Experimental investigation of the screen vacuum heat insulation for photo detectors of the infra-red viewing space vehicles

V.I. Zinovyev[1], A.I. Dovgyallo[2], E.K. Krasnochub[1]

[1]State Scientific and Manufacturing Center for Space Rocketry TsSKB Progress, Samara, Russian Federation
[2]Samara State Aerospace University, Samara, Russian Federation

Abstract: The experimental investigation of the screen-vacuum heat insulation of the photo detectors of the IR-channel of the spacecraft viewing devices has been performed. The necessity of the experimental and development works by selection of the screen-vacuum insulation (blanket) has been shown. The blanket composition with the minimal thermal conductivity has been specified.

Keywords*:* screen-vacuum heat insulation, photo detector of the IR-channel, blanket composition, experimental data, equivalent thermal conductivity.

1. INTRODUCTION

One of the important tasks of maintenance of work-capacity on-board equipment of aircraft is to provide the required level of operating temperatures. To solve these problems it is necessary to take into account the temperature distribution inside the lander [1] and on the surface in order to optimize the location and performance of various optoelectronic devices, such as photodetectors.

A photo detector (PD) with a cooling system enables the survey of the objects from the space (or spacecraft board). The main indicator of the PD performance is the image quality depending on the temperature of thermal regulation and accurate maintenance thereof.

An important requirement for improvement of performance of PD as a heating unit is providing the minimal heat gain to the PD structure ensuring the minimal value of the required useful refrigerating capacity and therefore that of the electric capacity supplied to the gas cryorefrigerator (GCR).

The PD structure shall provide the minimal heat leakages at the temperature levels (20..80 K), ensure the minimal background noises of the photosensitive cells of the PD during the device operating mode. Requirements to ensuring the minimal heat leakages are fulfilled in respect of a PD through application of the high-efficiency heat insulation and thermal bridges, accurate technology of the heat insulation applying to the cooling elements, preliminary preparation of heat insulation in the PD composition. In order to reduce the external and internal heat gain to the structure components in the PD the screen-vacuum heat insulation (SVHI) is used that is effective under conditions of high vacuum (up to 10÷6 mm of mercury) and cryogenic temperatures (20..80 K).

SVHI consists of a large number of layers with low emissivity serving as screens reflecting the thermal emission. These screens may be separated by heat-insulation blankets from the materials with low thermal conductivity. The vacuum of about $10^5 \div 10^3$ mm of mercury is maintained within the heat-insulation space.

The mechanism of the heat transfer in SVHI is determined by the intrinsic thermal conductivity of the insulation layers, gas heat conduction (if the SVHI is not degassed completely) and emission. The heat transfer in a solid body is significantly influenced by the density of the layers packing $n = N/\delta$, where N is the number of layers, δ – heat insulation thickness. The packing density also influences the heat transfer by emission and the effective heat conductivity of SVHI in whole. In order to reduce the heat conductivity of solid bodies it is needed to use the spacing materials with low heat conductivity and not allow the squeezing the heat insulation layers resulting in the increase in the contact heat conductivity. A spacing material should feature the minimal gassing in vacuum, sufficient mechanical strength up to cryogenic temperatures against low density, be chemically-stable and feature good gas permeability.

Heat transfer by residual gases is determined by the distance between the screens. To reduce the heat conductivity of gas in the insulation cavity (not only around insulation but also inside of it – between the screens) the pressure not exceeding $5 \div 10^1$ mm of mercury shall be maintained. This is hindered by emission by the heat insulation materials of gases that are removed through the long narrow slots between the screens. To ensure high vacuum in insulation the gas liberation capacity is increased by the screen punching and the gas withdrawal is reduced through pre-heating by degassing.

The experience in the SVHI operation shows that it is efficient only upon uniform density of the layers packing (15-22 layers per 1 cm of packing). The effective heat conductivity of such insulation is minimal.

At $n > 20$ 1/cm the prevailing heat transfer mechanism is the solid body conductivity increasing almost proportionally to the square of density.

By the experimental development of the PD structure components the authors identified significant differences between the design and experimental values of the heat gain to the items under test.

The analysis of results of preliminary testing has shown than the most probable cause of the specified differences is a lower thermal resistance of the screen-vacuum heat insulation of the tested items in comparison with the thermal resistance of the SVHI taken as a reference data [1, 2].

Since the SVHI structure consists of a multi-layered package of polymer metallized films laid as a mesh veil such multi-layered structure has a lot of the contact points between the film layers that cannot be theoretically estimated in terms of thermal resistance.

The objective of this research was the experimental validation of selection of the SVHI composition and structure with account for the unspecified values of thermal resistance and special features of the insulation structure.

