ASSESSMENT OF CLEANLINESS REQUIREMENTS
FOR SPACE OPTICAL INSTRUMENTS.

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Abstract

This paper critically analyses recently launched or planned to launch mission contamination budgets and preventive measures, regarding to their sensitivity and performance requirements. Contamination effects are reviewed on the basis of instrument type, wavelength range and performance requirements. Then preliminary guidelines are drawn up for budgeting contamination. In parallel, some suggestions are proposed to reasonably improve or relax cleanliness requirements without degrading a mission. Among others, prevention methods and cleaning possibilities. The costs of cleanliness control are also examined. It leads to investigate future activities needed for making the guidelines easily understandable and routinely applicable by all intervening people, for more effective contamination control and optimised cleanliness cost.

I. Introduction.

In order to minimise performance degradations induced by contamination, instruments to be part of space optical missions require a very severe control of the environment they are submitted to, during their ground and orbital life. In the last years, cleanliness requirements on scientific payloads have been very high, especially for assembly, integration and verification (AIV) operations.

The high costs of cleanliness and contamination control, as much in terms of time schedule and working procedures as in terms of money, make necessary to specify the cleanliness level on the basis of instrument performance requirements, but also available cleaning procedures and facilities, and cleanroom working procedures. Simple copy from closely connected preceding missions must be avoided. We believe that numerous missions are overspecified in their required cleanliness level.

II. Previously flown/integrated experiments.

It is evident that some missions failed, because of a lack of contamination controls and prevention, and even when stringent controls are in place, contamination can be a problem. However, it is also manifest that the specifications imposed to several missions are simply copied from closely connected preceeding ones, without any analysis of instrument requests. On the contrary, the requirements are generally enhanced, to ensure security. Budget distribution is not optimised, yielding to overcostly or sometimes even unrealistic constraints, as much in terms of money and time as in complexity and manpower. The largest budget is generally reserved to launch preparation and launch. The level of cleanability for optics is close to zero. The use of heaters and protective covers is extremely low. The price for satisfying such cleanliness conditions is penalising.

We have compared contamination budgets of some previous or planned for launch missions, on the basis of achieved levels or expected performances [1]. As it appears in table 1, despite the large diversity of instrument functions and wavelength ranges, the specifications extends on a reduced range of tolerance. It confirms that requirements are rarely scientifically justified.

But mission reports do not furnish necessary information to allow general conclusions. Achieved levels are often unknown, and in-orbit performances are not analysed from a contamination point of view. Nevertheless, it is admitted that the EIT mission works successfully thanks to the heaters allowing monthly CCD bakeouts. The behaviour of the mission dramatically shows that in-orbit bakeouts can be essential.

For MERIS, the basis was to consider specifications as a goal, and to define more realistic, acceptable levels. The gains are effective in terms of both time and money, because accepted levels are those routinely achieved in CSL facilities.

III. Contamination effects on scientific instruments.

The main effect of a molecular film is a variation of signal intensity by absorption, providing a degradation of the signal to noise ratio. Signal absorption by the contaminant film also modifies the thermo-optical properties of the optics. If film thickness equals a multiple of $\lambda/4$, a destructive interference can occur. Practically, molecules do not deposit uniformly, and light scattering also arises.

Particles on a surface affect the signal intensity by a factor equal to the obscuration ratio OR, expressed in ppm [mm^2/m^2] or in %. The other effect is light scattering, which degrades stray light rejection performances and SNR by off-axis sources. A critical parameter is the ratio of the radiative power outside and inside the field of view. When particles become $\gg \lambda$, scattering phenomena are treated by diffraction theory.

326

For small wavelengths (EUV, X), diffractive scattering by surface roughness also becomes important and both effects, resulting in an enlargement of the point spread function PSF, must be separately evaluated.

