VHITAL-160 thermal model building and 3D thermal modeling carrying-out

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Abstract: A computer modeling of the high power Bi-fueled thruster with anode layer thermal modes was carried out. The radiant cooling scheme on the one hand and Bi saturated vapor temperature keeping in the anode unit on the other hand were the criteria for the thermal analysis. The 3-demensional thermal model of a very high impulse Bi TAL (VHITAL-160) was developed. The thermal model was verified using the earlier obtained thermal mapping of the thruster D-200. After energy balance elaboration the accurate value of the heat losses was determined. The thorough thermal computer modeling of VHITAL-160 using 3D finite element method was carried out for the most important thermal modes. The conducted analysis confirmed the VHITAL-160 design feasibility under radiant cooling conditions and possibility of operation in the self-heating mode.

I.   Introduction

An interest to condensable propellants has turned back all over the world after decades of very low related activity. This is because of natural difficulties associated with design and testing of high specific impulse and high-power gas-fuelled thrusters currently under consideration for space flights to outer planets of solar system. Condensable propellant allows to overcome basic limitation of gas-fueled thrusters – huge pumping systems and vacuum tanks required for testing high-power thrusters under ground conditions. There are a number of research programs oriented to future interplanetary missions, and this goal has pre-determined a range of the parameters of studied condensable propellant laboratory thrusters - high specific impulse up to 8000 sec, power range of a thruster from dozens to hundreds kilowatts[1],[2].

The high power Bi TAL (VHITAL-160) was developed at TSNIIMASH within the VHITAL (Very High Specific Impulse TAL) project under the contract between Jet Propulsion Laboratory and Joint Stock Company TSNIIMASH-Export. The VHITAL-160 is considered by NASA as a candidate to put into practice the projects of a space vehicle with electric propulsion for outer planet investigations. The thruster design ensures a high specific impulse and thrust parameters. The VHITAL-160 design operation regimes are 25 kW and 36 kW. The thruster specific impulse and thrust at the first regime are 6000 s and 650 mN and at the second regime are 8000 s and 710 mN, respectively. The high intensity magnetic field is necessary to operate the thruster at such regimes. A design value of the magnetic field in the discharge gap is of 0.2 Tesla.

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Due to high power of the thruster the VHITAL-160 thermal analysis was a very important milestone of its development. The VHITAL-160 design must ensure radiant cooling during thruster sustained operation at both regimes. A range of permissible temperatures at the thruster operation is determined by not exceeding of design material tolerable temperatures on the one hand and by lack of bismuth vapor condensation on the thruster working surfaces on the other hand[3].

The 3-dimensional thermal modeling of the VHITAL-160 was carried out using Cosmos works software to analyze thermal conditions of the thruster. The thermal model took into account both the heat conduction and heat radiation.

To verify VHITAL-160 thermal model the thermal modeling of the radiant cooling Bi thruster with anode layer D-200 earlier developed at TSNIIMASH was conducted. Then the results of the D-200 thermal modeling were compared with the thruster temperature experimental data earlier obtained at TSNIIMASH. To match more the thruster physical model with its thermal model the thermal contact resistances were introduced, which increased an accuracy of the

Figure 1. VHITAL-160 in assembly with the feed system

thermal analysis. The value of thermal loads, i.e. heat generation from the plasma discharge, was verified with the D-200 thermal model and then used for VHITAL-160 thermal modeling. The mean error of the D-200 thermal analysis matched with the temperature experimental data was about 5 %.

Then the thermal analysis of the VHITAL-160 verified thermal model was carried out. As a result, the distributions of temperatures at both thruster operation regimes were found. A possibility of the thruster operation at a self-heating mode (when working temperature condition, lack of bismuth condensation, is provided by discharge heat losses only) was also investigated. The VHITAL-160 thermal analysis ascertained that the temperatures of all thruster parts are within permissible limits, and at the same time there is no bismuth condensation on the anode unit elements. Moreover, at the self-heating mode there is also no bismuth condensation for the obtained temperature span.

