Defined Emission Area and Custom Thermal Electron Sources

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We report on electron emission defining and stability techniques use for specialized thermionic cathodes. Primarily lanthanum hexaboride and cerium hexaboride have been used for cathode materials but we have also use hafnium carbide for particular uses where background atmospheres preclude the use of hexaborides. A common form of emission suppression is to embed an oriented single crystal in graphite to suppress side emission and to help shape the electric field. Single planar discs 50 microns in diameter have been tested for use in high brightness, stable, and long life thermal sources. Line sources have also been developed with line width/lengths to 10/500 microns. Emission tests performed have shown that instabilities can originate from mounting methods. Improved mounting techniques can yield emission with short term beam current stability <0.05%.

I. INTRODUCTION

Rare-earth hexaborides[1], specifically LaB_6 and CeB_6, are used commercially in a wide array of SEM, TEM, and lithography systems and can be mechanically held using a Vogel type mount (see Fig. 1). However, they do have limitations needed for certain applications. Our research has covered emission from single-crystal boride and carbide thermionic and carbide field emitters[2,3]. These materials have electron emission properties making them attractive candidates for stable emission sources in moderate vacuum applications. $CeB_6(310)$ has a work function of 2.4 eV and a relatively low evaporation rate in low 10^{-7} Torr pressures and operation at <1800 K gives commercial lifetimes >2000 hours.

For particular low current and extreme operating conditions and environments we fabricate embedded cathodes from HfC(310). This is an extremely robust cathode material capable of operation in poor vacuum conditions and able to withstand ion back streaming successfully.

Several thermionic electron sources are shown which have unique properties including a defined emission area without edge effects. These are beneficial for a range of applications including x-ray generation, electron microscopy, lithography, and microwave devices. The source can be a $LaB_6(310)$ cylinder mounted flush in a specially shaped carbon guard-ring. We have made these carbon guard-ring structures[4] from graphite which is mounted in a conventional mini-Vogel type system, using separate pyrolytic carbon blocks as the heating element (see Fig. 2). These mini-Vogel mounts (MVM) can also be configured with shunts (SMVM). The work function of the carbon guard ring is >1.5 eV higher thereby suppressing emission from its surface and limiting the emission to the LaB_6 emitter. Cathodes have been built with source diameters from 50 μm to 1 mm and guard ring diameters from 100 μm to 3 mm.

Spatial and emission current stability for these SMVM are excellent for uses such as SEM and similar electron beam application. However, with the need for exacting beam current stability for certain inspection and new lithography applications, we have studied and made certain improvements to the Vogel mount to eliminate both long drift and short term fluctuations.

II. EXPERIMENTAL

A. *Defined emission area*

Oriented single crystalline material is prepared in our facility utilizing a floating zone refining system. The oriented rods are centerless ground generally to 0.5-mm diameters for round cathodes and larger dimensions for line sources. To form a circular emission surface 50 microns in diameter we use a technique of electrochemically etching the material to the finished diameter and roughly 400 microns long. This is then pressed into a prepared pure graphite section. The emitting surface is finally polished to the desired finish and the whole structure is mounted between pyrolytic graphite blocks as a more conventional Vogel-type mount (see Fig. 3).

For line sources, a slab is formed from a crystal of diameter suitable for the length of the source needed with the thickness the desired source width. This is then embedded into a slot machined into pure graphite (shown in Fig. 4), the emitter surface polished, and again Vogel mounted.

In a standard Wehnelt triode type electron gun the electric field is shaped in such a way that the full brightness of emission from the truncation in the standard, un-embedded geometry cannot be realized due to unwanted emission from the cone. The electric field lines dip into the Wehnelt, enhancing the field at the edge of the cathode truncation and cause electrons emitted from this region to follow a diverging trajectory after cross-over. When our guard-ring cathode is mounted in this same Wehnelt configuration, the resulting edge enhancement is on the carbon and the field lines remain relatively planar across the emitting surface. The reduced emitting area can result in a reduction of the spot size of the optical system and a dramatic increase in brightness of the source.

