AERODYNAMIC AND THERMAL ANALYSIS OF THE SOYUZ LAUNCHER IN KOUROU, FRENCH GUIANA

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ABSTRACT

The Russian launcher Soyuz is expected to be launched from the Guiana Space Centre – Europe's Spaceport - beginning in 2008. Before any launch authorization can be approved, the Flight Safety Department has to ensure that the launcher and its performance satisfy the national regulations and the security restrictions. If the launcher is classified as dangerous during its ascent, the propulsion is deactivated (command called AVD) and the ballistic trajectory of the different stages of the launcher still has to follow the safety regulations at every moment.

The main focus of this study was to analyse the behaviour of the Soyuz launcher during the first powered flight phase but especially during the ballistic flight phase after a potential propulsion deactivation in case of an emergency. For the Flight Safety Department, it is important to know how the entire Soyuz launcher and its single stages (boosters and central body) behave on the ballistic trajectory and where the flying bodies impact.

After propulsion deactivation AVD, the flight attitude of the flying body is not exactly known. For that reason, the two extreme cases have been analysed where the body is flying with a minimum drag coefficient or with a maximum drag coefficient, enduring the greatest possible atmospheric breaking. (see FIG. 1)

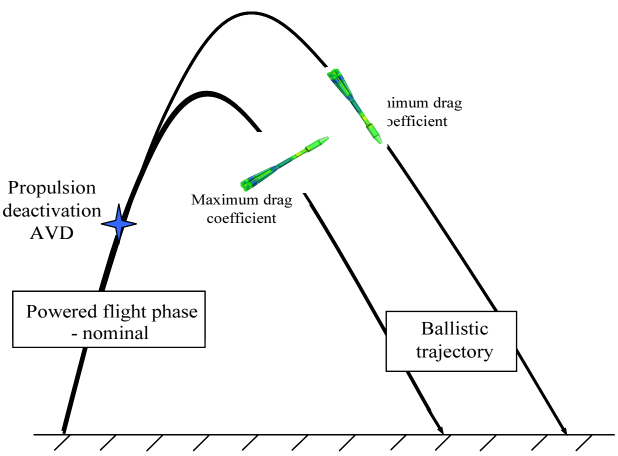

FIG. 1: Flight trajectory of the Soyuz launcher after propulsion deactivation

Within the framework of this thesis, the aerodynamic behaviour of the launcher has been firstly analysed, including the determination of the minimum and maximum drag coefficients of the flying stages. The second part of the study has treated the aspects of atmospheric heating of the launcher during the ballistic flight phase and the probability of an explosion.

The necessary calculations for this study were based on given Russian data and documents that had to be verified and as a consequence validated or not on the basis of the obtained results. This examination is part of the certification process of the Flight Safety Department for the future launch of the Russian launcher Soyuz from French Guiana.

1. INTRODUCTION

1.1. Guiana Space Centre - Europe's Spaceport

In 1964, French Guiana was chosen by the ESA – European Space Agency as the future launch base. The favorable geographic situation near to the equator – 5.3° of northern latitude – ensures the maximum use of the Earth rotational speed. The propellant savings represent, as a result, a considerable gain in payload capacity. The large opening of the site towards the see (see FIG.2) allows a great variety of launch axes against the east for geostationary satellites as well as north for polar satellites.

Without flying over inhabited areas, the launch risks for the population and the environment are minimized. In addition, the stable climate in French Guyana keeps the launch base free from harmful influences of cyclones, tornadoes or earthquakes. These are only three of the advantages of the Spaceport or CSG – Centre Spatial Guyanais, as it is named in French Guiana. [1], [2]

FIG. 2: Launch opening in French Guiana

The European launch capabilities are restricted to either the heavy lift launcher Ariane 5 or the lightweight Vega. The currently operating Ariane 5 is designed to place payloads of up to 6 tons with the Generic version and up to 10.5 tons with the ECA version into the geostationary transfer orbit GTO. In contrast to Ariane 5, Vega could place payloads of only 1.5 tons into a circular low earth orbit (~700 km) beginning in 2007, when the first launch is planned.

However, these launch possibilities do not cover the full spectrum of possible payload configurations and accessible missions. ESA's decision to introduce the Soyuz launch capability in French Guiana represents an important step in completing the European launcher family and enhancing the European flexibility and competitiveness on the commercial market. [3], [4]

FIG. 3: The European launcher family – Ariane 5 (left), Vega (middle) and Soyuz (right) – proportions not in the right scale [5], [6], [7]

1.2. Soyuz (Союз)

The Russian Soyuz launcher is an offspring of the R-7 ballistic missile. The Soyuz launcher family is the most used and the most reliable in the world, with some 1700 launches of satellites or manned flights since 1957.

The current Soyuz version used by STARSEM for commercial payloads is Soyuz-Fregat. STARSEM is the Franco-Russian company marketing the launcher. Soyuz-Fregat is a three-stage launcher with a Fregat upper-stage. It is due to be replaced by the new launcher, named Soyuz/ST (or Soyuz 2), which will have a new digital guidance system and a strongly modified third stage with a new engine. This modernized version has been selected to be launched in French Guiana from 2008. [8]

Soyuz/ST is a four-stage launch vehicle. It mainly consists of four boosters (first stage), a central core (second stage), a third stage, a restartable Fregat upper stage (fourth stage) and an upper composite or Fairing. [9]

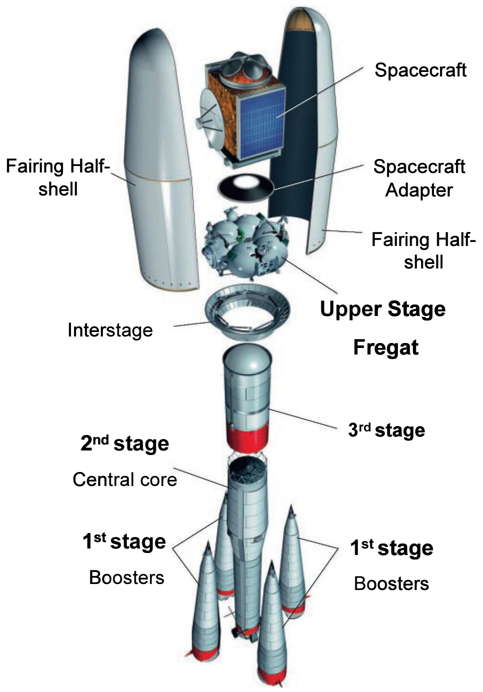

FIG. 4: Soyuz ST overall view [6]

