Cranfield University

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POGO LOOP

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Presentation Outline

- Introduction
- POGO loop – Theoretical Background
- Loop POGO ARIANE 1
    - Criteria for stability of POGO cycle
    - Research Results for Loop POGO ARIANE 1
- Loop POGO ARIANE 2, ARIANE 3 and ARIANE 4
- Conclusions

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Theoretical background

The fluctuating force F^* and the corresponding pulse Ω excite the structure. The structural response corresponding n[th] mode,

$$q_n = \frac{F^*}{\mu_n} \frac{1}{-\Omega^2 + i2\zeta\omega_n\Omega + \omega_n{}^2} \qquad (1)$$

Where ζ is a coefficient of damping.

The displacement of the structure causes the oscillation of the hydrostatic pressure in the tank and in the pipes to engine

$$p_a^* = -\rho h q \Omega^2$$

If the thrust of the engine is stable F_0 the corresponding pressure in the combustion chamber is:

$$F^* = -F_0 \frac{\lambda \rho h q \Omega^2}{p_0} e^{-i\omega t} \qquad (2)$$

Equations (1) and (2) show two branches (simplified) of the loop. To be stable, it is necessary that the gain is

$$G \leq 1$$

Hence, for $G = 1$

$$\varsigma_{cr} = \frac{M}{\mu_n} \frac{\lambda p_H / p_O}{2} \cos\Psi$$

Critical damping coefficient

$$\zeta_{cr} = \frac{M}{\mu} \frac{\lambda \quad p_H / p_o}{2} \cos\Psi$$

Where:

M - launcher mass;

μ - generalised mass of the n-th mode;

$$\lambda = \frac{p_0^*}{p_a^*}$$

$p_a{}^* = -\rho h q \Omega^2$ - oscillations of the inlet pressure;

$p_0{}^*$ - oscillation of the pressure in combustion chambre;

$p_H = \rho \gamma_0 h$ - quasistatic pressure;

p_0 - pressure in the combustion chambre;

Ψ - phase;

Criteria for stability of POGO Loop

- definitions -

- critical damping coefficient

$$\zeta_{cr};\ \left(\bar{\zeta}_{cr},\ \sigma_{\zeta cr}\right) \quad \text{where} \quad \sigma_{cr} = \sqrt{\sum_{1}^{n}\left(\frac{\partial \zeta_{cr}}{\partial p_i}\Delta p_i\right)^2}$$

- damping coefficient of the structure

$$\zeta_{st};\quad \left(\bar{\zeta}_{st},\ \sigma_{\zeta st}\right) \quad \text{where} \quad \sigma_{\zeta st} = \sqrt{\sum_{1}^{n}\left(\frac{\partial \zeta_{st}}{\partial p_j}\Delta p_j\right)^2}$$

- damping safety factor (damping coefficient reserve)

$$\Delta\zeta = \zeta_{cr} - \zeta_{st} \quad \left(\Delta\bar{\zeta}, \sigma_{\Delta\zeta}\right) \qquad \sigma_{\Delta\zeta} = \sqrt{\sigma^2_{\zeta cr} + \sigma^2_{\zeta st}}$$

$\Delta\zeta < 0$ - POGO loop stable

$\Delta\zeta > 0$ - POGO loop unstable

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Criteria for Stability of the POGO Loop

1) POGO cycle is stable if the probability of a positive damping safety factor is less or equal 2.2%, i.e.:

$$\Pr\left(\Delta\zeta > 0\right) \leq 0.022 \qquad \text{or:} \qquad \Delta\bar{\zeta} + 2\sigma_{\Delta\zeta} > 0$$

2) Time interval for which $\Delta\zeta > 0$ is limited to:

$$\int_{t1}^{t2} \omega\left(\Delta\bar{\zeta} + 2\sigma_{\Delta\zeta}\right) dt \leq \ln\frac{\Gamma_m}{\Gamma_0}$$

t_1 , t_2 $[s]$ - beginning and the end f the time interval for which $\Delta\zeta > 0$

ω $[s^{-1}]$ - angular frequency of the identified mode;

