Keysight Technologies
Automated X-Ray Inspection System
Sealed X-Ray Tube

Technical Overview
To produce cross-sectional X-ray images, Keysight’s Automated X-Ray Inspection (AXI) systems use a sealed X-ray tube that is designed and built in-house to exacting standards. The AXI systems are integral to customers’ assembly processes; they must operate consistently with minimal downtime.

For this reason, Keysight has developed a sealed, ultra-high vacuum X-ray tube that provides stable output throughout a significantly long life. Other X-ray inspection systems use demountable X-ray tubes that are designed to allow field replacement of tube components to suit diverse applications. However, the poor vacuum levels of demountable tubes adversely affect their stability and reliability, and require the use of simple filament cathodes, which have relatively short lives.

Cathode

The Keysight AXI sealed X-ray tube uses a dispenser cathode (see Figure 1) which consists of a porous tungsten “sponge” impregnated with barium. To emit electrons, the cathode is heated by a separate tungsten heater. This design results in very reliable and efficient electron emission. It has a life beyond 20,000 hours while providing a small spot size and high current density for high resolution imaging. The typical failure mode involves the gradual depletion of the barium, which can be compensated for to maintain stable operation.

No cathode in any AXI sealed tube has ever fully depleted in the field, even after years of use. In contrast to sealed tubes, demountable tubes use a filament cathode (see Figure 1).

Vacuum Level

In addition to the type of cathode used, the vacuum level in the tube is another major factor affecting tube life and stability. A poor vacuum or “soft” tube contains more gas molecules than a high-vacuum sealed tube. As electrons accelerate from the cathode to the anode, they collide with these gas molecules. In the process, the electrons lose energy and cause the gas to emit secondary electrons. Furthermore, the ionized gas molecules accelerate towards the cathode and strike it with considerable kinetic energy due to their high molecular weight. This further shortens the life of the cathode and may affect the electron beam’s quality and the ability to focus and steer it. Consequently, a “soft” tube is less stable and has a greater probability of arcing.

To achieve an ultra-high vacuum, a completed X-ray tube assembly must be baked at a high temperature under hard vacuum for an extended burn-in period. This process substantially removes any gas molecules from surfaces within the assembly. High quality sealed vacuum devices, such as those used in NASA space missions, military applications and AXI systems, all undergo such a process to ensure that they provide long-term stable operation. Because demountable X-ray tubes cannot be baked, and need to be opened to replace components, they cannot achieve the same high vacuum of sealed tubes.
New Improved X-Ray Tube Housing

Keysight has improved the current X-ray tube housing design to enable the following benefits:

1. To increase the supply chain capability
2. Ability to ship the new improved x-ray tube with improved housing under 'Non-Dangerous Good' classification.
3. The weight is lighter at 32 kg compared to the current design which is 48 kg.
4. Transportation cost is less.
5. Materials cost for the new improved x-ray tube housing is lower and easily available.
6. Materials availability turn-around time is shorter.

Comparing the current and new improved X-ray tube housing:

<table>
<thead>
<tr>
<th>Current X-ray tube housing</th>
<th>New improved X-ray tube housing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The materials are made of stainless steel for the top plate and bottom plate.</td>
<td>1. The bottom plate, top plate and pressure vessel is made of aluminum.</td>
</tr>
<tr>
<td>2. The pressure vessel is made of extruded aluminum.</td>
<td>2. The pressure vessel rods are also made of aluminum.</td>
</tr>
<tr>
<td>1. The top plate is round.</td>
<td>1. The top plate is square.</td>
</tr>
<tr>
<td>2. There are three lifting support brackets.</td>
<td>2. There are only two lifting support brackets instead of three.</td>
</tr>
<tr>
<td>3. The plate thickness is 25.4 mm.</td>
<td>3. The plate thickness is 19.05 mm.</td>
</tr>
<tr>
<td>4. The diameter of the top plate is 203.2 mm.</td>
<td></td>
</tr>
<tr>
<td>1. The SF6 gas in the tube is pressurized at 63 psi.</td>
<td>1. The SF6 gas in the tube is pressurized at 26 psi.</td>
</tr>
<tr>
<td>Current X-ray tube housing</td>
<td>New improved X-ray tube housing</td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>1. The wall thickness of the pressure vessel is 12.44 mm.</td>
<td>1. The wall thickness of the pressure vessel is 3.18 mm.</td>
</tr>
<tr>
<td>2. The length of the pressure vessel is 495 mm and the total tube length is 102 cm.</td>
<td>2. The length of the pressure vessel is 507.7 mm and the total tube length is 102 cm.</td>
</tr>
<tr>
<td>3. There are no support rods for this X-ray tube.</td>
<td>3. There are four support rods for this X-ray tube.</td>
</tr>
<tr>
<td>4. The diameter of each rod is 19.98 mm</td>
<td>5. The length of each rod is 507.60 mm</td>
</tr>
<tr>
<td>1. The base plate length is 254 mm.</td>
<td>1. The base plate length is 247.65 mm</td>
</tr>
<tr>
<td>2. The base plate has no outer groove on the top.</td>
<td>2. The base plate has an outer groove that is 195.83 mm in length.</td>
</tr>
<tr>
<td>3. The thickness of the plate is 23.23 mm.</td>
<td>3. The overall thickness of the plate is 19.05 mm.</td>
</tr>
<tr>
<td>4. The groove thickness is 6.65 mm.</td>
<td>4. The groove thickness is 6.65 mm.</td>
</tr>
<tr>
<td>1. The tube has a standard L-shaped bracket.</td>
<td>1. This tube has an improved design VACION pump bracket mounting.</td>
</tr>
<tr>
<td>1. It is supported by two screws on the top plate only.</td>
<td>1. It is also supported by two screws on the top plate.</td>
</tr>
</tbody>
</table>
Comparison of Operating Costs

The operating costs of a typical demountable tube and 5DX sealed tube are compared based on three shifts per day, five days a week, resulting in approximately 6000 operating hours per year. The dispenser cathode of the sealed tube is conservatively assumed to have a life of 20,000 hours. Its replacement cost is $28,500 in parts and 8 hours of labor at $200/hour. The filament cathode of the demountable tube is assumed to have a life of 1,000 hours. Its replacement cost is $40 in parts and 6 hours of labor at $200/hr.

Though the repair costs are similar, the short life of the filament cathode in demountable tubes results in significant production downtime every year.

The cost of this down-time far outweighs any savings associated with demountable tubes, particularly if failure occurs during peak production times. Furthermore, another aspect of demountable tubes that is not quantified here is the increased cost of maintaining the vacuum pumps.

Summary

The sealed X-ray tube used in the 5DX system has significant advantages over demountable tubes used in other inspection systems.

Because of their cathode design and ultra-high vacuum level, sealed tubes are more reliable and stable, resulting in higher quality, lower production costs and lower cost of ownership.

X-Ray Tube Parts List

<table>
<thead>
<tr>
<th>Part#</th>
<th>Description in custom invoice/oracle</th>
<th>Specification</th>
<th>Pressure vessel (Pressure of SF6)/psi</th>
<th>High resolution</th>
<th>Standard resolution</th>
<th>New tube</th>
<th>Refurbished tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>E7200-89009</td>
<td>RSTRD E7200-80009 x-ray tube</td>
<td></td>
<td>62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E7200-89059</td>
<td>RSTRD E7200-80059 hi resolution x-ray assy</td>
<td></td>
<td>62</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E7200-89066</td>
<td>Zero pressure vessel standard res x-ray tube exch</td>
<td>26</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E7200-89067</td>
<td>Zero pressure vessel hi res x-ray tube exch</td>
<td>26</td>
<td>√</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>N7210-80066</td>
<td>Zero pressure vessel standard res x-ray tube</td>
<td>26</td>
<td>√</td>
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<td></td>
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</tr>
<tr>
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<td>Zero pressure vessel hi res x-ray tube</td>
<td>26</td>
<td>√</td>
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</tr>
</tbody>
</table>

Glossary

<table>
<thead>
<tr>
<th>Hi Resolution</th>
<th>High resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Res</td>
<td>Standard resolution</td>
</tr>
<tr>
<td>HI RES</td>
<td>High resolution</td>
</tr>
<tr>
<td>Zero Pressure Vessel</td>
<td>Denotes 26 psi</td>
</tr>
</tbody>
</table>

Note: The maximum operating voltage and current for all the tubes are 165 KV and 105 micro Amps.
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(BP-02-06-15)