The characteristics of the Soyuz/ST launcher are the following:

Liftoff Mass	308 ton
Liftoff Thrust	4146.5 kN
Number of stages	4
Propulsion	Liquid oxygen (LOX) and Kerosene for the stages one to three

TABLE 1: Main characteristics of the launch vehicle [6]

1.3. Soyuz in French Guyana

With regard to the competition, the market prices and the priority assigned to launch flexibility by the satellite operators to dispose of a launch vehicle at a fixed date, Europe had to find a solution to maintain its competitiveness. A medium-class launcher, such as Soyuz, will complement perfectly the performance of the ESA launchers Ariane and Vega and offers a strategic position on the supplier market. [4]

At the same time, Russia will also benefit from a launch possibility in French Guiana. An access to an optimal location from which to launch telecommunication satellites enables the Soyuz launcher to place nearly 2.8 tons into geostationary transfer orbit instead of 1.7 tons from Baikonur.

Concerning the Soyuz launcher adaptation for Kourou, there are three main driving points: [10]

- the telemetry and localization
- the climatic conditions and
- the flight safety.

The safety aspects of the implementation of Soyuz in the Guiana Space Centre were in the focus of this study.

They include:

- the flight trajectory analysis
- the analysis of explosion scenarios
- the analysis of flight attitude and trajectory (after launch)
- the intervention in case of emergency: application of the flight neutralisation command AVD

2. AERODYNAMIC STUDY

2.1. Trajectory analysis

As already mentioned , the first step of the thesis was to analyse the behaviour of the Soyuz launcher during the powered flight phase but especially during the ballistic flight phase after a potential propulsion deactivation in case of an emergency.

The Russian trajectory data has been analyzed in terms of plausibility and coherence. The main parameters analyzed were the velocity and the altitude but also the flight distance or the dynamic pressure of the given trajectories.

The following example represents the booster ballistic flight trajectory – velocity over time – after propulsion cut-off. The trajectory strongly depends on the instant of propulsion deactivation AVD (85 s to 118 s) and of the flight attitude of the booster (minimum drag coefficient Cx min or maximum drag coefficient Cx max). The employed trajectory data dates from 2003 and 2005 and is extracted from different Russian documents.

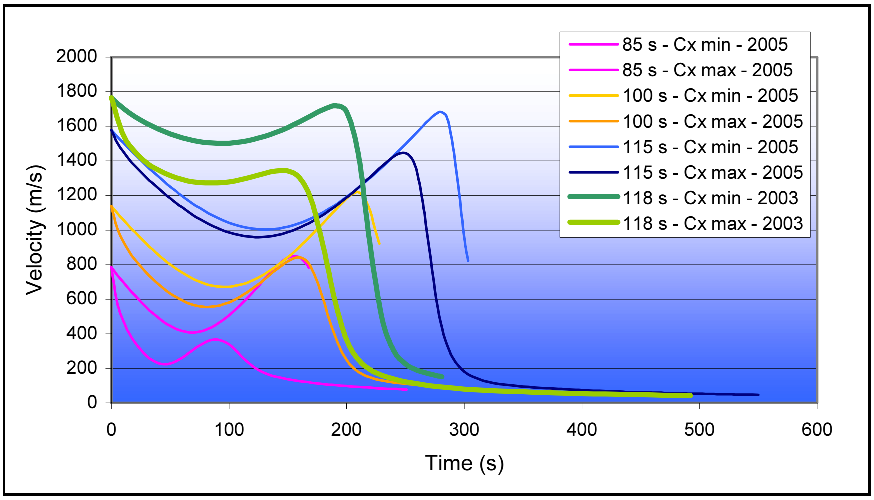

FIG. 5: Booster velocity after separation as a function of time

The comparison reveals discrepancies between the given trajectory data. As an example, the initial velocity of an AVD at 118 s is greater than the one of an AVD at 115 s, as is logical. The trend of the graphs of an AVD at 118 s however does not correspond to the general trend of the other velocity graphs.

Firstly, the minimum velocity achieved at the maximum altitude of the booster (point of deflection of the graph at t=100 s for a booster flying with a Cx min after an AVD at the 118th flight second) is much higher than the minimum velocity for an AVD at 115 s. Secondly, the velocity peak achieved during the descent phase (after the point of deflection) is not as high the general trend would suggest. For a booster flying with a Cx max, the velocity peak is even inferior to the velocity peak for an AVD at 115 s. Thirdly, the low points and the peaks of the velocity occur at a much earlier moment than the general trend might imply. These inconsistencies allow scrutinizing the correctness of the Russian data.

2.2. Determination of the drag coefficient

In order to accomplish the safety tasks at the Guiana Space Centre, the Flight Safety Department has to analyse the flight trajectories and simulate the different failure scenarios. The simulations are made with in situ simulation software that has to be updated for Soyuz. One of the most important inputs required for the software update and exploitation is the drag coefficient of the space vehicle.

The drag coefficients were calculated on the basis of the trajectory data described in the previous chapter and the results have been used for comparison with the Russian data.

2.2.1. The aerodynamic principles

For the calculation of the drag coefficients, the aerodynamic principles have been firstly applied to the powered flight phase and the entire launcher. In a second step, the calculations have been made for the different launcher stages during the ballistic flight phase.

The following figure FIG. 6 represents the forces that act on a body during the powered flight phase. For the ballistic flight phase no thrust occurs.

