The last mystery of Soviet lunar rocket

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Just seven seconds were missing in the last launch for second stage ignition and continue the flight that could have changed fate of N1!
B. Chertok

Summary

This paper demonstrates that catastrophic explosion of Soviet N1 lunar rocket during final phase of first-stage boost during the fourth launch was caused by the occurrence of an auto-oscillating Pogo process with hydroacoustic oscillations in oxygen supply lines to outer ring engines. The oxygen supply lines to inner ring engines were equipped with dampers that suppressed this type of auto-oscillations, which is the only reason that these rockets 3 times weren't exploding at the very beginning of the flight. However, similar dampers weren't installed in the oxygen supply lines to the outer ring engines because both project decision-makers and their consultants failed to understand that positive feedback between hydroacoustic and elastic oscillations, leading to Pogo, is possible not only at resonance of their frequencies but also at their multiple ratios.

In this regard, it is obvious that if a fifth launch of the modernized N1 rocket with NK-33 engines had been carried out, it would have ended with the same explosion as the fourth.

Key words: *N1 rocket, fourth flight, longitudinal auto-oscillations, Pogo, resonance, multiplicity*

I. Introduction

As is well known, between February 21, 1969 and November 23, 1972, four launches of Soviet super-heavy lunar rocket N1 were carried out [1]. All of them ended in failure, and during the second launch on July 3, 1969 (17 days before the first landing on the Moon by American astronauts on lunar module Eagle of Apollo 11 spacecraft [2]), launch pad was destroyed, and adjacent one, located at a distance of 1.1 km, was noticeably damaged [3].

The primary cause of N1 rocket's maiden launch accident has previously been attributed to failures of highly innovative, but then insufficiently tested NK-15 engines. On 6th and 25th seconds into the flight, vibration caused the measuring tubes of hot oxidizer gas pressure sensors downstream of gas generator and fuel pressure sensor upstream of it to break off. A cloud of combustible mixture formed in the rocket's tail section, igniting on 55th second into the flight. A fire broke out, and at 68 seconds, the insulation in cable network was damaged, causing interference from power cable to reach the cables of the measuring channels of the engines operation, diagnostic, and shutdown (KORD) system. Due to the false signal, KORD system immediately shut down all 28 first-stage engines that were operating at that point, and the rocket fell, exploding upon impact with the ground [4]. Recently, the occurrence of such strong vibrations, which cause the measuring tubes on the engines to tear off, began to be associated with auto-oscillations of Pogo type [1], but no evidence has been found for this assertion. Moreover, as is known, in pre-flight testing, means for suppressing such auto-oscillations were installed on N1 rocket's fuel lines [5].

During second launch on July 3, 1969, as accident committee concluded that the cause of the accident was destruction of oxygen pump in outer ring engine no. 8. This engine exploded when entering operating mode, 0.25 seconds before the rocket lifted off from the launch pad. The remaining engines operated some time, and the rocket lifted off. However, after 12 seconds, KORD system shut down all but one engine – outer ring engine no. 18 – and on the 23rd second, the rocket crashed onto the launch pad and exploded [4].

During third launch on June 27, 1971, all 30 first-stage engines fired for a significant period of time for the first time. Furthermore, as was definitively established from much later studies (completed by 2000), the stable state of system of supersonic jets from 24 N1 engines of the outer ring is a configuration with helical symmetry [5]. As a result, the rocket experienced a roll moment (moment of rotation around the longitudinal axis) during the third flight that exceeded roll capabilities of steering nozzles. Because of this rocket's rotation speed exceeded permissible limits, and KORD system shut down all engines at 50th second, after which the rocket fell to the ground and exploded.

Before fourth and final launch of N1 rocket on November 23, 1972, everything possible was done to ensure success. However, after the longest flight, a few seconds before the scheduled shutdown of the outer ring engines (the inner ring engines had already been shut down by that time), an explosion occurred, "more intense" than even that in the first flight [4]. However, no clear explanation for the incident followed. Chief Designer of N1 complex, V. P. Mishin, and Chief Designer of NK-15 liquid-propellant rocket engines, N. D. Kuznetsov, wrote a letter to General Secretary of CPSU Central Committee, L. I. Brezhnev, in which the following was stated about the accident: "... it occurred as a result of structure's vibration, accompanied by additional, alternating loads acting on the pipelines, rocket units and their assemblies at the end of their designated service life, which could have led to their subsequent destruction..." [5]. In this phrase, which is the quintessence of political nature compromise of two Chief Designers, literally everything is wonderful: the vibrations of the structure that appeared out of nowhere, the alternating loads (and are there any other ones during vibrations?), which "could" but, perhaps, "couldn't" lead to the destruction of pipelines, units and assemblies of the rocket, and the unprecedented "designated service life", slightly exceeding a hundred seconds.

