Design and Performance of a 2-Megawatt High Voltage DC Test Load*

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Abstract

A high-power water-cooled resistive load which simulates the electrical load characteristics of a high-power klystron, capable of 2 MW dissipation at 95 kV DC, is designed and installed. The load utilizes wirewound resistor elements suspended inside G-11 insulated tubing contained within a single-wall 316 stainless steel pressure vessel with flanged elliptical heads. The vessel supplies a continuous flow of deionized water. Baffles fabricated from G-10 sheets support the tubing and promote water turbulence to maximize heat removal. A companion oil tank houses resistive filament and mod-anode power supply test loads, plus an electrical interlock system which provides protection from inadequate water flow, excessive water temperature, excessive water conductivity, excessive oil temperature, and arcing in either the pressure vessel or oil tank. A secondary safety system consists of both hydrostatic and steam pressure relief valves on the pressure vessel. Power supply tests indicate the load simulates the electrical load characteristics of a high-power klystron to a degree sufficient to accurately performance-test the rf high voltage power supplies used at the Advanced Photon Source.

1. INTRODUCTION

A water-cooled resistive load, capable of dissipating 2 MW at 95 kV DC, was designed and built by Argonne National Laboratory for use as a full-power test load for klystron power supplies at the Advanced Photon Source. This test load was designed to simulate the beam, mod-anode, and filament load characteristics of the Thomson TH2089A klystron [1], thereby allowing maintenance and testing of power supplies to be performed without risking damage to the klystrons in the event of a power supply system malfunction.

Initial construction of the load assemblies was completed in January 1994, and preliminary testing of the load began in February. These early tests indicated that leakage currents in the cooling water were greater than had been anticipated, and the load was then modified to reduce these currents. The load was first used successfully in high-power testing of power supplies on May 10, 1994.

2. SYSTEM DESIGN

The load consists of two sub-systems, one composed of water-cooled wirewound resistor elements contained within a stainless-steel pressure vessel which simulates the beam load of the klystron, and the other housing resistors in an oil tank to simulate the mod-anode and filament loads (see Figure 1). The beam load resistors are cooled by a continuous flow of high-purity deionized water. There is a safety interlock system which prevents operation of the load in the event of inadequate cooling water flow, low water resistivity, excessive water temperature, excessive oil tank temperature, or arcing within the pressure vessel or oil tank.

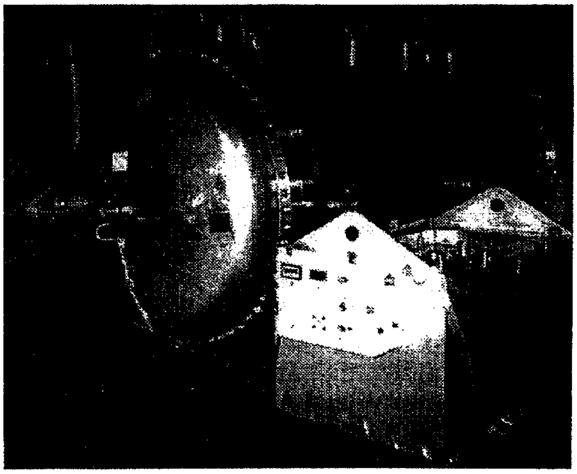

Figure 1

The power supply under test is connected to the oil tank with the same Pantak high-voltage cables that are used to make connections to the klystron. The beam load current is then looped through the oil tank and connected to the beam load resistors, located within the pressure vessel, using a 400-foot-long coaxial high-voltage cable.

3. ELECTRICAL DESIGN

The beam load consists of a series string of 100 wirewound resistors (Ohmite #082), each having a resistance of 43.2 Ω cold. The resistors are cooled by a deionized water flow of between 250 and 500 gpm, which allows the resistors to safely dissipate a maximum of 20 kW each (see Figure 2) [2]. Under full load, the positive temperature coefficient of the resistor material raises the total resistance of the series load resistor string to 4750 Ω, resulting in a theoretical current (ignoring leakage currents in the cooling water) of 20 A at an input voltage of 95 kV.

The mod-anode load consists of a series string of eight 850-kΩ non-inductive resistors (Power Film Systems #PFS6-8540P), providing a 10-mA load for the mod-anode supply at an output voltage of 85 kV. The filament load is a 1-Ω vitreous enamel wirewound resistor (Ohmite #280), providing a maximum filament current load of 25 A.

The safety interlock system consists of a series-string of normally open contacts which close upon satisfaction of the following parameters: supply and return water flow of at least 250 gpm, supply and return water temperature below 140°F, return water resistivity above 3 mΩ·cm, oil tank temperature below 150°F, and no high-voltage arcing within the system. Two arc detectors are poised to view the interior of the pressure vessel

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* Work supported by U. S. Department of Energy Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.

