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# RESULTS OF THE FIRST STAGE DEVELOPMENT FOR THE ROMANIAN ORBITAL LAUNCHER NERVA

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## ABSTRACT

The NERVA small satellite launcher is under development in Romania and has recently been sponsored by the research authority CNMP under the contract no. 82076. The target of the project is to achieve a launching capability for a payload of up to 4 kg, into a low Earth orbit of 100 miles, at 45 degrees inclination with the equator. The research is first focused on the development of the booster stage of the space launcher during the year 2009 and 2010. The development of this first stage of the NERVA vehicle is presented, consisting of a cluster of three small size, identical solid rocket motors with an individual sea level thrust of 600 kN. The program is targeted at achieving the launch capability with minimal modifications of the obsolete military source vehicle, of its launch platform and of its logistics. This target posed severe design problems regarding the reliability of the solid motor cluster and regarding the compulsory modifications of the launching platform, consistent with the given requirements. The design condition is focused on preserving the present technology of the solid rocket engine unchanged and to only modify the geometry of the exhaust nozzle in order to accommodate the clustering requirements. Although a major improvement would have been introduced by the redesign of the propellant grain geometry and its manufacturing technology, the first series of experimental developments is only focused on collecting statistical data on the present grain configuration, relevant for the thrust balancing of the triple-booster construction. Statistical tests are being performed with the cluster in a minimal configuration and flight engine performance data are collected during a series of experimental launches of the single stage version of the NERVA vehicle into the Romanian research facility during the spring of 2009. The level of the actual thrust into the real flight and the combustion instability due to propellant fragmentation are addressed during the real flight tests. The initiation phase of the ignition and the first transient combustion of the grain is investigated by means of numerical simulations in comparison to the experimental measurements on the pressure history in the combustion chamber. The start of combustion timing and scattering proves mainly produced by the random action of the pyrotechnical devices of the igniting system and far less by the gas-dynamic transient of the internal flow along the motor. The gas-dynamic time constant of the booster engine falls well within a 20 ms maximal duration. The conclusions of these tests for the further development of the three-staged rocket vehicle are debated.

## INTRODUCTION

University "Politehnica" of Bucharest (UPB) is a partner of the in FP7 European Space priority project ORPHEE and participated in a long series of project proposals, most recently in NANOPROP. As a national priority, the experience in designing of rocket engines for space launchers is capitalized the development of the *NERVA* launcher [10], as a national project sponsored by the Ministry of Education and Innovation under the grant no. 82076.

NERVA runs through 2008-20011. The launcher design consists of a readily available, low cost demonstrator for achieving half of the orbital velocity at 100 miles altitude for the three-axes controlled (3AC) satellite *PUBSAT*. The new, very small rocket transporter stands within the Romanian technology frames, addressed through a high level industrial consortium (Electromecanica, Aerofina, Powders Factory in Fagaras and ELAROM), with UPB as project coordinator. The foreground of the NERVA vehicle is the known soil-air SA-2 Guideline weapon.

This missile is subjected to a precisely controlled re-conversion from a military weapon into the civil space transporter. SA-2 is a derivation in fact of the famous *Rheintochter* missile, successfully developed at Peenemunde in early 1945 by the rocket team of Wernher von Braun. The new NERVA is perhaps the first orbital project developed from such a conventional rocket. Another envisaged first is the low-mass 3AC minimal PUBSAT. The expertise of the ADDA SME (Association Dedicated to Development in Astronautics) and the existing capabilities of industrial partners give confidence in this project [17]. A third stage with the performance of 5000 meters per second ideal velocity is at the limit of the current Romanian rocket engine technology. All align into building a cheap, ground launch vehicle by a minimal modification of the SA-2 rocket system. This requires however a drastic improvement of the structural efficiency of the SA-2 Guideline system, to accommodate higher thrust enhancement of the solid motor (SM) booster, thrust vectorization of the liquid motor (LM) and lightweight sustainer structure for the second stage, with highly extended propellant tanks and lightweight guidance. They are a continuation of the NERVA study of the author, where relative effects of structure and specific impulse enhancements were analyzed [10]. The prediction of the available performance is performed by computer simulations, proving the feasibility of the NERVA vehicle as an orbital system with composites technology applied in parts of the structural design.