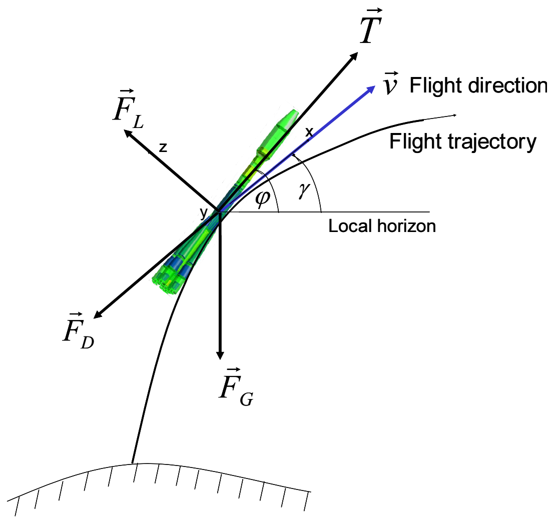

FIG. 6: Equilibrium of forces on the flying Soyuz vehicle

The forces acting on the launcher are defined as following:

- $\vec{F}_D$ - Drag force
- $\vec{F}_G$ - Force due to gravity
- $\vec{T}$ - Thrust
- $\vec{F}_L$ - Lift

With

- $\vec{v}$ - Velocity
- φ - Angle between the thrust vector and the local horizontal
- γ - Flight path angle - angle between the velocity vector and the local horizontal

The sum of forces acting on the flying body is equal to the product of body mass and acceleration.

(1) $\boxed{\vec{F}_D + \vec{F}_L + \vec{F}_G + \vec{T} = m\vec{a}}$ [11]

For the powered flight phase, resolving the forces along the x-axis (direction of flight) and the z-axis (perpendicular to the direction of flight) in the launcher internal coordinate system results in:

(2) $-F_D - F_{Gx} + T_x = ma_x$

(3) $F_L - F_{Gz} + T_z = ma_z$

For the ballistic flight phase:

$$T_x, T_z = 0$$

With:

a - Acceleration

m - Mass of the flying body

These equations assume that the movement of the launcher is in a plane, with no force components in y-direction. This hypothesis is based on the fact that there is nearly no movement along the Y-axis of the local coordinate system (launch pad fixed) of the given data, and as a consequence neither along the y-axis of the launcher internal coordinate system.

In order to obtain the drag coefficient, only the x-direction forces will be exploited. The different forces occurring in the equation are defined as the following:

(4) $$F_D = \frac{1}{2}\rho v^2 S C_X \quad [12]$$

(5) $$F_{Gx} = mg\sin\gamma \quad [11]$$

(6) $$T_x = T\cos(\varphi - \gamma)$$

ρ - Density of surrounding atmosphere

S - Surface of reference of the flying body (=25,86 m²) [13]

C_X - Drag coefficient of the flying body

g -Acceleration of gravity

After substituting the force components into the force equilibrium equation in x-direction, equation (1) becomes:

(7) $$-\frac{1}{2}\rho v^2 S C_x - mg\sin\gamma + T\cos(\varphi - \gamma) = ma_x$$

Making C_X the subject of the equation gives:

(8) $$\boxed{C_X = \frac{ma_x + mg\sin\gamma - T\cos(\varphi - \gamma)}{-\frac{1}{2}\rho v^2 S}}$$

Some of the variables which make up the equation such as the total thrust T or the angle φ between thrust and the local horizontal are already given with the set of trajectory data. Others had to be calculated on the basis of the trajectory data. The following chapter presents the results obtained and compared with the given Russian drag coefficients.

2.2.2. Results

The calculations show that for the Soyuz launcher as a whole on the nominal trajectory, before booster separation, the calculated drag coefficients are almost identical to the given values. (see FIG. 7)

In contrast to the satisfactory results obtained for the powered flight phase, the drag coefficients for the ballistic flight phase do not correspond to the expectations.

The calculated drag coefficients for a booster and for the central body behave in a similar manner. Several remarks can be made, which raise questions about the calculation method employed or about the given trajectory data.

Firstly, it should be noted that the calculated values of the minimum drag coefficient are superior to those for a maximum drag coefficient, and that generally, the calculated values are superior to the given values. The graphic FIG. 8 shows as an example the central body of the launcher flying on its ballistic trajectory with a minimum drag coefficient after an AVD at different instants.

Secondly, the calculated values for different AVDs of one body – booster or central body – are not proportional. The later the AVD occurs, the greater are the calculated coefficients, reaching the limits of the model at altitudes of about 70 km, where the altitude is already very thin. If we look at the calculation methods employed, the influence of the atmospheric density on the drag coefficients is important even at that altitude, where the atmospheric influence should be neglected. The limits of the model become clear for high altitudes.

