BLACKBODY Technical Note

Evaluating performances of vacuum dedicated blackbodies

Vacuum blackbodies have to combine performance of traditional infrared reference sources with specific features in order to operate in vacuum chamber. As their usual applications are calibration and tests of IR sensors to be loaded on satellites, earth or space radiation simulation and test of IR sensors for scientific applications, their usual features are emission over an ultra extended temperature range, knowledge of the radiated temperature with a high accuracy, extremely high uniformity of the emissive surface and extremely high emissivity. HGH developed tools to demonstrate such performances since they surpass the accuracy of usual tools.

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GENERALITIES ON BLACKBODIES AND THEIR THERMAL EXCHANGES

Calibrating and measuring specifications of IR sensors require the use of infrared reference sources, known as blackbodies, which optical radiation only depends on their temperature according to the Planck's law. Another important property of blackbodies is that they absorb all incident radiations whatever their wavelength.

The emissivity factor quantifies the ability to absorb and to emit radiation with respect to a true blackbody. For a true blackbody the emissivity ε(λ) equals 1 whatever the wavelength. However, such bodies do not exist and manufacturing IR reference sources consists in creating sources with emissivity value as high and as constant as possible over the widest spectral range.

At usual pressure conditions, the thermal exchanges between a blackbody and its environment are made through radiation, convection and conduction.

- Radiation exchanges power is given by the Stefan-Boltzmann law:

$$P_{rad} = \sigma \cdot A \cdot \varepsilon \cdot (T^4 - T_{amb}^4) \qquad (1)$$

where σ is Stefan constant, σ=5.67 10-8 W/m²/K⁴, A is the aperture of the blackbody, T is the temperature of the cavity in Kelvin and Tamb is the temperature of the environment. ε is the emissivity factor of the blackbody.

- Taking into consideration the stable environment of a laboratory, convection exchanges are through natural convection only:

$$P_{conv} = h \cdot A \cdot (T - T_{amb}) \qquad (2)$$

Where h is the thermal exchange coefficient between air and blackbody.

- Conduction exchanges through coupling points between the blackbody and its mechanical support

$$P_{cond} = \frac{\lambda \cdot S}{e} \cdot (T - T_{amb}) \qquad (3)$$

Where λ is the thermal conductivity of coupling parts and S/e is the ratio between the surface of contact of the coupling parts and their thickness.

The above equations assume that the thermal exchanges between the non-emissive surfaces of the blackbody structure and the environment are negligible, i.e. the temperature of these non-emissive surfaces equals the temperature of the environment. If not, the above formulas also apply to non-emissive surfaces and these exchanges also have to be taken in consideration.

When the blackbody is stabilized, the total thermal exchange power equals the thermal power brought by the heating or cooling system of the blackbody. Depending on the temperature range, this system may be through resistances, thermoelectric elements, heating/cooling fluid circulation, etc.

THERMAL EXCHANGES IN VACUUM CONDITIONS FOR AN EXTENDED BLACKBODY

In vacuum conditions, only remain exchanges through radiation and conduction.

"Ambient temperature" definition

The radiation exchanges depend on the temperature difference between the emissive surface and the environment. Whereas the temperature of the environment is easy to understand at usual pressure conditions – it can be considered as the temperature of the surrounding air and it is assumed that its emissivity is 1-, the temperature of the environment is more difficult to define in vacuum. For radiation exchanges, the ambient temperature is the temperature radiated by the objects located around the blackbody. These may be the vacuum chamber walls, the instrument being tested by the blackbody, other testing tools, etc. And this radiated temperature and the emissivity of these objects may be different depending on the considered face of the blackbody structure (emissive and non emissive surface). Consequently, equation (1) becomes:

$$P_{rad} = \sigma \cdot A \cdot F_{BB\to E} \cdot (T^4 - T_E^4) \qquad (4)$$

where $F_{(BB\to E)}$ is the view factor of thermal exchange through radiation from the blackbody BB toward its environment E. This view factor is the proportion of the radiation which leaves the blackbody and strikes the surrounding objects which make up its environment.

