Propulsion and Energy Forum
July 25-27, 2016, Salt Lake City, UT
52nd AIAA/SAE/ASEE Joint Propulsion Conference

AIAA 2016-4685

On the Use of a Pulsed Nuclear Thermal Rocket for Interplanetary Travel

Francisco J. Arias[1,*]

[1a] *Department of Fluid Mechanics, University of Catalonia*

ESEIAAT C/ Colom 11, 08222 Barcelona, Spain

Abstract

The objective of the present work is a first assessment for the use of a pulsed nuclear rocket for thrust and specific impulse (I_{sp}) augmentation for applications on interplanetary space flights.

The basis of the novel space propulsion idea is the possibility of working in a bimodal fashion where the classical stationary nuclear thermal rocket (NTR) could be switch on or switch off as desired by the mission planners.

It was found that the key factor for I_{sp} augmentation lies in the capability of rapid quenching of the fuel and the working at low Fourier numbers where the energy form the pulse can be considerably larger than the classic stationary mode. The I_{sp} enhancement, is based on the instantaneous heating of the propellant by the use of the huge neutronic flux from the pulse which is not limited by thermodynamic constraints. However, within the framework of this concept -and if important I_{sp} augmentation is pursued, the energy from the fission fragments is an "unwanted energy" and must be evacuated by a solidary quenching system working in-parallel with the propellant channel. This is in clear contrast with all the currents nuclear thermal rocket approaches. It was found that liquid metals are the only coolants which allow the fast quenching required, and preliminary estimates reveal than lithium is featuring a remarkable performance for this purpose, albeit with some neutronic drawback associated with its isotope ^{6}Li. In addition, thin geometries of the fuel are mandatory to keep intimate contact with the quenching-coolant. Theoretical treatment is properly developed for the basis of the concept, and some preliminary thermohydraulics and neutronic simulations performed. The proposed pulsing mode could endows the classical NTR with the missing "first gear" necessary for interplanetary fights.

.

Keywords. *nuclear thermal rocket, thrust and I_{sp} augmentation, pulsed nuclear reactor, fast quenching*

[*]Corresponding author: Tel.: +93 73 98 666; Electronic address: `frarias@mf.upc.edu`

I. INTRODUCTION

A pulsing nuclear reactor, is a nuclear reactor that operates in the pulse mode. In contrast with the stationary nuclear thermal reactor (NTRs), whose power level is constant with respect to time, in a pulse reactor short but strong power pulses could be generated. The object of this work, is to see what benefits in terms of thrust and I_{sp} augmentation can be drawn from pulsing the classical nuclear thermal rocket.

The proposed concept should not be misconstrued as an attempt to produce a new radical technology, rather, it must be observed as the final refinement or evolution of the conventional NTR, and then all the investment, know-how, skills and maturity gained in the past years of NTR development are inherited by the proposed concept.
All in all, the proposed pulsing mode endows the classic NTR with the missing "first gear" necessary for interplanetary fights.

II. STATEMENT OF THE CORE IDEA

To begin with, let us consider that, we have our classical NTR which has been adapted to work in a bimodal fashion, i.e., as stationary rocket and as pulsed rocket as well.

This pulsed mode can be produced using a different variety of configurations depending of the desired frequency of the pulsations. For instance, the use of standard control rods in a single or banked configuration with motor driving mechanism or the use of standard pneumatically operated pulsing mechanisms are suitable for generating up to 10 pulses per minute, [1]; for the production of pulses at rates up to 50 pulsations per second, the use of rotating wheels introducing alternately poison and fuel or poison and non-poison can be considered. However, for pulsations ranking the thousands of pulses per second (kHz), optical choppers or modern flywheels employing magnetic bearings allow to revolve at 10 kHz, [2]. If even fast pulsations are desired, then, it would be necessary the use of a new type of pulsing mechanism that does not involve mechanical motion, for example, lasers (based in the ^{3}He polarization) as early proposed by Bowman,[3], or proton and neutron beams. For our problem, frequencies in the order or 1 kHz to 10 kHz are the choice.

Our first step is to asses the maximum obtainable energy by using the pulsed mode rather than using the stationary mode during a given mission-time, for example, during the lift off of planetary bodies, space transfer orbits, etc...