Γ_m $[ms^{-2}]$ - maximum amplitude allowed

Γ_0 $[ms^{-2}]$ - amplitude of the noise

Figure 1

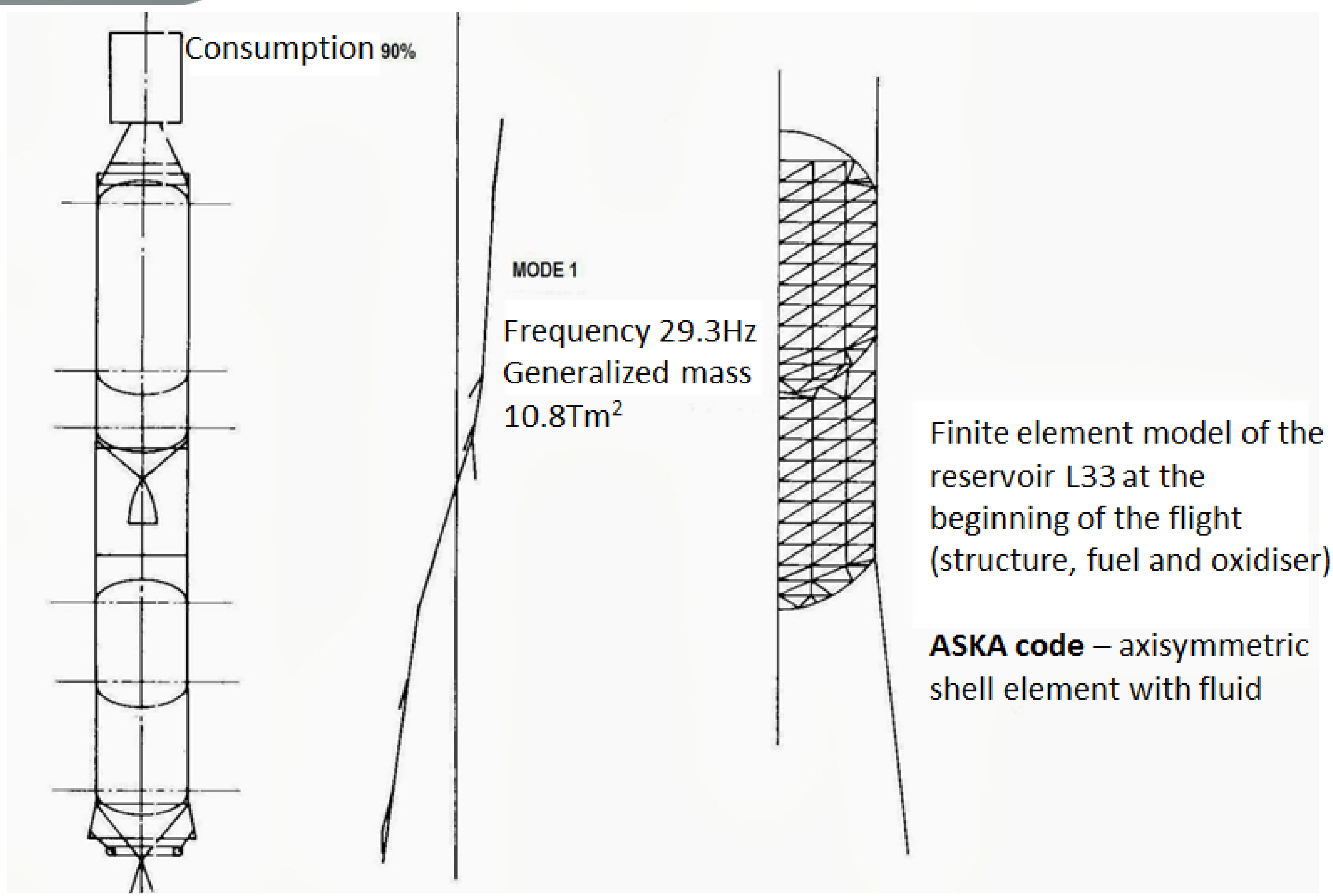
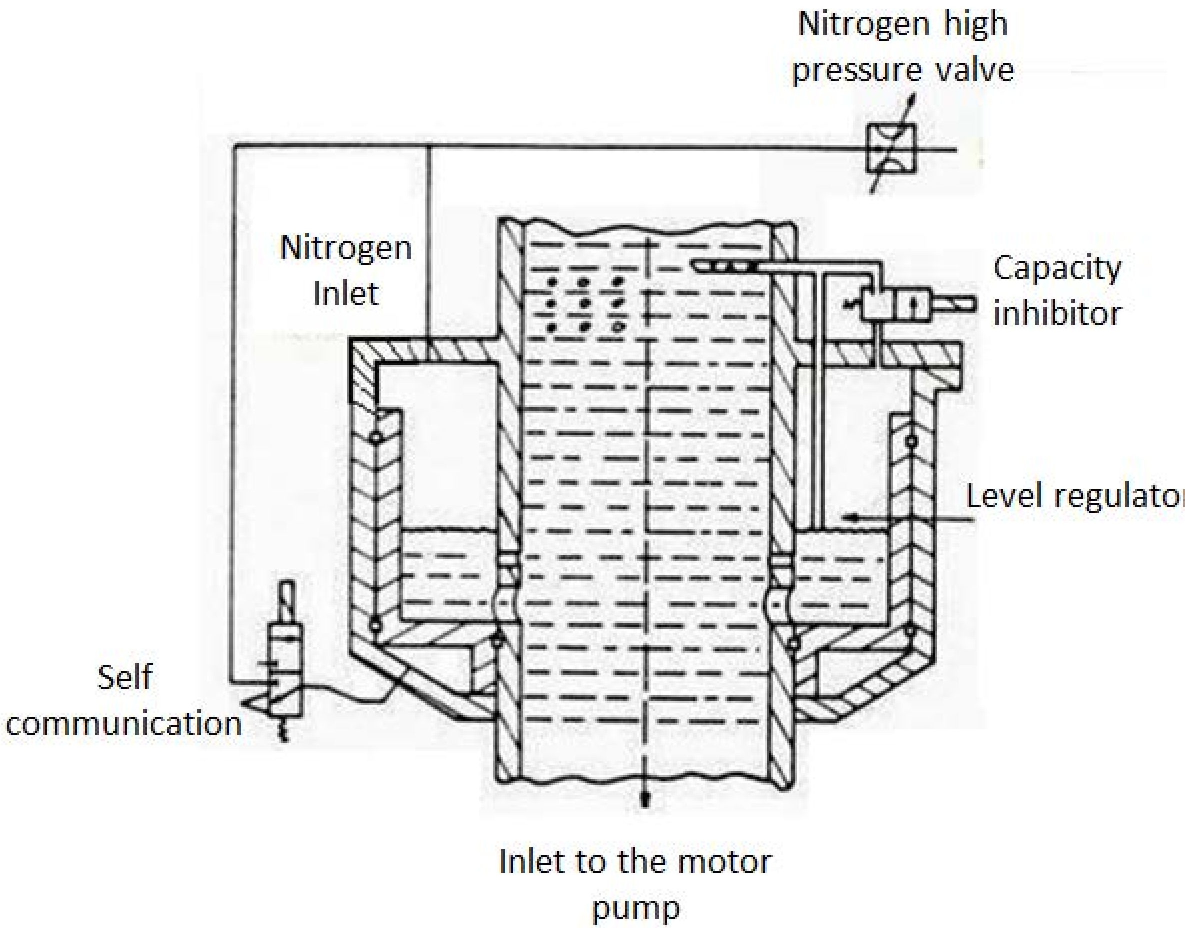