B. Emission stability

Through detailed lifetime studies, we have noted resistance changes associated with the pyrolytic graphite heating blocks used with the Vogel-type mount. It has long been known that there is a slow decrease in resistance over the life of the cathode during operation. Historically, this decay has not been an issue for uses such as SEMs. However, long exposures needed for applications as lithography and inspection this decay cannot be tolerated. Data are generally a recording of heater resistance over cathode run-times (see Fig. 5); since the beam current is a function of cathode temperature, recording heater resistance is a viable method to judge emission current stability.

III. RESULTS AND DISCUSSION

Our efforts to understand and enhance emission stability of Vogel mounted sources has entailed experimentally examining the interactions of boron from the metal boride with the carbon in the graphite blocks as well as the carbon-metal interactions between the heating blocks and the support post or shunt material.

Generally, the SMVM is inherently more stable than the non-shunted variety but still suffers from a slight decline in resistance over time as seen in Fig. 6. In either case by preventing the boride from direct contact with the pyrolytic heater blocks the resistance change over time is essentially eliminated. To document this effect of boron interaction we substituted a standard built HfC cathode. As also seen in Fig. 6 the drift in resistance is eliminated by using the carbide cathode and eliminating the boron-carbon interaction evidently caused by the heating current flow at the interface which causes this longer term drift.

During these drift studies a secondary short-term instability or noise was noted. This manifests itself as spike like changes in the heater resistance such as shown in the bottom curve of Fig. 7. These short-term fluctuations generally do not result in a resistance change but random abrupt changes and re-adjustments back to the original resistance value.

During operation of the cathode the temperature at the top of the Mo/Re clamping post on a MVM can reach over 1000 ˚C. This high temperature can lead to a carbonization of the Mo in the Mo-Re post material between the post-PG interface[5]. It is this process which can be shown to cause these fluctuations in the resistance of the heater circuit. This reaction is predominantly with the molybdenum at lower temperatures. Placing a rhenium (Re) shim or barrier between the PG block and the post eliminates short term resistance fluctuations (see Fig. 7) for a graphite-metal interface operating at such a temperature. Generally rhenium does not form carbides at ambient pressures though the clamping force can create elevated pressures still temperatures >1000 K are required for carbide formation in rhenium .[6]

Figure 8 then illustrates the two main changes to the standard mini Vogel mounted (MVM) thermionic cathode that allows for better temperature stability and hence greater emission stability. First, by removing the LaB_6 or CeB_6 crystal from between the pyrolytic graphite (PG) heater blocks and embedding or mounting the crystal in the top of the graphite blank, the interaction between the PG and the active metal elements of the crystal are eliminated from the heater circuit. In the standard MVM thermionic cathode the interaction of the boride crystal and PG results in a gradual but continuous resistance change over time of the PG block. The resistance change leads to a temperature change of a cathode operating with a constant current or constant voltage power supply and results in a very slow drift over the life of the cathode. Figure 5 shows the change in resistance for LaB_6 cathode and graphite blank cathode. It is clear from the graph that the cathode with the graphite blank shows much better stability when compared to the standard LaB_6 cathode. Secondly, by removing Mo contacting the heater block through the use of a Re barrier (see Fig 8) we can considerably reduce or eliminate the short-term noise and gain beam current stability.

IV. SUMMARY AND CONCLUSIONS

Stable thermionic sources are desired for several applications including electron beam lithography. Mechanical and emission stability have been realized using a Vogel type mount. Boron interaction with the pyrolytic carbon blocks results in small resistance changes in the heater blocks over the life of the cathode. Removing the boride cathode material from the heater circuit eliminates this drift. A small, secondary short term instability was noted and determined to be an interaction of the pyrolytic carbon with Mo in the support posts. This instability is eliminated by insertion of a Re shim at those interfaces.

Emission limited and stable thermionic sources are desired for several applications including small spot x-ray systems and electron beam lithography. Side emission is eliminated via a carbon guard ring and emission stability have been realized using a modified Vogel type mount. In cathodes incorporating both embedding the emitter in graphite and using a Re shim we have obtained exceptional beam current stability. Long term drift is very low and short-term beam current fluctuations of 0.01% rms are realized.

