SELF CONTAMINATION EFFECTS IN THE TAUVEX UV TELESCOPE: GROUND TESTING AND COMPUTER SIMULATION

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ABSTRACT

The contamination effects due to outgassing from construction materials of the TAUVEX (Tel Aviv University UV Telescope) were evaluated using a combination of ground testing and computer simulations.

Tests were performed from the material level to the system level including:

- High sensitivity CVCM (10^{-3}%) measurements of critical materials.
- Optical degradation measurements of samples specially contaminated by outgassing products at different contamination levels.
- FTIR studies of chemical composition of outgassed products on above samples.
- High resolution AFM studies of surface morphology of contaminated surfaces.

The expected degradation of TAUVEX performance in mission was evaluated applying a computer simulation code using input parameters determined experimentally in the above tests. The results have served as guidelines for the proper selection of materials, cleanliness requirements, determination of the thermal conditions of the system and bakeout processes.

1. INTRODUCTION

Contamination during mission due to outgassing of spacecraft materials is a major failure mode of space optical systems in general and of UV optical systems in particular(1). The contamination levels accumulated on spacecraft surfaces are very often evaluated for specific space projects(2-4). The degradation of the system's optical performance is then calculated(4), taking into account experimental relations between contamination levels and transmission losses. The present paper focuses on the degradation of the optical performance of TAUVEX due to outgassing in mission for a simplified geometry but for the actual materials and temperature profiles. The study gives a critical review of the system's design as far as contamination in mission is concerned, attempting to assure that its optical performance would be within specification limits.

The work consists of two main phases: (a) contamination measurements at the material level providing input data for the second phase and, (b) Monte Carlo calculations of the transmission losses of TAUVEX vs. time after launch. This paper is thus organized in two parts corresponding to the above phases.

PART I - CONTAMINATION MEASUREMENTS AT THE MATERIAL LEVEL

2. EXPERIMENTAL

2.1 Materials and Test Samples

Several types of materials were selected to represent typical contamination sources:

(i) Two critical materials that were identified to be the two major possible contamination sources for TAUVEX: (a) the graphite/ester cyanate composite structural parts, and (b) the silicone rubber that serves as a sealant in several locations of the telescope.

(ii) Two other materials that were studied to evaluate the influence of their chemical nature on the contamination effects (using the same contaminant thickness): (a) Solithane 113, a typical polyurethane based elastomer used as a thermal conductive conformal coating, and (b) a "Buna N" O-ring, a butadiene acrylonitrile polymer, a typical elastomer with a high contamination potential.

Various test plates on which the contamination products were deposited were used. For UV and visible transmission measurements CaF_2 and quartz plates were chosen. CaF_2 is transparent down to 130nm while quartz is transparent only down to about 200nm. The quartz surface is however smoother, a fact which is beneficial for atomic force microscopy (AFM) measurements. For FTIR measurements NaCl and germanium plates were applied.

The contaminated samples were prepared using a standard micro VCM (Volatile Condensable Materials) outgassing measuring system (conforming to the ASTM E-595(5) method). The contaminating materials were heated to 125°C for 24 hours under vacuum conditions ($p<10^{-6}$torr). The outgassed condensable contaminants were collected on test plates kept at 25°C. The areal contamination density (or thickness) was determined by precise (±1μg) measurements of the weight gain of adjacent collector plates exposed to the same heated materials simultaneously with the test plates.

2.2 Optical Measurements

Optical measurements (190nm-800nm) were performed using a diode array 8452 Hewlett Packard spectrophotometer. Vacuum UV (VUV) measurements will be performed when a VUV sprectrophotometer is available. Since the contamination was nonuniform, 8mm diameter slits were employed for the optical and FTIR measurements (paragraph 2.4) at several (~5) different positions (to achieve an averaged value of the contamination effects).

2.3 Atomic Force Microscopy (AFM) Measurements

The AFM measurements were performed under ambient conditions using a Digital Instrument Nanoscope II system. The surface morphology of the test samples (pristine and contaminated samples) was measured with a resolution up to 1nm. The measurements were performed using the minimal force possible since the adherence of the contamination to some of the test plates was very poor and the AFM probe could displaced the contamination molecules. At present best results were obtained for CaF_2 test plates having stronger adhesion compared to other substrates.

2.4 FTIR Measurements

FTIR measurements were performed using a Nicolet model 740 system. A 8mm diameter slit was used and several measurements were performed for each test sample at different locations, applying the same method adopted for the optical measurements in order to overcome the problem of the nonuniformity of the contaminant distribution on the test samples.

2.5 CVCM (Collected Volatile Condensable Materials) Measurements

CVCM measurements were performed using a standard micro VCM system conforming to the ASTM E595 method. The accuracy of the standard CVCM measurements is $5 \times 10^{-3}\%$. This accuracy is insufficient for the present project. A special adaptor enabling the introduction of 3g of the tested materials to the heated crucible (10 times larger than in the standard method) was developed, achieving an accuracy of $5 \times 10^{-4}\%$. The equivalence of the extended method to the standard one was confirmed by testing high CVCM materials using the two methods. The same system was used for preparation of contaminated test samples as described above.

3. RESULTS

3.1 Optical Measurements

Optical transmission measurements were performed on test plates with different contamination thicknesses for the four contaminated materials mentioned before. Typical spectra of plates with three different thicknesses of outgassing products of graphite/ester cyanate are shown in Fig. 1. The optical measurements of all contaminated test plates revealed loss of transmission characterized by:

1) loss of transmission for the entire spectrum (190-800nm) with different absorption peaks for different materials.

2) all test samples exhibited an absorption peak at ~206nm.

3) the transmission loss (or the optical density $OD=\log_{10} I_0/I_t$) tends to increase with the weight of the contaminating material but the behavior is highly irregular, probably due to the nonuniformity of the contamination layer.