If a certain initial time, let us say, at $t = 0$, a strong pulse is generated, then as result, the temperature of the fuel will increase instantaneously up to the maximum permissible temperature fixed by struc ... nperature of the fuel T_r ... hanism of the fuel -namely the fuel temperature reactivity coefficient -FTC, will stop the induced nuclear excursion. Because typical pulsations have a very high resolution -with full width at half power less than $\approx 1\mu$ sec, the energy from the pulse will be released with a very narrow "tail", therefore, it is permissible to assume that, immediately after the pulse the reactor is working at zero power (neglecting the comparative very low heat decay background), and also there will be not overlapping between consecutive pulsations (this point will be discussed a little deeper in the last section).

Under theses conditions, the problem is simplified to calculate the maximum energy deposited into the fuel between pulsations, which is reduced to a simple transient conduction problem in which we wish to calculate the maximum energy that can be evacuated from the fuel during a given quenching time equal to the time between pulsations. During the mentioned quenching time, the fuel temperature drops from its initial melting temperature T_m to a colder temperature T and then is ready for a second pulsation and so on.

The most simple, yet common, method for solution of this simple transient conduction problem is the well-known *lumped capacitance method* which yields the following relationship, [4]

$$\frac{T - T_c}{T_m - T_c} = \exp^{-\frac{t}{\tau_f}} \tag{1}$$

where T_m is the initial temperature of the fuel (its melting temperature), T its final colder temperature after a quenching time t, T_c is the average coolant temperature and τ_f is the fuel time constant, given by

$$\tau_f = \frac{\rho_f c_f V_f}{h A_s} \tag{2}$$

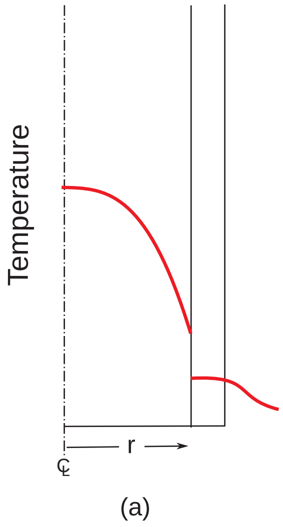

FIG. 1: Fuel pin temperature profiles for transient conditions. (a) Quasi-steady state state. (b) Nuclear excursion. (c) Cooling failure. from [7]

where ρ_f, c_f, V_f and A_s are the fuel density, specific heat, volume and surface area, respectively., and h is the coolant heat transfer coefficient.

This thermal time constant τ_f, can be interpreted as a measure of how much time is required to transport heat from fuel to coolant.

For the sake of generalization, let us assume that our fuel is a cylindrical geometry with radius r_f and length l_f., and therefore we have $A_s = 2\pi r_f l_f$ and $V_f = \pi r_f^2 l_f$, whence Eq.(2) may be rewritten as.

$$\tau_f = \rho_f c_f \frac{r_f}{2h} \tag{3}$$

Unfortunately, the *lumped capacitance method* is based in the assumption that the temperature of the solid (the fuel in our case) is *spatially uniform* at any instant during the transient process. This assumption implies that the temperature gradient within the solid is negligible which is certainly a not valid assumption for our studied case.

Nevertheless, an allowable assumption is to assume that the fuel temperature immediately after pulsation is initially uniform. This assumption is easy to see in Fig. 1, where some typical fuel pin temperature profiles are shown after several special transient conditions, nothing that a pulsation is nothing more than a controlled short nuclear excursion.

Under this assumption, exact solutions to the transient problem, have been developed for the interesting geometries (infinite cylinders, plates and spheres). Full details on the resolution of these equations are beyond the scope of the present work, but the interested reader can find extensive treatment in classical heat transfer books dealing with transients conduction problems, e.g., [4] or [5], just to name a few.

For our specific infinite cylinder, the solution of the total energy transfer, yields

$$Q = Q_o \left[1 - 2 \sum_{n=1}^{\infty} \theta_n^* \frac{J_1(\zeta_n)}{\zeta_n} \right] \tag{4}$$

where Q is the total heat energy obtained after the transient and Q_o is the initial internal energy of the fuel relative to the fluid temperature given by

$$Q_o = \rho_f c_f V_f (T_m - T_c) \tag{5}$$

which can be interpreted as the maximum theoretical energy that could be extracted if the fuel is quenched up to the temperature of the coolant. Also,

$$\theta_n^* = C_n \exp\left(-\zeta_n^2 \mathbf{Fo}(t)\right) \tag{6}$$

being $\mathbf{Fo(t)}$ the Fourier number given by

$$\mathbf{Fo}(t) = \left[\frac{1}{\mathbf{Bi}}\right] \left[\frac{1}{\tau_f}\right] t \tag{7}$$