ACKNOWLEDGMENTS

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REFERENCES

[1] L.W. Swanson and D.R. McNeely, “Work functions of the (001) face of the hexaborides of Ba, La, Ce, and Sm,” Surface Science 83 11-28 (1979).

[2] W.A. Mackie, R.L. Hartman, M.A. Anderson, and P.R. Davis, "Transition metal carbides for use as field emission cathodes," *Journal of Vacuum Science and Technology B*, 12(2) March/April (1994).

[3] K.J. Kagarice, G.G. Magera, S.D. Pollard, and W.A. Mackie, "Cold field emission from HfC(310)," J. Vac. Sci. Technol. B 26 (2), Mar/Apr (2008).

[4] W. A. Mackie, K.J. Kagarice, C.L. Fast, "Development of a (100) hafnium carbide thermionic electron source with built-in guard ring and heater," *IVEC/IVESC 2006 Conference Proceeding*, IEEE Electron Devices Society, Apr (2006).

[5] E.V. Rut'kov, A.Ya. tontegode, M.M. Usufov, and N.R. Gall, "Carbon interaction with heated molybdenum surface," Applied Surface Science, 78, 2, 179-184 (1994).

[6] E.A. Juarez-Arellano, et al., "Reaction of rhenium and carbon at high pressures and temperatures," Zeitschrift fur Kristallographie, 223, 8, 492-501 (2008).

Figure Captions

Figure 1. Typical shunted mini-Vogel mount (SMVM) used for a LaB_6, CeB_6, or HfC cathodes. Historically, the shunts were introduced to mimic the I(V) characteristics of a tungsten hairpin filament.

Figure 2. (a) Vogel mount showing graphite guard ring and 100 μm HfC(100) cathode. (b) View of a 0.25mm radius HfC(100) cathode surrounded by graphite guard ring and centered in Pierce type housing.

Figure 3. a) Vogel mount using pyrolytic carbon blocks sandwiching a shaped graphite structure, b) & c) end view of the shaped graphite structure showing central flat with embedded 50 μm CeB_6(310) crystal.

Figure 4. : HfC(210) line cathode embedded in carbon for emission suppression; top-hat style and standard geometry on right.

Figure 5: Emission current over time showing longer term stability a) top curve for a standard LaB_6 cathode and b) bottom curve for the cathode material embedded in graphite.

Figure 6: Depicted here are several curves plotting cathode heater resistance change over time. The top two curves compare a standard (non-shunted) MVM cathode with a

similarly mounted HfC cathode; blue and red curves respectively. As can be seen the drift is essentially eliminated by changing the cathode material from boride to carbide. The bottom two curves show similar curves for standard (shunted) SMVM LaB_6 and graphite cathodes; yellow and green curves respectively. Even with shunts there is a small amount of drift attributed to the cathode material; eliminated by embedding the crystal in graphite.

Figure 7: Bottom (black) curve shows the short term instability which is eliminated through use of Re shims in top (red) curve.

Figure 8. : Modified Vogel mounts a) showing CeB_6 cathode held in a carbon crucible mount and b) central carbon embedded crystalline cathode. Pyrolytic carbon heater blocks are used with both styles and have the added barrier or shim next to the Mo/Re clamping posts.

Figure 1

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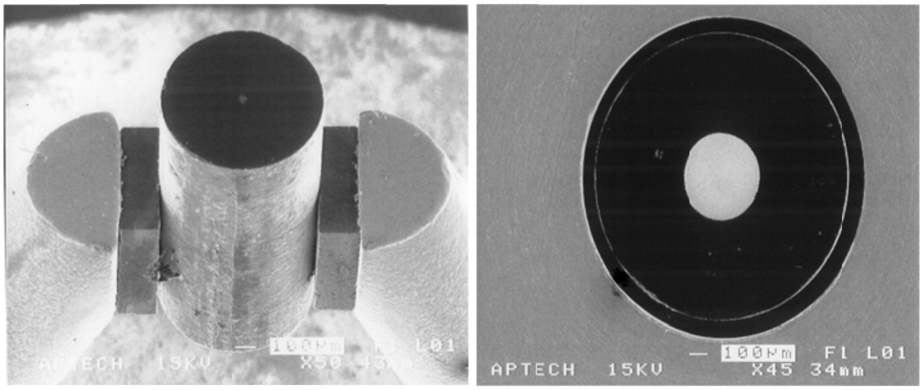

