed collector Inductive Output tubes (IOT's) have been introduced as standard product by all the major tube manufacturers. There are now well over 50 such tubes in full power broadcast service in the US and that number is expected to climb significantly as the DTV transition progresses. The use of this technology offers the broadcaster uncompromised signal performance at previously unattainable power consumptions – far bettering those attainable with standard tube and solid-state amplifiers.
Initial applications were in digital transmitters using oil as the primary coolant for the IOT collector stages. These early transmitters were capable of operation in digital service at power levels equivalent to their non-depressed brethren. However, the design decisions made in optimising for digital service resulted in analog power levels more than 2 dB below standard IOT transmitters of a similar configuration. More recent applications have featured depressed collector IOTs that use water as the primary collector and IOT coolant. These water-cooled depressed collector IOTs are capable of operation at full power analog and digital rating. Since these tubes became available they have become the preferred choice as the final amplifier in UHF TV transmitters, with 3 of the 4 major US transmitter manufacturers placing so-equipped product into service in the past 12 months.

THE WATER COOLED DEPRESSED COLLECTOR IOT

Water has, for several decades, been the preferred choice of tube designers to cool high power vacuum tube anodes and collectors. There are other choices – air for one - but water is the standard against which all other choices of coolant are measured. It is ubiquitous, inexpensive, completely safe and has thermal properties perfectly suited to cooling vacuum tubes. The use of any other coolant involves compromises in cooling capability, and perhaps safety, which must be carefully evaluated in the context of the end application in order to establish the validity of the compromise. There are, undoubtedly, some applications in which water is the not the best choice but these applications are few and far between. High power broadcasting is not one such application.

The first depressed collector tubes used in broadcasting were klystrons and they used air to cool a single depressed element. The power handling of these tubes was very limited and not suited to the power levels required by transmitters over the past 30 years or so. In the late 1980's multi-stage depressed collector klystrons became available using water as the coolant. Although the IOT eventually led to the demise of klystron technology in broadcasting, several hundred depressed collector klystrons were installed throughout the US. Many continue to operate today and there is much to learn from reviewing their operational histories. This water cooled technology has logged many millions of hours of operation in a wide variety of environments providing outstanding reliability and life. One interesting observation has been that the average lives of these klystrons are greater than that of non-depressed klystrons. Contrary to the claims of some, the use of pure water proved to be a feature that contributed to longer lifetimes. As will be shown shortly, today's water-cooled depressed collector IOTs operate at collector voltages and coolant flows which place much lower stress on the coolant than the equivalent depressed collector klystron. This leads to the very reasonable expectation that these IOT systems will achieve similar, if not better, performance and lifetime.

The Plug-in IOT

3 of the 4 major tube manufacturers offer IOT systems featuring plug-in technology. The IOT plugs into the cavity and magnet assembly establishing electrical contact using several concentric flexible contact fingers. There are a number of advantages to the use of this technology – lower cost to manufacture for the tube company, simpler tube installation and replacement for the end-user to name two. A less obvious, but equally important advantage, is the fact that the collector does not have to pass through the cavity and magnet assembly during installation or removal. The tube designer, freed from those constraints, can size the collector appropriately for adequate headroom in the most severe operational application – namely analog service. 3 of the 4 depressed collector IOTs, available today, are based upon plug-in standard IOT designs. The authors are aware of three US transmitter manufacturers that have installed water-cooled versions of the plug-in depressed collector IOT in operational transmitters – both digital and analog - since April 2004.

THE ESCIOT TRANSMITTER

One such water-cooled IOT, the **E**nergy **S**aving **C**ollector **IOT** (or ESCIOT) 5130W, from e2v technologies, is based upon the D3130W plug-in IOT (ref. 1) first introduced in the US in 2000 in Ai transmitters. There are now several hundred operating in analog and digital service.