where $\mathbf{Bi}$, is the Biot number given by

$$\mathbf{Bi} = \frac{h l_f}{\kappa_f} \tag{8}$$

being κ_f the fuel thermal conductivity and l_f the characteristic length of the body (the fuel, in our case) which is commonly defined as the volume of the body divided by the surface area of the body, or $l_f = \frac{r_f}{2}$ for a cylindrical geometry. Thus, Eq.(8) may be rewritten as

$$\mathbf{Bi} = \frac{hr_f}{2\kappa_f} \tag{9}$$

where the discrete values (eigenvalues) of ζ_n in Eq.(4) are the positive roots of the transcendental equation

$$\zeta_n \frac{J_1(\zeta_n)}{J_o(\zeta_n)} = \mathbf{Bi} \tag{10}$$

and the coefficients C_n in Eq.(6) are calculated as

$$C_n = \frac{2}{\zeta_n} \frac{J_1(\zeta_n)}{J_o^2(\zeta_n) + J_1^2(\zeta_n)} \tag{11}$$

being J_o and J_1 the Bessel functions of the first kind. Roots of the transcendental Eq.(10) are tabulated and can be found in any book dealing with conduction transients, for example, [4] or [5]. Specific solutions for plates and spheres are presented in the appendix.

Finally, for comparison with the stationary rocket, we need to calculate the total energy in this mode, i.e., by using a constant nominal power during the same time analyzed in the pulsed mode. Let us call this nominal power as P_s (the subscript s stands for stationary). The total energy, Q_s in this stationary mode during the same time t employed in the quenching of fuel in the pulsed mode is given by

$$Q_s = P_s t \tag{12}$$

On the other hand, the power P_s is limited by thermodynamic constraints, and its maximum value yields the following well-known expression, [6],

$$P_s = 4\pi\kappa_f \left(T_m - T_s\right) l_f \tag{13}$$

where T_s is the temperature at the surface of the fuel.

Inserting Eq(13) into Eq.(12) one obtains

$$Q_s = 4\pi\kappa_f \left(T_m - T_s\right) l_f t \tag{14}$$

and by dividing Eq.(4) with Eq.(14) and taking into account Eq.(5) and the definition of Fourier number given in Eq.(7) and after certain easy arrangement of terms, we obtain for the ratio of energies between the pulsed and stationary mode the following relationship.

$$\frac{Q}{Q_s} = \left[\frac{1}{\mathbf{Fo}(t)}\right]\left[\frac{T_m - \bar{T}_c}{T_m - T_s}\right]\left[1 - 2\sum_{n=1}^{\infty}\theta_n^* \frac{J_1(\zeta_n)}{\zeta_n}\right] \tag{15}$$

To obtain some idea of the shape of the curves predicted by Eq.(15), we assume some typical values of the Fourier and Biot numbers as fundamental parameters in the calculation derived as follows:

First, it is necessary to calculate the fuel thermal constant τ_f given by Eq.(3). For UO_2 metal-clad fuel elements with radius about $\simeq$ 1 cm with densities about $\rho_f \simeq 10^4$ kg/m^3, thermal conductivities on $\kappa_f \simeq 5$ W/mK and heat capacities above $c_f \simeq 400$ J/Kg K and with typical heat transfer coefficients as high as $h \simeq 3 \times 10^4$ W/m^{2}K or thereabouts,[7]., we obtain a thermal time constant $\tau_f \simeq 0.5$ sec. For HTGR lattices is often much larger, because the heat must be transported through a large fraction of the graphite moderator before reaching the coolant channels, [8]. Second, we need to calculate the Biot number given by Eq.(8), which using the above parameters and assuming a typical pin-radius of, say, $r_f \sim 1$ cm, we get for the Biot number $\mathbf{Bi} \simeq 30$ or thereabouts.

Using the calculated Biot number and fuel thermal constant, the Fourier number yields the following expression,

$$\mathbf{Fo}(t) \sim 0.07 \times t \tag{16}$$

Finally, for the temperature values in Eq.(15), we assume: a melting temperature of fuel, $T_m = 3000$ K., the surface temperature of the rod may well be 200 to 300 K degrees lower than the internal temperature, [9], then, let us take $T_m - T_s = 200$ K. For the coolant temperature of hydrogen as propellant, we consider an inlet and outlet temperatures as $T_i = 140$ K and $T_o = 2800$ K, respectively,[9], which by using a simple approximation for the average coolant temperature as, [7]

$$T_c = \frac{T_i + T_o}{2} \tag{17}$$

we obtain $T_c = 1470$ K.