Consumption 90%
MODE 1
Frequency 29.3Hz
Generalized mass
10.8Tm^2
Finite element model of the reservoir L33 at the beginning of the flight (structure, fuel and oxidiser)
ASKA code – axisymmetric shell element with fluid

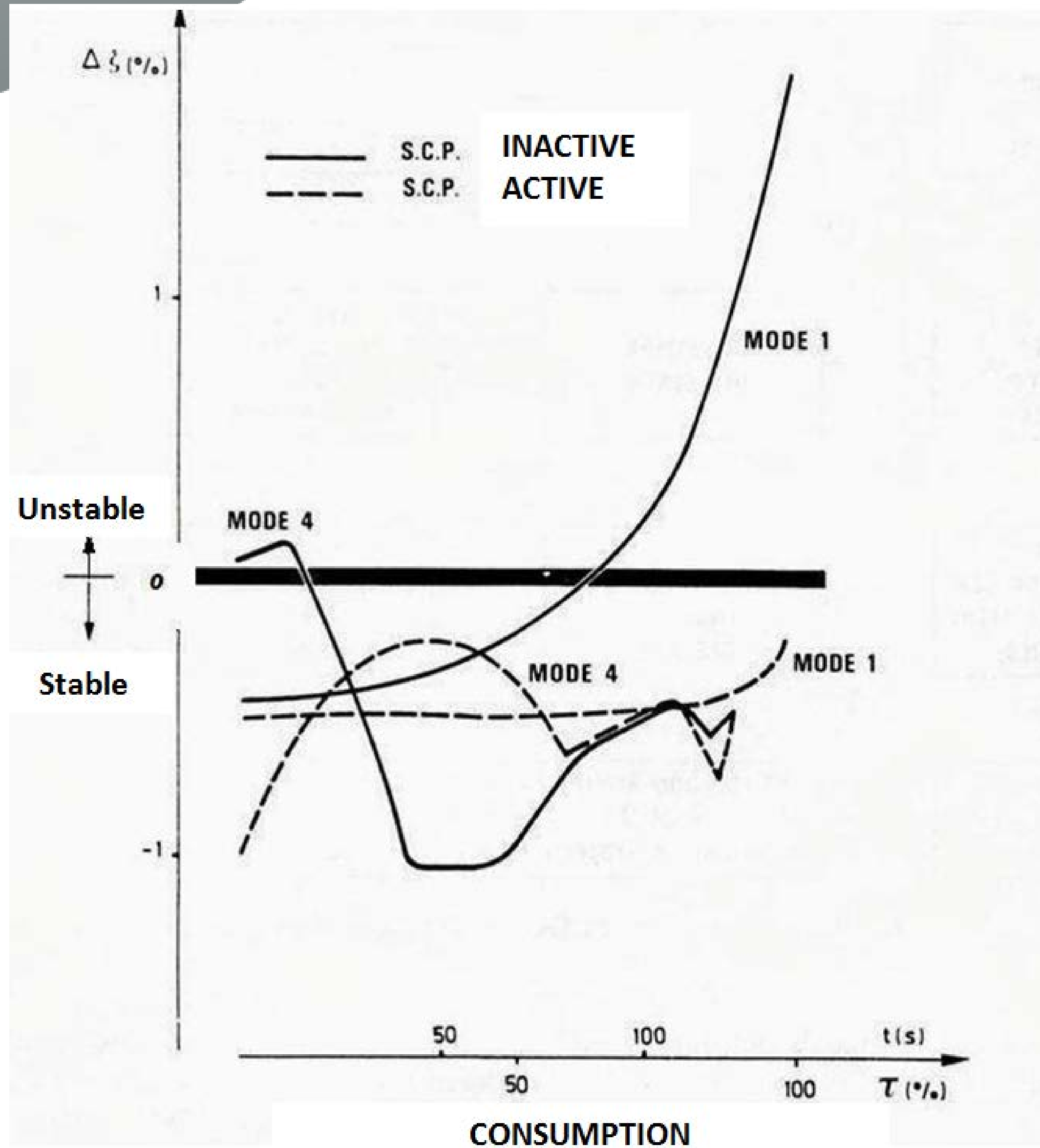
Figure 2


Nitrogen high pressure valve
Nitrogen Inlet
Capacity inhibitor
Level regulator
Self communication
Inlet to the motor pump