High Voltage considerations

The 5130W has a collector with 5 segments, yet only 3 different voltages are required from the HV Power supply – see Figure 1, which shows a simplified schematic of a digital system. Collectors 1 and 2 both operate at ground potential and Collector 5 is connected to the IOT Cathode. Collector 3 operates at 30% of Cathode voltage and Collector 4 operates at 50% of Cathode voltage – both referred to ground potential. The collector has been designed to achieve optimum efficiency enhancements in both digital and analog service with the same collector operating voltages – resulting in a single HV Power Supply design for both modes of operation.

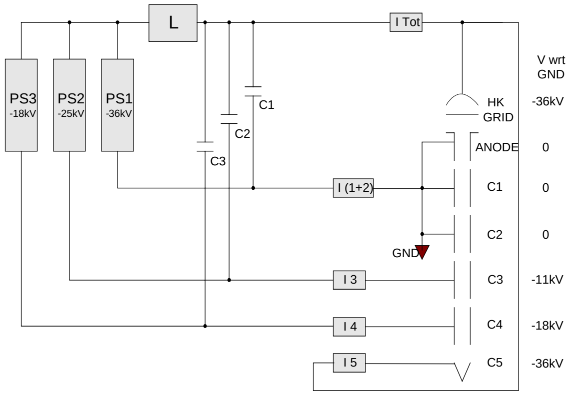

Figure 1 – DTV HV Schematic

The HV Power Supply uses three independent secondary windings and diode stacks to create the three voltages: 36 kVDC, 25 kVDC and 18 kVDC. The negative terminals of each supply are tied together and connected to the IOT cathode resulting in the difference voltages of -11kV and -18kV with respect to ground on Collectors 3 and 4 respectively. This method of operating the HV power supplies has proven to be the most practical to achieve in service and it provides limitation of fault currents should faults develop between collector segments. Although the fundamental magnetic and rectifying components can be the same in digital and analog service, the other components – HV capacitors and current limiting resistors – are specific to the application. Figure 2 shows the typical HV schematic of an analog system.

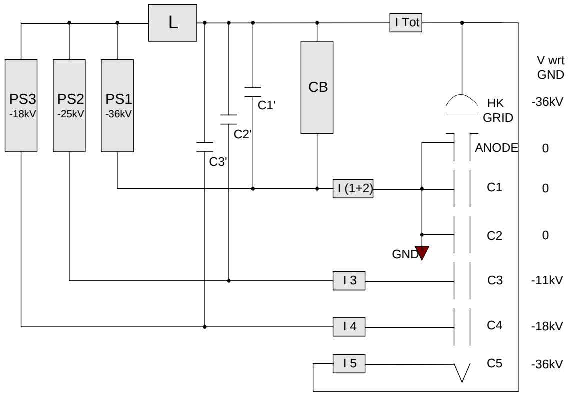

Figure 2 – Analog HV Schematic

In our first testing of the ESCIOT system, we chose values of C1 and C1' to be similar to those used in a standard non-depressed system and much lower values of C2 and C2’ as well as C3 and C3’. This was based upon the belief that ac line related ripple on PS2 and PS3 would not have any effect on the output signal since the IOT beam current is determined solely by PS1. This was, in fact, the case - but we observed an interesting phenomenon at HV shut off that led us to increase the value of C3 and C3’.

Table 1 shows some typical values of total and individual collector currents for this system in both analog and digital service.