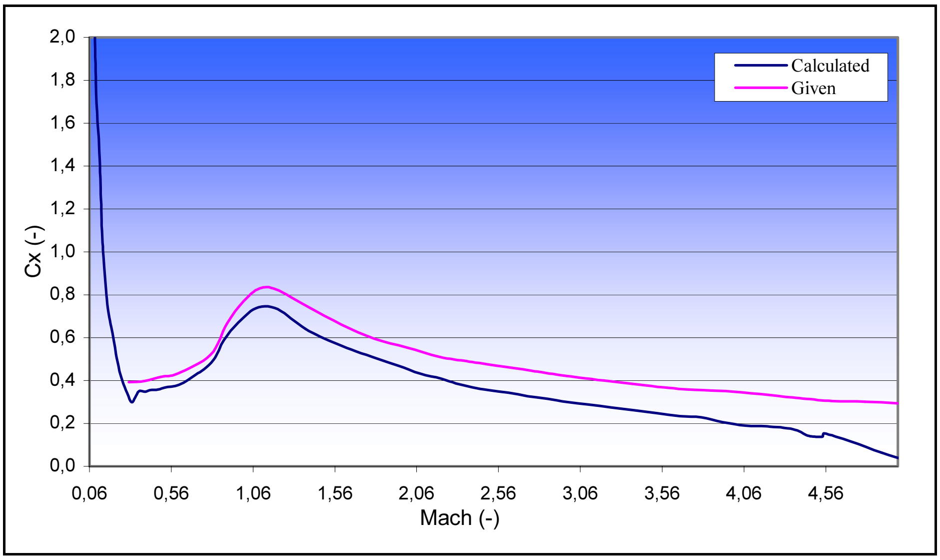

FIG. 7: Drag coefficients for the powered flight phase of the nominal trajectory

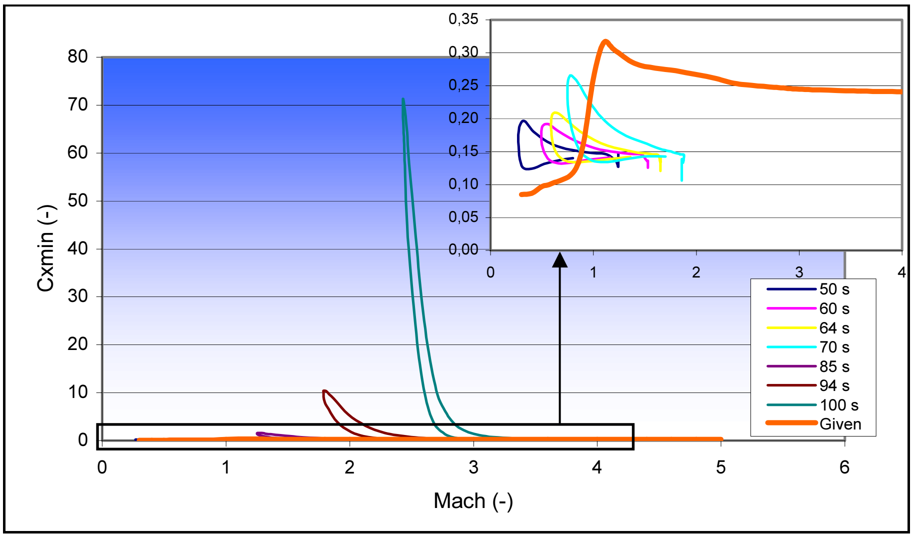

FIG. 8: Drag coefficient Cx min for the central body during a ballistic flight as a function of the Mach number

In order to verify if the discrepancies are due to either calculation errors, data incertitude or other errors, a validation procedure has been developed as explained in the following chapter.

2.2.3. Validation of the results and the calculation methods

In order to validate the calculation methods, several comparisons have been made. Trajectory data of the launchers Ariane 5 and Vega is available at the Guiana Space Centre and has been used for the validation of the powered flight phase. The calculated drag coefficients on the basis of this trajectory data have been compared to the drag coefficients of the Soyuz launcher. The comparison could confirm the calculated results.

In order to validate the results also for the ballistic flight phase, the drag coefficients have been compared to those of different ballistic re-entry payloads of sounding rockets. For this comparison, data was available from some rocket flights of the VSB-30 (Vehículo de Exploración Brasileño-30), the TEXUS (Technische Experimente unter Schwerelosigkeit) and the MAXUS (combination of the German TEXUS- and the Swedish MASER-program) programs.

The VSB-30 data set for example, used for the comparison with Soyuz, is taken from the rocket's test flight. The rocket has been launched from Brazil early 2005 and it will serve as the new vehicle for the TEXUS program [14]. The general geometric shape of the rocket is similar to a Soyuz booster, and the velocity attitude corresponds approximately to that of a Soyuz booster flying on its ballistic trajectory after a late AVD.

The drag coefficients obtained for this flight during re-entry, beginning with the 420th flight second, after the zero-g phase, are presented in FIG. 9. The sign of the drag coefficients is intentionally negative in the graphs, and for comparison, only their magnitudes have been used.

It can be noticed that the drag coefficient achieves a peak value of approximately 24 for a Mach number of 1 and an altitude of 20 km, and that it mainly remains above 7 for all other Mach numbers between 0 and 6.

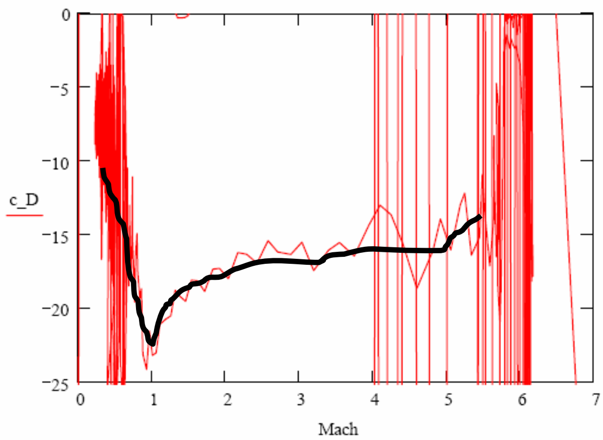

FIG. 9: Drag coefficient of the VSB-30 rocket as a function of the Mach number [14]

Comparing now these values to the *given* drag coefficients for the Soyuz first stage presented previously, it becomes obvious that the maximum values for Soyuz of 0.1 to 2 remain far below the drag coefficients of TEXUS and MAXUS.

On the other hand, the *calculated* drag coefficients for Soyuz are close to the values found for VSB-30. The calculation results then appear more plausible and the comparison confirms that the order of magnitude of these calculated drag coefficients is absolutely reasonable. In addition, the comparison made clear that re-entry bodies with very similar shapes have different drag coefficients for different altitudes for the same Mach number. It has to be scrutinized why the given Russian drag coefficients are only as a function of the Mach number and not as a function of the altitude, too. It should have been outlined for which specific altitudes they have been determined.

3. THERMAL ANALYSIS

The Flight Safety Department is responsible for the protection of people and their surroundings from risks due to space activities at the Guiana Space Centre. These risks are mainly due to the manipulation of dangerous products as launcher propellants or to launcher failure during flight, as already outlined.

In order to fulfil this objective, one of the tasks of the Flight Safety Department is to define the different explosion scenarios that can occur during flight from the CSG and to evaluate the impact of these on people and the environment, in order to minimize any risks.