The resulting curves for Eq.(15) are shown in Fig. 2 for several values of the Biot number and some interesting geometries for our nuclear rocket project. Referring to Fig. 2, it is seen that, for typical velocities of the propellant in the chamber less than the speed of sound and considering meter-sized cores-chambers, the residence time of propellant, i.e., the time needed to fill the chamber with fresh propellant is on the order of $t \leq 10^{-2}$ sec or thereabouts. This means that, with pulsation frequencies on 0.1 kHz or so, a single pulse can by itself generates energy hundreds of times much more larger than in the stationary mode. For quenching times smaller than that, this amount of energy can be considerably larger -leaving aside the possibility of multiple pulses during the residence time of the propellant. From this preliminary assessment, we can see that, seems that the key factor relies in the possibility of very rapid quenching times.

Now that the fundamental argumentation in the use of a pulsed mode has been inferred, it is time to discuss how we can harness this excess of energy offered by the pulsed mode.

III. THRUST AUGMENTATION

The most immediate use of the excess of energy resulting from pulsing our nuclear rocket is in the augmentation of the thrust (F) by increasing the propellant mass flow rate $\dot{m}_c$. Increasing the thrust in a stationary mode -where the power is limited by Eq.(13), is not a good option as can be easily inferred below. Let us say,that we want increase the thrust in a stationary core by, say, n-times its nominal value, then, taking into account that the power of the rocket is given by

$$P = \frac{\dot{m}_c v_e^2}{2} \tag{18}$$

where $\dot{m}_c$ and v_e are the propellant mass flow and exhaust velocity, respectively. And likewise

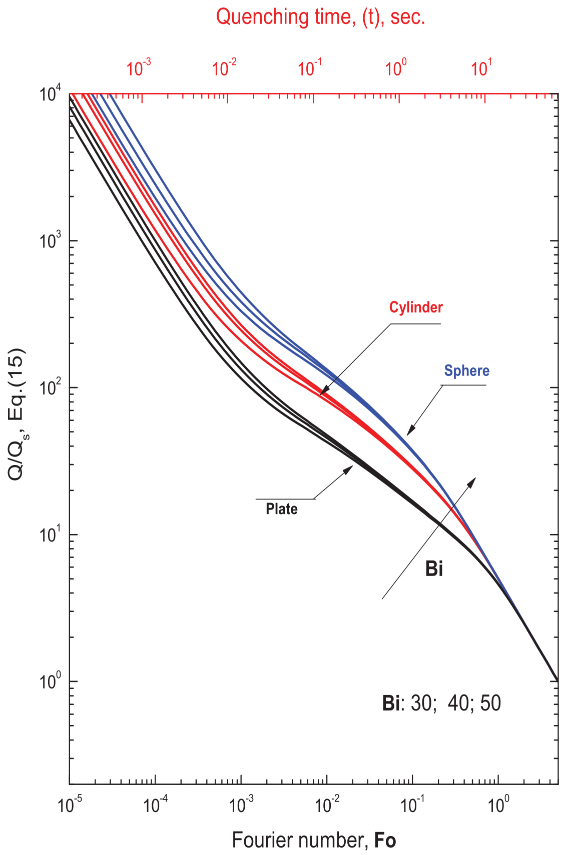

FIG. 2: The total heat energy transfer ratio between the pulsed mode and the stationary mode as a function of Fourier number, $\mathbf{Fo}(t)$ according with Eq.(15) and using several values of Biot number with the considered parameters.

the thrust is given by

$$F = \dot{m}_c v_e \tag{19}$$

Therefore, by combination of Eq.(18) and Eq.(19) at constant power, we obtain for the final thrust F, propellant mass flow $\dot{m}_c$ and exhaust velocity v_e the following relationships

$$F = n \times F_o$$

$$\dot{m}_c = n^2 \times \dot{m}_{c,o}$$

$$v_e = \frac{v_{e,o}}{n} \tag{20}$$

In other words, by increasing the thrust, say, 2 times, that implies increasing the propellant mass flow 4 times and even worst, the exhaust velocity is halved. It is clear that this is not a wise option.