As a result, the following year, Soviet N1-L3 lunar flight program was canceled, and N1 rocket project, its blueprints, and all documentation were destroyed. An order was also given to destroy several dozen completed NK-33 rocket engines – already made and tested, improved, reusable version of NK-15 engine. However, they were hidden [6], and 40 years later, they were successfully used on new Russian and American launch vehicles [7, 8].

II. Description of key events that took place during the fourth flight of N1 rocket

So, the causes of N1 rocket's fourth flight failure weren't identified either immediately afterward or much later. Even 42 years after these events, one of the active and competent participants in them continued to be perplexed: "...all the calculations independently conducted at the time at OKB-1, NII TP, and TsNIIMash, taking into account the presence of these devices [dampers], led to the unambiguous conclusion about the stability of the closed system of hull – liquid in the lines – liquid propellant rocket engine throughout the entire flight of the rocket's first stage. Nevertheless, what happened, happened…" [5]. This was written 20 years ago, and since then no new explanations have emerged for that now distant catastrophe – the final mystery of Soviet lunar rocket remains unsolved.

However, in connection with the fact that N1 tragedy repeats over the past three years, perhaps even as a farce, during tests of the even larger and more complex Starship reusable rocket system, an integral theory of Pogo-type auto-oscillations was developed immediately after its first launch [9]. And after the necessary factual data on N1 rocket fourth flight and its design had been collected, and after applying this theory to them, it took only two to three days to solve the mystery, that is, to understand what happened then, in November 1972.

First, let us describe what happened during this flight using two of the most complete and authoritative sources:

1. Up to 107th s, the first stage flight proceeded normally, except for undamped longitudinal oscillations of the hull and pressure in the combustion chambers of the engines, which appeared starting approximately 50th s into the flight [5].
2. "According to data from some longitudinal acceleration sensors located near the head unit, the oscillations had the following nature: their frequency was approximately 6 – 7 Hz, being close to the frequency of the first tone of the hull's own longitudinal oscillations, and the amplitude gradually increased: at 70th s it was approximately 0.3 g, and at the moment of engine explosion – 0.6 g" [5].
3. At 94.5th s, the six central engines of block "A" (first stage) were shut down according to the flight program [4].
4. Flight mode didn't undergo any fundamental changes after the shutdown of the six central (inner ring) engines [5].
5. At moment of time 106.93 s, "nothing abnormal was detected" for all 24 peripheral (outer ring) engines [4].
6. At 107th s, one of the liquid-propellant rocket engines exploded, leading to the almost instantaneous destruction of the hull structure [5]. This was outer ring engine no. 4, the time of "impact" – 106.97 s [4].
7. From moment of time 106.9 s, first stage telemetry recorded a sharp drop in pressure in the oxidizer and fuel tanks at the last moment before its shutdown [4].
8. The explosion of rocket was "more intense" than during the first flight of N1 no. 3L on February 21, 1969 [4].
9. "The rocket flew without any problems for 106.93 s, but 7 s before the estimated time of separation of the first and second stages, the oxidizer pump of engine no. 4 suffered an almost instantaneous destruction, which led to the destruction of the rocket" [4].

Let us now consider some characteristics of systems and units of N1 rocket that are important for further investigation.

III. Values of parameters determining the process of auto-oscillations

Next, we will explicitly define all the data necessary to construct a numerical model of the process that led to the explosion and the destruction of N1 rocket in the fourth flight:

1. Length of the sections of the liquid oxygen supply pipelines was approximately 3 m for the inner ring engines and approximately 7 m for the outer ring engines of the first stage, see Fig. 1, which is a fragment of the image given in the paper by Chief Designer of N1 rocket V. P. Mishin [10]. The oxygen tank, unlike typical rocket configurations, is located at the bottom; the distance between axes of the outer ring engine nozzles, which is 14.0 m, was used as a scale [4].