3.1. Explosion scenarios

According to the National French Agency [15], [16] the following explosion scenarios may occur at the CSG and are of interest for the Flight Safety Department:

1. Explosion of a container under pressure
2. Hypergolic explosion
3. VCE - Vapour Cloud Explosion
4. BLEVE – Boiling Liquid Expanding Vapour Explosion

The DLA (Direction des Lanceurs), the leadership of CNES responsible for launcher activities, has stated that a BLEVE accident must be prevented under all circumstances if Soyuz launches from the Guiana Space Centre [16]. It will be explained in the following how dangerous a BLEVE can be. The consequences at close range to the CSG and the town of Kourou would be catastrophic. Considering that a BLEVE has already happened twice during a flight of the Soyuz launcher from Plesetsk or Baikonur, according to TsSKB (Russian acronym for the Central Specialized Design Bureau – CSDB), it is understandable that the analysis of a BLEVE at the CSG is vitally important for the Flight Safety Department.

3.2. BLEVE explosion of the Soyuz launcher

An explosion of type BLEVE is an explosion of a mixture of liquid and gas under pressure. During a BLEVE, the liquid goes through a violent vaporisation that will generate a very rapid increase of the fluid volume. The risk of a BLEVE appears if a liquid is stored in a tank at a temperature higher than its own boiling temperature at atmospheric pressure. This is the case for the storage at low temperature and pressure or at ambient temperature and high pressure. Of particular interest and a central point of this study are liquids stored at low temperatures, namely the liquid oxygen (LOX).

As already detailed, Soyuz (stage one to stage three) is flying with LOX as the oxidizer and Kerosene as the fuel. LOX is stored at a much lower temperature than Kerosene, as its boiling temperature is also much lower than that of Kerosene: 90 K for LOX and 420 K for Kerosene [17]. Therefore, it represents a much greater danger from the point of view of a BLEVE accident.

At present, the Russian partners from TsSKB state that a BLEVE of Soyuz at the CSG can be prevented, in view of the flight trajectories and Soyuz adaptations for Kourou. Unfortunately, nearly none of the Russian analyses, calculations, hypotheses and results that lead to this conclusion were available. Therefore, the Flight Safety Department was forced to lead its own studies to confirm or reject the Russian statements.

During the powered ascent phase of the Soyuz launcher, its behaviour is known, from the aerodynamic as well as from the thermal point of view. It has been classified as not dangerous by the Russian engineers as well as by the Flight Safety Department. In this study, the analysis will concentrate on the *ballistic flight phase* of the launcher and its stages, after a potential emergency neutralisation command AVD.

At the moment of the AVD, the reservoirs of the different launcher stages are still filled with propellant to a certain extent. During the ballistic flight, the stages' structure heats up as a consequence of atmospheric friction [18]. The increased temperature of the structure leads to a rise in propellant temperature and could lead thus to a BLEVE.

As already explained, it is the liquid oxygen (LOX) that has been further analysed, as it represents a greater risk from the point of view of a BLEVE. The maximum temperature T_{max} that the LOX can achieve before a BLEVE is 120 Kelvin (-153°C), as defined by the CNES. [19]

3.3. Convective heat transfer rate

The processes that lead to the heating of a flying body at high velocity can be described as following: "As hypersonic flow encounters a vehicle, the kinetic energy associated with hypervelocity flight is converted into increasing the temperature of the air and into endothermic reactions, such as dissociation and ionization of the air near the vehicle surface. … Heat is transferred from the high temperature air to the surface. The rate at which heat is transferred to the surface depends upon many factors, including the freestream conditions, the configuration of the vehicle and its orientation to the flow, the difference between the temperature of the air and the temperature of surface". [20]

This process is designated as atmospheric heating. The incident heat flux, or heat transfer rate, is understood as the energy per surface and time unit penetrating the surface of a body. This energy is then carried off in the form of radiated energy, stored energy and energy conducted through the back face of the surface element. These three thermal boundary conditions at the wall determine together the temperature elevation of the reservoir material and as a consequence of the reservoir content, the LOX.

The general energy balance for a reservoir surface element exposed to aerodynamic heating can be described as the following:

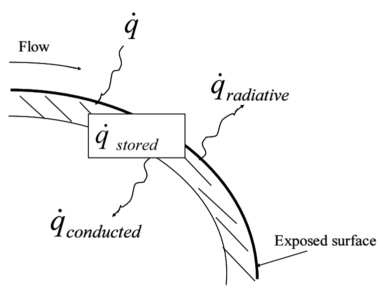

FIG. 10: Energy balance for a surface [2]

(9) $$\boxed{\dot{q} = \dot{q}_{radiative} + \dot{q}_{stored} + \dot{q}_{conducted}}$$ [20]

The incident heat transfer to the launcher surface can result from two transfer mechanisms: convection and radiation. Convection occurs when the heated air around the space vehicle "bathes the wall in a hot fluid stream" [18]. The "radiative heat transfer becomes significant [only] when a blunt vehicle flies at superorbital velocities" [20] and more precisely when the velocity is greater than 10 km/s [18]. For the analysed case, the Soyuz launcher, superorbital velocities are not attained and therefore only the convective heat transfer rate has been considered.

The first step of the thermal analysis was to find an appropriate approach in order to determine the convective heat transfer rate. For a launcher (or its stages), the total heat load and the body-averaged heat load can be determined. They are both important for regular re-entry analysis, as they "may constrain the trajectory". [18]

For this study, however, only the maximum local heating rate was of importance, as it determines the most severe local thermal load and "this is known to be critical" [21]. The point or region where the heating rate is maximized is called the stagnation point or stagnation region. The stagnation region is mostly a blunt nose or a wing leading edge of a space vehicle. [18]

The Russian data relating to Soyuz gives information only about the stagnation heat transfer rate or the maximum attained temperatures. This is one more reason why other far-reaching calculation methods have not been taken into consideration for this study.

Numerous theories can be applied for the determination of the convective heat transfer rate to the launcher wall. It will turn out gradually that "the convective heat transfer [rate] is roughly proportional to $\rho_\infty{}^{0.5} \cdot U_\infty{}^3 / R_N{}^{0.5}$" [20], with:

ρ_∞ - Freestream density
U_∞ - Freestream velocity
R_N -Nose radius of the flying body

The different approaches to calculate the heat transfer rate of a blunt sphere were based on theories such as the theory of Fay and Riddell, of Detra et al or of Lees. Among these, the approach of Lees has been chosen for the application on the Russian trajectory data. First, the approach of Lees is precise enough and therefore applicable on general flying bodies, and not only on atmosphere re-entry bodies. This is indispensable for the analysis of the Soyuz launcher. Second, the approach has been chosen because the obtained results are situated in the middle field of those obtained by all other applicable theories.