However, by pulsing the nuclear core, we can increases the power *n-times* and proportionally increases *n-times* the propellant mass flow, and yet, keeping untouchable the exhaust velocity. Nevertheless, because our pulsed-NTR, is intended to work in a bimodal fashion (pulsed and stationary mode), some special considerations must be taken into account. For example, if we are pulsing our core to produce, say, two times more power than the stationary mode, it is not enough just throttling the propellant flow, but also some elements of the core should be displaced. This can be easy understood by analyzing the Dittus-Boelter correlation, given by

$$h = h_o \left(\frac{\dot{m}_c}{\dot{m}_{c,o}} \right)^{0.8} \tag{21}$$

as we can see, the non-linear dependence between the heat transfer and the mass flow suggest that thermal boundary effects at the wall are present, and then, its is necessary modify h_o by displacing some elements in the core at the moment the pulsed mode starts.

Now it is the turn of analyzing the possibility of exhaust velocity or I_{sp} augmentation. This is by far a more challenging task, but also offering a completely new alternative to attack the I_{sp} problem.

IV. I_{sp} AUGMENTATION

Because the first concern of the rocket engineer is the attainment of high exhaust velocity or I_{sp}, we will tackle the problem in this section.

TABLE I: Energy released from neutron induced fission of ^{235}U.

Products	**Prompt Energy** Kinetic (%)	Heat (%)	**Delayed Energy** (%)
Fission fragments	93.24	—-	—-
Fission neutrons	2.88	42.5	—-
γ emission	3.88	57.5	—-
β decay(electrons)	—-		29.50
β decay(neutrinos)	—-		44.54
γ emission	—-		25.96
Total	100	100	100

For a rocket working in a vacuum and with a given propellant, the most general formula for the exhaust velocity is given by

$$v_e \sim k' \sqrt{\frac{T_p}{M}} \tag{22}$$

and for I_{sp}

$$I_{sp} \sim k \sqrt{\frac{T_p}{M}} \tag{23}$$

where T_p is the temperature of the propellant in the heat-engine before expansion, M its molecular molecular weight and k' and k being constants. It follows that any attempt to increase I_{sp} implies increasing the temperature of the propellant which is ultimately limited - at least until now, by the melting temperature of materials. There have been attempts to overcome this limitation in nuclear solid cores by different strategies, for example, by the direct use of fission fragments to heat the propellant. In this section we will attack the I_{sp} problem from other point of view.

The key factor to be considered to attain I_{sp} enhancement by using a pulsed core lies in taking advantage of the huge neutronic flux instantaneously generated in the pulse, this flux can also instantaneously heat the propellant. However, this *prompt-energy* is directly transported from the

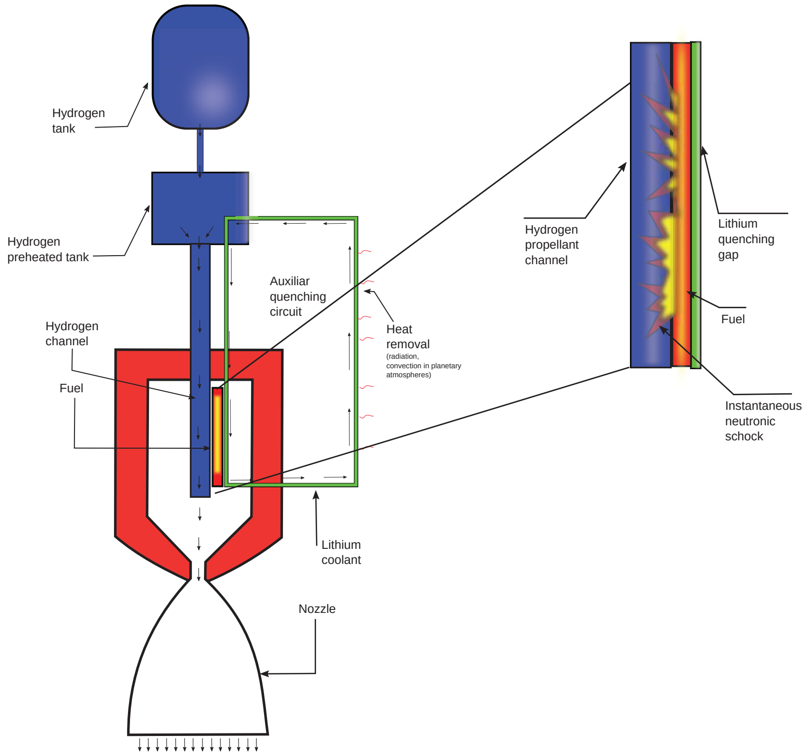

FIG. 3: A sketch showing the principle for a nuclear thermal pulsed rocket .

fuel to the propellant via kinetic energy and not by heat transfer mechanisms, and then, it is not constrained by the second law of thermodynamics as in current approaches, which means that we can obtain a *"propellant hotter than the fuel"* or higher I_{sp} without melting the fuel. Let us look in more detail the theoretical argumentation behind the idea.