II.   VHITAL-160 thermal loads

VHITAL-160 is a two-stage thruster with anode layer and its design is almost similar to a typical TAL design. However, high temperatures, currents and voltages, along with using of the condensed propellant, define some particular features of the VHITAL-160 thruster design. In a TAL on condensable propellant the most dependent on thermal conditions thruster parts are:

  – electrode unit parts
  – first stage cathodes
  – magnetic system parts

Working temperature conditions are defined by the lack of propellant condensation on the electrode unit parts, i.e. bismuth saturated vapor temperature keeping ($\approx$1100 ^{0}C). To heat and maintain the electrode unit at this temperature a special heater located inside the anode-distributor is used. The ring shaped heater is made of graphite and heated up to required temperature by current flowing through it. The heater power necessary to ensure lack of bismuth condensation in the anode unit is about 2 kW. To guarantee the ability of the thruster parts of operating under these thermal conditions refractory constructive materials, such as molybdenum and niobium, are used in the electrode unit design.

A very strong magnetic field of about 0.2 Tesla is necessary to operate such a high voltage TAL. Thus, the power generated in the magnetic coils is of 77 W for the central magnetic coil and 150 W for the each of the side magnetic coils. Since all the elements of the magnetic system are at the high temperatures during thruster operation, an alloy of high Curie point (permendure) is chosen as a magnetic circuit material and the magnetic coils are wound with the high temperature wires (maximum operating temperature is of 600 ^{0}C).

To feed the thruster with the propellant, bismuth in the reservoir is heated up to its melting point (271˚C) by the direct current. Liquid bismuth fills a tube of the evaporator due to gravity and evaporates on its walls. The evaporator is heated by means of direct passing of electrical current through the internal tube. The pipeline through which the vapor gets into the anode of the thruster is a continuation of the evaporator, and it is also heated up by

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passing of electrical current. Typical pipeline temperature that ensures necessary pressure of the bismuth vapor in the feed system pipeline is of 1600 K. This heat source is also considered in the thermal modeling.

The first stage cathodes are the most thermostressed thruster parts as the most part of the power entering from the discharge accounts for them. Graphite or molybdenum, which are applicable for longtime operation temperatures more than 1500^0 C, can be materials of the cathodes.

The definition of heat generation from the plasma discharge is of fundamental importance for the thermal analysis. Heat generation can be defined in two ways.

First, based on thrust efficiency design value of 0.79 and TAL testing experience it may be assumed that energy efficiency comes to the value of 0.9. Thus, theoretically up to 10 per cent of the discharge power could be lost inside the thruster, i.e. about 3.6 kW (1.8 kW for each first stage cathode) at 36 kW regime.

On the other hand, the main discharge heat losses are associated with the energy bringing by the electron back flow from the accelerating stage to the first stage cathodes. Maximum possible energy of these electrons corresponds to the applied accelerating voltage. As having been shown experimentally[4,5], accelerating stage current for a Bi TAL normal regime corresponds to the calculated ion current accurate about 5%, i.e. electron current percentage does not exceed 5 %. In that case not more than 5 % of thruster discharge power could come to the first stage cathodes, i.e. at the same regime of 36 kW it is 1.8 kW.

Since more accurate estimation of heat generation from the plasma discharge is impossible at present stage, the maximum value of heat generation from the discharge will be used (3.6 kW). Then this value will be verified with the thruster D-200, one of the VHITAL-160 prototypes, using the temperature experimental data earlier obtained at TSNIIMASH. Thus, the refined value of the heat generation from the discharge is used in the VHITAL-160 thermal analysis.

III.   Thermal modeling description

The thermal modeling took care of both heat conduction and heat radiation. The modeling of heat exchange by conduction does not pose any problems, but taking into account heat exchange by radiation requires the closer examination. There are two possible situations with the heat radiation. First one is when a body emits only into the outside ambient. In this case the emitting body is assumed to be enclosed by a blackbody, by way of which the ambient is presented. So all energy emitted by the body is absorbed by the ambient. In the second case surfaces of the emitted elements face each other and these elements are partially exchanged energy. To define mutual radiation the radiation view factors are introduced.

The first stage of thermal modeling is building of the thruster solid model. The number of thruster elements considered in the thermal model and exactness of their geometry representation are mattered a lot for the analysis accuracy.

After solid model building the meshing of the thruster elements is produced (Fig.2). The model is divided into the great number of the tetrahedral elements and it is necessary to select element size most closely fitting the thruster design. There is otherwise a risk of the analysis infinite looping or significant decrease of the thermal analysis accuracy.