To predict the behavior of the first stage of the launcher a special computer code TRANSIT was developed. Successful in describing continuous, isentropic flows in aerodynamics, the wave front method (Zannetti 1990) was greatly transformed (Rugescu 2001, Rugescu-Avasilichioaei 1999) into the so-called computational front method for extension to the non-isentropic flows with sharp discontinuities in solid rocket engines (SRE). Interesting to note the applicability of the new computational front method to unsteady flows in WINNDER solar mirror gravity-assisted draught tower (MGT) for aeroacoustics (Rugescu 2005, Rugescu et al. 2005, Tache et al. 2006, Rugescu et al. 2006). A concept of Schlaich-Bergermann for solar-gravity acceleration of airflow was already practiced in an experimental draught power plant near the Manzanares River in Spain (Haaf 1984), but with a primitive and far less efficient solar heater (Weinrebe 2004). The innovative improvement we introduce in the sun-driven gravitational draught technology was already modeled by the 0-D (integral) method, during a previous CNCSIS grant in Romania, with remarkable applications in aeroacoustics.

## THE CLUSTERED FIRST STAGE

To triple the performance of the basic SA-2 vehicle the solution of clustering three identical solid rocket motors is adopted, which stands as the new first stage of the launcher (see fig. below).

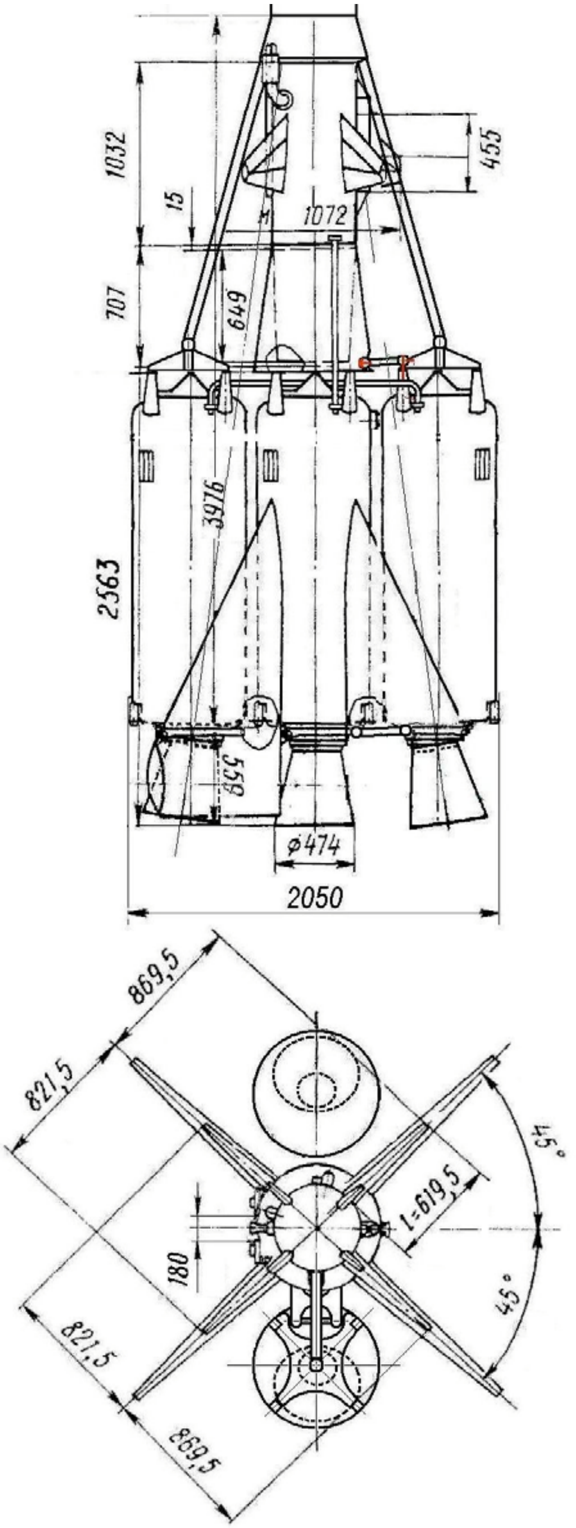

Fig. 1. The first stage of the NERVA launcher.

The cluster is formed of three parallel motors, with only lateral constraints on their fixture and independent transmission of the three thrusts directly to the mid-frame of the second stage. The propulsion part of the second stage is also drawn in the upper part of the figure.

The minimal modifications of the propulsion system are shown in Fig. 3 and consist of the following main chapters:

-reinforcement of the inter-stage fixture mount for higher boost thrust;

-clustering of several boosters;

-gimbal mounting of the liquid propellant engine of the second stage;

-transforming the fixed turbine exhaust into a roll control system;

-extending actuators action over the rotating LM;

-stirring fins transform into fixed.

As an alternative, the fins may remain mobile and the position control of the thrust chamber will be achieved in parallel with the basic air fins control from the second stage vehicle. These small The nozzles of the lateral engines are transformed to align on a 15º inclination against the longitudinal axis in order to minimize the couple unbalance during the burn of the three boosters. Some undesired unbalance could still persist and the scope of the present phase of research is to confidently predict the margin of these unbalances.