Table. I shows the typical distribution of energy after a fission event. Referring to this table, the reader may notice that, additionally to the division between *prompt-energy* and *delayed-energy* appearing in classical literature, here we take the liberty of doing a second subdivision to differentiate between *prompt-heat* and *delayed-heat*, which as we will see, is a key factor in our argument.

We call *prompt-heat*, all the kinetic energy which is instantaneously dumped into the propellant and transformed into heat in the propellant. This energy is mainly from the moderation of neutrons in the propellant with typical times on μ sec or so. Conversely, we call *delayed-heat* all the energy which although being *prompt-energy*, however is instantaneously transformed into heat in the fuel, and then it takes a larger time to be transported from the fuel to the propellant by conductive heat transfer (this time is the thermal constant time which we discussed in preceding sections). This *delayed-heat* is mainly due to the fission fragments.

Now, in a stationary reactor, the important heat, is the *delayed-heat* from the fission fragments and this is the fraction considered for heating the propellant, and the neutronic fraction is only considered for keeping self-sustainable the reactor.

This is easy to understand from Table I, where the *prompt-heat* from neutrons is only above a 6% of the bulk energy.

However, as was demonstrated in preceding sections, a pulsed nuclear core can generates hundreds or even thousands of times more energy than a stationary core depending of the capability for fast quenching (See Fig. 2).

So, here is the key question: Albeit that the *prompt-heat* from neutrons (and possible gamma rays) is only a tiny fraction in comparison with the *delayed-heat* from fission fragments, however, -it is possible that this tiny fraction of *prompt-heat* from neutrons in a pulse, might actually be larger than the *delayed-heat* from fission fragments operating in a stationary mode? if yes, then the *prompt-heat* from neutrons in the pulse will be able to heat the propellant instantaneously much more than the total bulk of energy in the stationary mode. in other words I_{sp} augmentation.

By looking at the Fig. 2 and Table.I, we can see that this is the case.
For example, if we are producing a pulse, let us say, 100 times larger than in the stationary mode -working with discrete quenching times, then the instantaneous *promp-heat* from neutrons and gamma rays will be according with Table. I, above $\simeq 6\%$ or 6 times the energy than the stationary mode (the original pulse in this example was 100 times larger). All this neutronic energy will be "dumped" instantaneously into the propellant in a fraction of microseconds, and then heat losses (even radiative heat loses) will be limited. Now, because the energy is directly related to temperature by Eq.(23) then, we have that after a pulse of energy N times larger than the stationary mode, the I_{sp} might be amplified as

$$I_{sp} = I_{sp,o}\sqrt{f_t f_n N + 1} \tag{24}$$

where I_{sp} and $I_{sp,o}$ are the specific impulses after and before pulsation, respectively., f_t is the number of pulsations during the time of residence of the propellant in the chamber., f_n is the fraction of *prompt-heat* which according with Table I is above 6% or $f_n \simeq \frac{1}{16}$ if we are considering both neutron and gamma radiation, and above $f_n \simeq \frac{1}{30}$ if only prompt neutrons are taken into account.

However, we are still far from solving the problem. If we are producing a pulse, say, N times larger than the stationary mode, and only a tiny fraction of this amount equal to $f_n N$ is available as *prompt-heat* from neutrons for I_{sp} augmentation, then for every energy increase in the propellant we need to remove an "unwanted energy" deposited into the fuel at least $\frac{1}{f_n}$ times larger. For example, by increasing instantaneously 2 times the energy of the propellant, we need to evacuate above 32 times more energy from the fuel deposited by the fission fragments i.e., the *delayed-heat*. Worsening the situation, this unwanted energy must be removed during a very short time (the quenching time or time between pulsations), at least if we desire a continuous I_{sp} amplification.