Parameter	Idle	Digital @ 30kW	Analog @ 60/6 kW	
Signal level	No signal	Constant	White APL	Black APL
C1 current	0	180 mA	100 mA	178 mA
C2 current	0	0.5 A	0.25 A	0.83 A
C3 current	0	0.5 A	0.35 A	0.80 A
C4 current	0.6 A	1.1 A	1.05 A	0.94 A
C5 current	0	1 mA	0.4 mA	0.2 mA
Total current	0.6 A	2.28 A	1.75 A	2.75 A

Table 1 – Typical Collector currents

You will note that, at idle, all the current flows through Collector 4. Under normal signal conditions there is significant variation in other collector stage currents as the signal varies but the current in C4 stays fairly constant. When the HV power supply is turned off, the effect of this relatively high Collector 4 current is to rapidly discharge the C3 or C3’ HV capacitor – not in and of itself a bad thing, but the consequence of a rapid discharge of C3 and a slow discharge of C1 is that the negative voltage on Collector 4 can increase towards Cathode potential after the HV is turned off. The same thing can and does happen on Collector 3 but this stage has a lower negative potential to start with. The magnitude of this post turn-off swing will vary depending on the current through the collector stage. Since the current through Collector 4 is always high, the effect is fairly repeatable under all signal conditions.

As noted above, this effect is not necessarily harmful to the IOT or the HV Power Supply. However, concern was raised over the high altitude operation of such a system and whether the voltage hold-off of the ESCIOT collector jacket might be compromised if this issue was not addressed. The solution to minimize this effect was quite simple – increase the value of C3 and C3’ to the same value as that of C1 and C1’, leaving C2 and C2’ at the smaller values. PS3 now discharges at a similar rate to PS1 and the voltage swing of Collector 4 is greatly reduced.

The other obvious difference between the HV systems shown in Figures 1 and 2 is the omission of the thyratron crowbar in the digital system. As in Ai standard IOT transmitters, the amount of stored energy available is limited by the use of smaller HV capacitors and larger current limiting resistors (not shown). The amount of follow-through energy from the HV power supply itself is limited by the use of a solid-state step start assembly which uses SCR devices to remove primary mains voltage within a half-cycle of a fault condition. The resulting total energy allowed to flow into the IOT during an internal fault is well below the tube manufacturer’s requirement.

We attempted to achieve the same result with the analog system but found that the compromises in signal performance did not warrant what amounted to marginal IOT protection.

Further reference to Figures 1 and 2 shows the innovative solution to collector current monitoring at the elevated potentials of the various collector stages. Rather than introduce several isolation transformers to power conventional monitoring circuits, the individual collector stage current itself drives the telemetry circuits, which are then coupled via fiber optics to the transmitter control circuitry. An early concern of the design team was the protection of these collector current sensors under fault conditions. Appropriate use of HV diodes in the sensors eliminated that concern and enabled the sensors to withstand full HV short circuits to ground on either input or output with no damage or change in performance.

One last look at these two figures highlights a change we were forced to make in the electrical location of the three 0.1 μF collector by-pass capacitors. Initially, we located these capacitors at the HV entrance to the cabinet – see Figure 3 - so that capacitor charging currents did not have to flow through the collector current sensors, but still close enough to the ESCIOT to isolate the HV supply leads from the high frequency current variations.

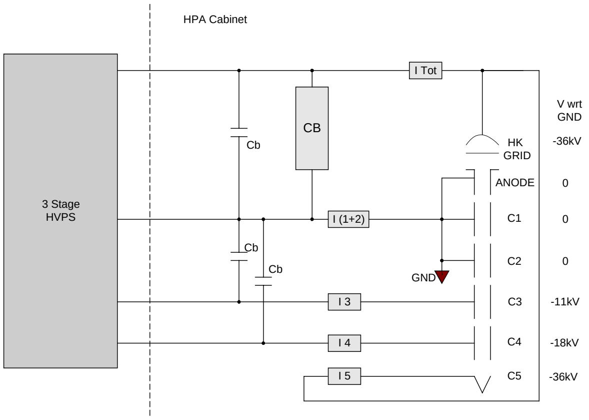

Figure 3 – Original HV Bypass

This proved to be an unnecessary precaution that actually introduced unwanted monitoring effects, particularly in analog service, since the high frequency collector current components showed up as noise in the current sensors. This did not cause problems in the digital system but the relatively large and rapid signal level changes in analog service did result in occasional spurious overcurrent trips. Most of our lab testing was done with static test signals and the relatively short period of lab testing using a program source did not reveal this problem. It was very simple to correct this problem in the field. The three HV bypass capacitors were rewired so that, electrically, they were as close to the tube as possible – see Figure 4 – effectively eliminating spurious overcurrent trips.