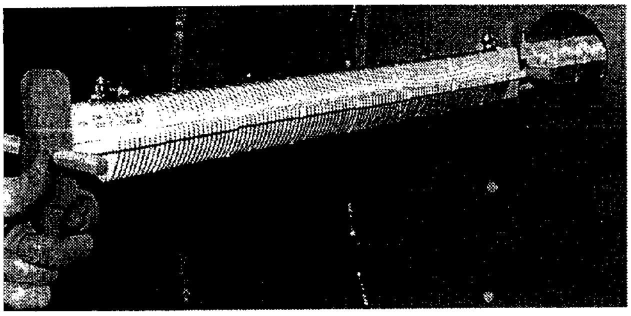

Figure 2

via sight-glass lenses located at each end of the vessel, and one arc-detector is submerged in the oil tank. If an arc is detected, the arc detectors latch in the alarmed state, and must be reset to again satisfy the interlock chain. The closed interlock chain completes the ground return for an interlock relay, which then energizes and provides a closed NO dry contact which is used to enable an external interlock circuit on the power supply under test. Any interruption of the test load interlock chain will result in an immediate shutdown of the power supply under test.

The operator controls for the load are located in an electrical enclosure mounted on the oil tank. These controls include status indicators for the interlock chain, oil tank and oil temperature detectors, and remote metering for pressure vessel water flow and temperature.

4. MECHANICAL DESIGN

The 304 stainless steel pressure vessel was built to ASME Boiler and Pressure Vessel Code, section VIII and IX specifications. The operating pressure for the vessel is 85 psig, with a MAWP of 110 psig. The vessel operating pressure is achieved using a pressure reducing valve, thereby reducing the pump output pressure from 150 psig to 85 psig. The pressure drop through the vessel ranges from 1 to 5 psig, depending on the given flow rate. Two ASME-stamped relief valves have been installed to relieve internal pressure on the vessel in the event of an interlock failure. The hydrostatic relief valve has a set-pressure of 130 psig with a rated capacity of 75 gpm and is vented to atmosphere. The steam relief valve has a set-pressure of 110 psig with a rated capacity of 18,100 lbs/hr and is vented to atmosphere through a roof penetration. The calculated maximum external pressure for the vessel is 20 psi, based on a vessel wall thickness of 1/4".

The load resistors are mounted within 5" ID fiberglass resin tubing. G-11 was chosen for the tubing over G-10 because it provides increased strength and support for the resistors at elevated temperatures. Holes drilled into the top of the tubing enhance cooling of the resistors by allowing warmer water to rise and be carried away, and also provide an escape path for gas bubbles. G-10 plates support the tubing and resistor array and promote turbulence within the vessel (Figures 3 and 4).

The primary level of resistivity for the deionized water is set at the utility building. This value currently varies between 3 to 6 mΩ. Secondary deionizing polishing stations are capable of raising the water resistivity level to 10 mΩ. For the test load water, an additional polishing station has been placed at the vessel inlet to assure a minimum resistivity level is maintained despite fluctuations from the site utility building as new components requiring deionized water are brought on-line. Based on a deionized water inlet temperature of 90° at 350 gpm, the operating temperature is 115°F. The maximum temperature for the vessel is 350°F, which is based on the saturation temperature of steam at 135 psia.

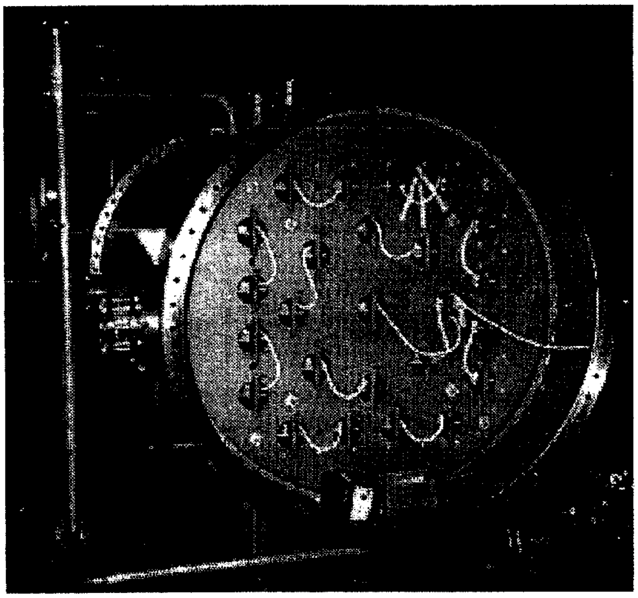

Figure 3

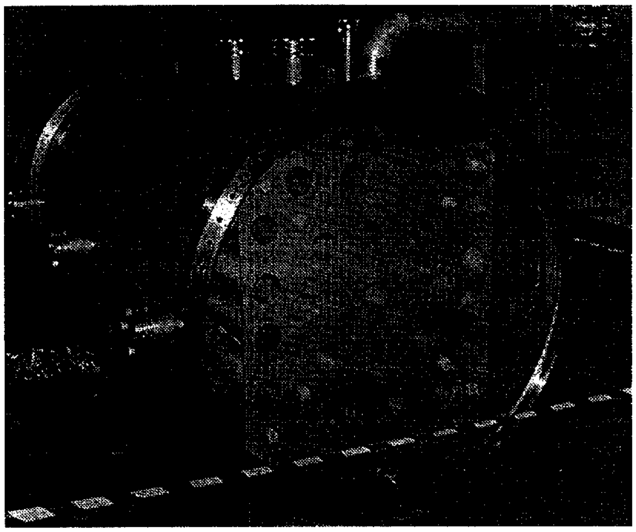

Figure 4

5. PERFORMANCE DATA

Initial DC resistance tests on the beam load, taken both before and after the pressure vessel was filled with water, indicated that leakage paths in the water were shunting significant current around the load resistors. Enough data was taken to isolate the predominate leakage current paths through the water. These paths were determined to be the "water column" paths naturally created across the length of the pressure vessel, and leakage current to the interior surface of the pressure vessel.