To put things into perspective, we are talking about fast quenching in the order of 2×10^6 K per second -for a fuel temperature drop between pulsations of $\Delta T_f \simeq 2000$ K and quenching times not larger than $t = 10^{-3}$ sec.

This cooling capabilities are beyond of the cooling capabilities of hydrogen which means that the hydrogen used as propellant cannot be used simultaneously for quenching the fuel rod. Therefore, it would be necessary new approach to solve the situation. This will be the topic of our next section.

V. HYDRAULICS CONSIDERATIONS

From our preceding sections, it was found that if important I_{sp} enhancement is desired using a pulsed rocket, it would be necessary a dedicated auxiliary coolant system with a powerful working fluid operating in solidary quenching channel with intimate contact with the fuel. To fix ideas, we will need something as schematically depicted in Fig. 3. To begin with, we need to know if such coolant exist. If yes, we have a go ahead to continue with this idea for I_{sp} augmentation. If not, this seems the dead of our discussion, and then the pulsed mode will be only limited to thrust augmentation by increasing the propellant mass flow rate.

A. The auxiliary coolant

To know if there are coolants with the quenching capabilities required, we shall proceed as follows.

From the balance of energy between the fuel and the hypothetical coolant, we have

$$c_f \rho_f V_f \Delta T_f = h A_s \Delta T_c t \tag{25}$$

where c_f, ρ_f, V_f and ΔT_f are the heat capacity, density, volume and temperature drop (between pulses) of fuel., respectively, during a quenching time t (the time between pulsations). Likewise, h, A_s and ΔT_c are the coolant heat transfer coefficient, fuel surface and axial temperature increase of coolant (averaged between inlet and outlet temperatures)., respectively.

For our illustrative case, considering a cylindrical fuel geometry, we have $\frac{V_f}{A_s} = \frac{r_f}{2}$, and then, Eq.(25) may be rewritten as

$$h = c_f \rho_f \frac{\dot{T}}{\Delta T_c} \frac{r_f}{2} \tag{26}$$

where $\dot{T} = \frac{\Delta T_f}{t}$ is the fuel quenching rate. Now, by considering typical heat capacities for fuel about $c_f \sim 400$ J/Kg K., fuel densities about $\rho_f \sim 10^4$ kg/m^3 and our required fast quenching rate about $\dot{T} = 2 \times 10^6$ K/s., and assuming a reasonable $\Delta T_c \sim 1750$K for coolant, one obtains

$$h \simeq 2.28 \times 10^9 \times r_f \tag{27}$$

This is a huge number but may be reduced by using a proper thin geometry. Let us take, for practical purposes, a fuel radius about $r_f \sim 75\ \mu m$, which is smaller than traditional fuel rods, but by far much more larger than the required for other approaches (see for example the fission-fragment rocket where geometries at least 1 μ m thickness are mandatory and then a very high enrichment of fissile material or the use of exceptional reactive elements as ^{242m} Am are needed to keep self-sustainable nuclear reactions). Thus, the heat transfer coefficient for this thin geometry yields

$$h \simeq 1.7 \times 10^5 \quad W/(m^2)(K) \tag{28}$$

which is in the regime of liquid metals, with typical heat transfer coefficients between 10^5 $W/(m^2)(K)$ to 10^6 $W/(m^2)(K)$, [10],[6]. Therefore, seems that we have a go ahead to continue with our project. Next step is to know the most suitable liquid metal for our application.

The first potential candidate as liquid metal for space applications is without doubt lithium. Lithium has several desirable features for high-temperature applications such as low vapor pressure,

TABLE II: Parameters for CFD simulation under constant $\Delta p = 1$ MPa.

Property	Lithium (Li) ($T_i = 500$K)[a]	Lead (Pb) ($T_i = 600$K)	Water (H_2O) ($T_i = 300$K)	Hydrogen (H_2) ($T_i = 140$K)
Density, kg/m^3	401	11340	998	0.8×10^{-1}
Heat capacity, J/(kg)(K)	4169	128	4182	14.28×10^{4}
Thermal conductivity, W/(m)(K)	64.7	34.7	0.6	0.17
Viscosity, (N)(sec)/m^2	0.14×10^{-3}	0.1×10^{-2}	0.140×10^{-3}	8.41×10^{-6}
Prandtl number	8.65×10^{-3}	0.1×10^{-1}	9.47	0.16

[a]inlet temperature

low density, high heat capacity, low dynamic viscosity, and very important, is featuring a very low pumping power requirement, [11]. To evaluate the performance of liquid metals for fast quenching and in comparison with other coolants, some preliminary simulations were carried out.