Figure 2

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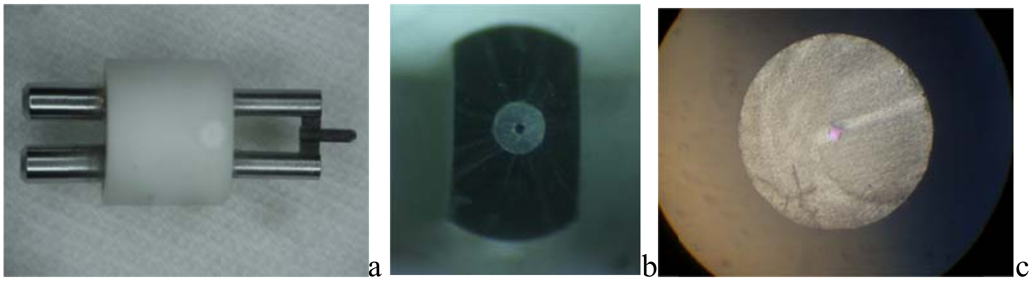

Figure 3

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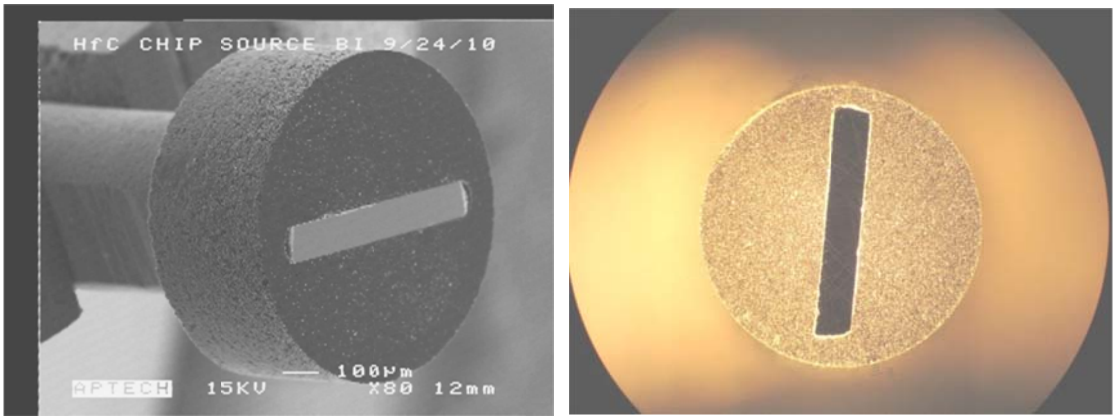