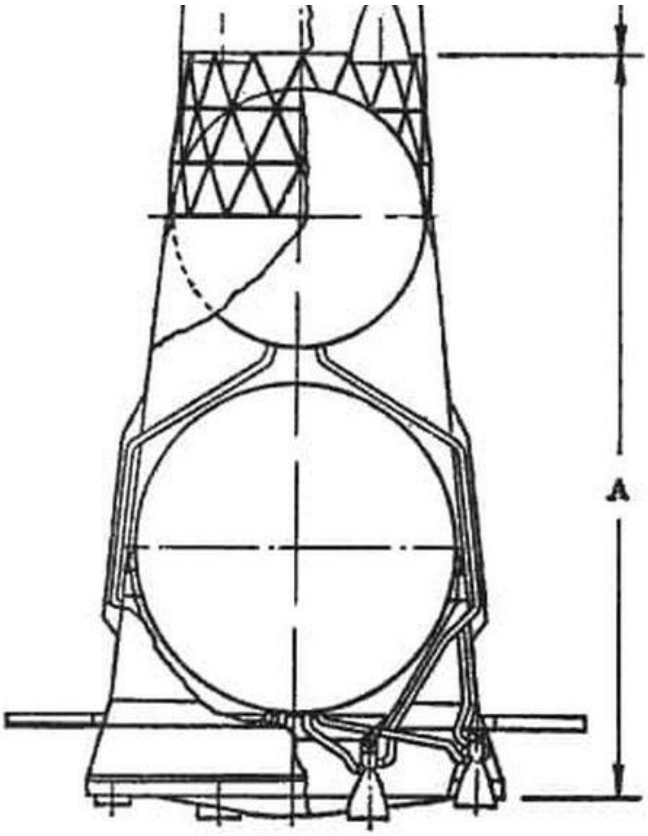

Fig. 1 – Images of the fuel lines of N1 rocket first stage

2. The length of the pipeline from the oxygen pump to the oxidizer gas generator of NK-15/33 engine was 1.5 – 1.6 m, see Fig. 2, compiled from two images presented in sources [11, 12].

