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Atmospheric Simulator and Calibration System for Remote Sensing Radiometers

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SUMMARY

The design of the calibration system which serves as the radiometric calibration standard for the MAPS (measurement of air pollution from satellites) instruments is described. The system, the Atmospheric Simulator and Radiometer Calibration System, is capable of simulating a broad range of source temperatures and atmospheric pressures, temperatures, and pollutant concentrations for a single-slab atmosphere. Although it was designed to support the MAPS instruments, the system can be used to calibrate other nadir-viewing remote sensors of atmospheric constituents.

INTRODUCTION

The Atmospheric Simulator and Radiometer Calibration System ground support unit (GSU) was designed to serve as the radiometric calibration standard for the MAPS (measurement of air pollution from satellites) instruments. The calibration system provides a capability for simulating a broad range of source temperatures and atmospheric pressures, temperatures, and pollutant concentrations for a single-slab atmosphere. It allows a complete end-to-end checkout and calibration of each MAPS channel. The MAPS instrument is a gas filter correlation radiometer designed to remotely measure the amount of carbon monoxide in the atmosphere using the Earth's surface as the radiation source. A detailed description of the MAPS is contained in reference 1.

The input radiation sensed by a nadir-viewing infrared instrument, such as MAPS, consists of a combination of the radiation emitted by the atmospheric gases and the radiation emitted by the Earth attenuated by these gases. Therefore, for a realistic ground simulation, the calibration system must contain a blackbody source to simulate the Earth viewed by the instrument through an absorption gas cell. (See fig. 1.)

The calibration system consists of a blackbody radiation source, which can be adjusted over the range of 240 K to 350 K, and a 0.5-m-long absorption gas cell, which can be placed between the target source and the measuring instrument. The cell atmosphere can be adjusted over the temperature range of 255 K to 320 K and a pressure range of approximately 0.03 to 760 torr with any partial pressure of pollutants within this range. In the sections that follow, the calibration objectives for the MAPS instrument and a detailed description of the calibration system are discussed.

CALIBRATION OBJECTIVES

The objective of the calibration system is to provide laboratory calibration of the MAPS instrument. This is accomplished by providing a set of simulated Earth background temperatures using an accurate blackbody source and by simulating the total atmospheric burden. The calibration system design specification and achieved performance figures for various parameters of interest are shown in table 1. As indicated in the table, the range of Earth temperatures of interest is from 240 K to 350 K. The Earth brightness temperature differs from these simulated blackbody temperatures because of emissivity variations of the surface of the Earth. These differences are compensated for in the data reduction routine. To simulate the total burden of the atmospheric pollutant of interest, an absorption gas cell contains this gas as part of its mixture. For typical atmospheres, a partial pressure of CO in the absorption cell ranges from 0.5 to 1.5 torr. To prevent moisture from condensing on the absorption cell windows and on the blackbody source, an evacuated shroud is necessary.

DETAILED DESCRIPTION

The GSU is made up of three major subsystems: the blackbody source, the absorption gas cell, and the shroud.

Blackbody Source

A blackbody source is required to simulate the radiation emitted by the Earth. It must be temperature controllable over the range of interest and must include a provision for accurate temperature readout.

The GSU blackbody source has a clear aperture with a diameter of 12 cm. It has an operating range from 240 K to 350 K, the lower temperature being achieved by a thermoelectric cooler backed by a refrigerator system. The blackbody is contained within a cylindrical stainless-steel housing 25 cm in diameter and 25 cm in length. The mounting extension is an integral part of the rear cylinder flange. A stainless-steel baseplate supports the internal components and provides mounting locations for the electrical connectors and coolant feedthroughs.