Figure 4

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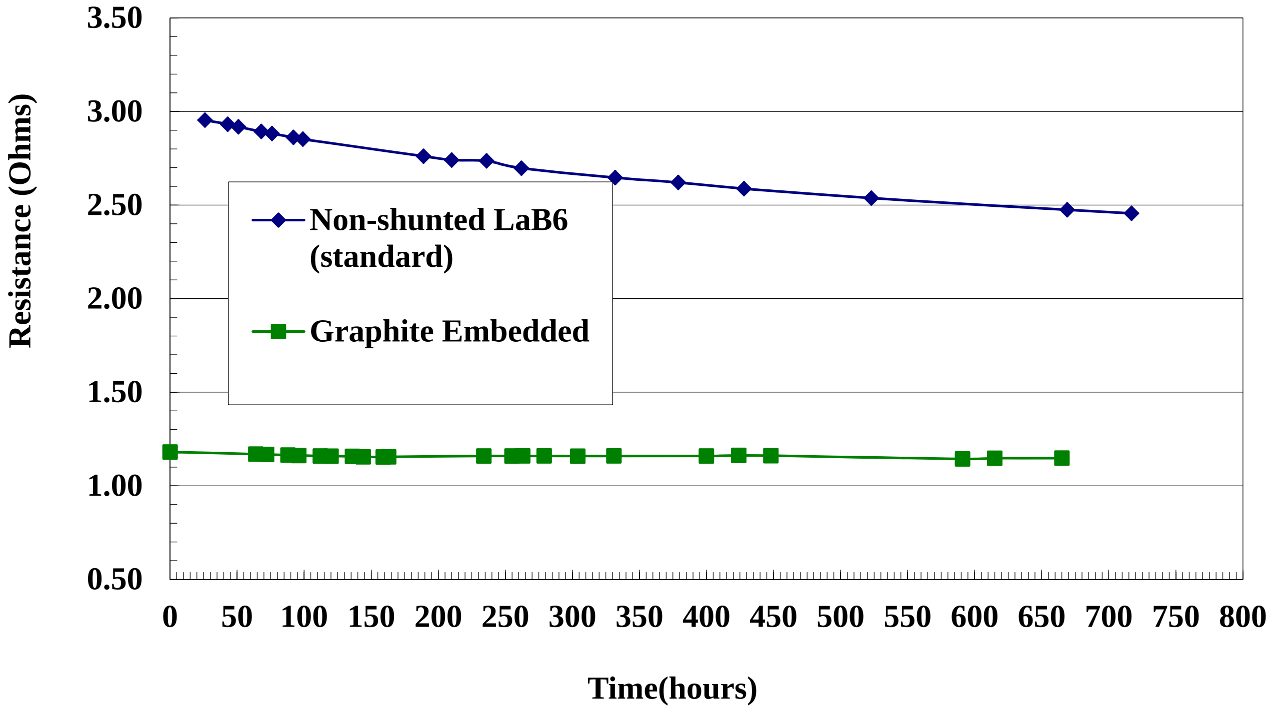

Figure 5

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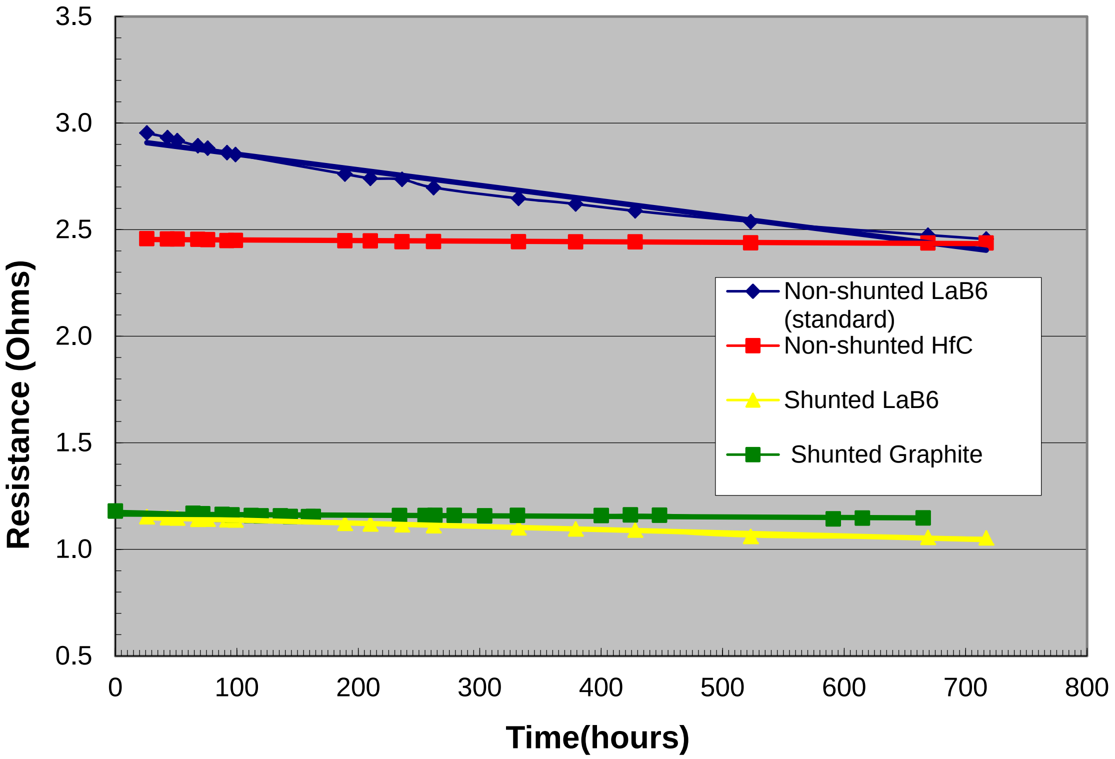