Loop POGO ARIANE 1

Figure 3

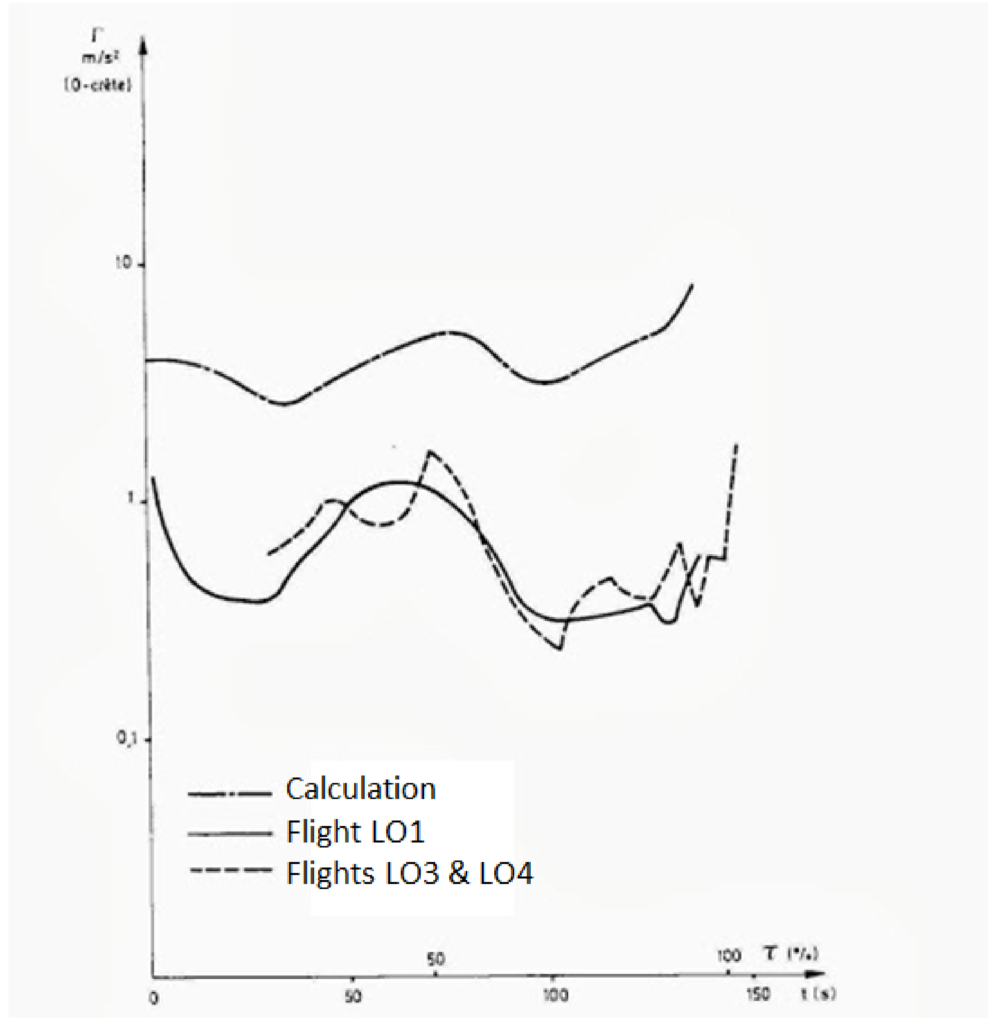
First stage POGO



Loop POGO ARIANE 1

Figure 4

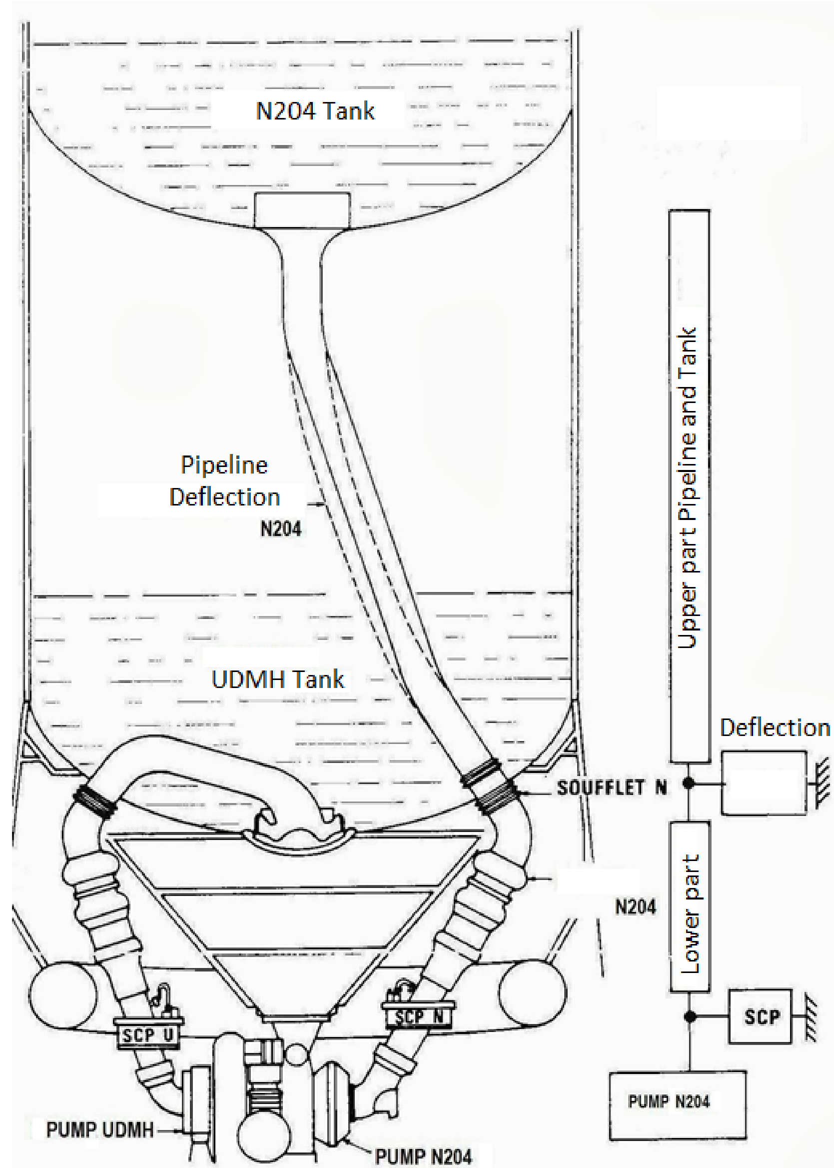
First stage POGO



Vibrations of the motor drive shaft