VUV measurements were available only for Solithane 113. Again, a strong absorption peak at λ=206nm was observed, with a smaller peak at λ=165nm. This result suggests that the 206 nm absorption peak represents a conservative measure of the transmission losses for the spectral region of 140nm-280nm relevant for TAUVEX (for a variety of materials).

3.2 AFM Measurements

Reliable AFM measurements were performed at present time only with CaF_2 test plates contaminated with outgassing products of graphite/ester cyanate and Solithane 113. In both cases the contaminated area was irregular and consisted of randomly dispersed islands (Fig. 2).

3.3 FTIR Measurements

The FTIR measurements exhibited absorption peaks that characterize the outgassed products (OP) of the contaminating materials. The graphite/ester cyanate OP exhibit the typical absorption peak of hydrocarbons at λ=2925cm^{-1} and a peak at λ=1735cm^{-1} which is typical of esters. The OP of the silicon rubber exhibits peaks at 805, 1026, 1090, 1260cm^{-1} which are indicative of methyl silicones and at 2963cm^{-1} which was not identified. The OP of Solithane 113 showed peaks at 1465, 1735 and 2925cm^{-1} indicating a hydrocarbon/ester nature of the contaminant. The intensities of the peaks can be translated to contamination areal densities using published calibration curves (6). This option was found to be important especially for graphite/ester cyanate where the CVCM values were lower than the detection limit of our system.

3.4 CVCM Measurements

The CVCM of the two critical materials of TAUVEX (graphite/ester cyanate and the silicone rubber) were precisely measured. The CVCM of the graphite/ester cyanate composite is less than the detection level (CVCM $< 5 \times 10^{-4}$%) while for the silicone rubber an average value of CVCM = 0.028% was determined. The measured CVCM were used also for evaluation of the contamination level of the test plates.

4. DISCUSSION

The purpose of the contamination measurements was to establish the correlation between the contamination areal density and the optical transmission loss. This correlation is needed as an input parameter when evaluating the optical degradation of TAUVEX due to molecular contamination during mission. Complementary studies were performed aiming at a better understanding of the contamination buildup on the optical surfaces.

If one assumes a linear correlation between the incremental transmission loss dI and an incremental areal contaminant density dC then

$$dI/I = a\, dC$$

or

$$I_t = I_0\, e^{-aC}.$$

If α is defined as $\alpha = a\,(\log_{10} e)$, then the optical density $OD = \log_{10}(I_0/I_t)$ is given by $OD = \alpha \,.\, C$.

A linear correlation between the optical density and the contaminant areal density is thus expected. In our previous work (7) performed with Solithane 113 and "Buna N" O ring, such a correlation was indeed obtained and the linear coefficient α was derived and used for the calculation of the expected optical degradation of TAUVEX. In the present work two independent measurements were used in order to evaluate the contaminant areal density C: (i) the measured CVCM value of the contamination source (ii) the FTIR peak intensity using conventional calibration curves. For both methods no linear correlation between OD and C was found for the two critical materials of TAUVEX (graphite/ester cyanate and silicone rubber). Moreover, different α values were obtained for different contaminants for similar contamination areal densities. The UV and visible OD spectra had different absorption peaks for different materials except a common peak at 206nm that can serve for a conservative evaluation of TAUVEX performance. The AFM analysis indicates that the contamination builds up in an irregular way, i.e. by chaotically dispersed island growth, rather than a continuous smooth layer. This result may explain the nonlinear dependence of OD on C.

The OD spectra indicates some material dependent absorption, but scattering due to the rough nature of the contamination is also possible. The IR spectra apart from being used for the α values also reveals the chemical nature of the deposits (i.e. a hydrocarbon type contaminant has a strong absorbtion band at $2925cm^{-1}$, a methyl silicone type contaminant at $805cm^{-1}$ etc.). These results suggest that the best input data for evaluation of the optical degradation in mission is a table of the maximal OD's (i.e. at λ = 206nm) vs. C and not a single value of α as was done in the previous work.

PART II. MONTE CARLO CALCULATIONS OF THE TRANSMISSION LOSSES OF TAUVEX OPTICAL SYSTEM VS. TIME

5. THE SOREQ CODE FOR CALCULATION OF CONTAMINATION

Calculations of outgassing induced contamination of spacecraft surfaces are performed by either analytical models(2,8) or computer codes(9,10,11). This section briefly describes a code that was developed for the present work. The Soreq 3D code for evaluation of the contamination of spacecraft systems due to outgassing follows the history of contaminant molecules. The approach is based on classical trajectories with initial conditions randomly selected applying a Monte Carlo technique. The initial distribution of the contaminant molecules is introduced as an input to the program. Each molecule represents a finite fraction of the contaminant material and has a probability of escaping its initial position (depending on its outgassing "kinetic" properties(2,8,9) and the temperature profile of the system). The direction of the escaping molecule is randomly chosen by the program and it moves in a straight line until it impinges on the next surface where it can either be trapped or reflected according to its "sticking probability"(2,8,9). The program follows the individual trajectory of each of the preselected number of different molecules. The number of contaminant molecules on each surface of the system is counted at certain specific times thus giving the contaminant molecules areal density vs. time. The input parameters are: (i) the geometry of the system, (ii) the temperature profile of the surface, (iii) the quantities and kinetic constants of the contaminants, (iv) the initial distribution of the contaminants in the system, and (v) the definition of the sensitive surfaces for which the contaminant areal distribution should be calculated. The output files include the contaminant areal density (C) of each individual surface vs. time. The data derived in part I (transmission loss vs. C for different thicknesses and different materials) was introduced to the program and calculations of the transmission losses of each optical surface as well as the total loss of the system are also available.