Heat sources may be defined both as energy power generated in a body and as a temperature applied to all body or to the separate surfaces. The radiation is defined as a boundary condition on the surfaces.

After all heat loads applying and meshing of the model the computation of the thruster temperature distribution is produced taking into account geometry of the thruster parts, emissivity of the materials, thermal-conductivity coefficient, mutual surface radiation and radiation to the background.
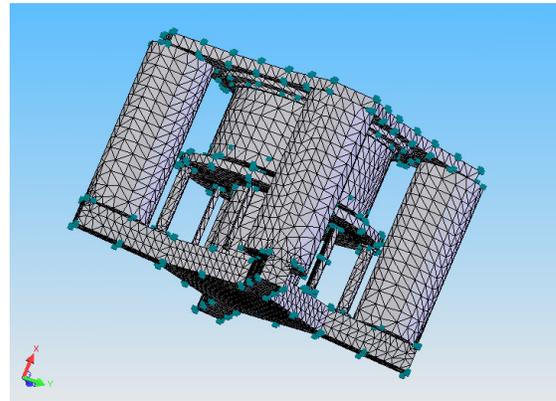

Figure 2. VHITAL-160 thermal model meshing

IV.   VHITAL-160 thermal analysis

A. Thermal model verification
Since the VHITAL-160 thermal analysis was conducted at the design stage there was no possibility to verify the thermal model using experimental data of this particular thruster. So it was necessary to carry out the thermal

modeling of another thruster, which experimental temperature data were available, to verify VHITAL-160 thermal model.

The Bi TAL D-200 earlier developed at TSNIIMASH was chosen for that verification (Fig.3). This thruster, one of the VHITAL-160 prototypes, was radiationally cooled and tested[6] at the power levels up to 34 kW and specific impulse about 5200 s. The thrust of 1130 mN and efficiency of 67 % were demonstrated at the power level of 25 kW and specific impulse of 3000 s. The temperatures of thruster parts were defined with the thermocouples both during thruster initial preheating and operation.

The D-200 thermal modeling was conducted for three regimes: thruster preheating, thruster operation at power levels of 20 kW and 25 kW. The following heat sources were considered:

- heater, 5000 W;
- magnetic coil, 245 kW;
- heat generation from the discharge to the first stage cathodes, 1250 W (at the mode of 25 kW) and 1000 W (at the mode of 20 kW) for each of two cathodes (Percentage of discharge power left in the thruster was discussed above).

Figure 3. TAL D-200

To define if the thermal model conforms to the real thruster the modeling of the thruster preheating mode was carried out. There is the only heat source, heater, at this mode, and its power is exactly known and amounts to 5000 W. The matching of the D-200 thermal modeling results with the experimental data of the thruster preheating mode showed a necessity of incorporation of the thermal contact resistances into the thermal model. After modeling of the same mode taking into account thermal contact resistances the analysis accuracy noticeably increased. The average divergence of the experimental temperature data and modeling results was about 4 %.

Then to define more exactly a value of the heat generation from the discharge into the thruster the thermal modeling of the D-200 operating modes (20 kW and 25kW) was conducted. As it was expected the best coincidence of the results of the thermal modeling with experimental data was observed at a value of heat generation from discharge into the thruster of 10 % of thruster power, i.e. 5% in each of the first stage cathodes.

To verify thruster thermal model the D-200 experimental data earlier obtained at TSNIIMASH were used. Thruster body temperatures were measured using embedded chromel-alumel thermocouples. The drawings of the thruster in Fig.4 and Fig.5 show thermocouple locations at 20 kW and 25 kW regimes.
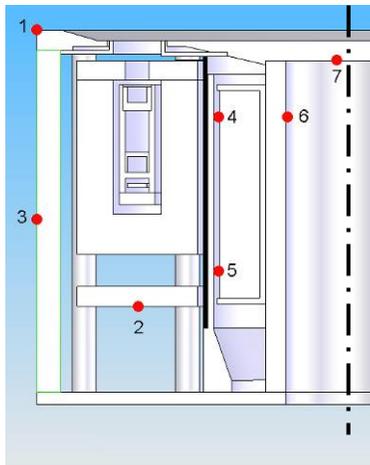
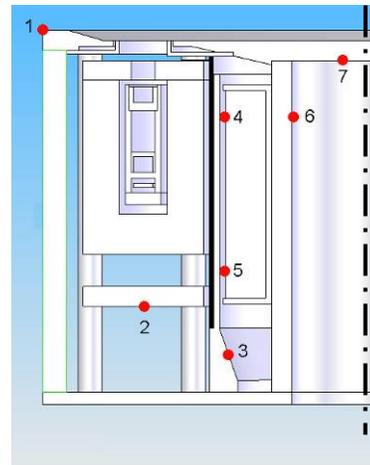**Figure 4. Thermocouple location at 20 kW regime**