Contamination consequences depend on operational wavelength range, contaminant absorption spectrum and instrument function. Muscari has measured the UV absorption spectra for some typical space materials: table 2 [2] gives the fitted straigth line absorption coefficients α for 115 nm $< \lambda <$ 180 nm, $\alpha = m\lambda + b$. Table 3 from Austin [3] gives the absorption coefficients, averaged from condensed molecules outgassed from 28 material specimens. Fig. 1 gives the degree of blue light cumulative absorption after 9 crossings of given contaminant layers, on the basis on values given in table 3 [4]. Fig. 2 shows the transmittance of H_2O, CO_2 and N_2O from 1 to 24 μm [5]. For photo-chemically deposited film, absorption is increased by at least one order of magnitude. Influence of temperature on residence time is shown in fig. 3 [6].

1/ Wavelength range

For uncooled IR sensors, molecular deposition is not critical: about 1500 nm are tolerated, regarding absorption. But IR sensors are generally cooled down to limit the instrument background noise. A film is deposited rapidly, most of molecular species condensing on cryogenic surfaces. Moreover, IR sensors are often high contrast scene observers, for which design of stray light rejection system is critical, making them highly sensitive to scattering by contaminants. Before absorption to become critical, the optical quality of surfaces is destructed by the cryofilm, degrading imaging quality for a very small deposited quantity.

Visible instruments are mostly sensitive to particles or irregularities of molecular films. Imaging performances are rapidly degraded by the loss of surface quality and scattering. Photometry is affected by reduction of signal throughput (and SNR decrease), for a slight surface obscuration. Molecular deposition limit for absorption is generally less severe: $10 \cdot 10^{-6}$ g/cm^2 corresponds to about 10% absorption for a typical contaminant mixture [6].

UV instruments are highly sensitive to absorption by molecular contamination (hydrocarbons) : about $2.5 \cdot 10^{-7}$ g/cm^2 for 10% absorption [6]. In the case of solar UV irradiation, contaminants are polymerised. They are darker, change of colour and are more absorbent. They are often definitely fixed to the surface. Warmer surfaces become sensitive to contamination under solar exposition.

In the X and EUV wavelength range, effects are slightly different. Molecular contamination (hydrocarbons) modifies the reflectance, but in a complex way: 1/ at a given X-ray energy, reflectance may increase or decrease, depending on the relationship between X-ray grazing incidence angle and contaminant critical grazing angle (function of

contaminant density); 2/ reflectance varies with X-ray energy, depending on the absorption edges in the spectrum of the concerned materials: surface coating and contaminant if any; 3/ for definite film thicknesses, and if contaminant layer is sufficiently uniform, interference may occur between incident and reflected rays. These instruments also suffer from particle-induced scattering.

A critical concern is the very accurate calibration of the detector effective area. In absence of in orbit X-rays photometric standards, it is crucial to maintain the calibration, during ground operations, through transfer from ground to orbit and during orbital life. A very small change in contaminant quantity may compromise that goal.

2/ Instrument function

Spectrometers, gratings are sensitive to molecular absorption and scattering resulting in SNR degradation. Imager performances are sensitive to deposition of particles or agglomerated molecules, which act as scatterers and degrade the quality of the surface. Radiometers are mostly sensitive to molecular absorption. Cooled instruments are rapidly covered by cryofilms, degrading image quality and stray light rejection performances. If a detector is cooled, it will act as contaminant trap. High contrast scene observing instruments and coronographs present a very high sensitivity to stray light due to scattering by particles and coming from the occulted area. Contamination also reduces the contrast.

Diffusers onboard Earth observation missions, used for in orbit system calibration, are highly sensitive to contamination. Their cleanliness requirements are imposed by the radiometric accuracy of the system to be calibrated. For the baffles, the tolerated contamination level is given by the required performances for stray light rejection and then diminishes as the contrast increases between observed scene and neighbours.