(10) $$\boxed{\dot{q}_{Sphere} = 1.8213 \cdot 10^{-8} \cdot \left(\frac{\rho_\infty}{R_N}\right)^{0.5} \cdot U_\infty{}^3}$$ [22]

with [$\dot{q}$ in W/m]

The different flying stages of the Soyuz launcher can be roughly compared to cylinders. However, the calculation method of Lees is only applicable on a flying sphere, and not on a cylinder. Therefore, it had to be modified to meet the needs of this specific case.

The graph of FIG. 11 represents an example of the calculated heat transfer rate in comparison to the Russian given data. For the central body of the Soyuz launcher on its ballistic trajectory after an AVD at the 115th second, flying with a Cx max.

For the comparison of the results, the Russian documents present only one graph for the heat transfer rate. It would be logical that this graph corresponds to the most severe occurring heat flux, as this one would be the determinant state. The most severe occurring heat flux is calculated for the smallest nose radius. Comparing the given Russian heat flux and the calculated one (see FIG. 11), a difference of nearly 50 kW/m² could be observed. Nevertheless, the calculated graph had a similar general shape as the given one, and this confirmed that the right approach has been chosen.

The problem was then to find out what hypotheses the Russians have applied in order to receive the presented values, and if these hypotheses were justifiable. Several approaches have lead to the following result: employing the maximum occurring radius of the flying body (the nose radius of the Fairing) instead of the smallest occurring one and in the same time a velocity that is not officially defined and that does not correspond to the trajectory data name, the given Russian heat transfer rate could be found. This not officially defined velocity corresponds to a data set that has been found among the Russian documents, "hidden" behind the heat flux graphs for the central body. It does not correspond to the officially given trajectory data outlined previously. The discovered facts allowed in the following to doubt the accuracy of the Russian values.

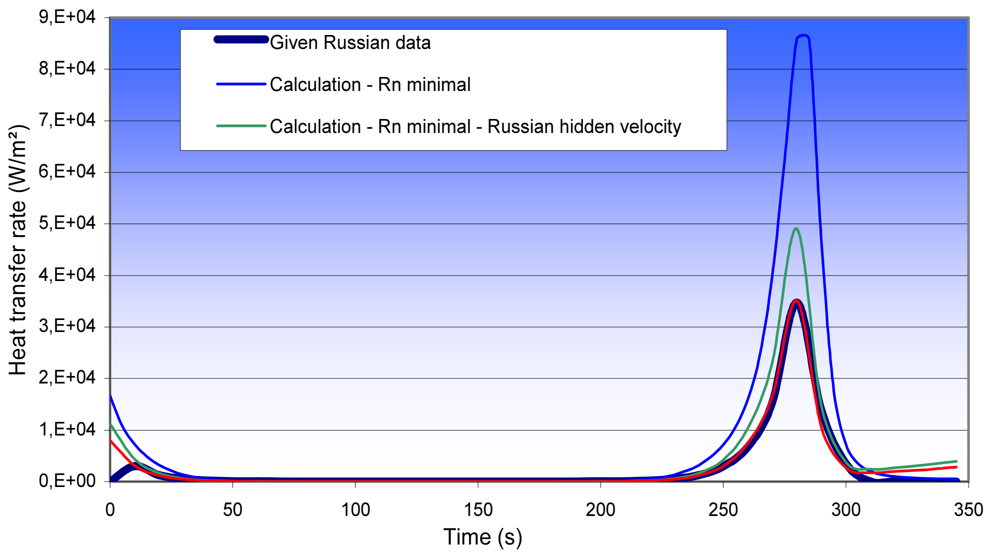

FIG. 11: Convective heat transfer rate of the central body – Cx max

3.4. Determination of the maximum wall temperature

In order to determine the wall temperature of the LOX reservoirs and as a consequence the increase of temperature of the LOX, equation (9) must be solved. Solving this differential equation is quite complicated, in particular without software or other helping devices. Therefore, simplifying hypotheses had to be made for our specific case in order to estimate the temperature increase.

3.4.1. Hypothesis 1 – Re-entry body

The first simplifying hypothesis is that the Soyuz stages behave as re-entry bodies during their ballistic flight. This hypothesis is based on the fact that space vehicles enter the atmosphere with orbital velocities. As a consequence, the incident convective heat transfer rate is carried off only in the form of radiation. [21]

In the form of an equation, hypothesis 1 states:

(11) $\boxed{\dot{q}_{convective} = \dot{q}_{radiative}}$ [18]

With this first hypothesis, the calculated temperature values are a lot higher than the given data. The temperature difference exceeds 1500 K for example for the central body flying after an AVD at 287 s on the ballistic trajectory. The reservoirs of the stage are empty at that instant.

These great temperature differences are due to the fact that the main condition for the first hypothesis, namely a body re-entering the atmosphere with orbital velocity, is not fulfilled. The negligence of the heat transfer rate due to conduction and to storage into the reservoir wall also contributes to these high temperature results.

3.4.2. Hypothesis 2 – Empty reservoirs

The second simplifying hypothesis is that the incident convective heat transfer rate is carried off in form of radiation and of stored heat inside the wall. The heat transfer rate due to conduction is neglected, making the assumption that the LOX reservoirs are empty. That means, if there is no propellant that can absorb the heat passing across the reservoir wall, the temperature of the external and the interior side of the wall are nearly equal, assuming that the remaining gases inside it do not absorb a significant amount of energy.