6. BASIC ASSUMPTIONS AND INPUT PARAMETERS

6.1 TAUVEX Geometry

The TAUVEX telescope system consists of three boresighted 20 cm aperture telescopes mounted in a rectangular housing as shown in Fig. 3. All three telescopes have an identical Ritchey - Chretien optical layout. Each telescope consists of nine optical surfaces which are sensitive to contamination effects: the primary mirror, the secondary mirror, the first correction lens (2 surfaces), the second correction lens (2 surfaces), the filter (2 surfaces) and the detector window. A detailed description of TAUVEX is given elsewhere(12). For the present work, a simplified geometry was used. Only one telescope was taken into account assuming that the contaminant distributions in each separate telescope would be the same (to a good approximation) as in the entire system. Fig. 4 describes the simplified geometry assumed for a single telescope. Three sensitive surfaces were evaluated: (i) the primary mirror (ii) the secondary mirror (iii) the front lens. The pumping apertures leading to the other optical surfaces are so small that they cannot be treated by the computerized code, but are treated with a good accuracy by simplified analytical calculations(2,8).

6.2 Modes of Operation and Temperature Profiles

TAUVEX temperature profiles are affected by its operation modes. TAUVEX orbiting duty cycle consists of two main phases: (i) operational phase in which it serves for astronomical observations (ii) survival mode (10 h duration) when it passes through the earth radiation belts. At this mode, the power is off and the telescope cover may be closed. During the operational phase different telescope orientations may result in "hot" and "cold" modes. Additional "outgassing mode" is planned for the beginning of TAUVEX flight mission. Special heaters attached to the telescope optical elements are operated, aiming at a forced outgassing and cleaning of these elements during the first weeks in space. This mode may be operated also further in mission, in case of severe optical degradation due to contamination. Table 1 gives the different temperature profiles of TAUVEX calculated by El-Op for the above modes. This table served as input data for the present work for evaluation of specific (extreme) conditions. Intermediate profiles are however also possible. It can be immediately observed that the outgassing cycle only affects the temperature of the optical surfaces, but does not affect the main body of the telescope (compared to operational conditions) for hot conditions and only slightly affects the temperature of the body for cold (nominal) conditions.

6.3 Materials

In this section the critical materials, their quantities and outgassing properties are presented.

6.3.1 Critical materials of TAUVEX

TAUVEX was specially designed to be constructed mostly from inorganic (i.e. metals and ceramics) materials, that are contaminant free as far as outgassing is concerned. All the organic materials used for TAUVEX were however selected to meet the ASTM E595 specifications(5), were listed, and a budget of their potential contaminant hazard was prepared. It was found that the critical materials, contributing to more than 95% of the total potential contaminant weight are: (i) the graphite/ester cyanate composite structural parts and (ii) the silicone rubber from which two sealings pads are made: an external sealing pad between the shield and the external cover, and an internal one between the bezel and the shield.

6.3.2 Quantities of critical materials and potential contaminant hazard

The total weight of the graphite/ester cyanate in the system is 250g and its CVCM is less than 5×10^{-4}% as derived in part I. The total weight of the silicone rubber is 220g and its measured CVCM equals 0.028%.

6.3.3 Outgassing properties (kinetic constants)

The kinetic constants of the critical materials for TAUVEX calculations were taken as equal to those of similar materials cited in other works. For graphite/ester cyanate an activation energy E_b = 11.3 kcal/mole and a residence time τ(298°C) = 26.6 h cited (12,13) for graphite epoxy were adopted, while for the silicone rubber two sets of values for two different silicone based polymers were used (for PSG - 120 D(9) E_b = 8.35 kcal/mole, τ(298°K) = 91.5h, and for Methyl-Phenyl 3-siloxane(2) E_b = 25 kcal/mole and τ(298°C) = 77.8 h). Only the higher contamination levels obtained using the PSG - 120 D values are presented in this work.

6.4 Maximal Permissible Contamination Level

The maximal allowable contamination levels for NASA and ESA projects range from 10^{-7} g/cm^2 to 10^{-6} g/cm^2 (4,14). These levels are derived from optical properties losses. For a level of 10^{-7} g/cm^2 our own data for λ = 206 nm show a transmission loss of 4% for the graphite/ester cyanate and 2% for the other meassured materials. Since the TAUVEX telescope has 9 optical surfaces it follows that even contamination levels of

10^{-7} g/cm^2 on all surfaces is associated with a total transmission loss of ~30% (it may be larger if reflections are taken into account since a contaminant on a reflecting surface absorbs light twice$^{(15)}$, i.e. should cause a higher transmission loss per 10^{-7} g/cm^2).

A maximal permissible contamination level of 10^{-7} g/cm^2 thus seems logical and not too conservative for TAUVEX. The following evaluations will consider this value for the elucidation of the necessary CVCM values for the graphite/ester cyanate and the silicone rubber.

7. RESULTS

7.1 General

Calculations of contamination levels vs. time were done for the following operational modes: (i) nominal (cold) operational conditions, (ii) hot operational conditions, (iii) forced outgassing and (iv) survival conditions with a closed cover. As an example, only the first two will be presented here, since they are the most important modes of operation in which the TAUVEX telescope is used for astronomical observations. The calculations will be presented using CVCM = 5 x 10^{-4}% for graphite/ester cyanate and CVCM = 0.028% for the silicone rubber.

7.2 Contamination Levels for Nominal (Cold) Operational Conditions

Figure 5 shows the contamination levels accumulated vs. time after launch on the three main optical surfaces of TAUVEX, i.e. the primary mirror, the secondary mirror and the front lens. The contamination initially increases with time, reaches a maximal value of ~7 x 10^{-8} g/cm^2 after ~800 h and then decreases with time to reach the 10^{-8}g/cm^2 level in ~4000h. The contamination is concentrated mainly on the primary mirror while the levels on the secondary mirror and the lens are much lower. The main contaminant is graphite/ester cyanate while the contribution of silicone rubber is negligible. Since the maximal allowable areal contaminant density is 10^{-7}g/cm^2 it follows that the assumed CVCM of 5 x 10^{-4}% for graphite/ester cyanate is in accordance with this criterion.

