ASSESSING THE CONTINUED SUITABILITY OF AN EXISTING WATER SYSTEM FOR AN ACCELERATOR UPGRADE*

W.C. Barkley#, C.E. Buechler, E.N. Pulliam, LANL, Los Alamos, NM 87544, USA

Abstract

This paper assesses the continued suitability of an existing Water Cooling System (WCS) used for cooling intermediate and high-power RF power amplifiers at the Los Alamos Neutron Science Center (LANSCE). At LANSCE, the high-power and intermediate power amplifiers installed in the 1970s were at end-of-life with obsolete parts and no suitable replacements available to extend their life. The LANSCE Refurbishment Project was initiated to replace these amplifiers and to utilize already existing WCSs. Two existing WCSs were repurposed and one new WCS was designed and installed. Unscheduled, intermittent water system trips on one of the WCSs has prompted the engineering group to reevaluate the original decision, build a flow model and assess some of the legacy components' suitability to solve the problem. This paper discusses the general approach, troubleshooting and solution recommendations to be made for resolution of the intermittent issues.

Introduction

Many accelerators in the United States and abroad were built years and sometimes decades ago when particle physics was an emerging scientific discipline. Finding the new elementary particle or developing new uses for particle beams was an attractive choice for young scientists and engineers. As those accelerators have aged, the discipline still attracts top prospects from universities.

The accelerator at LANSCE was built in the late 1960s and early 70s to perform meson research. Over the years since, the meson capability has been replaced by proton and neutron research as well as isotope production. Each of the new experimental areas was built as an upgrade, increasing the capability of the facility. One such upgrade was devised and performed beginning in 2012 to replace the obsolete power amplifiers used to accelerate the beam in the Drift Tube Linac [1].

Amplifier cooling requirements were formulated and determined to meet both the existing deionized WCS (A01) and an additional, treated WCS (A06) [2]. The flow, pressure and temperature requirements [3] for the deionized system were calculated to be less than what was needed for the previous high-power amplifiers. To acquaint the reader with the size and magnitude of the high-power amplifiers, each of the new amplifiers is powered to nearly 240 kW and is about 60% efficient. Figure 1 depicts one of the six new LANL high power amplifiers. As seen, the main cooling circuit is fed by hoses coming up from the bottom into the tetrode amplifier tube.

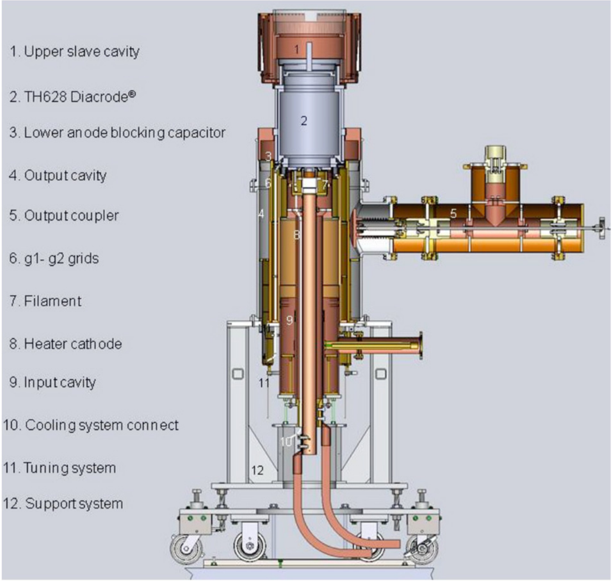

Figure 1: LANL high power RF amplifier.

A01 Water Cooling System

The A01 is a deionized WCS comprised of two, 100-hp pumps, heat exchanger, expansion tank, bypass circuit and distribution piping. It was originally sized to provide up to 1,300 gpm of water flow rate with a 90 psi pressure head. The intent was that one pump would be in service while the other would be on standby to minimize downtime if failure occurs. Since the new amplifier cooling systems and one legacy system required only around 1,000 gpm water flow, 70 psi pressure and a similar heat load, this water system was not replaced.

Instead, the A01 WCS was re-purposed to provide water cooling for the intermediate and high power RF amplifiers designed by LANL. The pumps, heat exchanger, make-up circuit, expansion tank, deionization slip stream and bypass loop were all kept intact without modification. The distribution piping, which distributes water from the pump room to each power amplifier module, was also kept intact. The new installation simply tapped off of the distribution piping at each of the three modules [4] while keeping the legacy module piping in place. From the supply and return manifolds in a trench, the water feeds into the amplifiers by means of a main water manifold where it is distributed to the various circuits (Figure 2) that require cooling. At installation and commissioning, the A01 WCS met the requirements for temperature, flow rate and pressure drop.