In the form of an equation, hypothesis 2 states:

(12) $\boxed{\dot{q}_{convective} = \dot{q}_{radiative} + \dot{q}_{stored}}$

It could be remarked that the calculation results significantly approach the given temperature data. For the same example of hypothesis 1, instead of a temperature difference of 1100°C for a body flying with a Cx max, the difference amounts to only 70°C and instead of 1550°C for a body flying with a Cx min, the difference amounts to 800°C. The small temperature difference of only 70°C for the body flying with a Cx min allowed the validation of the calculation approach. In addition, the general shape of the graphs became very similar, with the maximum occurring temperature of the calculation being now at the same instant as the given temperature peak. For the first hypothesis, the two peaks have still been shifted.

3.4.3. Hypothesis 3 – Filled reservoirs

The third hypothesis tries to take into account the heat transfer rate carried off in form of radiation, of stored heat inside the wall and of conducted heat. In contrast to hypotheses 1 and 2, this hypothesis is also applicable in the case of filled reservoirs, assuming that the propellant absorbs the energy passing across the wall.

In the form of an equation, hypothesis 3 states:

(13) $\boxed{\dot{q}_{convective} = \dot{q}_{radiative} + \dot{q}_{stored} + \dot{q}_{conducted}}$
(see equation (9))

For the hypothesis 3, different initial wall temperatures have been considered, as well as variations in the contact surface between the LOX and the reservoir wall or the thermal wall conductivity. The results obtained by means of Fortran simulations are always analogous, more precisely that only the initial LOX temperature determines the maximum temperature of the LOX and of the wall. These two, in general, do not exceed the initial LOX temperature of more than 4-5 K. It can be concluded that with an initial LOX temperature of 90-100 K, as it would be logical, a BLEVE can be excluded.

The great influence of the initial LOX temperature however makes clear that the chosen model has reached its limits. Thermal models are very complex and require more detailed approaches than the employed ones. The statements made should therefore be re-examined with future thermal models.

3.4.4. Hypothesis 4 – No reservoir walls

The fourth and simultaneously the most conservative hypothesis is that the incident energy is absorbed entirely by the LOX. The heat transfer rate due to radiation, conduction or storage into the wall is neglected, making the assumption that the LOX reservoir walls are infinitesimally thin, nearly not existent. If, in this case, the maximum temperature of the LOX remains below the BLEVE temperature of 120 K, then a BLEVE could be excluded. The advantage of this hypothesis is a calculation independently of the material properties of the launcher.

In the form of an equation, hypothesis 4 states:

(14) $\boxed{\dot{q}_{convective} = \dot{q}_{absorbed\,/\,LOX}}$

The calculations show that the initial temperature of the LOX that has been chosen is still determinant for the maximum LOX temperature, as for hypothesis 3. The second observation is that the temperature determined with the *calculated* convective heat transfer rate is on average higher than the one calculated with the *given* heat transfer rate. This is logical, since the calculated heat transfer rate is also higher than the given heat transfer rate. For a body flying with a Cx max the difference is about 1-2 K, whereas for a body flying with a Cx min the difference amounts to even 10-13 K.

With an initial LOX temperature of 90-100 K, as logical, a BLEVE can still be excluded. Nevertheless, the attained maximum temperature of 115 K for a body flying with a Cx min approaches considerably the BLEVE temperature limit of 120 K.

3.4.5. Russian calculation hypotheses

It was interesting to know what variables the Russian engineers have employed in order to yield the given temperatures. Therefore, while using the presented calculation approach, the properties of the reservoir material have been varied. These variations have been made for a stage flying with a Cx min, as the calculation values in this case still diverged clearly from the given values.

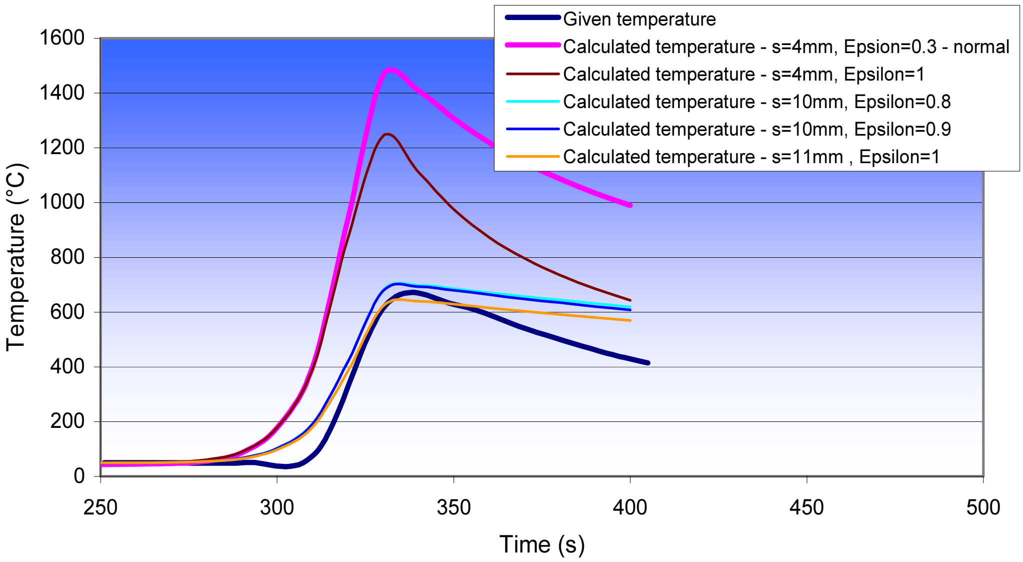

FIG. 12: Hypothesis 2 – Temperature comparison – Central body, AVD at 287 s – Cx min – Variation of material properties

It could be realized that the calculated temperature strongly depends on the material properties of the LOX reservoir. Varying the thickness of the reservoir wall to a value of 10-11 mm instead of 3-5 mm, as indicated in the Russian technical notes [23], and assuming that the flying stage is a black body with an emissivity (Epsilon) of nearly 1 instead of 0.3 as determined for the AlMg6 alloy of the reservoir material, then the calculated temperature can be almost identical to the given temperature, as shown in FIG. 12. Once more, this discovery allows the close scrutiny of the values used by the Russian engineers for the determination of the maximum temperature.