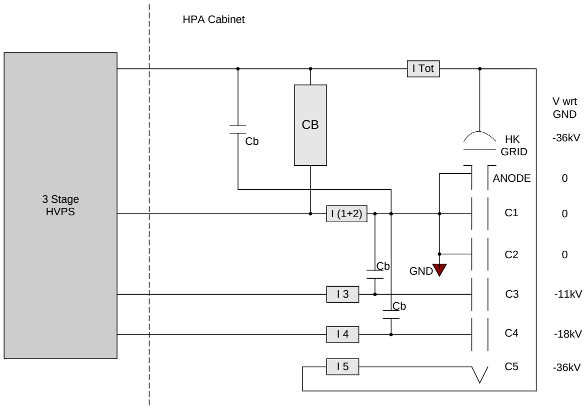

Figure 4 – Final HV Bypass

Cooling System considerations

The decision to use water as the sole direct coolant of the IOT was a simple one. As noted earlier in this paper, millions of hours of operation have been accumulated on water-cooled multi-stage depressed collector klystrons. The average collector power dissipation of the klystron is higher than the IOT due to the significantly lower inherent efficiency of the device. Also, the highest voltage on any water-cooled element of the klystron is greater than that of the ESCIOT. Refer to Table 1 again. The maximum current into collector 5, which operates at Cathode voltage, is a few milliamperes. This electrode can be easily cooled with a modest flow of air, tapped off the IOT cart assembly cooling manifold. Thus the maximum voltage on any ESCIOT water-cooled element is -18kV with respect to ground, significantly lower than the -26kV of the depressed collector klystron or the oil-cooled depressed collector IOT. Since the rate of galvanic transport of material from one electrode to another is strongly dependent on the voltage for a given coolant resistivity, it follows that corrosion due to such effects will be reduced as well. Attached to this paper is an appendix showing that metal corrosion is an insignificant concern in water systems with coolant resistivities as low as 1 MΩ.cm. This value of resistivity is readily achieved and maintained in simple de-ionizing systems. Typical operational values are in excess of 5 MΩ.cm. The transmitter has an alarm at 2 MΩ.cm and an executive trip at 1 MΩ.cm. One factor, which can significantly affect the life of the cartridge filters used in such systems, is material selection. A review of operational information from a sampling of the installed base of depressed collector klystron systems led to a decision to use only stainless steel components in the water-cooled transmitter. We found that systems using copper plumbing had to change the cartridge filters frequently. Also, after a few years small leaks were observed in small bore tubing presumably as a result of corrosion. Using stainless steel eliminates this problem.