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#barkley@lanl.gov

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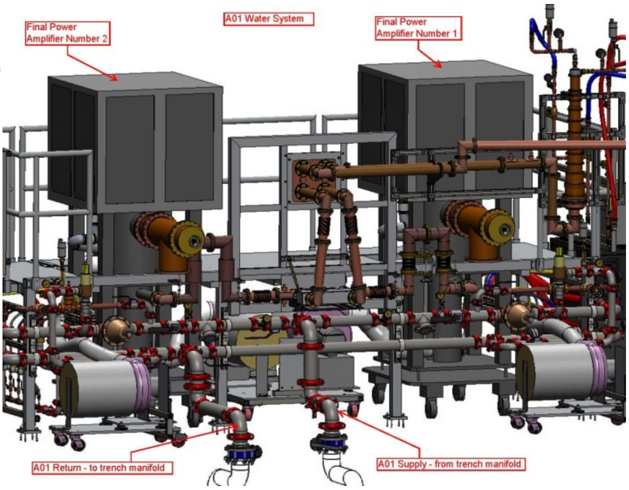

Figure 2: High power amplifier module and A01 water distribution manifolds.

A closed water system confined in pipes and pipe components obeys the law of conservation of energy. Using Bernoulli's equation in the following form [5]:

$$Z_1 + \frac{144P_1}{\rho} + \frac{v_1^2}{2g} = Z_2 + \frac{144P_2}{\rho} + \frac{v_2^2}{2g} + h_L \qquad (1)$$

where Z is elevation, P is pressure, ρ is density, v is velocity, g is the gravitational constant and h_L is the head loss allows us to compute the total energy from one point in the system to another in units of feet of head. When the number of branches in the water system becomes large, Bernoulli's equation is better solved using a flow model. It is useful to construct a flow model of the system to determine if the system components are sufficiently sized and constructed to deliver the water required for cooling. Data for the model is obtained using manufacturer's information supplied with the components. The pump curve, a representation of total energy gain (in feet of head) versus flow rate was obtained for the original pumps (Figure 3) [6].

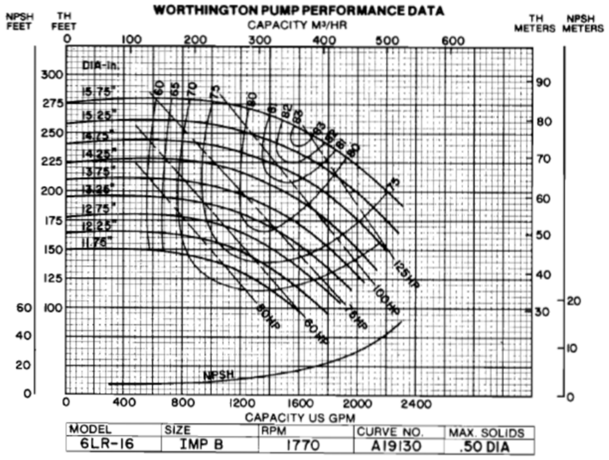

Figure 3: Worthington pump curve.

The flow curve was used to construct the pump feature in the system model, thereby representing the actual pump characteristics for flow and head in the simulations.

The plate and frame heat exchanger, manufactured by Accu-Therm (Figure 4), was sized according to the following specifications:

Table 1: Heat Exchanger Specifications

System	Flow Rate (gpm)	Pressure Drop (psi)	Temperature Change (°F)
A01 Process Water	1,300	3.22	106 → 93.5
Tower Water	545	<1	70 → 99.7

Figure 4: Accu-therm plate and frame heat exchanger.

For an incompressible water system, the First Law of Thermodynamics reduces to the following equation:

$$Q = \dot{m} c_p \Delta T \qquad (2)$$

where Q is heat transfer, $\dot{m}$ is the mass flow rate, c_p is the specific heat and $\Delta T$is the change in temperature. Evaluating the heat exchanger for sufficiency in meeting the demands of the new amplifiers requires the simple calculation of Equation 2.