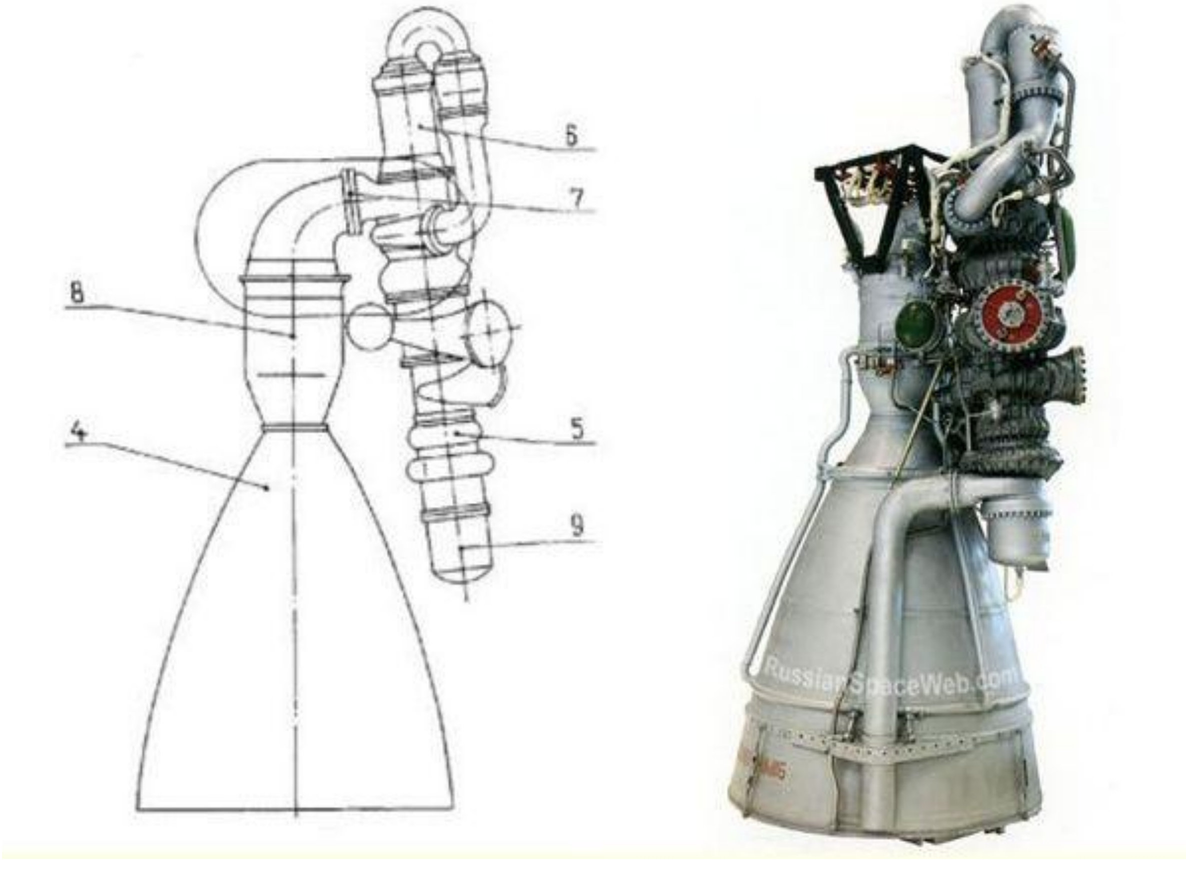

Fig. 2 – Scheme and appearance of NK-15/33 engine

Scheme (left side of the figure) shows the following positions: 4 – nozzle, 5 – turbopump assembly (TPA), 6 – gas generator, 7 – junction of main combustion chamber with the TPA, 8 – combustion chamber axis, 9 – TPA axis.

The oval shows pipeline that supplies hot gas from outlet behind TPA turbine to the main combustion chamber, as well as upper (outlet) part of oxygen pump and the turbine that drives it and kerosene pump located below. In this case, high-pressure oxygen from the pump enters the gas generator through a pipe located at the top of the engine structure, which is highly curved in two planes, the length of which, based on the two images shown in Fig. 2, was estimated as indicated above. In this case, diameter of the nozzle exit was used as a scale – 1.49 m [11]. In the right figure, the outlet from the pump is clearly visible, and below it is the inlet to it, closed by a red cap.

3. The combustion chamber pressure of NK-15/33 engine was 14.8 MPa [11], and the pressure behind the oxygen pump was estimated based on data for BE-4 and RD-170 engines, which operated in the same configuration with an oxidizing gas generator. At the same time BE-4 had a lower combustion chamber pressure than NK-15/33 (13.4 MPa), while RD-170/171 had a higher pressure (24.5 MPa) [13]. As a result, the pressure behind NK-15/33 pump was estimated at 33.5 – 34 MPa.

4. The pressure in the first stage spherical oxygen tank was lower than typical for rockets of that time [14], that is, no more than 0.25 – 0.3 MPa.

5. During fueling, the oxygen in the main tank was supercooled to a temperature of 82 K [4].

6. "The pressurization systems for the tanks of all blocs [of N1 rocket] were identical. The oxidizer tanks were pressurized with acid gas bled from the gas generators. The fuel tanks were pressurized with helium gas contained in the launch vehicle gas cylinders and heated in the engine heat exchangers" [14].

7. The boiling point of liquid oxygen at a pressure of 0.25 MPa is 100 K [15].

IV. Construction of Pogo-type auto-oscillations numerical model in the fourth flight of N1 rocket

From paragraphs 1 – 4 and 9 of Section II, it follows that, no later than the end of the first half of the first stage's boost phase, N1 rocket began experiencing increasingly intense longitudinal oscillations, close to the frequency of the first tone of the hull's own oscillations, accompanied by similar pressure fluctuations in the engine combustion chambers. The frequency of these oscillations gradually increased over time, as the rocket mass decreased due to fuel consumption, and the frequency of elastic oscillations of a structure is, to a first approximation, inversely proportional to the square root of its mass. The amplitude of the oscillations also increased until they led first to the destruction of the oxidizer pump in the first stage's outer ring engine, then to the explosion of that engine, and ultimately to the explosion of the entire rocket. Since the oxygen pump had been destroyed, it means that pressure fluctuations were in the oxygen supply lines to the outer ring engines (the inner ring engines had already been shut down).

Generally speaking, this is a typical picture of the external manifestations of the process of emergence and development of Pogo auto-oscillations. Exactly the same thing was stated by B. I. Rabinovich — famous Soviet/Russian specialist in the field of dynamics of elastic solids interacting with liquids, who headed the dynamics laboratory of NII-88 (TsNIIMash) from 1960 to 1974 [16], who for at least three decades tried to understand why N1 rocket no. 7L perished during the fourth launch. In 2006, he wrote: "Isn't it true that this is alike as two peas in a pod with POGO-type oscillations observed at the end of the first stage flight on Saturn V AS-502...?" [5].