The main components (or subassemblies) of the blackbody are the source and baffle assemblies, which are attached to the baseplate through insulating standoffs. The baffle assembly is employed to reduce thermal loading on the cavity radiator. The source assembly consists of a copper honeycomb cavity array with cells 0.635 cm wide and 2.54 cm deep, coated with high-emissivity black paint and soldered to a copper uniformity plate. Five calibrated platinum-resistance-temperature (PRT) sensors are located in the uniformity plate to monitor the source temperature (± 0.1 K) and to measure gradients. Also located near the center of the underside of the plate is the source-temperature-control thermistor sensor.

The five PRT sensors employed for temperature monitoring in the blackbody have been calibrated in a controlled temperature chamber against a reference platinum-resistance thermometer which is traceable to the National Bureau of Standards. For calibration, the sensors were mounted in an aluminum block with the reference thermometer, and calibration data were obtained at five points over the operating range: approximately 238 K, 273 K, 298 K, 318 K, and 345 K. PRT values were read out on the digital thermometer through the selection switch. (See table 2.)

The digital thermometer reads out the five PRT sensors with a resolution of 0.01 K through the selector switch. The selector switch and digital readout are mounted side by side for convenient use with a standard 19-in. relay rack.

Seven thermoelectric modules, which provide the required heat pumping, are sandwiched between the uniformity plate and the fluid-cooled copper heat-sink plate. Silver soldered to the back of the heat-sink plate is a coil of copper tubing with a diameter of 0.25 in. through which the stabilizing coolant flows. A high-temperature limit switch is mounted on the heat-sink plate.

A proportional temperature controller is employed to supply power to the thermoelectric modules. Located on the front panel are the power switch, a mode (heat or cool) selector switch, an overload (over temperature) indicator, a reset button, and the temperature-setting components, which include a decade switch and a 10-turn potentiometer. On the back of the controller are located the input power, control, and sensor connectors.

A series of six gold-plated copper baffles contained in a stainless-steel shell constitutes the passive baffle assembly. This system is supported from the intermediate baseplate and extends above the source radiator to the outer aperture.

The temperature-controlled circulator provides a fluid-stabilized heat sink for the thermoelectric modules. Denatured alcohol is used as the circulating liquid.

An evaluation of the emissivity of the blackbody was performed using a radiometric calibration technique. The measurement employs a transfer thermopile-type detector to compare the emissivity with a recognized standard. Since the thermopile intercomparisons with the standard were performed in a dry nitrogen atmosphere, the same conditions were produced for the blackbody evaluation.

Test results indicated that the blackbody emissivity was 0.997 ± 0.003. Uniformity of the source was determined at several temperatures between 238 K and 345 K. Gradients did not exceed ± 0.1 K at any observed temperature using the corrected PRT values. An error of 0.22 K (combined emissivity and temperature uncertainty) in blackbody temperature can translate into a worst-case error of 10 percent in the inferred amount of CO.

Absorption Gas Cell

An absorption gas cell is required to simulate the atmosphere for calibration of the MAPS instrument. In order to simulate a broad range of atmospheric conditions, the cell temperature, total pressure, and partial pressure of the pollutant gas must all be adjustable.

The absorption gas cell consists of a type 304 stainless steel, double-walled cylinder 0.50 m in length between germanium windows. The cell has four ports, two for cell windows and one each for pressure and temperature feedthroughs and pump and manifold couplings. Multiple circular baffles are located between the double walls of the cell to restrict the coolant fluid flow, reduce any dead space within the volume, and remove any thermal nonuniformities within the cell. Six copper-constantan thermocouples are located within the cell to measure thermal uniformity of the gas within the cell. Three are located at the entrance end and three at the center of the cell.

The cell window is made of germanium (Ge), which has transmission properties with broadband antireflectance coatings >90 percent required per window in each of the required spectral regions to achieve a cell transmission >80 percent. It is also chemically compatible with small concentrations of the proposed test gases and its absorption coefficient does not change significantly over the temperature test range. The entrance-window clear aperture is 10.9 cm in diameter and 0.5 cm thick, and the exit-window clear aperture is 7.18 cm in diameter and 0.3 cm thick. The antireflectance coatings have a vapor pressure $<10^{-3}$ torr.