An expansion tank, installed on the return side of the closed loop, limits the water pressure swings that occur with temperature fluctuation, such as ambient air fluctuations and cooling tower temperature variability. Another temperature fluctuation contributor occurs during an unscheduled system trip and subsequent cool down, causing the system water volume to contract. After a cold start, the expansion tank limits the water pressure increase by allowing the increase in water volume to enter the tank. The water entering the tank displaces an equal volume of air, which initially fills the tank at the desired cold-start pressure. The volume of air in the tank changes from V_1 to V_2, which is V_{tank} minus dV_{water}. As the water heats up, it expands and displaces more volume in the expansion tank.

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The A01 system has an automatic make-up circuit that restores volume when pressure is detected below a threshold. This is accomplished via a Mercoid switch that activates a make-up valve which restores lost water and raises the pressure. The switch has a deadband of about 4 psi and, although a precise return pressure cannot be guaranteed, it is recommended that the switch be set to have the lowest pressure and smallest deadband as possible. The lowest possible pressure setting is that which protects the pump by ensuring an adequate suction pressure. Curves for pump performance and Net Positive Suction Head (NPSH) are shown in Figure 3 for the Worthington pumps.

Issues Prompted System Analysis

The amplifier replacement occurred over the course of three consecutive annual maintenance periods of the LANSCE accelerator (2013-2015). Module 2 was the first to be upgraded followed by Module 4 and finally Module 3. As each successive amplifier replacement occurred, a subsequent run cycle would ensue. The mix of old, analog equipment with new, state-of-the-art, digital equipment, proved challenging in operational interfaces. However, with much consternation, the Operations Group at LANSCE was able to properly integrate the systems.

Of many issues that were addressed and overcome, the low-flow trip on the modules was one of the most challenging. Very sensitive instrumentation was installed in the amplifier systems to prevent reflected power from the accelerator tanks to damage the ceramic tubes. Because of this, a certain amount of nuisance trips were status quo in the initial stages of start-up, but this caused other unintended problems. In particular, when a nuisance trip resulted in a downtime long enough for the A01 water system to cool down, the resulting decrease in pressure could initiate the system make-up water, which over pressurized the suction pressure. Since supply pressure was limited to protect the ceramic tubes from cracking, an increase in suction pressure invariably cut down the flow rate cooling the amplifiers. This lower flow caused additional nuisance trips which are hard on ceramic amplifier tubes due to the thermal cycling. This issue prompted an investigation to determine a solution to the nuisance trips.

A flow model was constructed from the P&ID and from field measurements of the actual pump and distribution system. Using AFT Fathom software [7], pipe types, lengths, components and sizes were all carefully built in the model to accurately depict the actual system. Although the pump and distribution piping were all relatively old, the degradation caused by corrosion is minimal because of the deionized water medium. In the model, smooth pipe friction coefficients were used although the pipe is over 40 years old. Inspection of the legacy pipe's inner surfaces has confirmed that the use of smooth pipe friction coefficients in the model is a valid representation of the actual pipe conditions.

Module 1 is modelled as a single component with a known flow rate and pressure drop. The intricacies of the piping distribution are not modelled separately since this is the remaining legacy amplifier. Flow rate was measured with a clamp-on acoustic flow meter, and pressure drop was read directly from dial gauges. Modules 2, 3 and 4 were measured using new flow meters installed with the systems and dial pressure gauges installed during the upgrade. Table 2 depicts the flow rates, pressure drops and temperature changes of each module:

Table 2: Amplifier Module Deionized Water Metrics

Module	**Flow Rate (gpm)**	**Pressure Drop (psi)**	**Temperature Change (°C)**
1	285	40	unk
2	236	50	21 → 26
3	236	50	21 → 26
4	236	50	21 → 26

Because of the working system, the values tabulated in Table 2 are real system values and this fact translates into a flow characteristic that can be represented in the model. Therefore, each of the modules is represented by a component in the model which has a flow characteristic generated based on the real values in Table 2.

The heat exchanger has a similar pressure drop versus flow rate curve based on manufacturer data, and the bypass circuit model feature is set up to be varied, showing the effects of varied flow. The model solves Equation 1 allowing the engineer to ascertain the applicability of this water system to deliver the required flow rates and pressure heads to each of the modules. Since the simulation results revealed sufficient flow rates and pressure delivery, other components were investigated to troubleshoot the low flow nuisance trip.