Indeed, during the final seconds of Saturn V rocket's AS-502 first stage combustion, the oscillation amplitude reached the same level – ± 0.6 g; one of the four panels of adapter housing lunar module mockup was lost; the fuel systems of the second and third stages were damaged, which led to an incomplete fulfillment of the flight program [17]. However, there were still differences. Saturn V rocket's AS-502 first stage, launched on April 4, 1968, fully accomplished its task delivering second and third stages and the payload to the calculated point of the trajectory, despite the fact that no Pogo suppression measures had been taken on it prior to the launch; and N1 rocket no. 7L perished despite the fact that its oxygen supply lines to the engines contained Pogo suppression dampers. It seems that providence was on the side of Wernher von Braun, not Sergei Korolev.

We will apply the integral theory of Pogo-type auto-oscillations and, based on it, calculate several possible auto-oscillation scenarios for N1 rocket, corresponding to extreme values of the parameters determining this process. From paragraph 2 of Section III, it follows that the length of the oxygen pipeline from the pump to the gas generator L_1 = 1.5 – 1.6 m, and from paragraphs 3 and 4, that the ratio of the pressure at the outlet and inlet of the oxygen pump at the nominal operating mode of NK-15/33 engines is p_2/p_1 = 115 – 135.

Let's consider the frequency of hydroacoustic oscillations at N1 rocket's launch and immediately before its explosion. We'll assume that their frequency is the same as that of the elastic oscillations of the hull and is equal to f_n = 6.00 Hz in the first case and f_n = 7.00 Hz in the second.

At the start, the temperature of supercooled oxygen is 82 K (see paragraph 4 of Section III), and according to source [15], the average speed of sound in the pressure range of 0.25 – 35 MPa is $c \approx 950$ m/s. Then, with a pressure ratio on the pump of 115, it turns out that the length of the oxygen supply line should be from 3.45 to 3.65 m, which significantly exceeds the specified value of $L_2 \approx 3$ m, see Table 1. And, with a pressure ratio of 135, excellent agreement between the calculated and a priori values of L_2 is observed. Moreover, if the practically average value of L_1 = 1.56 m from the range under consideration is adopted, then the agreement of all process parameters is practically ideal. It is clear that the pressure in the oxygen tank of N1first stage should be close to 0.25 MPa.

So, if during the process of ground testing of the rocket, "the devices proposed by I. M. Rapoport, which were a combination of a hydraulic accumulator and a damper" [5] hadn't been inserted into its oxygen lines, then already at the launch, all copies of N1 rocket would have exploded due to the occurrence of Pogo on the engines of the inner ring, see the fourth row from the first group of rows of the table at a frequency of f_n = 6.00 (parameter L_3 is the sum of the lengths of sections L_1 and L_2, that is, the full length of the hydroacoustic oscillatory circuit, L_{eq} is the length of the equivalent circuit with the same frequency at the same speed of sound c, but without a pressure break on its wave).

Table 1

Rocket Stage Engine	**p_2/p_1**	**L_1 (m)**	**L_2 (m)**	**L_3 (m)**	**L_{eq} (m)**	**f_n (Hz)**
N1 First Stage NK-15	**c = 950 m/s**					
	115	1.50	3.65	5.15	39.6	**6.00**
		1.60	3.43	5.03		
	135	1.50	3.12	4.62		
		1.56	**3.00**	4.56		
		1.60	2.92	4.52		
	c = 845 m/s					
	135	**1.56**	**3.00**	4.56	39.6	**5.34**
	115	1.50	8.42	9.92	60.4	**3.50**
		1.60	7.91	9.51		
	135	1.50	7.20	8.70		
		1.56	**6.93**	8.49		
		1.60	6.76	8.36		
	c = 950 m/s					
	135	**1.56**	**6.93**	8.49	60.4	**3.94**

Immediately before the explosion, the temperature of small residues of cryogenic oxygen in the first stage tank must have significantly exceeded the starting temperature T ≈ 82 K due to its displacement process by hot gas taken from the gas generators. It is known that still on R-9A, the first rocket fueled by supercooled oxygen, design documentation included an operational range of oxygen temperature at the engine inlet from the initial temperature of 88.5 K to the boiling temperature of 100 K [18]. As shown above, the pressure in the oxygen tank of the first stage of N1 was about 0.25 MPa, and from paragraph 7 of Section III it follows that at this pressure the boiling temperature of liquid oxygen is also 100 K. Thus, the speed of sound in liquid oxygen before the explosion of N1 must have been close to c = 845 m/s [15].