A pressure transducer with a 0 to 1000 torr head is used to measure gas mixture concentrations and cell total pressure in the range of 1 to 760 torr. The digital readout has a resolution of 0.01 torr under these conditions. Thermocouple gages installed in the absorption cell and on the manifold are utilized to measure ultimate vacuum and leak rates.

A double-stage rotary pump with a pumping speed of 100 L/min is used to evacuate the cell and manifold. For this pump in series with a molecular sieve trap, an ultimate vacuum of 1×10^{-3} torr was achieved in the absorption cell.

A refrigeration system is used to provide the cooling capability to the circulating fluid between the cell walls. This combination, with the probe immersed in an insulated, well-stirred, open-topped Dewar containing 8 L of a mixture of ethylene glycol and water at a room ambient temperature of 297 K, has a cooling capacity of ≈1200 W. A proportional thermocouple temperature controller with a 1.2-kW heater proportions power to the heater to achieve control accuracy of the fluid in the Dewar of 0.1 K.

The six thermocouples located within the absorption cell are read out on a multichannel digital thermometer with a resolution of 0.1 K.

The six thermocouples to be used in the gas cell were interconnected with the digital thermometer readout. The ends of the thermocouples were sheathed in plastic and attached to the cooler bath thermometer near the bulb. After a preliminary calibration run, the digital thermometer zero and span controls were set so that the readout corresponded to the bath thermometer. The bath was then cycled from 267 K to 322 K. Readings were taken for all six thermocouples at eight temperatures. (See table 3.) At a bath temperature of approximately 327.5 K, the potential across thermocouples 5 and 6 (6 in ice-water bath) was measured. Thermocouple 5 was supplied with an absolute calibration. The voltage across these thermocouples corresponded to 327.49 K compared with an average reading of 327.57 K for the other thermocouples. Thus, the maximum error in absolute temperature (at 327.56 K) is estimated to be 0.08 K.

The absorption cell is insulated with 7 cm of polyurethane foam to reduce the effect of conductive and convective heat losses when operating the cell at temperatures below ambient.

Shroud

The vacuum shroud consists of the volume on each end of the absorption cell just outside the cell entrance and exit windows. These volumes are evacuated to prevent moisture from condensing on the cell windows when the cell is operated at decreased temperatures, or on the blackbody source when the blackbody temperature is lowered. The shroud on the entrance-window end is made up of the blackbody containment cylinder and absorption-cell end flange and entrance window. The exit-window shroud consists of the absorption-cell end flange, exit window, flange adapter, and either the objective lens and mount (for the MAPS brassboard instrument) or an entrance window with antireflectance coating and its mount (for the OSTA-1* MAPS instrument). The flange adapter is isolated from the cell with a fiberglass ring with O-ring grooves

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*OSTA-1 was the first payload of the Office of Space and Terrestrial Applications flown aboard the Space Shuttle.

to reduce heat loading when the cell is operated at its lower temperatures. When the entrance window is used with the OSTA-1 MAPS instrument, a thermistor and heater are attached to the flange adapter and the flange adapter is maintained at room temperature.

OPERATION

Manifold

The manifold allows the selection of various gas species with which to charge the absorption cell. Whenever a different gas species needs to be injected into the absorption cell, the manifold is first flushed two times with the desired new species. This is accomplished by evacuating the manifold through the manifold valve. The vacuum is monitored with thermocouple gage 1. After a good vacuum is obtained, the manifold valve is closed, the desired gas species outlet valve is opened, and the manifold is filled to atmospheric pressure. The outlet valve is then closed, and the manifold valve is opened to evacuate the manifold. The manifold is again filled and evacuated. After the second fill and evacuation, the manifold valve is closed, and the desired gas species outlet valve is opened and left open. The absorption cell can then be filled to the desired pressure through the metering valve.