4. CONCLUSION

The main objective of this thesis was to contribute to the certification process of the Flight Safety Department for the future launch of the Russian launcher Soyuz from French Guiana. The aspects of flight safety that have to be analysed in order to authorize this certification are numerous, but only two of those have been examined in more detail within this study: the aerodynamic behaviour of the Soyuz launcher and the probability of an explosion scenario of type BLEVE – Boiling Liquid Expanding Vapour Explosion during the ballistic flight phase of the launcher.

The aerodynamic study has revealed discrepancies within the Russian trajectory data. The given data gave the impression that two different incoherent data sets were combined, one from 2003 and the more recent from 2005. The main objective, however, has been to determine the drag coefficients of the boosters or the central body, values that were needed for further trajectory simulations of the Flight Safety Department. The calculations have determined reasonable drag coefficients for the nominal flight phase, but for the ballistic flight phase, the coefficients were higher than the expectations and even unrealistic for altitudes above 70 km. Russian drag coefficient data has been accessible in a later point of the study, and the comparison of this data with the calculations has revealed that for the ballistic flight phase, the results are, in average, much too high.

In order to verify if the discrepancies were due to either calculation errors or data errors, a validation procedure has been developed. The calculation methods and the order of magnitude of the calculated drag coefficients have been compared to Ariane 5, Vega and other ballistic payloads, and both could be validated. This observation supplied a good reason to doubt the correctness of either the given Russian trajectory data or the given drag coefficients.

The thermal analysis of this study involved firstly the verification of the given heat transfer rate of the Soyuz vehicle. The results of the calculations made on the basis of correct velocity data and the appropriate geometric shape of the Soyuz launcher were clearly higher than the given Russian convective heat transfer rate. The Russian data, however, has been re-calculated, in order to determine the calculation hypotheses made by the Russian engineers. These hypotheses revealed that the employed velocity data came from an ancient data set of 2003 instead of the most recent trajectory data set of 2005, and that the nose radius of the Soyuz launcher has not been chosen in order to determine the most conservative heating regime, but the least conservative. As a consequence, the correctness of these Russian calculation hypotheses for the convective heat transfer rate could not be validated.

In order to verify the Russian temperature indications, too, four simplifying hypotheses have been made. These hypotheses allowed calculating temperatures without a thermal model of the Soyuz launcher. The obtained results were acceptable, but in average higher than the given temperature data of the LOX reservoir wall. The LOX temperature did not attain the critical temperature of BLEVE, but this result should be consolidated with more precise calculation methods within future studies.

The Russian scientists of TsSKB and Roskosmos have been informed about the discrepancies found. The results of this study have served as a basis, as foreseen, in order to justify the doubts in the Russian data. As a consequence, the Russian engineers are reviewing the trajectory data, as well as the heating analysis of the stages during the ballistic flight phase. At the end of the work on this thesis at CNES in the middle of October 2005, the reviewed Russian data has been expected for the coming months.

5. LIST OF REFERENCES

[1] **CNES**
Système de lancement Soyouz au CSG, Kourou, French Guiana, 2005

[2] **A. Jullien**
Etude du lanceur Soyuz, Kourou, French Guiana, 2004

[3] **Extrasolar-planets.com**
Neue Version der Soyuz Rakete gestartet, http://www.extrasolar-planets.com/news/2004/2004111002.php, access in 01.09.2005

[4] **STARSEM**
CEO's message (Jean-Yves LE GALL), http://www.starsem.com/starsem/ceomessage.htm, access in 25.07.2005

[5] **ESA**
Ariane 5 ECA, http://www.esa.int/SPECIALS/Launchers_Access_ to_Space/SEM0LR2PGQD_0.html, access in 12.09.2005

[6] **ESA**
VEGA, http://www.esa.int/SPECIALS/Launchers_Access_to_Space/ SEMH3E67ESD_0.html, access in 12.09.2005

[7] **ESA**
Soyuz, http://www.esa.int/SPECIALS/Launchers_Access_to_Space/SEMQ5P57ESD_0.html, access in 12.09.2005

[8] **Wikipedia**
Soyuz launch vehicle, http://www.answers.com/topic/soyuz-launch-vehicle, access in 09.09.2005

[9] **STARSEM**
Soyuz user's manual, Issue 3, Revision 0, Paris, France, 2001

[10] **CNES**
Soyuz/ST technical overview and adaptation for Kourou, Kourou, French Guiana, 2001

[11] **U. Walter, Prof.**
Raumfahrttechnik 1, Lehrstuhl für Raumfahrttechnik, Technische Universität München, 2003

[12] **G. Sachs, Prof.**
Flugmechanik 1 – Flugleistungen, Lehrstuhl für Flugmechanik und Flugregelung, Technische Universität München, 2003

[13] **TsSKB-Progress**
Drag coefficients of the Soyuz launcher as a function of the Mach-number, Russia, 2004

[14] **A. Stamminger**
Sounding rockets payload re-entry studies, Munich: DLR-RB-Mobile Rocket Base, 2005

[15] **CNES**
Recueil des méthodes de la Sauvegarde - Surpression, Kourou, French Guiana, 1998

[16] **CNES**
Recueil des méthodes de la Sauvegarde - Thermique, Kourou, French Guiana, 1998

[17] **astronautix.com**
LOX/Kerosene, http://www.friends-partners.org/partners/mwade/props/loxosene.htm, access in 23.07.2005

[18] **M. D. Griffin, J. R. French**
Space Vehicle Design, Second Edition, Reston, Virginia: AIAA, 2004

[19] **CNES**
Soyuz/ST – note technique, Kourou, French Guiana, 2004

[20] **J. J. Bertin**
Hypersonic Aerothermodynamics, Washington, DC: AIAA – American Institute of Aeronautics and Astronautics, Inc., 1994

[21] **W. L. Hankey**
Re-Entry Aerodynamics, Washington, DC: AIAA, 1988

[22] **M. Meyer**
Theoretical dimensioning with regard to worst case conditions of a two-stage payload recovery system for the TEXUS sounding rockets, München: Kayser-Threde, 2003

[23] **TsSKB-Progress**
Résultats d'études de l'immersion des blocs du lanceur Soyuz-STK, Russia, 2003