Loop POGO ARIANE 1

Figure 5



Loop POGO ARIANE 1

Figure 6

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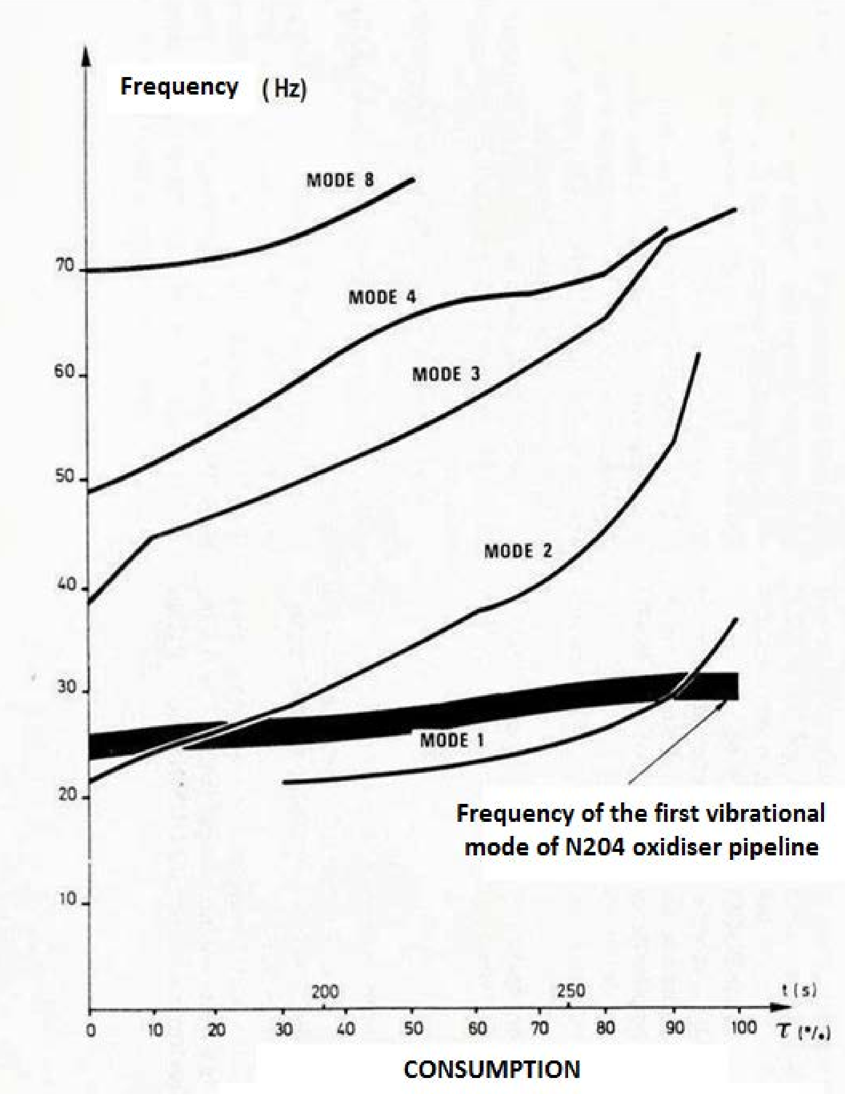
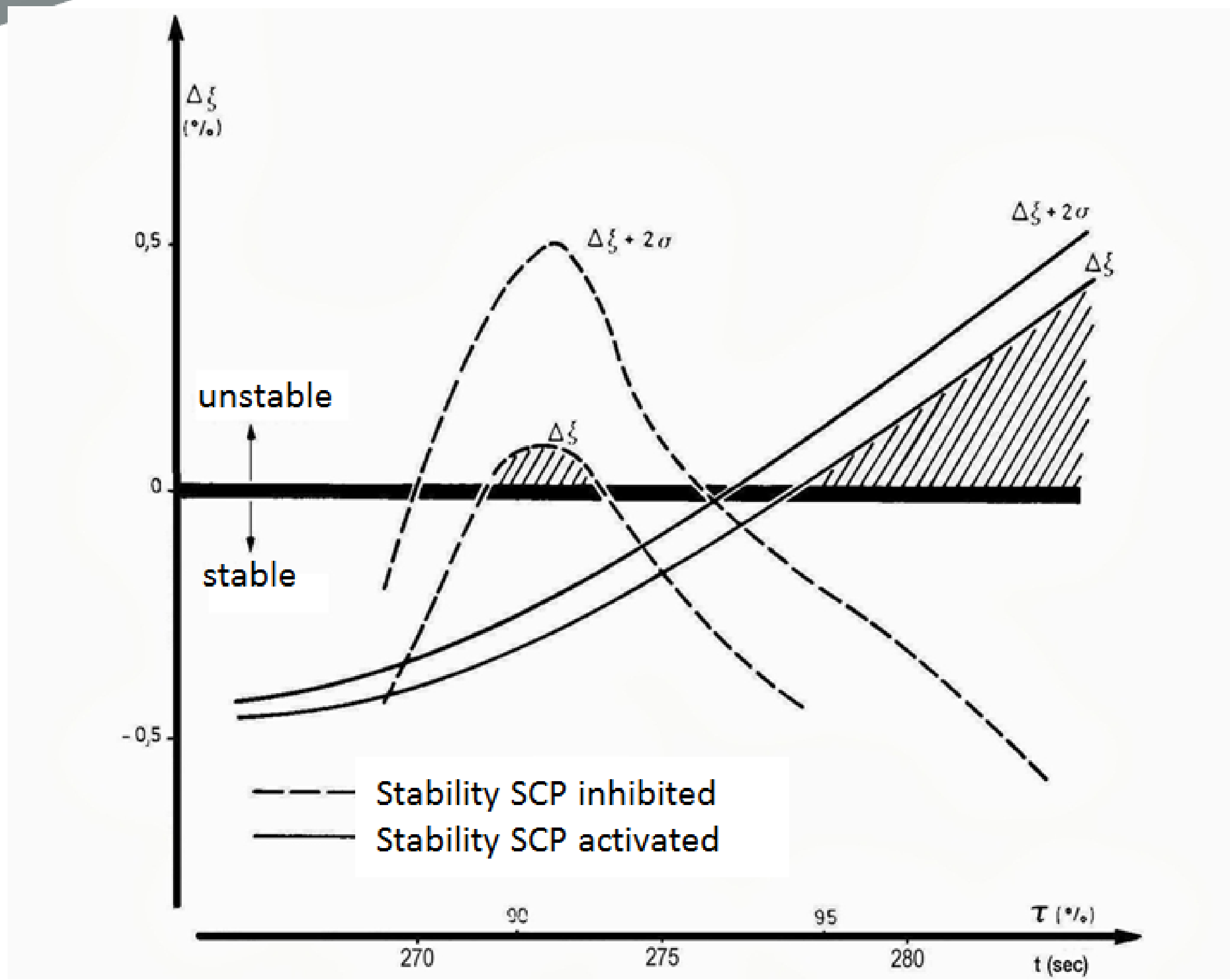
Frequency of the second stage POGO