Absorption Cell

In calibration runs with the MAPS instruments, the total absorption-cell pressure (pollutant species plus nitrogen) was either 150 or 380 torr. The partial pressure of the pollutant species varied from approximately 0.1 to 10 torr or more. During preliminary tests with the absorption cell and the MAPS instrument, if a small partial pressure of CO were injected into the cell with the cell at vacuum conditions, and if nitrogen were added to obtain the desired total pressure, the CO appeared to be absorbed into the walls of the chamber. The CO virtually disappeared.

A solution to this problem which gave stable, repeatable, and successful results was to first very slowly fill the absorption cell to approximately 100 torr with nitrogen. The cell pressure and temperature were allowed to stabilize while the manifold was being flushed and filled with CO. Just before adding the desired partial pressure of CO, the cell pressure and temperature were recorded. CO was then slowly added to increase the cell pressure by the desired partial pressure. The cell pressure and temperature were then recorded. After flushing the manifold, nitrogen was slowly added to change the cell to the desired total pressure and was allowed to stabilize. Cell pressure and temperature were again recorded. This charging procedure requires approximately 30 minutes.

Cell Stabilization

The absorption-cell temperature controller must be set to the desired cell temperature and allowed to stabilize before filling the cell. This requires about 1 hour at the lower temperature settings. Precooling the cell walls allows a more rapid stabilization of cell pressure and temperature after filling. Cell parameters stabilize fairly well within about 15 minutes. Gas mixing takes place within about a minute. The cell temperature controller is not normally readjusted during a calibration run, although the cell temperature decreases about 0.3 K to 0.4 K when changing the blackbody source temperature from 343 K to 243 K during a calibration sequence.

This decrease is caused by radiative heating of the gas. The temperature of the absorption gas is obtained by taking the average of the six thermocouple temperature readings.

Blackbody Source Temperature

The blackbody source temperature is controlled by a thermoelectric cooler backed by a refrigerated, circulated coolant fluid. The fluid-bath refrigerator must be operated for about 1 hour to cool the bath to about 263 K before the circulation pump and the blackbody temperature controller are operated. A heat/cool switch on the blackbody controller allows control above or below the coolant temperature. Temperature is adjusted by a decade switch and a 10-turn potentiometer.

In operation, PRT sensor 1 is monitored and the controls are adjusted to obtain the desired temperature within ±0.01 K. During the usual 3-minute data-taking period of a calibration run, it was necessary to readjust the controller to maintain this ±0.01 K reading. Actual blackbody temperature is obtained by correcting each PRT sensor reading by using the calibration data for that sensor and then averaging the five corrected readings.

Radiometer Channel Scale Factor Tests

Although the MAPS instruments are gas-filter-correlation radiometers, each has a radiometer channel separate from the correlation channels. For the radiometer channel calibration, it is desirable that the instrument look directly at the blackbody source and not through the absorption-cell windows. This can be accomplished by disconnecting the blackbody assembly from the absorption cell and rotating the blackbody assembly approximately 90°. The instrument can then be positioned to directly face the blackbody. To prevent moisture from condensing on the blackbody when operated below the room dew point, a plastic shroud was connected from the blackbody cylindrical container to the MAPS instrument entrance port, and dry nitrogen was injected into the blackbody container. Other nadir-viewing radiometers can be similarly calibrated by using only the blackbody source.