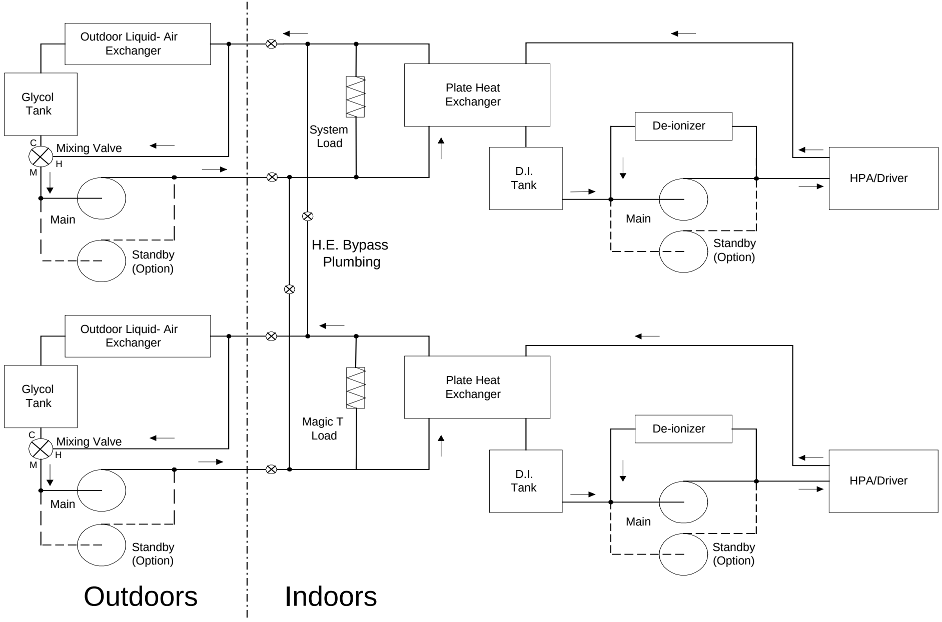

Figure 5 – Fully redundant Dual HPA Cooling System

Figure 5 shows the cooling diagram from several of the installed ESCIOT transmitters. These particular systems have the maximum redundancy possible. Each HPA has two coolant loops with main/standby pumps – the primary side uses de-ionized water to cool the IOT, the secondary loop uses a mixture of water and glycol to cool the plate heat exchanger and IOT. Each glycol pump and heat exchanger system is sized to handle the heat load of the entire system, bypassing being provided by the manual valves shown in the diagram. An additional advantage of using only water as the IOT coolant is the elimination of glycol and other coolants from the HPA cabinet – water spills are much easier to clean up!

Operational performance of the system has been good, as expected, in locations as diverse as Tampa, FL and Fond-du-Lac, WI. The challenge of protecting the system in freezing conditions was easily overcome using the thermostatic mixing valve shown in the diagram. This valve has three ports – hot, cold and mixed – and seeks to maintain a constant temperature at the mixed port by adjusting the flow through the external circuits. Reference to Figure 5 shows that, in extreme cold conditions, the mixing valve effectively bypasses the coolant reservoir and the heat exchanger, thus greatly reducing the volume of water flowing through the plate heat exchanger. As this reduced volume heats up, the valve "adjusts" automatically to allow some flow through the tank and heat exchanger. The "control" mechanism is very stable and requires no routine servicing for long, trouble free operation.

OPERATIONAL RESULTS

The whole point of this technology is to save the broadcaster money by reducing the power consumption of the transmitter - without compromising signal performance or life.

To illustrate this, we will look at the example of three transmitter projects completed in Baltimore last summer – WNUV-TV, WNUV-DT and WBFF-DT. WNUV-TV was operating a 5 klystron transmitter at 240kW peak sync Visual and 24kW Aural. The other two stations were operating low power solid-state DTV transmitters with the intent of installing standard IOT transmitters to raise power to meet FCC mandates, WBFF-DT to 30kW TPO and WNUV-DT to 40kW TPO.

The power budget for the three stations for fiscal year 2004, is presented in Table 2. Baltimore has an average power cost of 7.5 cents/kWhr, relatively modest compared to some markets, but the total annual power bill for these three stations was projected to be over $570,000.

Station	Power Consumption
WNUV-TV @ 240kW	604 kW
WNUV-DT @ 40kW	150 kW
WBFF-DT @ 30kW	118 kW
Total	872 kW

Table 2 – Original Power Consumption

WNUV-TV

This station operated a 20-year-old pulsed klystron transmitter using 4 visual klystrons and 1 aural klystron. The manufacturer was no longer in business and replacement parts were becoming difficult to obtain. As can be seen from Tables 2 and 3, replacing this transmitter with a new common amplification transmitter using 4 depressed collector IOTs offered the potential of major cost savings coupled with the advantages of improved signal performance, operator safety and reduced maintenance.