IV. Assess total contamination budget End-Of-Life (EOL).

The baseline to specify the required cleanliness level of a flight instrument must be the maximum of performance degradation that can be accepted EOL. Then a contamination-induced degradation impact analysis is necessary, considering the wavelength range, expected instrument performances and lifetime, operational temperature, specificity of sensitivity to each type of contaminant. The tolerance on instrument performances must be sufficiently large to suffer ground contamination. The cleanliness plan must be established together with the design phase and must be adapted for cost and technical effectiveness.

The key elements are the definition of adequate sensitivity criteria, and the relationship between degradation budget and contamination quantity. For this last point, adequate scientific models are needed.

In parallel, experiments are necessary, with involved materials and representative sample surfaces, in representative environmental conditions. To make free from these conversions between required performances and contaminant quantities, the use of functional criteria, based on instrument purpose and accepted degradation instead of contamination quantities, is to be developed. This implies to invest in the development of methods based on direct performance monitoring on contaminated elements: transmittance/reflectance, scattering measurements, thermal lensing...

V. Ventilate the budget into the successive steps of instrument life.

A contamination control plan is charted in fig. 3 [1]. Budgeting contamination takes account for the successive environments (clean room, test facility, container...) and exposure times, the impacts on working procedures, time constraints and financial costs, the capability of cleaning, allowing a (partial) cleanliness level recovery authorising equivalent specification relaxation, the choice of materials. It is imperative to assign a person to overseeing the project for cleanliness point of view.

Design, procurement and manufacturing phases are essential for contamination prevention by material selection, venting holes, protective caps, temporary shields, compartmentalisation, view angles, cold traps & heaters...

Assembly and integration as well as vacuum tests are the phases where it is most costly to avoid contamination, then a maximum budget must be allocated to these steps.

A large budget is generally reserved to launch preparation and launch. Slightly improving cleanliness control during these last ground steps would be few constraining and could allow to transfer a relatively small part of their budget to the most constraining phases. As a result, requirements for costly phases could be significantly relaxed, with direct benefit to time schedule, manpower and costs. Indeed, each working hour is much more expensive in very clean conditions. Actions should be taken in that way (protective cap up to fairing placement, purge over structure...).

The lack of measurements leads the users to reserve a budget often exaggerated to the orbital phase, while a better knowledge of on-orbit level could probably induce a less severe requirement on the level at launch. Theoretical models describe outgassing processes, transport and deposition mechanisms, synergistic effects of natural environment... A better knowledge and appropriate use of these is mandatory, while they have to be refined on the basis of recent space experiments.

Specifications for MGSE/OGSE do not need to be as severe as for the specimens. Contaminant transfer process from MGSE/OGSE surfaces onto sensitive surfaces are not 100% effective (highly depending on factors of view, temperature distribution...). It is significantly reduced if a cold surface with sufficiently large factor of view is installed at proximity. The possibility to submit them to outgassing/ baking sequences must be used, preventing them from being kept permanently at a constraining cleanliness level.

VI. Contamination prevention. Cleaning techniques.

The design will facilitate inspection and cleaning procedures, also after integration. Covers, internal windows, temporary shields, jettison caps will protect sensitive parts during critical contamination phases. Fasteners must be designed so that screw holes be drilled through the exterior whenever possible. Venting holes are to be designed so their location and size optimise the evacuation of internal contamination. When possible, the instrument will be equipped with cold traps. Heaters allow to evaporate (partially) condensed molecular film. Sensitive parts must be oriented facing downward during launch, for avoiding particle deposition. Solar UV protection baffles may protect sensitive surfaces.

Criteria for material selection will be respected. But practically, contamination depends on quantities to be used, viewing factors, temperature and vacuum. A "good" material may be not acceptable at critical locations. And, for small quantities, a study of contamination impact can lead to authorise not space-qualified material, which in most cases corresponds to a substantial cost reduction.