These improvements pretend a massive computational work of structure verification and suitable high level design technology, to preserve the good reliability of the basic SA-2 vehicle into the present limits or higher. A large series of structure details remain to be also improved, as for example the oxidizer and fuel sinks from the tanks that may be conveniently replaced with direct tank bottom sinks. We recollect that the very mobile sinks are compulsory on board an anti-aircraft rocket vehicle, aimed to perform large maneuvers in following the target airplane, to avoid discontinuities in propellant supply due to the inevitable large amplitude liquid sloshing. The problem of propellant sloshing is critical in all rocket vehicle systems and deserves a special attention. Developments on this subject will be presented in separate papers as one of the main research topics regarding the NERVA orbital launcher. We resume on saying that in most of the current LE space transporter systems a direct aspiration of the propellants from the tank is present. From this simplification some useful mass saving results. Other structural modifications are necessary to improve the stability of the much longer tank section, although a considerable contribution to the structural stiffness is induced by tank pressurization with helium gas, used to avoid pump cavitation.

They involve stiffening of the out-of-tanks sections of the coke, especially in the lower part of the second stage structure where the dynamic loading is much higher.

A considerable improvement in vehicle ideal velocity is obtained by replacing the current propellant A-100 of the first stage booster with the new PEI-400 high energy one, which is expected to raise the sea-level specific impulse from 2200 m/s to almost 2440 m/s [16]. The considerable previous experience of the UPB team in developing high energy colloidal propellants is successfully used again. A candidate solution for the NERVA launcher fuel tanks is a new composite material being developed within UPB. Carbon Fibers Reinforced Aluminum (CFRAl) is a new type of composite material being developed by the Chemical Engineering Department in cooperation with the Faculty of Aerospace Engineering at University "POLITEHNICA" of Bucharest, Romania.

Otherwise a special emphasis will also be directed towards improvements in the second stage of the vehicle by replacing the standard SA-2 bi-propellant combination with higher energy alternatives. Besides an increased specific impulse of the LRM a reduction of toxicity of the propellant components is targeted, accompanied by a reduction of its impact upon the environment, during the preparation for launch. Cost reductions of the operation will follow.

## STARTING TRANSIENT

To simulate the burning transients the conservation laws for a finite, material control volume within the grain channel consist of the continuity equation, along a slender, cylindrical channel are written [23]

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial x} = (\rho_p - \rho) U_a \frac{P_i}{A} , \tag{1}$$

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} , \tag{2}$$

$$\frac{\mathrm{d}e}{\mathrm{d}t} + \frac{p}{\rho} \frac{\partial v}{\partial x} = \left( h_a^* - h^* + \frac{p}{\rho} \right) \frac{\rho_p - \rho_a}{\rho} \frac{\partial \ln A}{\partial t} . \tag{3}$$

where the index *a* means fresh combustion products near the burning area of the propellant grain and $U_a$ is the burning speed of the propellant, taken as constant along the entire channel.

Specific precautions must be taken when the computational grid of characteristic lines are penetrating from one zone to another, with different equations of motion. The problem is discontinuous.

## COMPUTATIONAL DISCONTINUITIES

When special precautions are taken while addressing the differences, the regularity of the mesh is secured. A suitable form of the computational formulae must be offered for stability reasons [23], especially when the linear equations are badly conditioned due to the local geometry of the flow. These aspects of the numerical code were carefully refined and the delivered accuracy is good, as seen from the numerical examples from below.

The geometrical model of the mSRM cluster is given below. The effect of the interconnecting pipe upon the thrust build-up delay of the lateral engines is the most important feature of this engineering solution.

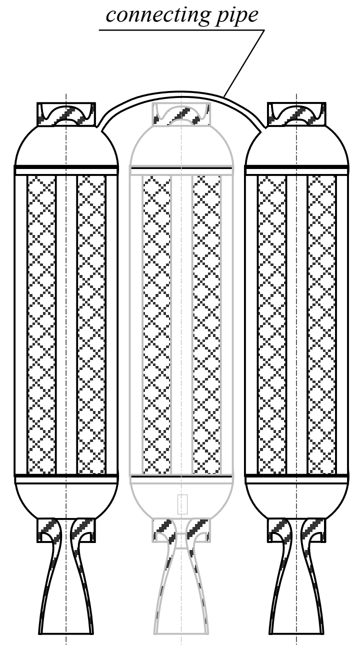

Fig. 2. Balance connecting pipe

Physical discontinuities accompany the flow along the motor core and originate from the following sources:

*a*) steep variations in the area of the channel as traveled by the flowing gas,

*b*) blunt pass from the non-isentropic zones with combustion and mixing to the isentropic or quasi-isentropic acceleration of the flow,

*c*) congruence of the characteristic lines and formation of the gradual shocks.