2. EXPERIMENTAL METHOD OF THE DEFINITION OF THERMAL BLANKET CONSTITUTION

2.1 EXPERIMENTAL SETUP FOR TESTING THERMAL-INSULATING COVER

In order to determine the type that is optimal for the SVHI package composition, its geometric and thermal and physical characteristics in respect to the thermal-insulating covers of the PD elements (bodies, background protective shields, etc.) under the cryogenic operating temperatures 20..80 K the heat insulation tests have been performed.

In order to carry out the tests there has been designed the experimental setup (Fig.1,2,3) allowing determining the values of thermal resistance and effective heat conductivity of models of the thermal-insulating PD covers on the basis of various SVHI with simulation of the real-life operational environment (Fig. 1).

The items under test were the models of the thermal-insulating covers of PD. The three types of SVHI were used for manufacturing thereof: EVTI -VV, EVTI -2V and EVTI -VV combined with the blankets from non-woven fiberglass cloth HSVN-7 made on the basis of the screens from the double metallized polyethylene terephthalate film (PET).

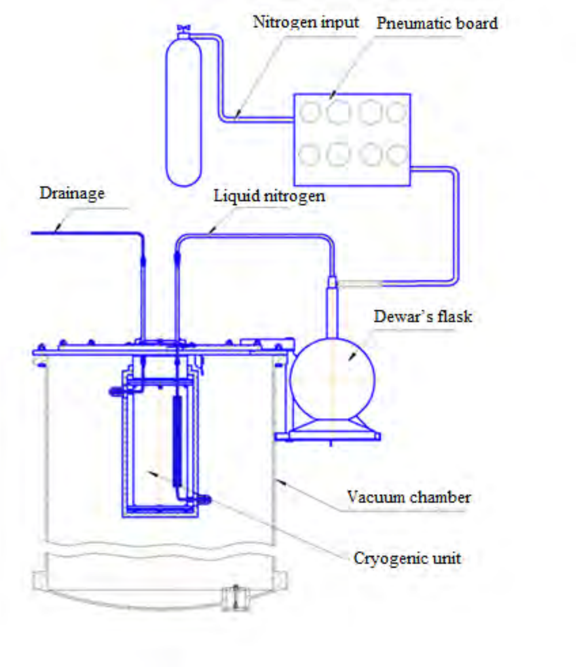

Figure 1 – Experimental setup scheme for testing thermal-insulating cover

The range of the operating temperatures of the SVHI under test satisfies the operational conditions: for EVTI-2V the operating temperatures make 4..423K and for EVTI-VV – 77..293K. The specified temperature level was maintained due to the structure of the vacuum chamber of experimental setup (Fig.2).

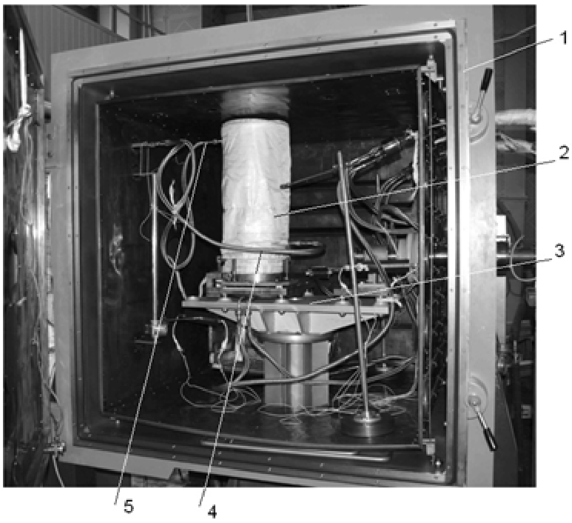

Figure. 2. Picture of the experimental setup vacuum chamber: 1 – vacuum chamber; 2 – cryogenic unit (with heat insulation mounted); 3 – base; 4 – line of the liquid nitrogen inlet to the cryostat of cryogenic unit; 5 – line of the gaseous nitrogen withdrawal from the cryostat.

The tested models of the thermal-insulating covers were placed in annular cavity between the cryostat inner wall with the testing temperature of 77 K and the screen the required temperature range for which 273..323 was provided by the radiator.