Let's calculate the required oxygen line length to generate hydroacoustic oscillations at this sound speed with half the known frequency f_n = 7.00 Hz. For a pump pressure ratio of 115, the oxygen supply line length must be between 7.9 and 8.2 m, which significantly exceeds the supply line length L_2 ≈ 7 m for the outer ring engines, see Table 1. And, for a pressure ratio of 135, excellent agreement between the calculated and a priori L_2 values is again observed, and again, especially for L_1 = 1.56 m, see the fourth row of the second group of rows in Table 1 at a frequency of f_n = 3.50.

Thus, we observe a matching of frequencies of hydroacoustic oscillations and own frequencies of the hull elastic oscillations with a factor of 2, which demonstrates the possibility of starting a process of Pogo-type auto-oscillations under such parameters. It is surprising that B. I. Rabinovich, who headed the dynamics laboratory at NII-88 (TsNIIMash) until the closure of Soviet lunar project, for many decades, as well as all them the probably dozens of people involved in analyzing the possibility of inducing auto-oscillations of Pogo-type in N1 rocket, even after the accident in the fourth flight, didn't come up with the simple, if not trivial, idea of the multiplicity, and not just the resonance of frequencies of two types of oscillations that together create an auto-oscillation process of Pogo-type! And 34 years after the disaster, Professor of Russian Academy of Sciences Space Research Institute Rabinovich wrote with visible despair: "And this [N1 rocket explosion on the fourth flight] happened despite the fact that the frequencies of the corresponding partial systems were no longer "close"!" [5]. Yes, "the frequencies of the corresponding partial systems were no longer close", but they were multiples – 7 and 3.5 Hz, and the gradual heating of the initially supercooled oxygen made it possible to achieve, with good accuracy, both a resonance of these frequencies at the start on the inner ring engines, and a multiplicity of 2 at the finish on the outer ring engines, with the corresponding consequences. But after all the excitation of processes of a similar type at multiples is known well in other areas of technology!

Two separate rows in Table 1 show what the hydroacoustic oscillation frequency would have been on the inner ring engines before the explosion if they hadn’t been shut down by that time – f_n = 5.3 – 5.4 Hz, which is ~25 % lower than the own elastic oscillation frequency of the hull – 7 Hz, and what this frequency was on the outer ring engines at launch – f_n = 3.9 – 4.0 Hz – 30 % higher than half the elastic oscillation frequency. So, on these modes, Pogo variants opposite to those being implemented would be completely impossible even without any measures to suppress them.

Finally, from all of the above, it follows that if a fifth launch of modernized N1 rocket with NK-33 engines had been carried out, it would have ended in the same explosion as the fourth. God wasn't on Soviets side in the Moon race.

Conclusions

1. Catastrophic explosion of Soviet N1 lunar rocket during the final phase of first-stage boost during its fourth flight was caused by an auto-oscillating Pogo-like process with hydroacoustic oscillations in the oxygen supply lines to the outer ring engines.
2. All three N1 rocket flights that didn't end in explosions directly over the launch pad were possible only because dampers were installed in the oxygen supply lines to the inner ring engines, reducing the frequency of hydroacoustic oscillations and thereby suppressing Pogo-like oscillations.
3. Similar dampers weren't installed in the oxygen supply lines to the outer ring engines because neither the rocket designers nor the damper developers understood that positive feedback between two oscillation channels, leading to Pogo-like oscillations, is possible not only at frequency resonance but also at multiples of frequencies.
4. Moreover, this idea apparently remained inaccessible to them to this day.
5. In connection with this, it is obvious that if a fifth launch of upgraded N1 rocket with NK-33 engines had been conducted, it would have ended with the same explosion as the fourth.
6. The gradual transition of liquid oxygen in the first-stage tank from a supercooled state to a near-boiling state due to displacement process by hot gas taken from the engines gas generators contributed to a more precise matching of the oscillation frequencies of both channels, which caused as a result catastrophic development of Pogo in the oxygen supply lines to the outer ring engines at the end of N1 rocket's first-stage boost.

Links

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