The project to replace the old transmitter was started in January of 2004. All internal cabinetry and RF hardware were first installed in front of the old equipment. Immediately after the February Sweeps period, the old transmitter was operated at reduced power on 2 visual and 1 aural amplifiers. This allowed the installation crew to remove HV Power Supplies and Heat Exchangers from half of the concrete pad allowing the installation of half of the new equipment. After commissioning the first 2 depressed collector HPAs, and a short bake-in period, the new transmitter was switched to the antenna. The second half of the old pad equipment was then removed to allow installation of the other half of the new equipment. Final full power operation was achieved in early May 2004.

WNUV-DT, WBFF-DT

These two transmitters were installed in the summer of 2004 at TV Hill in Baltimore. They operate with two other transmitters into a broadband panel antenna via a high power combining/switching system. Each transmitter has two D5130W ESCIOTs operating with the digital 8-VSB signal.

Table 3 shows the actual measured power consumptions of the three transmitters.

Station	Power Consumption
WNUV-TV @ 240kW	251 kW
WNUV-DT @ 40kW	107 kW
WBFF-DT @ 30kW	92 kW
Total	450 kW

Table 3 – Power Consumption ESCIOT

The total power consumption was reduced by almost a factor of 2 over standard technology. At 2004 power costs this represents an annual savings of over $270,000. Station personnel anxiously awaited the first power bills after WNUV-TV went on-air, to allow a comparison of the current bill over that for the same period 12 months earlier. More good news appeared! Unbeknownst to station personnel, the cost of power in Baltimore had increased during the project – from 7.5 cents/kWhr to 9.3 cents/kWhr, an increase of more than 20%.

Recalculating the costs with standard technology at these higher rates and comparing that with the costs using new technology revealed that the water-cooled depressed collector IOT technology was actually saving the stations a total of over $340,000 annually – as shown in table 4.

Station	Standard	ESCIOT	Savings
WNUV-TV	$490,018	$203,815	$286,204
WNUV-DT	$121,676	$86,796	$34,880
WBFF-DT	$95,719	$74,628	$21,091
Total	$707,413	$365,239	$342,175

Table 4- Final Savings at new power cost

Discussion of Results

It is clear, from reviewing the above table, that the bulk of the savings realized in Baltimore was achieved by replacing the old, separate amplification klystron analog transmitter with the modern, depressed collector IOT operating in common amplification. Although there are other situations in which replacing an old klystron transmitter may still prove to be financially worthwhile, the reality is that most stations will not seek to make such an investment – particularly in light of last year's FCC Report and Order. The emphasis is definitely on either installing new high power DTV transmitters or upgrading existing low-power units. However, in those cases where it is deemed necessary to install a new analog transmitter the choice of anything other than a water-cooled ESCIOT equipped system would, based upon the savings realized in Baltimore, appear to be somewhat ill considered.

A closer look at the actual power consumption of the new transmitters confirms that these new IOT transmitters provide equivalent ratios of power reduction in both digital and analog service i.e. the depressed collector IOT and transmitter design is effectively signal agnostic. This should give some comfort to those stations finding themselves in the position of having to install new analog equipment in the next few years – all the high power equipment, bar channel specific RF components, can be used for digital service in the future.

Table 5 is based on actual field measurements and shows the power budget of two typical dual tube transmitters – using standard and depressed collector IOT technology. The reduction in IOT Beam power consumption is typically about 33%, whereas the reduction in transmitter power consumption is about 27%. This table is a good representation of what broadcasters might expect from the two technologies.