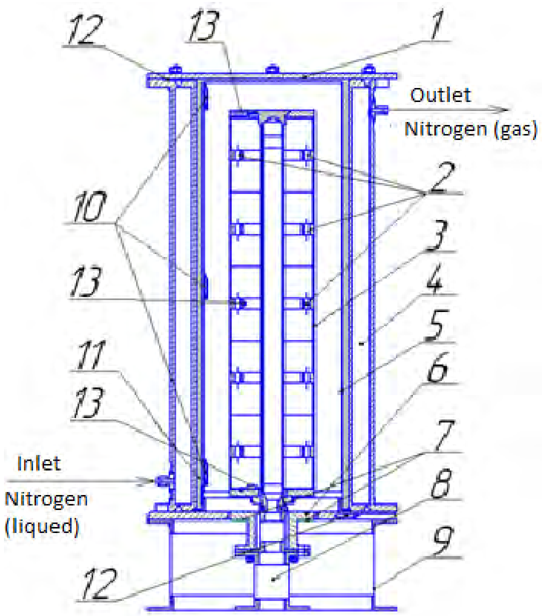

Figure. 3. Experimental setup cryogenic module for testing thermal-insulating cover: 1 – cryostat cover; 2 – radiator's heating elements 1;3 – radiator's housing; 4 – cryostat's fluid (liquid nitrogen); 5 – screen (measuring face); 6 – radiator's thermal screen 2; 7 – compensating radiator 2; 8 – radiator attachment fitting 2; 9 – cryostat attachment fitting; 10 – temperature sensors at the screen; 11 – the item under test (thermal-insulating covers from SVHI); 12 – temperature sensors at the cryostat; 13 – temperature sensors at the radiator.

The basic geometrical parameters of the cryogenic unit structural components:

- inside diameter of the cryostat housing – 180 mm;
- height of the cryostat body cavity – 560 mm;
- height of the radiator cylindrical body – 500 mm;
- diameter of the radiator cylindrical body – 100 mm;
- distance from the top edge of the radiator body 1 to the top edge of the cryostat – 40 mm;
- distance from the bottom edge of the radiator body (and screen) to the bottom edge of cryostat – 20 mm;
- diameter of the hole in the cryostat base wall – 106 mm.

2.3 CALCULATION ALGORITHM OF THERMAL-INSULATING COVER CHARACTERISTICS

Assumptions:

1 The heat flow of the radiator goes through the side and end walls of the thermal-insulating covers;
2 The temperatures of the inner lateral face of the cryostat body, cover and cryostat base are considered to be equal to 77 K;
3 The temperatures of outer surfaces of thermal-insulating cover (cylindrical and two end surfaces) are considered to be equal to 77 K;
4 The temperatures of the inner surfaces of thermal-insulating cover (cylindrical and two end surfaces) are considered to be equal to the shield temperature T9;
5 the thickness of the end walls of a thermal-insulating cover equals the thickness of the side wall;
6 the thermal-insulating cover is placed gapless in the annular cavity between the screen and cryostat wall without без зазоров.

The equivalent coefficient of heat conductivity of the thermal-insulating covers is derived from the expression:

$$\lambda_{SVHI} = \frac{N_1}{S}$$, where

$$S = \frac{2\pi H_S \cdot (T9 - T_{wall})}{\ln(\frac{D_{sout}}{D_{sin}})} + \frac{\pi D^2_{end\,face}}{4\delta_{top\,end}} \cdot (T9 - T_{wall}) +$$

$$+ \frac{\pi(D^2_{end\,face} - D^2_{notch})}{4\delta_{bottom\,end}} \cdot (T9 - T_{wall})$$

where:

N_1 – radiant power, W;

H_s– screen height, m;

T9 – screen temperature, K;

$D_{s\,out}$ – cover outer diameter, m;

$D_{s\,in}$– cover inner diameter, m;

T_{wall} – temperature of the cryostat inner wall, T_{wall} = 77K;

$D_{end\,face}$ – diameter of the top and bottom end cover face, m;

D_{notch} – diameter of the notch in the bottom end cover face, m;

$\delta_{top\,end}$ – thickness of the cover top end face, m;

$\delta_{bottom\,end}$ – thickness of the wall of the cover bottom end face, m.

Thermal resistance of the thermal-insulating cover material was calculated as follows:

$$R = \frac{T9 - Twall}{N1}, \ \frac{K}{W}.$$

The specific thermal resistance of the thermal-insulating cover:

$$\varepsilon = \frac{(T9 - Twall) \cdot F_4}{N1},$$

where F_4 is the total area of the thermal-insulating cover.

The examples of the test results and calculations of the thermal and psychical parameters of the thermal-insulating covers are presented in the section 4.

4. EXPERIMENTAL RESULTS AND DISCUSSION

More than 20 SVHI packages have been tested. The obtained test results allowed selecting the optimal type and structure of an SVHI package featuring the maximal thermal resistance as well as calculate the value of the equivalent heat conductivity of the investigated thermal-insulating covers. In the Table 1 there has been presented for comparison only a part of experimental data enabling to get an idea of the composition, structure and conditions of the SVHI assembly and testing. In the Table 2 you can find the sampling of separate data on the structure of the tested items.