Environment-dependent specifications of an extended blackbody

Let's consider the example of an extended area blackbody at 150 K with 0.25 m² emissive surface of 0.99 emissivity and 1 m² sandblasted stainless steel non-emissive surfaces at 105K with an emissivity of 0.3. The blackbody is located into a vacuum chamber which walls are covered with liquid nitrogen (LN2) circulating panels which emissivity can be considered closed to 1. The emissive surface is facing the instrument to be tested which temperature is 293K and is considered to be a grey body with an emissivity of 0.1.

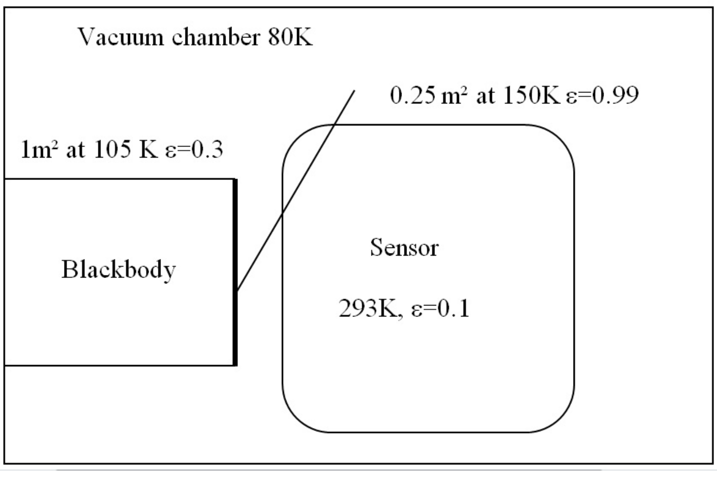

Figure 1 - example of different ambient temperatures in the same vacuum chamber

Considering the power radiated by the blackbody's emissive surface toward its environment, the view factor is the emissivity of the instrument, i.e. 0.1, and equation (4) gives:

$$P_{rad1} = \sigma \cdot 0.25 \cdot 0.1 \cdot (150^4 - 293^4) = -9.6\,W \qquad (5)$$

Considering the power radiated by the blackbody's non-emissive surfaces toward their environment, the view factor is the emissivity of the non-emissive surfaces of the blackbody, i.e. 0.3, and equation (4) gives:

$$P_{rad2} = \sigma \cdot 1 \cdot 0.3 \cdot (105^4 - 80^4) = 1.37\,W \qquad (6)$$

The power radiated by the blackbody toward its environment is the sum of the above calculations (5)+(6). It is obviously negative in this example: it means that the blackbody receives heat from its environment through radiation and warms up.

To remain stable, the losses through radiation must be compensated by thermal exchanges through conduction. To obtain a correct stability of temperature, the power through conduction is transmitted toward a cold foot which temperature remains at LN2 temperature. The strong heat absorbing effect of the cold foot is compensated by the heat provided by a resistance which current is adjusted in real time.

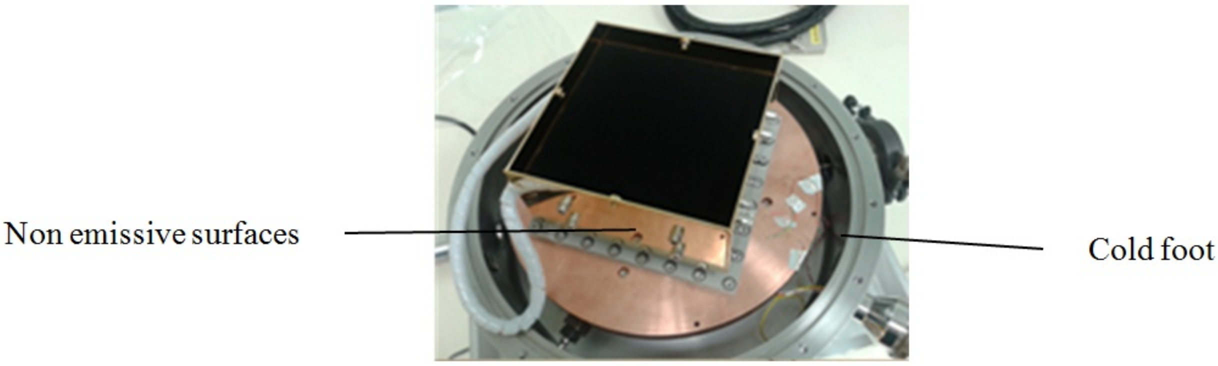

Figure 2 - extended area vacuum compatible blackbody [1]

This combination of controlled thermal exchanges toward radiation and conduction leads to a stability of temperature of the blackbody better than 20 mK.