The time of exposition during ground sequences will be as short as possible. As long as possible, sensitive surfaces will be kept at temperatures higher than the contaminant environment. Hardware and non-sensitive elements entering the test chamber will satisfy the cleanliness requirements to avoid contamination transfer. Vertical storage will be preferred. Contaminant accumulation can be avoided by maintaining the instrument in closed clean boxes, under a flow of dry compressed gas. Sensitive parts can be grounded to eliminate electrical charge that may attract and retain contaminants. All the cover doors will be opened after several days on orbit and closed each time an increase of contaminant level is expected. Molecular adsorbers can be used for in-situ collection of contaminant molecules.

Several cleaning techniques have been developed to clean contaminated surfaces before launch or on orbit. Their applicability depends on different parameters: contaminant species and surface material, coating if any, surrounding subsystems materials (baffles, mounting structures...), temperature of involved elements, operational wavelength range of the element....The optimisation of a procedure, especially for orbital cleanings, requires the knowledge of contamination context.

328

Cleaning efficiency is measured as performance recovery.

Local heating, charging, presence of residues and surface damages (roughness, pinholes or scattering sites, optical figure degradation...) are common drawbacks of cleaning operations. Then the efficiency of contaminant removal has to be balanced with the cleaned surface quality. A good contamination prevention always is better than making use of a cleaning procedure.

In all cases, it is necessary to experiment the process in the precise context of the instrument to be cleaned: a controlled contamination is generated on a representative sample, installed inside a thermal vacuum facility reproducing the environment to be encountered during the tests or in orbit. Contamination effect is monitored in parallel first with contamination growth, secondly with sample cleaning. A cleaning method is certified only in the specific context use for certification. The required hardware, complexity of process and costs, together with the possibility to work on orbit, are determinant factors for method selection.

VII. Financial estimates of clean room operations.

The cost of using a clean room of a given cleanliness is a key parameter to the AIV cost reduction. The CSL management data of clean room have been studied and the cost of a man/hour has been assessed for each cleanliness class.The following findings can be derived:

1. The installation and running costs are roughly doubled between class 10000 and class 100. It is important to note that operational times are also doubled.
2. In the fixed costs, extra costs are small for a class 100 compared with class 10000.
3. The variable costs are driven in class 100 by the gowning time, which represents half of the total costs.
4. All other expenses are very similar for total area costs; however they can be spread on a larger number of people, so that the cost per man/hour is lower for class 10000.
5. Working in class 10000 enhances the manpower cost by about 15%, whereas working in class 100 enhances the manpower by 30%. Moreover, working in class 100 further increases the cost of a given activity by a factor of 2 compared with class 10000. Hence the total cost factors can be roughly summarised as follows:
    - work in normal lab = 1
    - work in class 10000 = 1.15
    - work in class 100 = 2.6
6. An optimum solution for low cost cleanliness is to work under laminar flux (class 100), BUT as much as possible with class 10000 garments. This is technically feasible by establishing a severe working discipline, essentially by never passing between the test object and the laminar flux. Some 10% of the

hourly manpower rate can be saved, and most operation times are cut by half. This kind of operation should be facilitated by setting a concept of "gradient of cleanliness", i.e. a tunnel-like arrangement with the laminar flux and specimen at one end. The operators are coming from the other end in class 10000 garments, and add gowning accessories according to the needs when approaching the test object. Hence the local cleanliness along the tunnel is variable from 10000 to 100 or better.

7. There is no reason to impose an environment less clean than class 10000, owing to the small economy compared with the hourly gain in cleanliness. Test objects should be always kept under laminar flux (eventually mobile equipment).
8. In the optimum cleanliness scheme, the cleanliness measurements and monitoring come from useful to essential activities, because the margin is reduced and the risk of overpassing the specification is not. They should not be reduced in any way.