Figure 5. Thermocouple location at 25 kW regime

A comparison of the TAL D-200 thermal modeling results with the measured temperatures is presented in the Table 1 and Table 2. As can be seen, good matching was obtained with the average inaccuracy of 5%. This deviation is comparable to the inaccuracy of those thermocouples.

Table 1. D-200 experimental and calculated temperature values at 20 kW mode

№$_{term}$	1	2	3	4	5	6	7
T_{exp}, K	653	833	673	873	873	823	803
T_{calc}, K	697	874	669	847	844	849	857

Table 1. D-200 experimental and calculated temperature values at 25 kW mode

№$_{term}$	1	2	3	4	5	6	7
T_{exp}, K	723	813	723	893	893	823	853
T_{calc}, K	769	878	776	864	868	870	883

The verified thermal model of VHITAL-160, for which the values of heat generation from the discharge into the thruster were ascertained and which took into account thermal contact resistances, was used for further modeling of VHITAL-160 thermal modes. Thus, based on the D-200 thermal modeling results matched with the experimentally obtained temperature values, the accuracy of the VHITAL-160 thermal analysis is expected to be not worse than 5%.

B. VHITAL-160 thermal model structure
To make thermal modeling more accurate the VHITAL-160 thermal model followed the real thruster geometry as close as possible. The thruster thermal model structure is shown in Fig. 6, the main elements are pointed. Being the important element of the thermal analysis anode-distributor is assembled and matches the real geometry. There are also the thermal screens in the model, their taking into account influences significantly on the thruster temperature distribution.

The properties of different materials are incorporated into the thermal model by the assignment of the thermal conductivity and emissivity for each material[7].

The following thruster elements are pointed as heat sources:
- heater, 2000 W;
- central magnetic coil, 77 W;
- four side magnetic coils, 150 W for each;
- feed system pipeline, 1600 K;
- first stage cathodes, 1800 W at 38 kW mode and 1250 W at 25 kW mode.
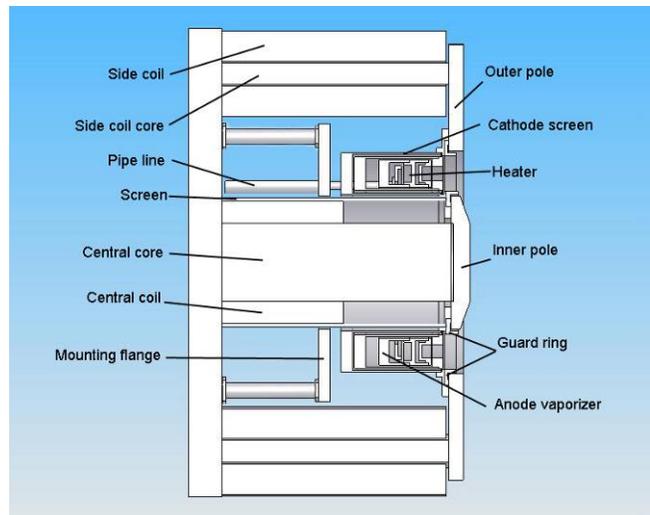

Figure 6. VHITAL-160 thermal model elements

C. VHITAL-160 thermal modeling results
The thruster thermal modes differ during thruster starting, operating and switching off. The thermal analysis was conducted for four most important thruster operating modes:
1. Thruster pre-heating when there is the only heat source in the thruster, heater.
2. Thruster operation at discharge power of 25 kW.
3. Thruster operation for the self-heating mode at 25 kW. At this mode only heat losses from the discharge are used to maintain the bismuth saturated vapor temperature and the heater is operated only during thruster pre-heating.
4. Thruster operation at discharge power of 36 kW.