VACUUM CAVITY BLACKBODY WITH 0.999 EMISSIVITY

Interest of a 0.999 emissivity

A sensor facing an IR emitting source with temperature T and emissivity ε receives the following irradiance I:

$$\frac{I}{\Omega} = \int_{\lambda_{min}}^{\lambda_{max}} \varepsilon(\lambda) \cdot \frac{dR_{BB}}{d\lambda}(T,\lambda) \cdot d\lambda + \int_{\lambda_{min}}^{\lambda_{max}} (1-\varepsilon(\lambda)) \cdot \frac{dR_{BB}}{d\lambda}(T_{amb},\lambda) \cdot d\lambda \qquad (7)$$

[1] Photo credit: ONERA

Where (dR_BB)/dλ (T,λ) is the radiance of a blackbody (i.e. ε=1) given by the Planck's law. The first part of equation (7) is the useful signal due to the emitting source and the second part is the irradiance due to the reflection of the environment radiation. This second part is considered as a parasitic signal which increases uncertainty on the total irradiance received by the sensor to be tested. In vacuum conditions, three methods are used to get rid of this parasitic signal.

Example: ε= constant = 0.99, wavelength range is 8 to 12 µm, T=150 K and T_{amb}= 293 K. With this quite usual configuration, useful signal equals parasitic signal equals 0.34 W/m²/sr.

The first method consists in taking the parasitic signal into account into calculations by removing it from the measurements. This requires having a good knowledge of the emissivity of the blackbody and the ambient temperature. As explained above, this may be particularly difficult in the case of multiple sources of radiation.

A second method consists in overcoming this signal by controlling the reflected radiation using another blackbody at very low temperature:

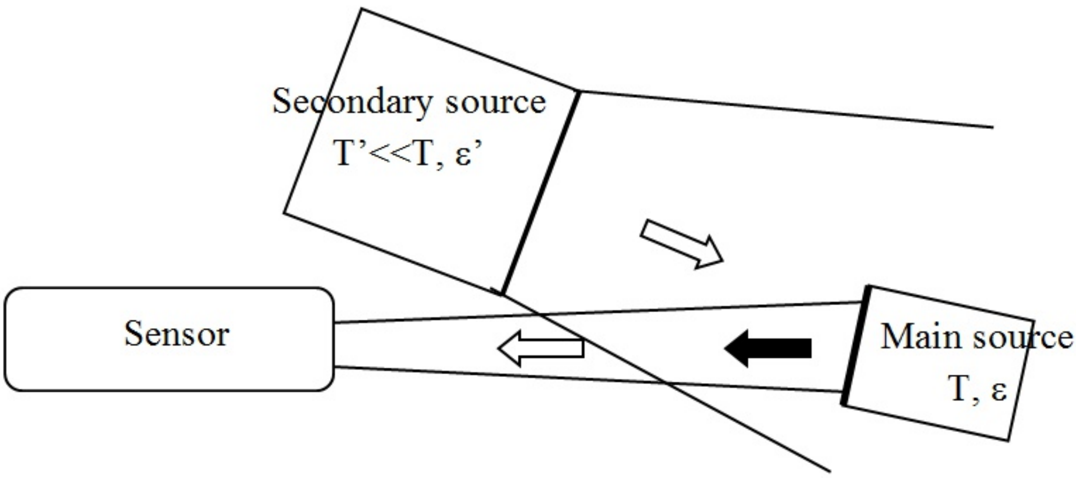

Figure 3 - controlled reflected radiation through a secondary blackbody

The obvious inconvenience of this method is that it requires an additional larger blackbody.
The third method consists in increasing the emissivity of the source. In the above example, if ε=0.999, the parasitic signal is then 10 times lower than the useful signal.

Principle of a cavity blackbody

A cavity blackbody operates as a light trap: incident rays entering though the small aperture reflects on the internal surfaces of the cavity. Since the cavity surface already has an intrinsic high emissivity, the incident radiation is partially absorbed every time it reflects on the cavity surface. Indeed, this reflection is diffuse. Finally very few incident radiation escapes from this light trap.