VIII. Conclusion. Future activities.

From the evaluation of previous missions, it appears that the problem of optimum cleanliness is not to limit the total EOL contamination requirement - some experiments have shown how contamination may be disastrous - but to more judiciously attribute partial budget to ground development steps, the purpose being to optimise both time and money necessary to respect contamination constraints. Though, EOL specifications must be justified by required mission performances, which makes necessary the crucial operation of correlating contamination effects to contamination quantity and nature. Then a compromise must be found between desired results and realistic constraints. The steps toward more appropriate specifications are a better knowledge of the contamination dynamics and effects including natural decontamination processes, a more realistic analysis of instrument life and objectives, an extensive use of prevention, the development of cleaning techniques. We recommended here a list (non-exhaustive) of activities that look attractive for improving our capabilities in contamination control:

1/The contamination data of materials used for space programs are not sufficient. The data, when available, are related to Total Mass Loss and Volatile Condensable Matter. Instead we suggest building a new database, containing operational information about the contamination generated by materials and components.

2/The standard measurement of molecular contamination during test phases is not optimal. We suggest to study other crystals as sensors, such as ZnSe (Zinc Selenide), because it is IR transparent up to the detection of silicones around 600 cm^{-1}.

3/The contamination data for performance degradation are not sufficient. The real need is a compilation of experimental data for changes in transmittance,

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BRDF, reflection, emissivity...as a direct function of contaminant layer present on various substrates and coatings.

4/The cleaning methods are not satisfactorily surveyed. Measuring the changes in performances could directly address the cleanability of the proposed space instrument or GSE. A substantial cost reduction could arise from this knowledge.

5/The qualitative interpretation of contamination spectra is not easily available to users. It is proposed to start with a database adapted to space programs, with a possible access via electronic networks. This database could be coupled with the contamination data for materials, which deals with the quantitative analysis and standard specifications.

6/The measuring methods for the knowledge of contamination are not fully exploited. Some scarce methods are accepted by the users' community, such as airborne particle counters, PFO and molecular witnesses. Numerous other ones are available, either for measuring contamination (RGA, QCM,...) or for measuring the degradation of properties (in situ non contact measurements such as reflection, emissivity). However, these methods are not yet developed concerning accuracy, reliability and standardisation.

Acknowledgements

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Mission	Wavelength range	Molecular level	
		at delivery	EOL
ISO	2 - 200 μm	2 10⁻⁷ g/cm²	
SILEX	815 - 853 nm	2 10⁻⁷ g/cm²	7 10⁻⁷ g/cm²
MERIS	400 - 1050 nm	2 10⁻⁷ g/cm²	7 10⁻⁷ g/cm²
GOMOS	250 - 900 nm	0.5 10⁻⁷ g/cm²	8.5 10⁻⁷ g/cm²
XMM-OM	160 - 1000 nm		1 10⁻⁷ g/cm²
EIT	17.1 - 30.4 nm	3 10⁻⁷ g/cm²	5 10⁻⁷ g/cm²
CDS	15 - 80 nm		20 10⁻⁷ g/cm²
EUVE	7 - 90 nm	2 10⁻⁷ g/cm²	10 10⁻⁷ g/cm²
XMM	0.1 - 10 keV	4 10⁻⁷ g/cm²	4 10⁻⁷ g/cm²

Mission	Wavelength range	Particle level	
		at delivery	EOL
ISO	2 - 200 μm	350 ppm	800 ppm
SILEX	815 - 853 nm	300 ppm	600 ppm
MERIS	400 - 1050 nm	300 ppm	800 ppm
GOMOS	250 - 900 nm	300 ppm	1300 ppm
XMM-OM	160 - 1000 nm		300 ppm
EIT	17.1 - 30.4 nm		350 ppm
CDS	15 - 80 nm		435 ppm
EUVE	7 - 90 nm	2 part.>25μm	10 part.>25μm
XMM	0.1 - 10 keV	300 ppm	> 1000 ppm

Table 1. Summary of instruments cleanliness requirements.