Figure 6

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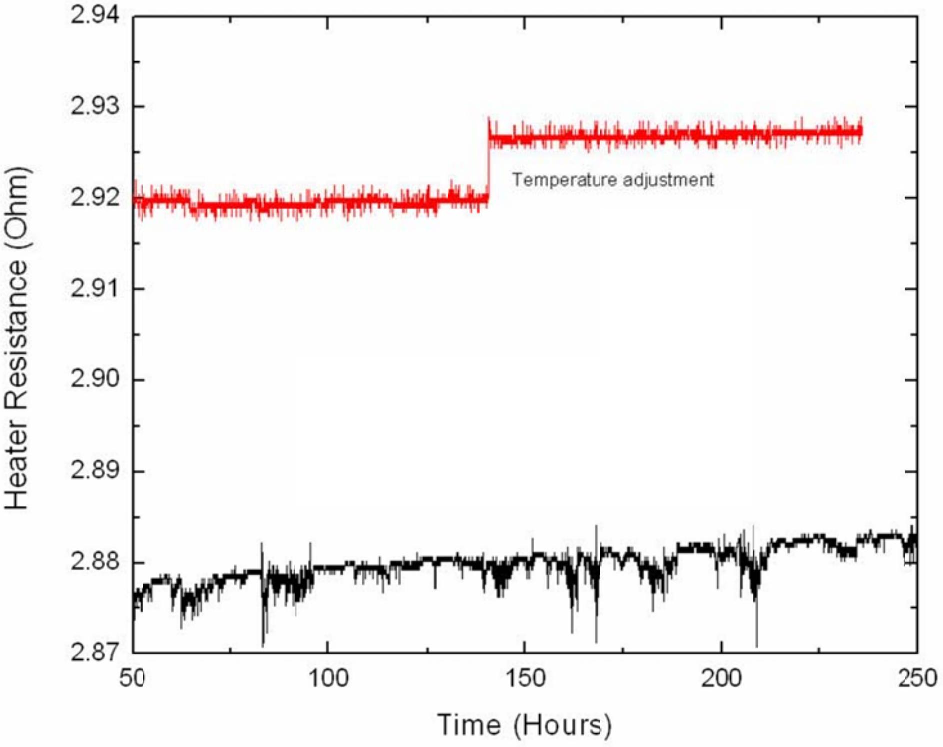

Figure 7

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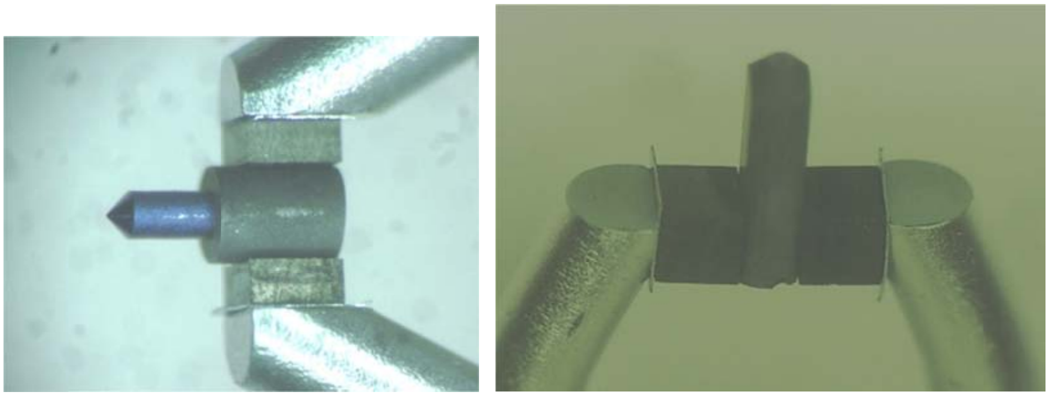

Figure 8

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