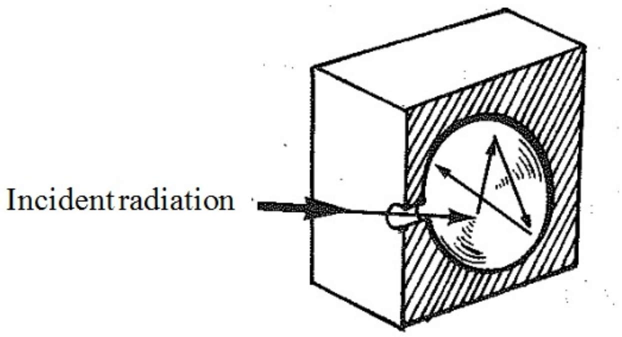

Figure 4 - light trap principle

Achieving an emissivity of 0.999 requires an appropriate design of the cavity shape combined with an internal cavity surface emissivity of at least 0.98. Compared to flat blackbodies, the output emissive surface of a cavity blackbody is not physically defined except through a diaphragm.

Method of measurement of spectral directional emissivity

The method described is in accordance with the bench used by the LNE (Laboratoire National d'Essai – the French national metrology institute) and with an example of results shown in reference [2].

The method consists in calculating the hemispheric directional spectral emissivity of a sample from the measurement of the hemispheric directional spectral reflection factor. The sample is a 30 mm diameter, 10 mm height cylinder; it is assumed that it is opaque. The measured parameter is the hemispheric spectral reflection factor at 8° angle from the normal to the sample surface. It is calculated by comparison to a reference sample. The measurements are made thanks to a Fourier transform spectrometer (Vertex 70 type) equipped with an integrating sphere, leading to a spectral resolution of 16 cm^{-1}. The temperature of the sample is 23°C.

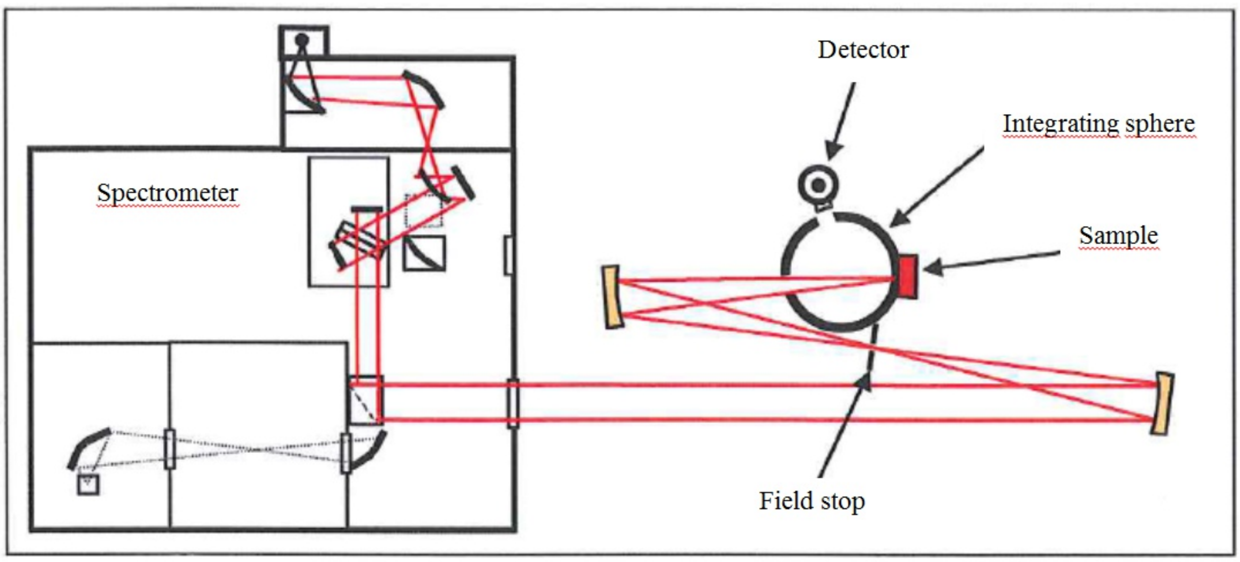

Figure 5 - spectral normal emissivity measurement bench principle

The spectrometer is equipped with an infrared source and delivers an output parallel beam. This parallel beam is focused on a sample and the signal is reflected over the hemispheric space into an integrating sphere and collected by the detector. The signal varies according to the position of the moving mirror of the Michelson interferometer of the spectrometer. The Fourier transform of this signal is the spectrum of this assembly. A golden coated mirror is first used as a reference sample to calibrate the system. This mirror is then replaced by the emissive coating sample under test. The spectral reflectivity factor is the ratio of the two measured spectrum.