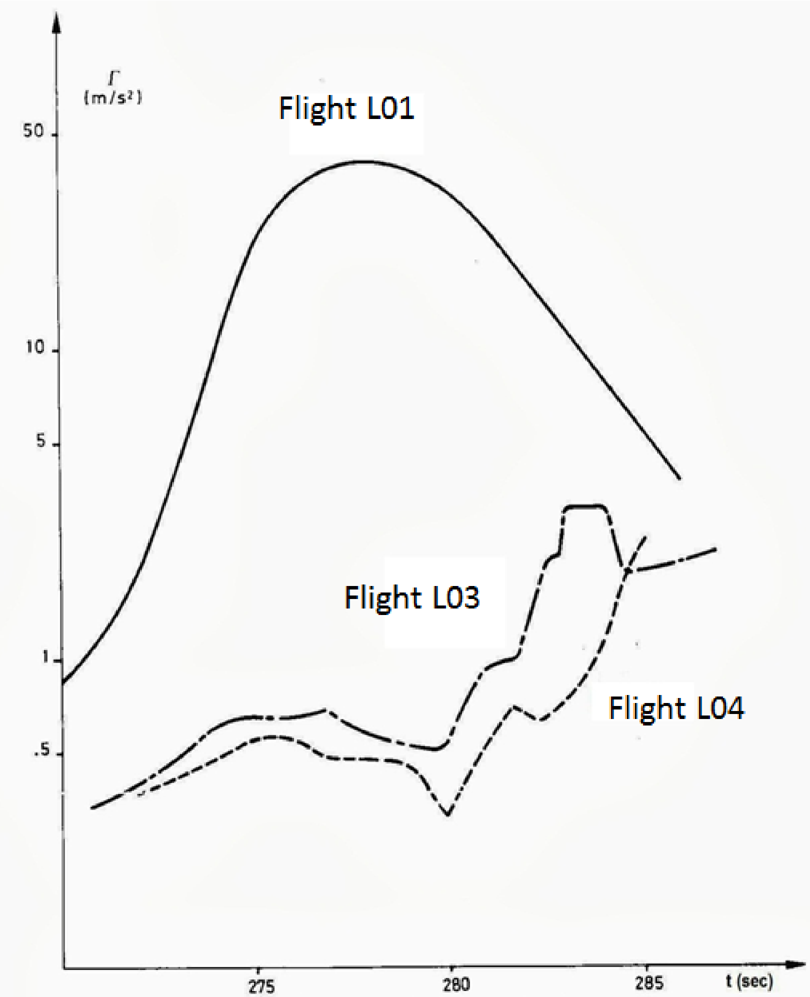
Loop POGO ARIANE 1

Figure 7



Loop POGO ARIANE 1

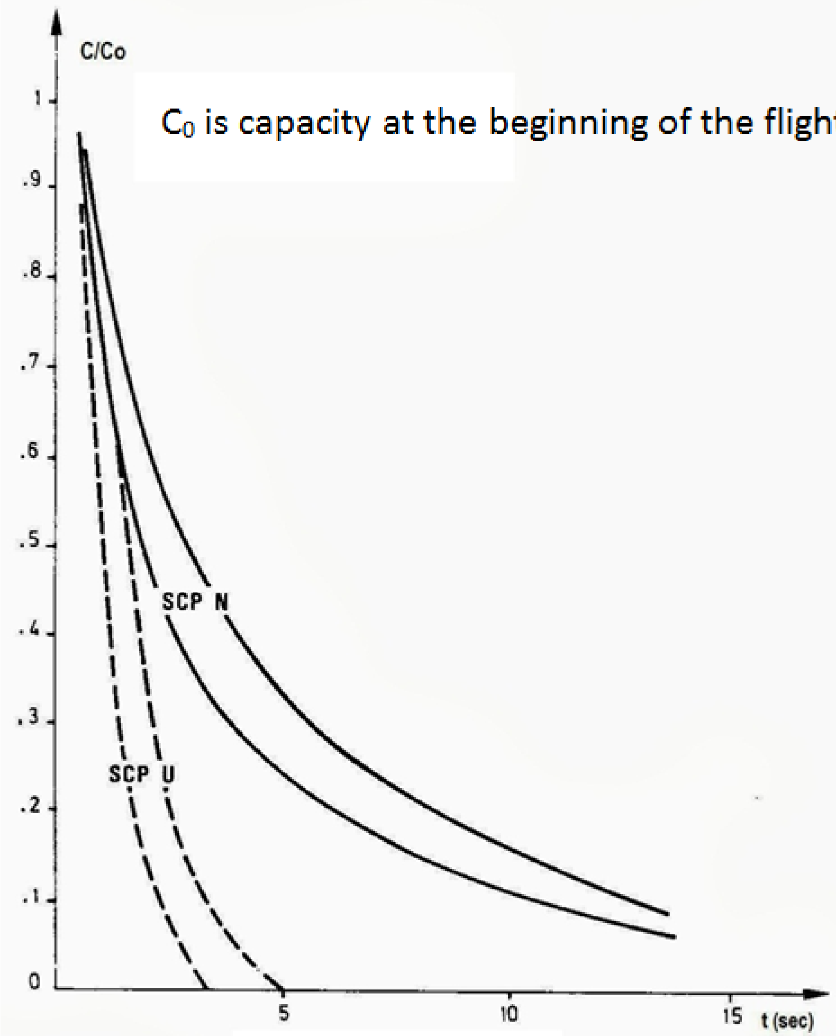
Figure 8



Vibrations of the motor drive shaft by the end of the flight L33

Loop POGO ARIANE 1

Figure 9

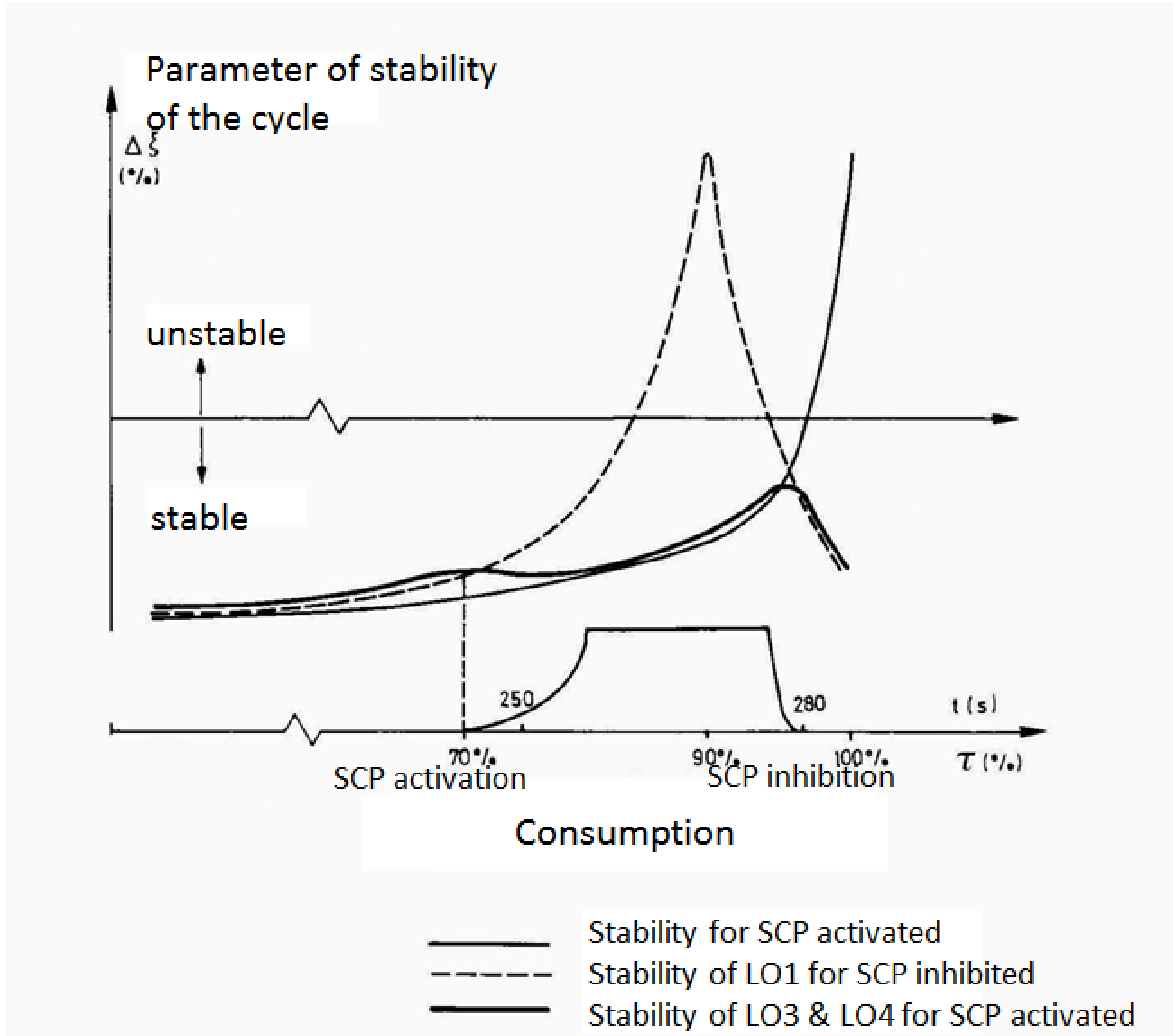


C_0 is capacity at the beginning of the flight

Inhibition size SCP

Loop POGO ARIANE 1

Figure 10



Loop POGO ARIANE 2, ARIANE 3 and ARIANE 4

- the upper parts of three launchers (L33 and H10 stage) are perfectly identical

- In the first synthesis POGO ARIANE 3, it turned out that the sequence of switching on SCP used for operational flying ARIANE 1 would not work for the flight of ARIANE 3 second stage (or second stage of ARIANE 2 flight). The upper mass of 2500 kg on the third stage and 2400kg payload caused a decrease of frequency of the first mode to the end POGO theft L33 some 1.6 Hz

Loop POGO ARIANE 2, ARIANE 3 and ARIANE 4

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- It follows that the intersection between the frequency of N2O4 online and POGO first mode occurs at 93% of consumption of propellant, so just 10 seconds before the end of the flight. It seemed obvious that the sequence of SCP, held to stabilize the loop L33 POGO during the flight of ARIANE 1, would not have the desired effect on the end L33 of the flight ARIANE 3.
- Setting the SCP had reached its limits
- The findings of the first synthesis POGO Ariane 3 confirmed settings and sequences to the first stage L140 and advocated stiffening of N2O4 on line L33 in order to completely decouple the bending mode of the line of the first mode POGO launcher.