7.3 Contamination Levels for Hot Operational Conditions

The contamination levels for the hot operational conditions are presented in Fig. 6 for graphite/ester cyanate and in Figs. 7 and 8 for silicone rubber. The maximal contaminant levels are ~5 x 10^{-7}g/cm^2 and ~1 x 10^{-7}g/cm^2 respectively and the time to reach the maximal values is ~80 h for graphite/ester cyanate and ~800 h for the silicone rubber. Initially it is the graphite/ester cyanate that contributes to the contamination, but after 800 hours the silicone rubber dominates. The CVCM values needed to achieve the allowable contamination level of 10^{-7}g/cm^2 are 10^{-4}% for graphite/ester cyanate and the measured 0.028% for the silicone rubber respectively.

8. DISCUSSION

The contamination levels on the TAUVEX main optical surfaces were calculated for the different operational modes taking into account two critical materials, i.e. graphite/ester cyanate and silicone rubber (in two locations.) It should be noted that the actual operational conditions and contamination levels can be intermediate between the different modes defined in paragraph 6.2 that correspond to extreme conditions. Calculation of the contamination levels of graphite/ester cyanate shows that the CVCM value for the hot operational mode should be kept below 10^{-4} % and for the cold mode below 5 x 10^{-4}% in order to guarantee a contamination level lower than 10^{-7}g/cm^2. The graphite/ ester cyanate parts were specially baked out at 90°C for 72h under vacuum conditions to guarantee a minimal CVCM value. However, we currently cannot measure the CVCM value with the proper accuracy (10^{-4}%). For the silicone rubber the measured CVCM value of 0.028% is sufficient to guarantee this contamination level.

Fig. 9 exhibits the transmission loss of TAUVEX for the hot mode due to its three main optical surfaces, assuming three different CVCM values (the recommended 10^{-4} %, 2x10^{-4}% and 5x10^{-4}% which is the detection limit of our sustem) of graphite/ester cyanate and the measured CVCM value of silicone rubber (0.028%). The calculations were performed for λ = 206 nm using the experimental correlation between contamination level and transmission loss (paragraph 3.1). For contamination areal density up to 5x10^{-7} g/cm^2, α values of 1.78x10^4 cm^2/g and 8.9x10^3 cm^2/g for graphite/ester cyanate and silicone rubber respectively were assumed. First the transmission loss of each optical surface was calculated, considerering both the contributions of the graphite/ester cyanate and the silicone rubber contaminants. Then the overall transmission loss was calculated by multiplying the transmission values of the three surfaces. In Fig. 9 it is assumed that each contaminated mirror surface contributes only once to the transmission loss. This leads to a maximal ~8% reduction in transmission for the recommended CVCM value. One may however consider a loss mechanism in which the light is alternated twice(15) (upon incidence and upon reflection). Using this assumption the maximal transmission loss for the hot mode is ~12%. Fig. 9 also indicates that even for the worst case (CVCM value of 5x10^{-4}%), the maximal transmission loss will be 30%, but within 1 month the surfaces will be cleaned by self outgassing so that the transmission loss will be lower than 10%. For twice the recommended CVCM (2x10^{-4}%) the maximal transmission loss of 15% will be reduced to below 10% within 3 weeks. Fig. 10 shows the TAUVEX total transmission loss in the cold mode, assuming the recommended CVCM=5x10^{-4}% for graphite/ester cyanate and the measured value of 0.028% for the silicone rubber. The maximal loss is 3% (~5% when each mirror is accounted twice). The thermal-vacuum experiment which is planned in the near future will supply evidence for the actual transmission vs. time behavior of the TAUVEX system.

The calculations assume kinetic outgassing parameters adopted from the literature (activation energies and residence times). The literature values however vary and may be very different from the actual values of the materials used in TAUVEX. Calculations of the contamination levels of the silicone rubber using two very different activation energies (8.35(9) and 25(2)kcal/mole) taken from different sources however show that similar maximal areal contamination densities are achieved and only the time scale of the evolution of the contamination (both increase and decrease periods) is significantly affected by the variation of the activation energy.

The calculations treated only the three main optical surfaces. The other optical surfaces are located in regions into which the flow of outgassing products from the main TAUVEX volume is negligible. The contamination of these surfaces should be treated by a much simpler analytical approach(2,8) assuming an even distribution of all potential contaminants on the system surfaces (a most conservative assumption). For TAUVEX the transmission loss due to these extra surfaces is less than 10% as long as the CVCM of the contaminating structural materials of the detector unit is kept below 0.01%.

9. SUMMARY AND CONCLUSIONS

The present work can be summarized as follows:

a) The contamination products of two TAUVEX materials (graphite/ester cyanate and silicone rubber) and two other materials were evaluated using CVCM, optical, AFM and FTIR measurements.

b) Optical measurements were performed in the 190-800nm range for all contaminants with additional VUV (140-190 nm) measurements for Solithane 113 contaminants. All contaminants showed an absorption peak at 206 nm. Optical degradation could be best described by a table of OD's (optical densities) vs. areal concentrations rather than a linear dependence between the two.

c) A 3D Monte Carlo program for the calculation of contamination due to outgassing of spacecraft materials was developed and applied for TAUVEX.

d) An evaluation of the degradation of the performance of TAUVEX optical surfaces due to self contamination by outgassing in space was carried out for different operational modes.