MATERIAL	CURE			SLOPE	INTERCEPT
	Temperature (°F)	Time (Hr)	Vacuum	m (cm⁻¹·nm⁻¹)	b (cm⁻¹)
Ablebond	257	1	No	-1.32x10⁴	2.52x10⁶
Trabond BB-2116	77	72	No	-4.42x10⁴	8.42x10⁶
EA-9309	Ambient	10	No	-7.83x10³	1.62x10⁶
EA-9309	125	5	No	-5.08x10³	9.82x10⁵
EA-9309	176	24	Yes	-8.67x10³	1.64x10⁶
Scotchweld 2216	Ambient	9	No	-6.36x10³	1.21x10⁶
Scotchweld 2216	125	5	No	-6.97x10³	1.43x10⁶
Scotchweld 2216	176	25	Yes	-4.15x10³	1.02x10⁶
JM-415	As Received	--	No	-2.43x10³	6.24x10⁵
X-306	Ambient	16	No	-6.40x10³	1.23x10⁶
X-306/9922	Ambient	16	No	-4.73x10³	9.29x10⁵
X-306/9922	176	24	Yes	-7.28x10³	1.38x10⁶
X-306/AP-131	Ambient	16	No	-4.17x10³	8.74x10⁵
X-306/AP-131	176	24	Yes	-6.60x10³	1.37x10⁶
CAT-A-LAC 463-3-8	Ambient	16	No	-1.18x10⁴	2.61x10⁶
CAT-A-LAC 463-3-8	176	24	Yes	-1.32x10³	6.79x10⁵
463-3-8/463-6-5	Ambient	16	No	-1.07x10⁴	2.11x10⁶
463-3-8/463-6-5	176	24	Yes	-5.13x10³	1.26x10⁶
JM Nextel 401-C10	150	1	No	-4.85x10³	9.72x10⁵
JM Nextel 401-C10	176	24	Yes	-9.98x10³	1.85x10⁶
401-C10/901-P1	150	1	No	-5.98x10³	1.10x10⁶
401-C10/901-P1	176	24	Yes	-6.34x10³	1.18x10⁶
GY 70/Fiberite 934	As Received	--	--	-8.81x10³	1.59x10⁶
Solithane 113/C113-300 Formulation 88	Ambient	24	No	-8.41x10³	1.52x10⁶
Solithane 113/C113-300 Formulation 88	130	16	Yes	-9.42x10³	1.72x10⁶
Solithane 113/C113-300 Formulation 11	Ambient	24	No	-7.96x10³	1.44x10⁶
Lubelok 4306	300	4	No	-9.66x10³	1.74x10⁶
RT/Duroid 5813	As Received	--	--	-1.55x10⁴	2.80x10⁶

Table 2. Fitted straigth line absorption coeff. α for some materials, λ= 115-180 nm, α = mλ + b.

Approximate absorption coefficient
values for outgassed molecular contaminants

Wavelength, μm	Absorption coefficient, $\overset{o}{A}{}^{-1}$
0.12	9×10^{-3}
0.2	2×10^{-3}
0.25	1×10^{-3}
0.3	1×10^{-4}
0.3 to 0.8	5×10^{-5} (estimated)
0.8 to 15	1×10^{-4} (estimated)

Table 3

Fig.2. Transmittance of H_2O, CO_2 and N_2O from 1 to 24 μm.

Wavelength (nm)	Absorption Coefficient (1/(ng/cm^2))	Contamination level(g/cm^2) 5.0e-7	2.0e-7	1.0e-7
120	0.0005	11%	41%	64%
140	0.0003	26%	58%	76%
160	0.00015	51%	76%	87%
180	0.00012	58%	81%	90%
200	0.00022	37%	67%	82%
250	0.00004	84%	93%	96%
300	0.00003	87%	95%	97%
400	0.000025	89%	96%	98%
500	0.00002	91%	96%	98%
600	0.000015	93%	97%	99%