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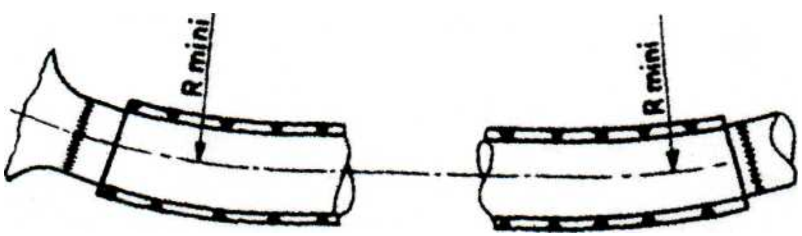
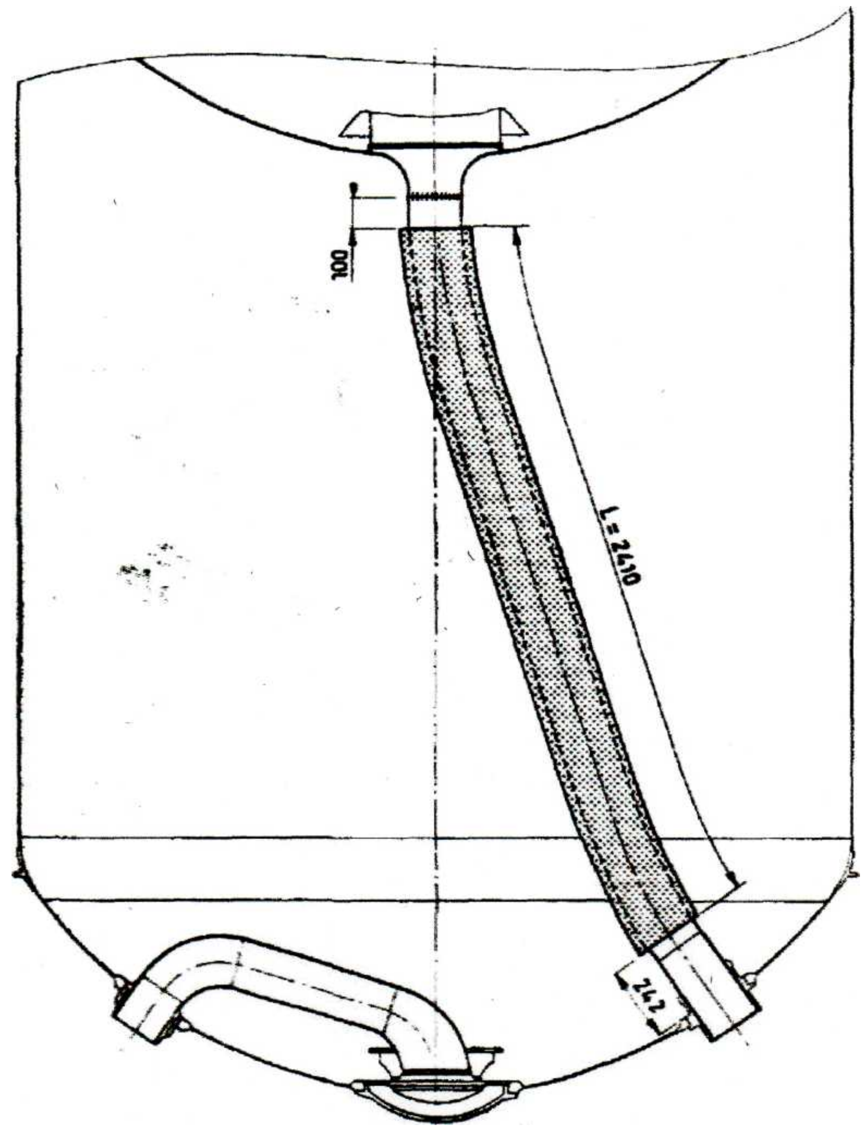
Changes of Hydraulic Engine Model for ARIANE 2, ARIANE 3 and ARIANE 4 (including dispersions)

- Change the type of propellant (UDMH + Hydrazine Hydrate 25%);
- Changing the pressure of the combustion chamber;
- Changing the operating point of the engine characteristics (residence time, ignition delay) and pump N204 (NPSP phase of capacity);
- **Parametric studies** of the stability of second stage POGO showed that the decoupling between the first mode POGO at the end of the flight and the line stiffened N204 will be available provided that the frequency thereof is at least 35 Hz (E ~ 23800MPa). For a material such as duralumin (E ~ 70 000 MPa) the frequency of the solid line and stiffener was around 57 Hz!

Loop POGO ARIANE 2, ARIANE 3 and ARIANE 4

Figure 11





Loop POGO ARIANE 2, ARIANE 3 and ARIANE 4

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- One might conclude that the problem has been solved by the stiffening of the N204 line and the use of SCP was not necessary.
- Nevertheless, these findings had to be confirmed by a frequency test of the full-scale N204 line, both stiffened and unstiffened.
- These tests were conducted by a company, manufacturer of L33 tank. Unfortunately, the results were not particularly useful. The major campaign ended in failure.
- Given the constraints of schedule, it was not possible to repeat these tests and, despite the very encouraging results of calculation, it was not possible to delete the SCP.
- **Taking the risk, albeit small, to fail during an operational flight was ruled inadmissible**.

Conclusions

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- All flights ARIANE 1 (11), ARIANE 2 (6), Ariane 3 (11) and Ariane 4 (116) are going **without** the occurrence of the phenomenon POGO
- Total number of 144 flights
- The ARIANE launchers are deemed, for the dynamic environment imposed on the payload, very little binding