In such above conditions, the final expanded uncertainty (level of confidence 95%) of the emissivity is ±0.008 for wavelengths between 3 and 14 µm.

Though this method is particularly accurate, it cannot be applied to cavity blackbodies since it applies on flat emissive surfaces only, not on emissive apertures.

Demonstration of the emissivity value on a cavity blackbody

The demonstration of the 0.999 emissivity factor on a cavity blackbody is made through the combination of the internal surface of the cavity emissivity measurement and the simulation of the ray path into the cavity. The simulation principle uses the main properties of a blackbody, i.e. its absorption coefficient equals its emissivity factor.

A virtual source is placed at the output aperture of the blackbody. The optical flux from this source enters into the cavity and the amount of flux coming out of the cavity is calculated. This output flux results from multiple random reflections of rays into the cavity.

The cavity blackbody is modeled with a lambertian internal coating: it means that each ray hitting the internal surface is reflected toward a random direction according to the Lambert's cosine law and the power of the reflected ray is multiplied by the reflectivity factor:

$$\rho_S = 1 - \varepsilon_S \qquad (8)$$

where ε_S is the emissivity of the internal surface measured thanks to the bench described in previous paragraph. After multiple random internal reflections, rays which attenuation factor is much lower than the required uncertainty for emissivity are supposed to be totally absorbed and interrupted. For a 0.999 emissivity factor, rays with a 10^{-6} attenuation factor are interrupted.

The ratio between the output flux and the input flux is the reflectivity factor of the cavity:

$$\varepsilon_C = 1 - \rho_C \qquad (9)$$

where ε_C is the apparent emissivity of the cavity seen by a sensor located at the position of the virtual source.

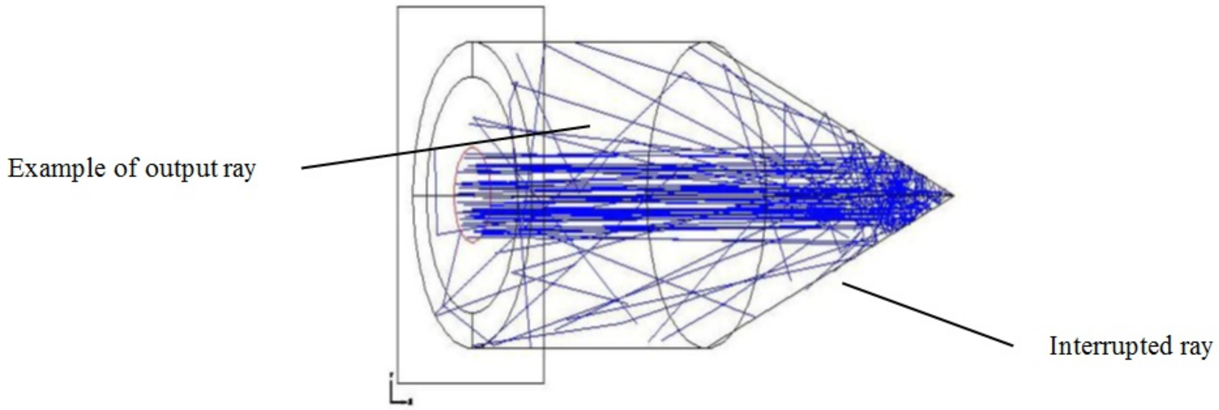

Figure 6 - Example of a ray tracing

Example:
Calculation data:

- Internal surface emissivity: 0.97: this is the minimum measured emissivity factor minus the uncertainty of the bench
- Virtual source diameter (equivalent to the entrance pupil of the UUT): 40 mm (centered), virtual source angle of aperture: 2.8°
- Output aperture of the blackbody: 100 mm

Results:

- Cavity emissivity: $1\text{-}4.44\ 10^{-4} = 0.999556$
- Repeatability of the calculation: $3\ 10^{-6}$
- Uncertainty due to interrupted rays: $7.5\ 10^{-7}$

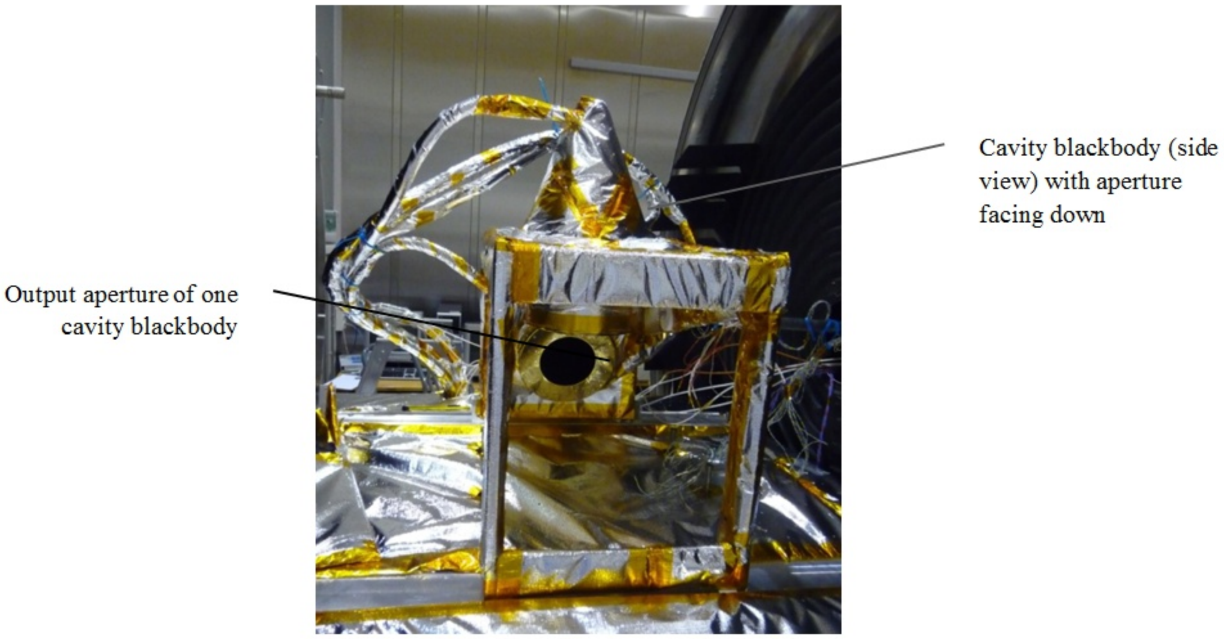

Figure 7 - Two cavity blackbodies entering into a vacuum chamber [2]

[2] Picture by courtesy of CNES

Such blackbodies were used for the calibration process, in long-wave IR domain, of SCARAB multi-spectral radiometer which is part of the MEGHA-TROPIQUES satellite launched in October 2011. The orbital calibrations confirmed ground test results made with the 0.999 cavity blackbodies.

CONCLUSION

HGH Infrared Systems has provided specific blackbodies to space agencies and laboratories, such as CNES and ONERA, to calibrate and test IR sensors for spatial applications. The space instruments characterizations are conducted in vacuum chamber, at cryogenic temperature. Moreover, the reference source characteristics (emissivity, thermal accuracy, uniformity and stability) have to be excellent to meet the required level of performance to be measured. This paper presents the necessary developments made on an extended area blackbody to maintain a temperature stability better than 20 mK despite the demanding testing conditions. Also it explains why a cavity blackbody with an emissivity of 0.999 was necessary to assess the SCARAB instrument (see reference [3]), and how we were able to demonstrate that the blackbody meets this specification, that surpasses the accuracy of usual test tools.

REFERENCES

[1] Gaussorgues, G., [Infrared Thermography], Chapman & Hall, London, chapter 3 (1994).

[2] Hameury, J., Lièvre, M., Scoarnec, V., LNE Test report number M031223 (2012) and personal interview of Hameury, J. (2014).

[3] CNES, SCARAB Instrument on MEGHA-TROPIQUES, <http://smsc.cnes.fr/MEGHAT/GP_scarab.htm> (9 September 2006).

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