Gas Filter Correlation Channel Weighting Function Test

To better characterize the MAPS instrument's weighting function of signal versus pressure altitude for the gas filter correlation channels, it was desirable to reduce the absorption-cell pressure in a logarithmic fashion. This was accomplished by plumbing in a constant-volume cylinder between the absorption cell and the vacuum pump with valves on each end. In operation, the absorption cell was charged to the desired partial pressure of pollutant gas and desired total pressure with nitrogen. The valve between the absorption cell and the constant-volume cylinder was closed. With the cell temperature controlled, the blackbody source temperature was varied and data were taken at each source temperature. The constant-volume cylinder was evacuated by opening the valve on the vacuum-pump side. The vacuum valve was then closed, the absorption-cell valve was opened, and the pressure was allowed to equalize. The new pressure corresponds to the old pressure multiplied by the ratio of absorption-cell volume to absorption-cell volume plus the volume of the constant-volume cylinder. (This ratio is approximately 0.933.) The absorption-cell valve is then closed, and the constant-volume cylinder is evacuated. The blackbody source is again varied and data are taken. This procedure is repeated until the desired lowest pressure is obtained.

CONCLUDING REMARKS

The Atmospheric Simulator and Radiometer Calibration System ground support unit described in this paper has been used to calibrate two MAPS instruments. These calibrations have demonstrated the capabilities of the system to provide simulation of a single-slab atmosphere and an accurate simulation of Earth-background source temperatures. Although this system was designed to support the MAPS instrument, it can be used to calibrate other nadir-viewing remote sensors of atmospheric constituents. The only limitations to be considered in using the system for calibration of other instruments are spectral range (4 to 12 μm) and throughput (combination of field-of-view and aperture size), which is determined by the absorption-cell entrance and exit-window apertures.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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REFERENCE

1. TRW Defense & Space Systems Group: Monitoring Air Pollution From Satellites (MAPS), Volume 1 - Technical Report. NASA CR-145137, 1977.

TABLE 1.- PERFORMANCE COMPARED WITH SPECIFICATION

Parameter	Specification	Performance achieved
Blackbody source temperature range	240 K to 350 K	232 K to 354 K
Source radiance uncertainty	<0.25 K equivalent	0.22 K
Source nonuniformity	<0.2 K	0.1 K
Absorption-cell optical transmission	>0.85, measured to 0.5-percent accuracy	0.83
Pressure range	0 to 760 torr	0.03 to >760 torr
Concentration control	2 percent or 0.005 torr, whichever is greater	1 percent plus 0.03 torr
Absorption-cell temperature range	240 K to 350 K	256 K to 320 K
Gas-temperature measurement accuracy	0.5 K after 5 minutes stabilization	1 K

TABLE 2.- BLACKBODY TEMPERATURE SENSOR CALIBRATION

Reference temperature, K	Indicated temperature, K, for sensor number -				
	1	2	3	4	5
344.27	344.36	344.27	344.48	344.01	343.86
318.42	318.63	318.55	318.74	318.32	318.19
298.06	298.34	298.28	298.45	298.05	297.94
273.86	274.26	274.22	274.37	274.01	273.92
238.40	238.96	238.94	239.07	238.75	238.68

TABLE 3.- ABSORPTION CELL THERMOCOUPLE CALIBRATION

Reference thermometer, K	Indicated temperature, K, for thermocouple number -					
	1	2	3	4	5	6
267.8	267.8	267.8	267.8	267.8	267.8	267.8
272.1	272.1	272.1	272.1	272.1	272.1	272.1
276.0	276.0	276.0	276.0	275.9	275.9	275.9
284.0	283.9	283.9	283.9	283.9	283.9	283.9
297.3	297.2	297.2	297.2	297.2	297.1	297.2
298.5	298.4	298.4	298.4	298.4	298.4	298.4
309.7	309.7	309.7	309.7	309.6	309.6	309.7
322.4	322.5	322.5	322.4	322.4	322.4	322.4