There was no need to simulate the self-heating mode at 36 kW; if the self-heating mode is possible at power level of 25 kW, hence, it is possible at higher power level of 36 kW.

As a result of thermal modeling the distributions of temperatures for thruster elements were obtained for all four modes. These distributions are given in Fig. 6,7,8,9.

The electrode unite at very high temperatures is typical for the thrusters of this type, especially at regimes with the operating heater. Nevertheless, due to large area of the emitting surfaces the temperatures of the magnetic system poles stay comparatively low. There is a difference between inner and outer cathode temperatures that is explained by the reduced heat flow from the anode unit to the central core and coil thanks to presence of the thermal screens.
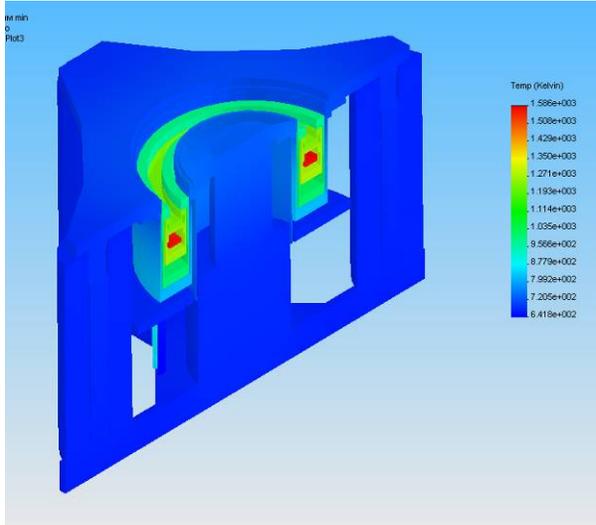

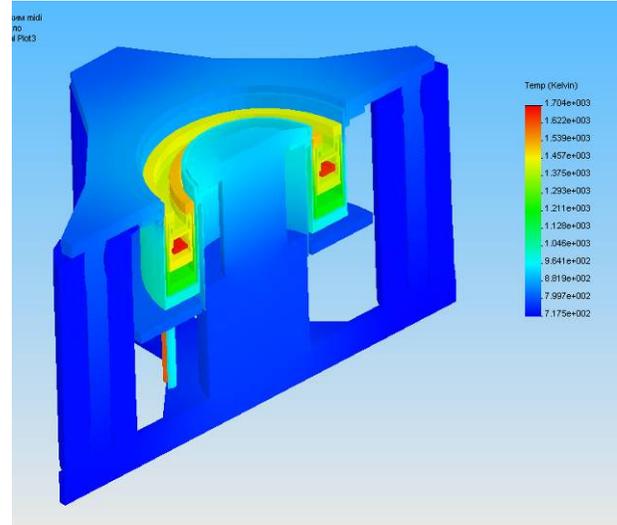**Figure 6. Temperature distribution at the preheating mode**

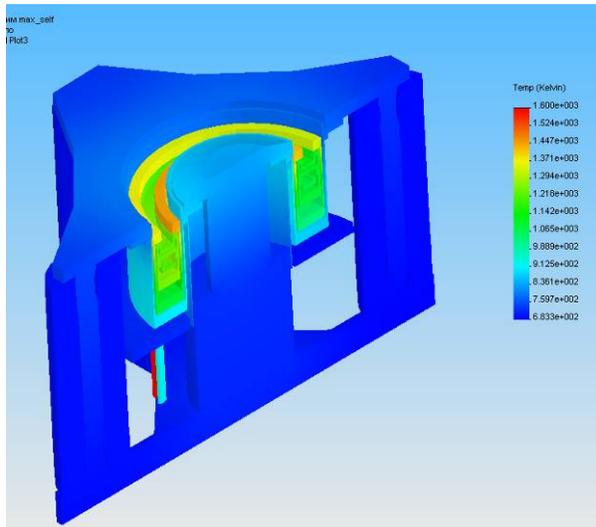**Figure 7. Temperature distribution at 25 kW mode**