	DTV	NTSC
Transmitter Output	50 kW avg.	120+12 kW
IOT Output – includes RF Losses	55 kW avg.	130/13 kW
Quantity of IOTs	2	2
Standard IOT efficiency/FOM	38 %	100 %
ESCIOT efficiency/FOM	58 %	149 %
Percentage Improvement	53 %	49 %
Standard IOT Power Consumption	144.3 kW	144.7 kW
ESCIOT Power Consumption	94.5 kW	97.1 kW
Reduction in IOT Power Consumption	49.8 kW	47.6 kW
IOT Percentage Reduction	34.5 %	33 %
Reduction in TX Power Consumption	47.4 kW	45.4 kW
TX Percentage Reduction	27.9%	26.7%
Annual savings at 8 cents/kW-hr	$33,218	$31,816

Table 5 – Typical savings comparison

It should be obvious that the potential savings with this technology are directly related to two factors – the transmitter power output and the local power cost. The lower the power output and the lower the power cost, then the lower will be the savings. In some cases, one or both of these factors may make the use of standard IOT technology perfecty satisfactory for the time being. However, as was experienced in Baltimore this past year, power costs are more likely to increase than decrease in the future.

APPENDIX – De-ionized water analysis

The practicalities of using de-ionized water as a coolant for the ESCIOT have been considered in great depth. At first sight, it can appear that even with a resistivity of 1 MΩ.cm, de-ionized water may lead to unacceptable corrosion. In reality, this is not the case, as a number of beneficial effects must also be taken into consideration. Firstly, the reactivity of the copper surfaces within the cooling channels decreases with time, in much the same way as many metals accumulate a thin oxide layer on their surfaces when initially exposed to oxygen. Once 'passivated' the rate of further oxidation is greatly reduced. This same mechanism holds true with de-ionized water on copper, the result being that the passivated surface has greatly enhanced resistance to corrosion and so the rate of erosion is reduced accordingly. Secondly, it has been assumed in early analyses on depressed collector klystrons, that any current passing through a conductive coolant is purely the result of it carrying eroded collector material. Again, this is not the case, and in reality, only about 10% (typical) of the measured current through the coolant may be the result of galvanic transport, with the remaining 90% being attributable to electrolysis of water and oxygen evolution, (ref 2). Together, these physical effects combine to allow use of de-ionized water as a coolant for many tens of thousands of hour’s operation.

Consider the following example, worked for copper:

De-ionized water resistivity	1MΩ.cm
Inter-electrode resistance (R)	100 MΩ
Voltage between collector stages (V)	10 kV
Current drawn (I)	0.1 mA

The theoretical mass of material eroded per hour from the collector by a simplistic analysis using Faraday’s Law and assuming a one-electron charge transfer process for copper dissolution:

I x 60(secs) x 60(mins) x M x 1/F

Where:
I is the current through the coolant in milliamperes
F is Faradays number (96,487)
M is the molar mass of copper

In this case, the theoretical mass of eroded copper in one hour is:

$1 \times 10^{-4} \times 60 \times 60 \times 63.57 \times 1/96{,}487$

$= 2.37\text{x}10^{-4}$ grams per hour.

By compensating this figure for the fact that only 10% of the observed current being the result of collector material being taken into solution, we see that:

Actual erosion rate $= 2.37\text{x}10^{-5}$ grams per hour,

Or less than 0.95 grams in a 40,000 hour life.

By carrying out a similar analysis for a complete 5-stage ESCIOT collector, it can be proved that the total mass of transported material that moves from one collector stage to another within a 40,000 operational tube life is less than 3.7 grams. To put this amount of material into perspective, it represents less than 0.01% of the weight of the whole collector.

REFERENCES

Ref 1; *A High Power, Low Beam Voltage, TV Broadcast IOT Amplifier, with an Optional Multistage Depressed Collector. Tim Crompton et al. NAB Broadcasting Engineering Conference, Las Vegas, April 1999*
Ref 2; *Principles and Prevention of Corrosion. Denny A Jones. ISBN 013-35999-0*

ACKNOWLEDGEMENTS

The authors wish to thank their colleagues at Ai for contributions to this paper and e2v technologies for their permission to reprint the analysis of corrosion in deionized systems – included in the appendix.