These discontinuities are either located at given stages of the engine (*a* and *b*) and require a combination in the description of the characteristics and compatibility equations along the characteristics, or appear as a result of the flow itself (*c*).

## NUMERICAL RESULTS

The value of this temperature is 2000K and the initial pressure of the gas is at 20 bar. At these values the membrane from the nozzle throat is broken and a fast expansion fan develops into the engine. The computational grid consists of 100 nodes into the motor and other 10 at the throat. The parameters of the inner channel are:

$$K \equiv 2\frac{U_a}{R_i} = 0.57143 \text{ s}^{-1};$$

propellant mean density, $\rho_p = 1700$ kg/m$^3$,
combustion temperature, $T_a = 2500$ K,
nozzle profile:
$\ln A(x) = a_1 x^2 + b_1 x + c_1$;
(nozzle only: $1.8 \text{ m} < x < 2.3 \text{ m}$)
$a_1 = 16.823609$;
$b_1 = -67.29444$;
$c_1 = 61.06141$;
Chamber / nozzle threshold $L_{ca} = 1.8$m
Nozzle throat station $L_{cr} = 2.0$m
Nozzle exit station $L_e = 2.3$m

The time history of the first few milliseconds from the start of the flow, subsequent to the burst of the diaphragm, are given in the figure below, for a single engine of the cluster, at the front end of the channel.

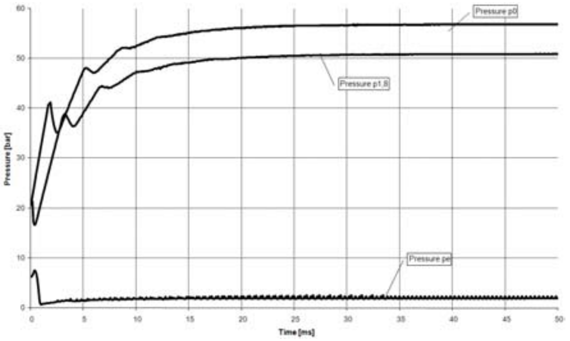

Fig. 3. Pressure and temperature build-up.

Effects of the clustering and interconnection of the engines are still under investigation, due to some delay in the funding of the national research programs in Romania during the year 2009.

Experimental investigations are also under preparation, where two scale engines are used with interconnecting pipe and simultaneous measurements of the front hood pressure will be performed. Delays of the experimental part are also due to the economic recession in the country and to the subsequent unavailability of propellant grains for the required experiments. This will probably produce an overall delay of the NERVA research program woth one calendar year.

## CONCLUSIONS

The one-dimensional method of characteristics appears as an accurate tool for the simulation of the purely gasdynamical transient work of rocket engines with high length-to-diameter ratios, if the method is augmented.

Thickening and leveling of the computational mesh were both used. Nevertheless, it was clearly observed that a double density mesh has a small effect on the results. The method proves stable and efficient.

The non-isentropic feature of the flow, as described by the governing equations, is smoothly covered by the computational scheme. The eigen-values of the matrix of the conservation equations remain unchanged in respect to the values encountered in the case of the isentropic flow. The free terms of the equations only differ and consequently the solutions of the PDE themselves. Repeated tests of the numerical code revealed that the thickening of the mesh nodes through spline-interpolation is very smooth and substantially contributes to the stability of the scheme. In connection to this aspect, it proved very useful to permanently store the changing position of the wave fronts as these propagate in the interior of the engine, as computational thresholds of the different zones of the flow characteristics.

Regarding the second stage LM propulsion system, emphasis will be put in designing and building a static test facility, presently nonexistent on the Romanian territory, where the propulsive efficiency characteristics of the stage could be definitely monitored. A distinct funding must be provided under a grant contract for this purpose. The main component of the propulsion system supposed to experimental evaluation will be the turbo-pump assembly, electrically driven to securely simulate the working conditions during the powered mission. A test stand should provide the true results of applying new solutions for the turbo-pump. This turbo-pump test rig will ultimately be used in providing practical information on how the actual turbo-pump will work with different propellant combinations, starting from HTP and nitrogen tetroxide as oxidizers, as alternatives to the present very efficient but hazardous IRFNA (Inhibited Red Fuming Nitric Acid) oxidizer, and up to methanol, nitro-derivatives of methane or even cryogenic liquid methane as liquid fuels. Aluminum powder in a suspension into the fuel will also be investigated. Possible changes in the design of the pumps and of the bearings in particular are expected. Extensive numerical simulations of the combustion process will be performed and will preclude the experimental work, based on the known previous expertise of the team in this field [20].

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