Figure 8. Temperature distribution at 25 kW in the self-heating mode
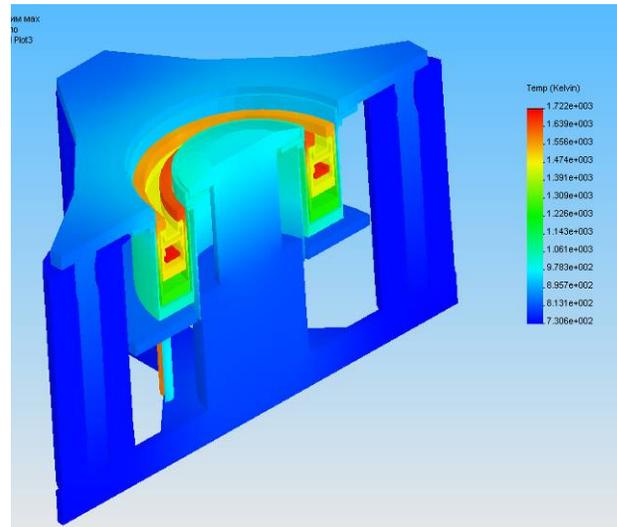

Figure 9. Temperature distribution at 36 kW mode

The temperature values for four simulated thermal modes are given below in Table 3. One can see that the magnetic circuit temperatures are within the range from 660 K to 1000 K. These temperatures exclude the possibility of using usual steel for the magnetic circuit parts. Thus, a necessity of using the iron-cobalt alloy, which Curie point temperature (1273 K) is higher than the magnetic circuit temperatures at any thruster operating mode, is confirmed.

The temperatures of the magnetic coils do not exceed the maximal working temperature (1000 K) of the high-temperature wire being used. Thus, the thermal analysis is confirmed that the temperatures of all thruster elements are within permissible limits and allow to apply the radiant cooling scheme to the thruster.

The electrode unit temperatures exceed the temperature of bismuth saturated vapor (1100 K) that ensures the propellant being in the vaporous state. Moreover, the temperatures of the accelerating channel elements prove the possibility of thruster operation at the self-heating mode.

Table 3. Calculated temperatures of some thruster elements

Thruster part	Regime							
	№1		№2		№3		№4	
	T_{min}[‡]	T_{max}[§]	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Heater	1554	1586	1629	1703	1076	1262	1655	1721
Anode bottom	1220	1281	1405	1600	1102	1107	1446	1600
Outer screen of first stage cathode	994	1029	1241	1435	1049	1338	1237	1549
Inner screen of first stage cathode	995	1030	1245	1513	1057	1413	1242	1634
Outer cathode	988	1003	1408	1459	1301	1382	1519	1578
Inner cathode	987	1002	1475	1522	1382	1452	1595	1659
Outer guard ring	712	719	865	895	770	808	911	941
Inner guard ring	744	748	958	973	863	880	1021	1039
Mounting flange	675	681	780	826	684	739	805	850
Central core	678	735	771	932	716	845	795	988
Central coil	678	683	771	785	716	726	795	812
Central magnetic pole	729	746	916	964	831	873	969	1027
Screen	715	754	839	973	752	879	868	1037
Side magnetic coil	673	675	727	730	692	694	740	743
Side coil core	672	690	728	817	695	747	741	849
Outer magnetic pole	684	717	797	887	722	801	828	932

V.   Conclusion

The feasibility of the VHITAL-160 thruster design was shown by both the absence of the Bi vapor condensation on the discharge gap surfaces and acceptable working temperatures of the all thruster subsystems. The necessity of the thermal analysis of the high power Hall thrusters on the condensable propellants was shown in the paper. All of the VHITAL-160 thermal modes were quite accurately simulated. The value of the two stage Hall plasma discharge heat losses was acknowledged by the way of thermal modeling. According to plan of thermal modeling verification the D-200 experimental data of the thermocouple measurements at the several operating modes were successfully used. The applying of the thermal screens, usage of the permendure and the high temperature wire, and feasibility of the self heating mode as well were proved by the 3D thermal computer modeling.

The authors are planning to enhance the thermal modeling method by its verification with the other thrusters and applying the transient mode of the modeling.

[‡] minimal temperature point of an element
[§] maximal temperature point of an element

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