The main conclusions of the above evaluation are:

a) Strict CVCM values are needed for the graphite/ester cyanate (10^{-4}% for the hot operational mode and 5×10^{-4}% for the cold operational mode).

b) Since no contaminants were found in outgassing tests of graphite/cyanate ester, its CVCM is lower than 5×10^{-4}% (detection limit of our outgassing system). This is acceptable for the cold mode. The behavior during hot mode operation will be tested in a future thermal-vacuum test.

c) The measured CVCM value of the silicone rubber (0.028%) is acceptable in all modes.

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Table 1. - Temperature profiles of TAUVEX at different operational modes.

Mode	Outgassing		Survival	Operational	
	Nominal	Hot		Cold	Hot
Primary mirror	45	45	-10	-10	30
Secondary mirror	45	45	-10	10	35
Lens	30	30	20	20	30
Filter	30	30	0	0	35
Sensor	30	30	10	10	35
Bezel	30	30	-10	0	30
Shield	-40	85	-40	-90	85
Secondary mirror baffle	-15	35	-35	-40	35
Primary mirror baffle	-5	35	-30	-30	35
Cover	-	-	-40	-	-
Struts	-20	30	-20	-20	30

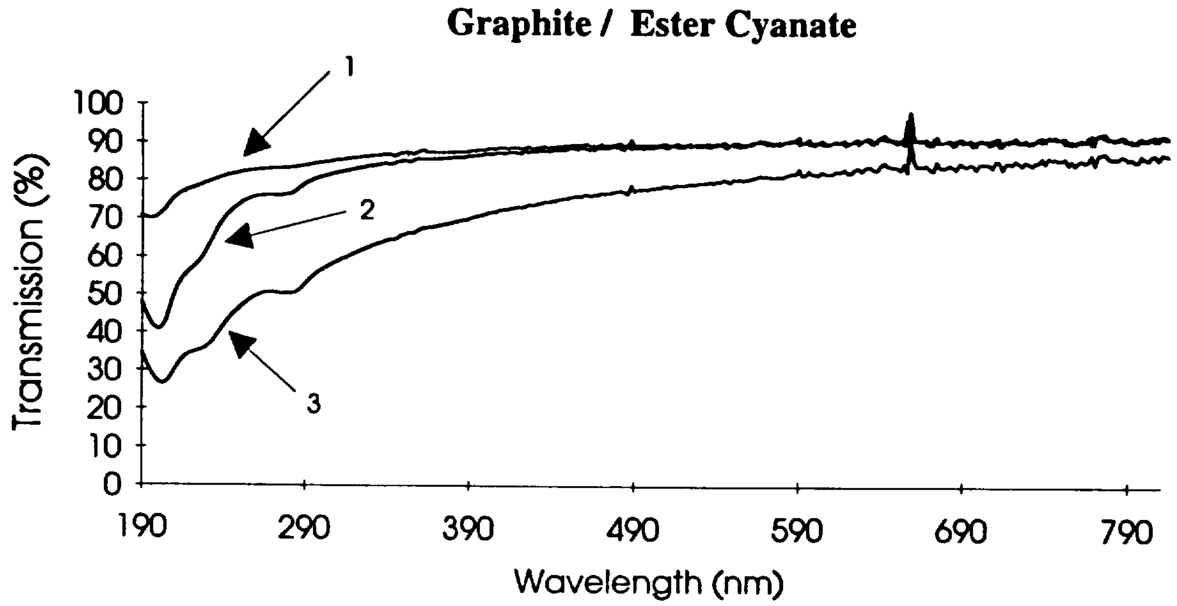

Fig. 1. Typical spectra of CaF$_2$ test plates contaminated with outgassing products of graphite/ester cyanate. Contaminant concentrations are: (1) ~3x10^{-7} g/cm^2, (2) ~5x10^{-7} g/cm^2, (3) 1.2x10^{-6} g/cm^2.