Resistance measurements taken after the pressure vessel was filled with circulating deionizing water (resistivity = $1.3 \times$

106 ohm·cm) indicated that "water column" leakage paths provided a shunt path of approximately 22 kΩ, and the leakage path to the tank interior was approximately 10 kΩ. At this point, the decision was made to disassemble the pressure vessel and line as much of the vessel interior as possible with an insulating material to reduce the effective area of the interior tank surface available to leakage currents. Silicone rubber material (.25" thick) was bonded to the interior surface of both end-bells and to approximately the first foot of the vessel body interior using GE RTV-20 silicone adhesive (Figure 5). The vessel was then re- assembled and prepared for use as a test load for the first klystron power supply.

Figure 5

The first power supply tests with the load occurred on May 10, 1994. Data taken during the testing period is shown in Table 1. The total equivalent resistance of the load was reduced to approximately 3.2 kΩ, due to the leakage currents in the water and some possible electromechanical activity between metallic components. The applied voltage was raised until the load current reached 20 A, at which point the power supply is designed to current-limit. As noted in Figure 6, data indicates that operation of the load at higher voltages tends to lower the equivalent resistance of the load, possibly due to increased electrochemical activity between metallic components accelerated by the effects of high-field emission. It is planned to accumulate more hours of high-power operation on the load and then inspect the interior of the pressure vessel for evidence of metal deterioration due to electrochemical activity. To date, the load has logged approximately 14 hours of use at power levels above 1 MW with no significant evidence of distress.

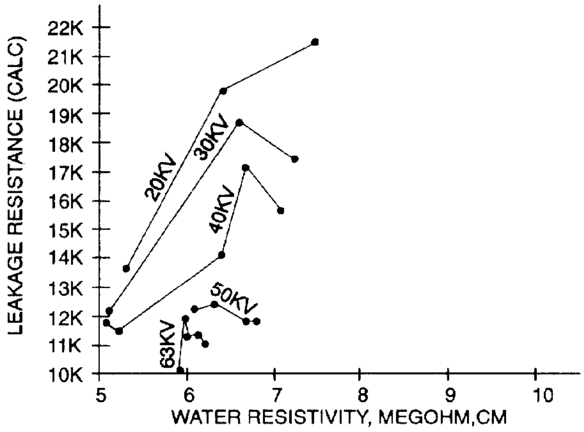

Figure 6. Leakage Resistance vs. Water Resistance

6. SUMMARY

The load will be used in its present form to perform full-power heat run testing of the remaining four klystron power supplies. Data accumulated during this testing period will then be used to develop improvements in the load design. Interpolating data taken during the brief testing period suggests that significant improvements in load performance could be achieved by operation with cooling water of at least 10 mΩ·cm, which would result in an equivalent load resistance of approximately 4 kΩ, allowing operation of the load at 80 kV before the power supply reaches current-limiting. Such water quality can be achieved by introducing slipstream polishing stations to the water supply during the upcoming testing periods. Also, if the leakage currents in the water are found not to cause any serious deterioration of metallic components inside the pressure vessel, the resistance value of the load resistors themselves could be increased, therefore utilizing the leakage current to reduce the overall equivalent load resistance to the desired 4750 Ω at full rated voltage.

7. ACKNOWLEDGEMENTS

We thank J. Bridges and H. Frischholz for discussions which produced vital input to this project, and to E. Wallace, E. Cherbak, and D. Chatkara for their efforts in constructing the load assemblies.

8. REFERENCES

[1] Thomson TH2089A Klystron Amplifier Operating Manual, UTH 2098, November, 1986.

[2] D. Horan, et al., 1993 Particle Accelerator Conference, 93CH3279-7, pp. 1294-1296 (1993).

Table 1

Applied Voltage (kV)	Load Current (A)	Total Resistance (kΩ)	Leakage Resistance (calc) (kΩ)	Power Dissipation (kW)	Water			
					Flow (gpm)	Supply Temp (°F)	Return Temp (°F)	Resistivity (MΩ cm)
39.92	11.18	3.57	17.28	446.3	338	75.6	82.4	6.79
50.36	14.30	3.52	16.18	720.1	321	76.0	88.4	6.69
60.08	18.04	3.3	12.37	1083.8	324	76.4	95.0	6.36
63.22	20.25	3.121	10.19	1280.2	319	76.4	99.0	5.9
64.61	19.87	3.251	11.72	1283.3	315.5	76.0	97.6	6.84