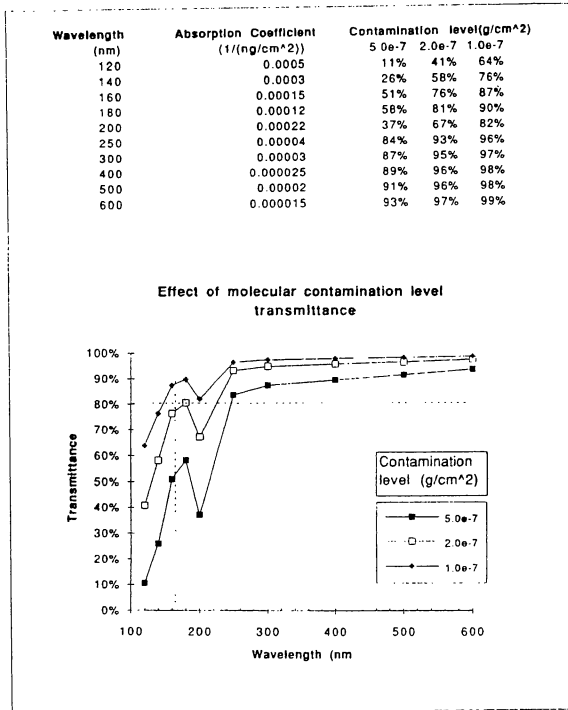Effect of molecular contamination level
transmittance

Fig.1. Blue light cumulative absorption after 9 crossings of
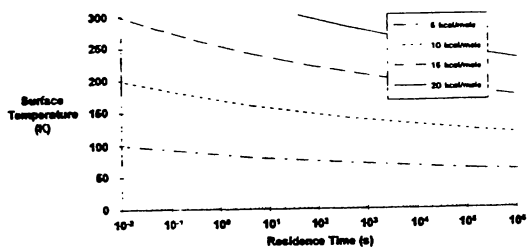the given contaminant layers, on the basis of table 1.

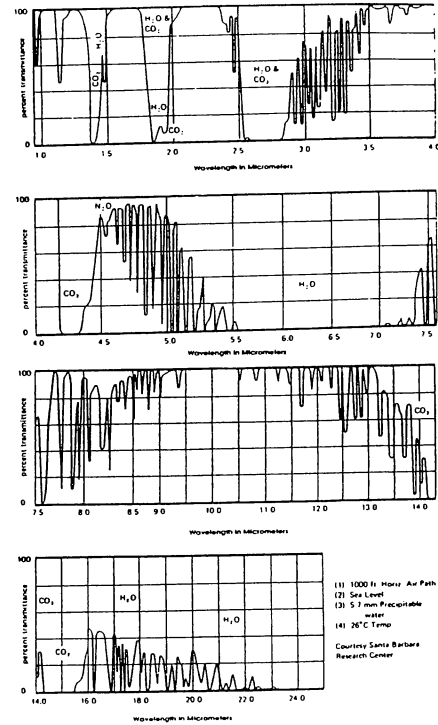Fig.3. Influence of temperature on residence time.
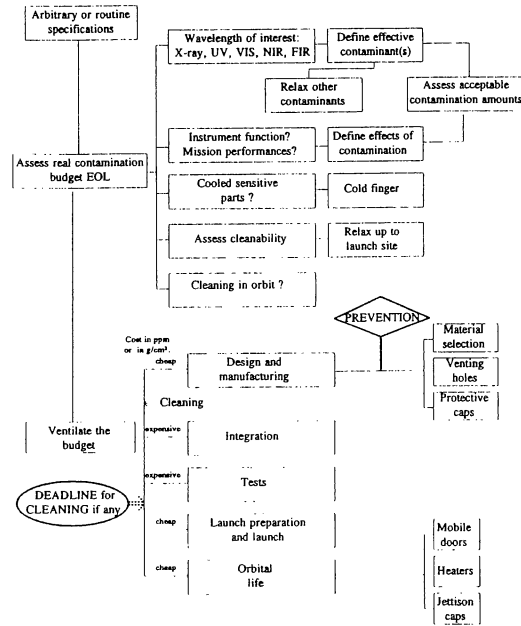
Fig.4. Cleanliness budget establishment chart

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Thermal Verification

Chairmen: **J-F. Redor & A. Popovitch**