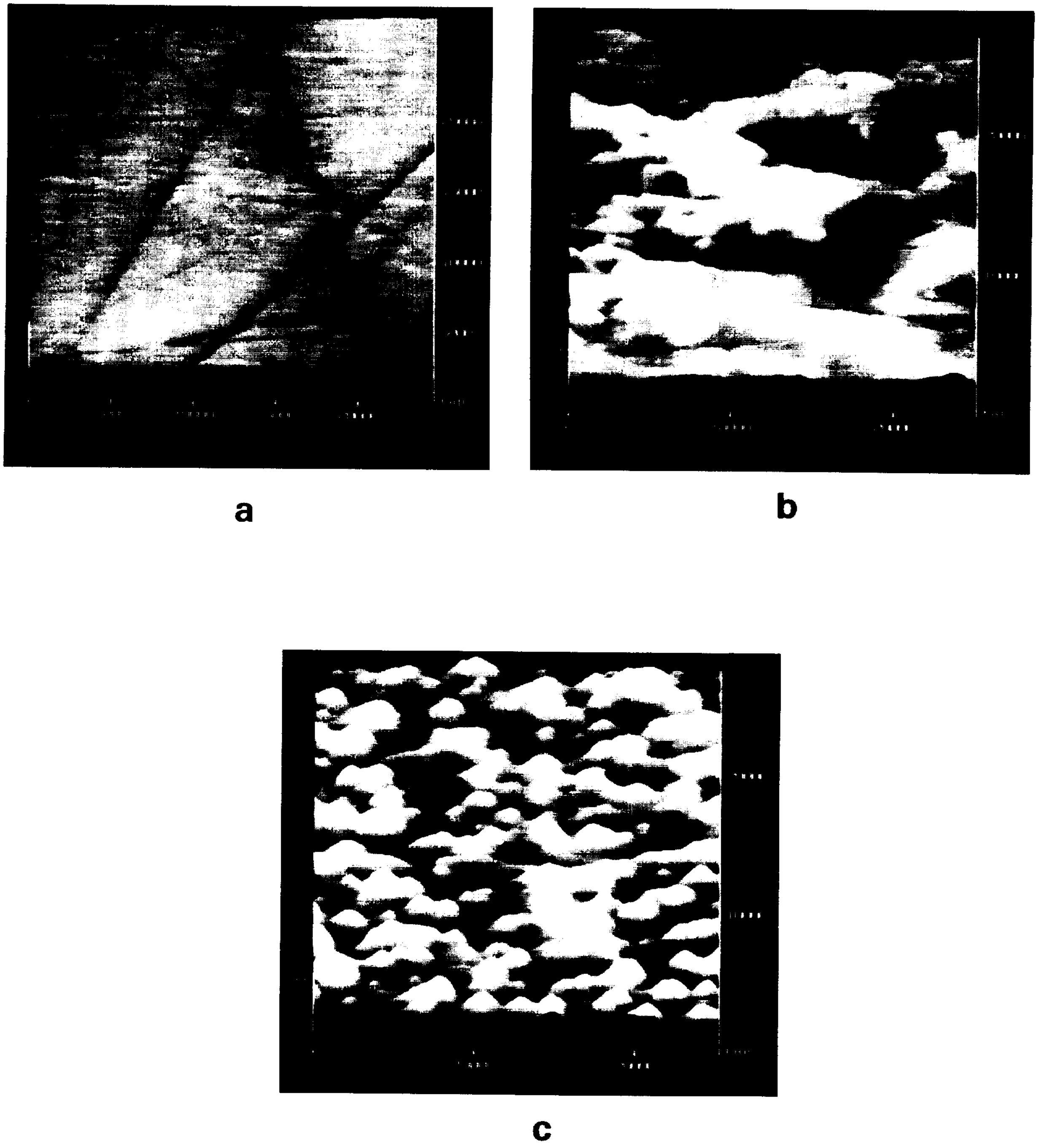

Fig. 2. AFM measurements of CaF_2 test plates contaminated with outgassing products of graphite/ester cyanate. Image size is 25 by 25 microns. Vertical dimension is 120 nm for (a) and (b) and 480 nm for (c). (a) Clean CaF_2, (b) CaF_2 contaminated with $\sim 1.5 \times 10^{-6}$ g/cm^2, (c) CaF_2 contaminated with $\sim 5 \times 10^{-6}$ g/cm^2.

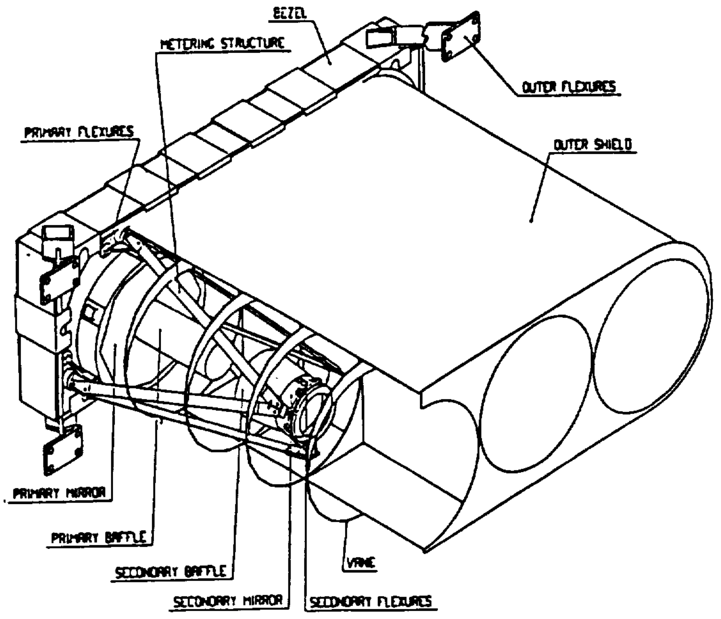

Fig. 3. TAUVEX - A view of the optical module.

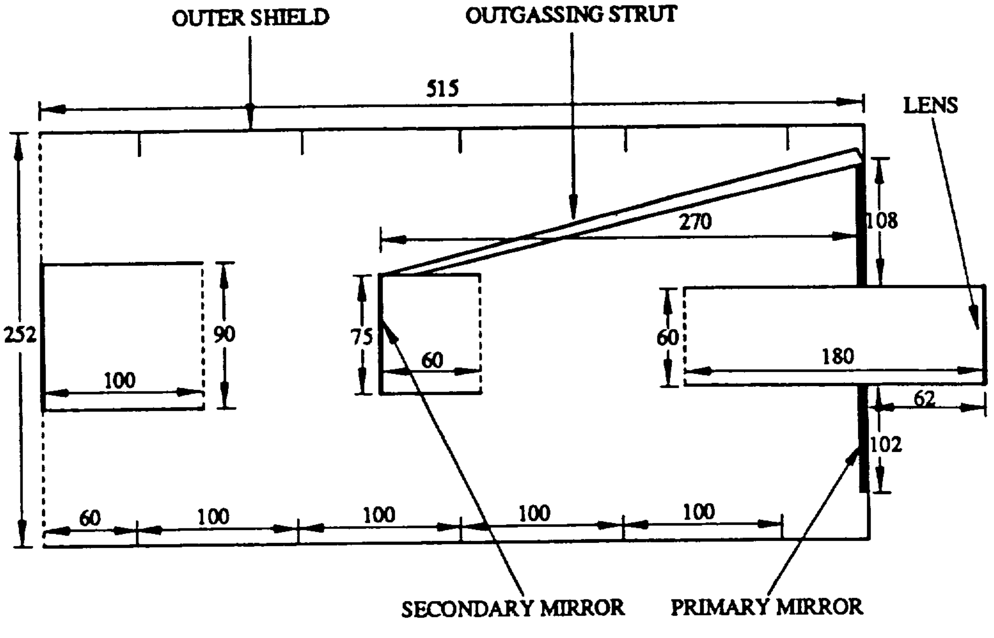

Fig. 4. A simplified model of TAUVEX used for 3D Monte Carlo calculations. Only one of the six struts is shown for the sake of clarity.