Further investigation yielded a high suction pressure condition reoccurring after cold start. This high suction pressure seemed to have been caused by make-up water overfilling the system while cold because of an inadequately sized expansion tank. To check this theory, an analysis was performed to calculate the increase in pressure with an increase in temperature of the closed system.

Expansion Tank Analysis

An edited excerpt from an internal memo follows regarding the analysis of the A01 expansion tank. The legacy expansion tank was a 13 gallon bladder-type charged with 15 psi of air. Expansion tanks are necessary in closed water systems to eliminate increases in pressure caused by volume increases due to temperature changes. To determine the adequacy of an expansion tank, the analysis was performed to calculate the increase in volume versus expected temperature increases:

The increase in volume of the water due to temperature rise may be calculated by using its coefficient of thermal expansion, β. The coefficient of thermal expansion of water at 300 K (80.3°F) is 0.0002761 K^{-1} [8]. The increase in volume is given by

$$dV_{water} = V_{water_1}\beta(T_2 - T_1) \qquad (3)$$

where V_{water1} and T_1 are the initial cold-start volume and temperature.

The expansion tank limits the water pressure increase by allowing the increase in water volume to enter the tank. Water entering the tank displaces an equal volume of air, which initially fills the tank at the desired cold-start pressure. The volume of air in the tank changes from V_1 or V_{Total}, to V_2, which is V_{Total} minus dV_{water}. The ideal gas law is used to determine the air pressure increase due to this volume decrease:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \tag{4}$$

or:

$$P_2 = \frac{P_1V_1T_2}{(V_1 - dV_{water})T_1}$$

The amplifier heat loads are expected to produce a temperature rise of 5° C at steady-state. Assuming an initial system volume of 2,377 gallons, a 5° C temperature rise results in a volume increase of 3.28 gal. If the initial system temperature is 25° C (298 K), and the expansion tank is initially pressurized to 15 psig (26.5 psia), the steady-state operating pressure is calculated to be:

$$P_2 = \frac{26.5\text{ psia} * 13\text{ gal} * 303\text{ K}}{(13\text{ gal} - 3.28\text{ gal}) * 298\text{ K}} = 36\text{ psia}$$
$$= 24.5\text{ psig}$$

for the legacy expansion tank. This result is a 9.5 psi pressure increase from the cold-start condition. This value roughly matches pressure measurements made on the system when power was on and off, so the volume of 2,377 gal will be used as the system volume in the analysis.

Return pressure values above 22 psig have been noticed to reduce the flow to unacceptably low levels. One remedy to reduce the pressure during operation is to drain water from the system. This returns the flow to normal during operation.

Fluctuations in cooling tower water temperature also contribute to pressure swings in the A01 system. Tower water temperature increases of 5° C must also be accommodated. A 10° C temperature rise results in a system volume increase of 6.56 gal. If a 53 gal tank is used, in place of a 13 gallon, and initially pressurized to 16 psig (27.5 psia), the steady-state operating pressure is calculated to be:

$$P_2 = \frac{27.5\text{ psia} * 53\text{ gal} * 308\text{ K}}{(53\text{ gal} - 6.56\text{ gal}) * 298\text{ K}} = 32.5\text{ psia}$$
$$= 21.0\text{ psig}$$

With this change, the pressure stays below the 22 psig limit above which the 201 MHz equipment flow is compromised.

Conclusion

A complicated, heavily interfaced system such as high and intermediate power amplifiers, has many requirements that are not immediately understood when teasing them out of a brainstorming process. As such, legacy systems, and in particular, water cooling systems are not necessarily adequate to meet all of the needs of the upgrade. Factors not considered could be more important than initially realized so that they become the apparent problem for intermittent trips. Installing sensitive equipment with stringent pressure and flow requirements makes an evaluation of the entire existing cooling system necessary. Water make-up systems and expansion tanks are particular to the overall system requirements and may not be adequate when an upgrade is performed.

The recommendation resulting from the expansion tank analysis is to increase the capacity of the tank from 13 to 53 or more gallons. An expansion tank volume of at least 53 gal should eliminate low-flow nuisance trips since the suction pressure would not increase above threshold for maintaining flow. As of this writing, the expansion tank has been replaced and the accelerator is returning to service after a long (4 months) maintenance outage. It is expected that low-flow nuisance trips will be eliminated.

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