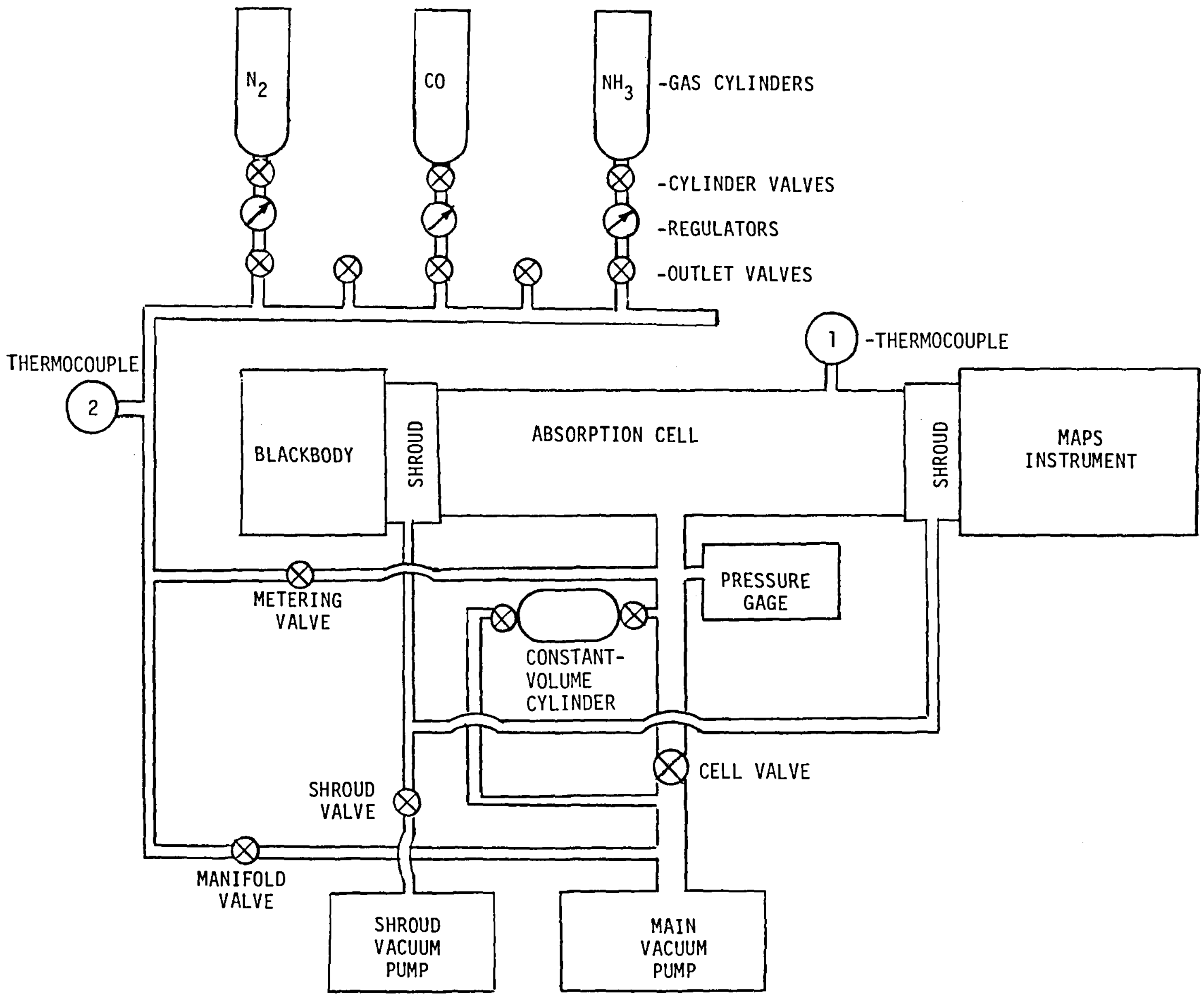

Figure 1.- Schematic of ground support unit.

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15. Supplementary Notes

16. Abstract

A system for calibrating the MAPS (measurement of air pollution from satellites) instruments has been developed. The design of the system provides a capability for simulating a broad range of radiant-energy source temperatures and a broad range of atmospheric pressures, temperatures, and pollutant concentrations for a single-slab atmosphere. The system design and the system operation are described in this paper.

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