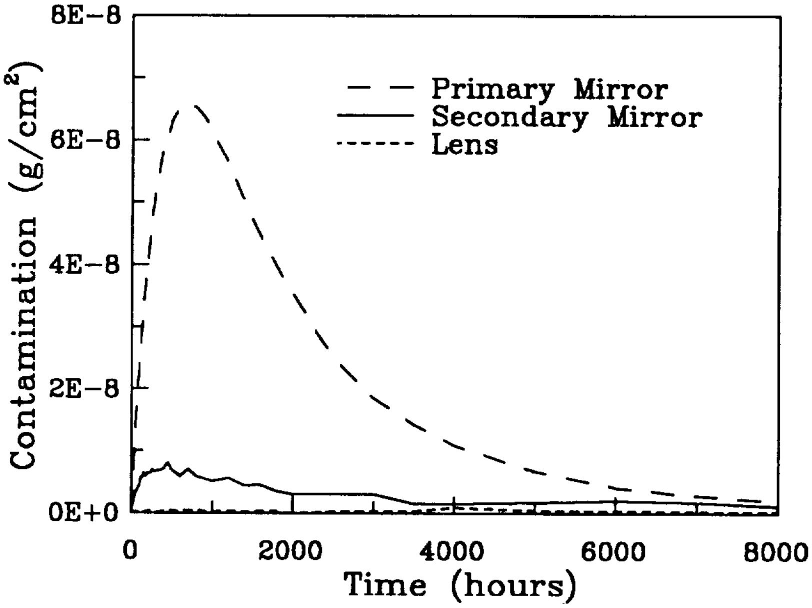

Fig. 5. Contamination levels vs. time after launch from graphite/ester cyanate for three TAUVEX principal optical surfaces: (i) primary miror, (ii) secondary mirror and (iii) front side of first correction lens. The calculations are for CVCM=0.0005% and assume cold conditions.

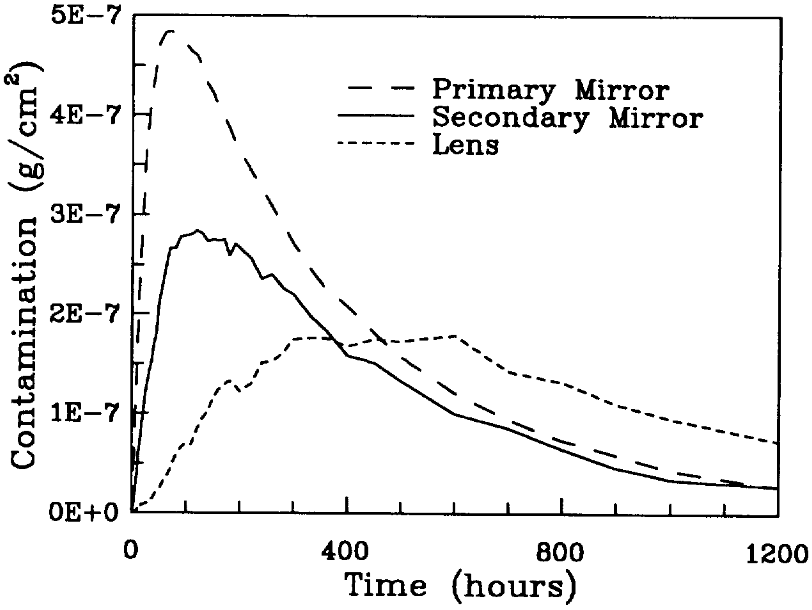

Fig. 6. Contamination levels vs. time after launch from graphite/ester cyanate for three TAUVEX principal optical surfaces: (i) primary mirror (ii) secondary mirror and (iii) front side of first correction lens. The calculations are for CVCM=0.0005% and assume hot conditions.

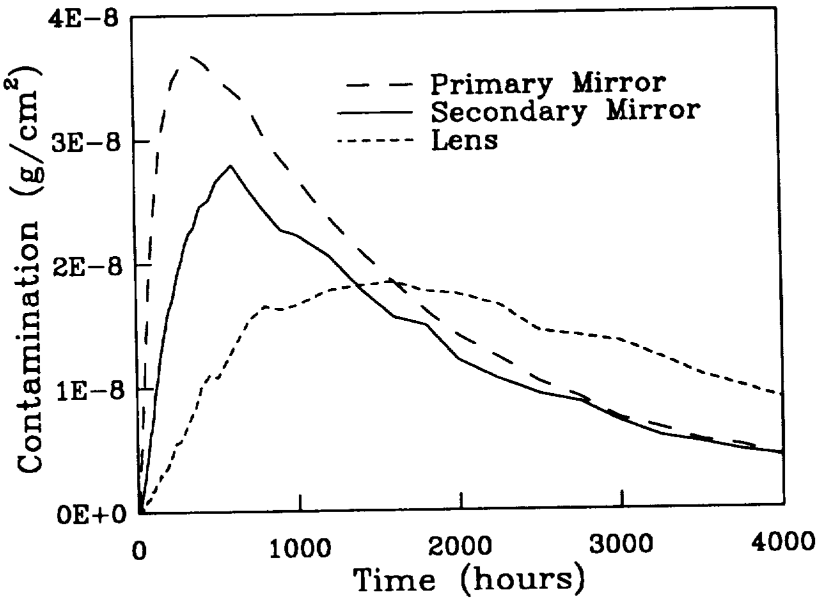

Fig. 7. Contamination levels vs. time after launch from external silicone rubber sealant for three TAUVEX principal optical surfaces: (i) primary mirror, (ii) secondary mirror and (iii) front side of first correction lens. The calculations are for CVCM=0.028% and assume hot conditions.