Table 1 Results of testing the models of the PD thermal-insulating covers

Test No.		Item under test	Code of the item under test	SVHI type	Number of film layers	SVHI package thickness, mm	Density of the film packing n, 1/cm	Pressure in vacuum chamber, mm Hg	Time of the package degassing before measurement
1		OI-1	-320	EVTI-VV-30	30	5	100	$1\cdot10^{-5}$	27h 46min
2		OI-2	-410	EVTI-2V-30 + 31 layers of cloth	30	18	27,8	$1\cdot10^{-5}$	27h 27min
3		OI-3	-510	EVTI-VV-50+ 51 layers of cloth	50	18	27,8	$1\cdot10^{-5}$	31h 50min
5	1	OI-3	-510	EVTI-VV-50	50	10	50	$1\cdot10^{-4}$	25h 09min
	2		-510	EVTI-VV-50	50	10	50	$1\cdot10^{-5}$	1h 39min

Table 2 Values of equivalent thermal conductivity of the investigated thermal-insulating covers

Total area of the cover surface, m^2	Radiant power N_1, W	Screen temperature, K	Temperature of the inner wall of the cryostat body, K	Thermal resistance of the thermal-insulating cover by the package thickness of 1 cm	Equivalent coefficient of thermal-insulating cover, W/m^2	Specific heat flow rate through thermal-insulating cover (exp.), q_{exp}, Вт/м^2	Specific heat flow rate through thermal-insulating cover (estim.), $q_{estim.}$, W/m^2	$\frac{q_{estim.}}{q_{exp.}}$ %
0,282	3,91	299,3	77	8	0,00125	13,87	9,06	65,3
0,282	4,455	299,2	77	7,04	0,00142	15,8	9,05	57,3
0,282	6,847	294,4	77	4,48	0,00223	24,28	8,45	34,80
0,282	4,97	298,6	77	6,29	0,00159	17,62	8,97	50,90
0,282	3,875	299,5	77	8,06	0,00124	13,74	9,08	66,1
0,282	3,48	298,8	77	9,09	0,00110	12,34	9,12	73,9
0,320	4,192	299,1	77	21,28	0,00047	13,1	18,84	143,8
0,320	4,16	299,2	77	21,41	0,000467	13,0	18,95	145,8
0,282	2,4	301,4	77	13,18	0,000759	8,51	4,66	54,8

1. Based on the results of tests Nos. 1, 2, 3 from among the three models of the thermal-insulating covers: 320, 410, 510, the maximum thermal resistance was shown by the model 510 made on the basis of EVTI-VV combined with blankets from HSVN-7 cloth. In this regard for the further tests the composition of the package 510 (Table 3) was taken as the basis for the composition of packages 610 used the PD thermal-insulating covers.

2. The tests showed that holding of the thermal-insulating cover 510 within 1...3 days does not increase the thermal resistance of the tested items sustained after the first day of degassing.

3. The tests showed that within the temperature range 284...320 K, temperature of the inner

cryostat wall 77 K and pressure in the vacuum chamber $1\cdot10^{-5}$ mm of mercury the thermal resistance of the model of thermal-insulating cover 510 slightly decreases against increase in the screen temperature.

4. The experiment results showed that at the pressure $1\cdot10^{-5}\div1\cdot10^{-4}$ mm Hg the thermal resistance of the cover model 510 remained constant. Upon further increase of pressure up to $1\cdot10^{-3}\div1\cdot10^{-2}$ mm Hg the thermal resistance of the cover model 510 reduced rapidly.

5. The test No. 5 (experiments Nos. 1, 2) has shown that reduction of the SVHI package thickness from 20 to 8 mm resulted in reduction in the package thermal resistance in comparison with a package that has not been squeezed.

Table 3 Thermal-insulating covers structures

Name of the tested item	Denomination	Composition of tested items
Thermal-insulating cover - 320	OI-1	Composition of OI-1: 1) EVTI-VV-50, 353У.4641.002 (50 layers of PET-film, double metallized, with the glued pile points from uncolored viscose fiber); 2) protective coat from a single layer of polyamide fabric, TU 8378-146-35227510-2007
Thermal-insulating covers - 410	OI-2	Composition of OI-2: 1) EVTI-2V-50, OST 92-1380-83 (50 layers of PET-film, double metallized, gauze fabric); 2) 51 layers of non-woven fiberglass cloth HSVN-7 TU 6-48-05786904-147-9; 3) protective coat from a single layer of polyamide fabric, TU 8378-146-35227510-2007
Thermal-insulating cover - 510	OI-3	Composition of OI-3 (option A): 1) EVTI-VV-50 353У.4641.002 (50 layers of PET-film, double metallized, with the glued pile points from uncolored viscose fiber); 2) 51 layers of non-woven fiberglass cloth HSVN-7 TU 6-48-05786904-147-9; 3) protective coat from a single layer of polyamide fabric, TU 8378-146-35227510-2007

6. Testing of the other SVHI with the number of shields of 25, 50, 100 layers, respectively, has shown that by the double increase in the number of shields in the SVHI package the package thermal resistance was reduced by approximately 35%. The tests were performed at the temperatures (77 – 300) K and pressures $1\cdot10^{-5}$, $1\cdot10^{-4}$ mm of mercury.

7. The effectiveness of use of two covers instead of a single one has been proved. The overall thermal resistance of the package from the two thermal-insulating covers exceeds the thermal resistance of the cover 510 with the same number of shields (50 layers) by 1,6 times and that of the thermal-insulating SVHI cover with 100 layers – by 1,5.

8. Testing of the thermal-insulating cover 510 fitted with a shield and protective coat from the industrial polyamide fabric with further replacement of the protective fabric shell through the wire cloth with the diameter of thread of 0,15 mm and cell size f 2 x 2 mm in clear and that without the protective fabric shell has shown that presence or absence on the SVHI package of a fabric shell with emissivity of ε=0,8 almost does not influence the thermal resistance of an SVHI package.

By analyzing the available data on the thermal conductivity coefficients [2, 3, 6-10] and data on the thermal conductivity coefficients obtained during testing (Table 2, Fig. 4) one should emphasize the significant differences in the values of the conductivity coefficients. It suggests that the processing works with SVHI upon their use in real-life structures result in the significant deterioration of the thermal and physical parameters of SVHI. This shall be taken into consideration by design and use of the real-life structures on the SVHI -basis.

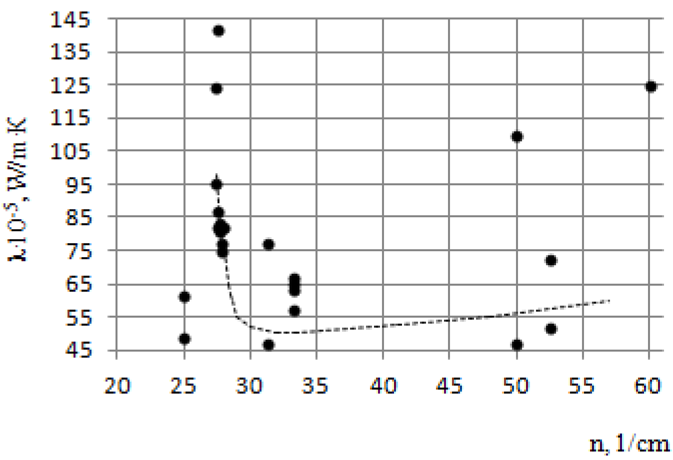

Рис. 4 - Values of thermal conductivity of insulation layouts insulation covers

5. CONCLUSIONS

1. The experimental investigation of the screen-vacuum heat insulation for design of the thermal-insulating covers of the IR-channel photo detector of spacecraft electrooptical equipment has been performed.

2. There has been specified the most appropriate SVHI type for production of the PD thermal-insulating covers.

3. The most advanced from the perspective of ensuring the maximal thermal resistance are the thermal-insulating covers on the basis of EVTI-VV, ADIS.370227.13TU (353У.4641.002) combined with the inter-shield blankets from the non-woven fiberglass cloth HSVN-7.

4. It is recommended to make the insulation of the PD focal node unit from the two coaxial thermal-insulating covers with not less than 50 shields per a cover.

5. It is recommended to leave a gap of $2 \div 3$ mm between the cryogenic insulated element and thermal-insulating cover.

6. The maximal permissible pressure in the vacuum cavity with thermal-insulating covers shall not exceed $1 \cdot 10^{-4}$ mm of mercury.

7. To increase the thermal resistance of the thermal-insulating covers it is recommended to reduce the temperature of the PD cryostat body

8. The thermal-insulating covers do not change their geometrical parameters by degassing.

6. CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

7. ACKNOWLEDGEMENTS

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8. ABOUT THE AUTHORS

Dovgyallo Alexander, Samara State Aerospace University, PhD in Engineering Sciences, professor. Area of the author’s expertise: operating processes of heating and refrigerating machines, aircraft energetics, energy saving.