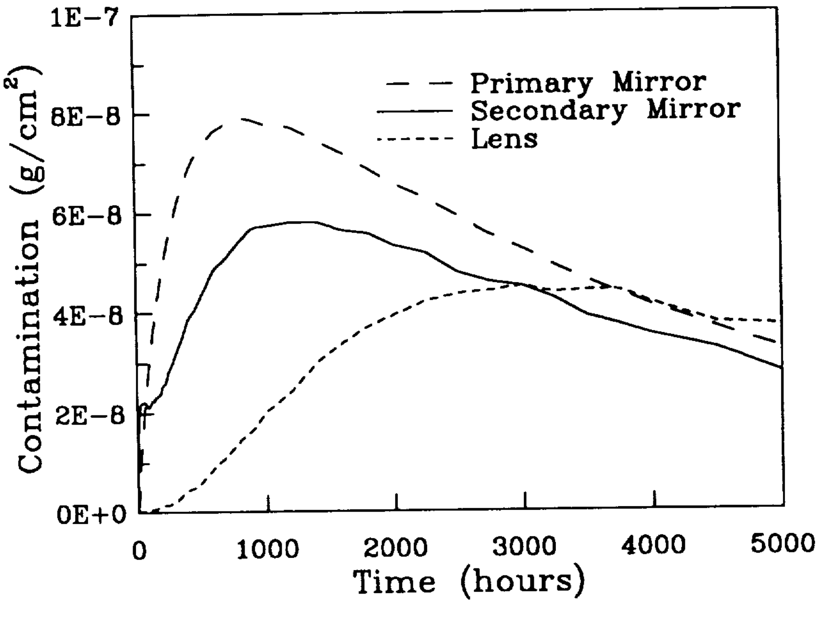

Fig. 8. Contamination levels vs. time after launch from internal silicone rubber sealant for three TAUVEX principal optical surfaces: (i) primary mirror, (ii) secondary mirror and (iii) front side of first correction lens. The calculations are for CVCM=0.028% and assume hot conditions.

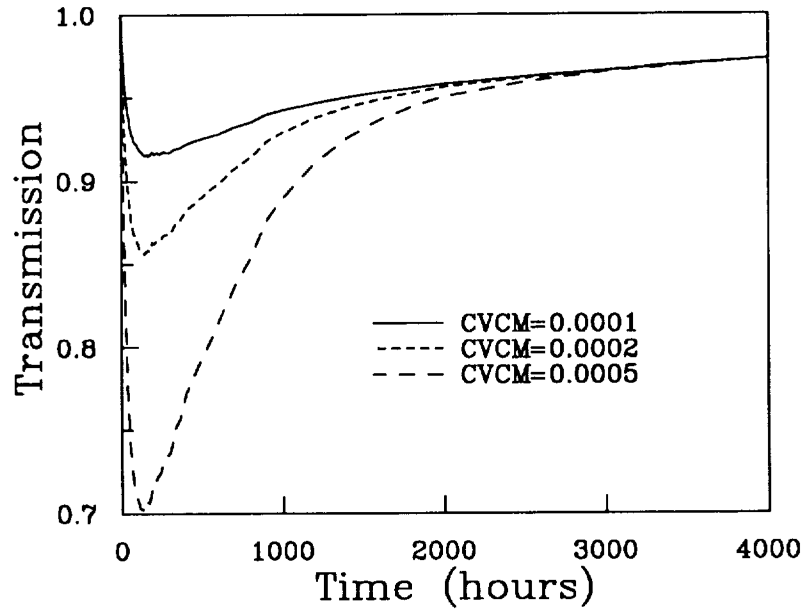

Fig. 9. Transmission loss vs. time after launch for TAUVEX. The calculations assume hot conditions. Results are shown for various CVCM values for graphite/ester cyanate (0.0001%, 0.0002%, 0.0005%) and the measured CVCM=0.028% for silicone rubber.

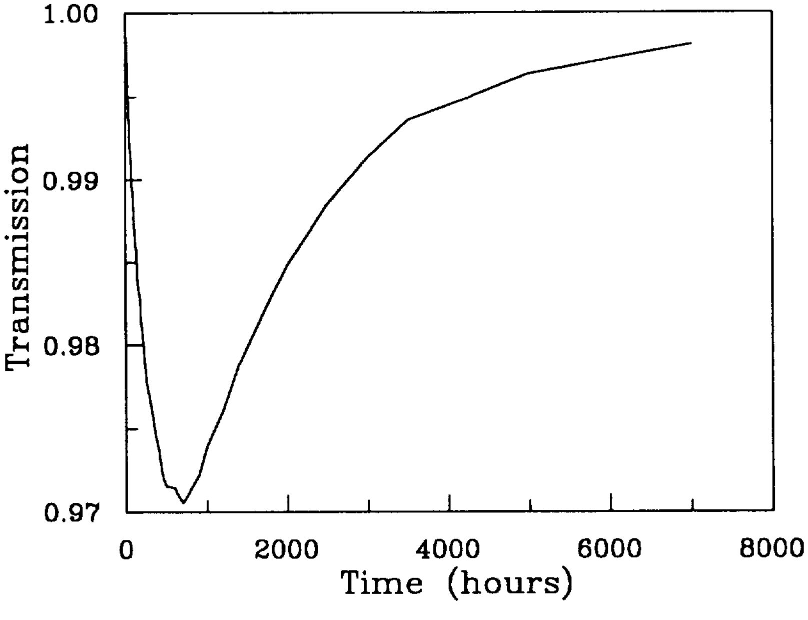

Fig. 10. Transmission loss vs. time after launch for TAUVEX. The calculations assume cold conditions. Result is shown for CVCM=0.0005% for graphite/ester cyanate and the measured CVCM=0.028% for silicone rubber.