B. CFD simulation

Although, as was derived in preceding subsection, heat transfer theory is validating the capability of liquid metal for the desired quenching rates, however it is interesting to perform some computational simulations. With this goal in mind, a series of CFD simulations were carried out to a 2D cylindrical pipe with unstructured mesh. In the present preliminary study, standard $\kappa - \epsilon$ model is chosen, which is most widely used. The thermophysical properties of Li, Pb, H_2O and H_2 as possible candidates are shown in Table II. The geometry is a pipe of radius 450 μm and 40 cm high with a central fuel-region of 75μm of radius. The coolant is flowing axially up-down. The pressure drop Δp was fixed to 1 MPa for all the simulations and coolants, and the inlet temperature used for each of them is also shown in Table. II. The fuel used was UC_2 with density $\rho_f = 10^4$ kg/m^3; heat capacity $c_f = 400$J/(kg)(K).; thermal conductivity $\kappa_f = 18$ W/(m)(K). All the physical parameters where assumed as constants and their dependence with temperature neglected. This fact must be properly addressed in future research considering the strong change in temperature experienced by the fuel. Nonetheless, this preliminary study will allow us to gain valuable insight and a global picture about the quenching rate expected.

Fig. 4 shows two particular quenching sequences for lithium at $t = 0.0$ sec (left side) and after $t = 10^{-3}$ sec (right side). Finally, Fig. 5, is showing the evolution of the hotter axial fuel

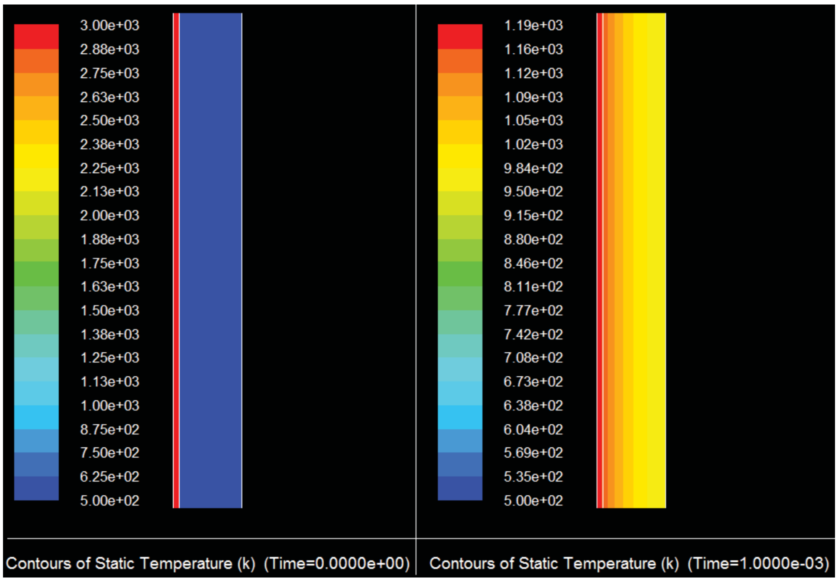

FIG. 4: Two quenching sequences for lithium during the CFD simulation.

temperature region during the quenching for lithium (Li), lead (Pb), and for water (H_2O) and hydrogen (H_2) for the sake of comparison. Fig. 5, speaks for itself, hydrogen cannot be used as auxiliary coolant for our quenching requirements and liquid metals are the required coolant for our application, with lithium featuring an special good performance.

Finally, it must be pointed out that, although quenching rates in the order of 2×10^6 K/sec are quite high and uncommon, however, it is not an unknown technology. In fact, the technological production of amorphous metals by melt-spinning are on the order of $10^4 - 10^7$ kelvins per second (K/s), [12]., and yet, amorphous metals production requires a phase change $liquid \rightarrow solid$ which is an isothermal process -resulting from the extraction of the latent heat, and this result in a "delay" in the quenching of the material. We don't have such a problem, our quenching rates would be equal or lower than required by amorphous metals production, and yet we will have the technical background of this technology.

C. Loss pressure: the thickness of the gap

An important parameters to be considered is the minimum thickness of the lithium-gap. This can be easily calculated as follows:

The pressure loss over the gap can be written by using the well-known Darcy-Weisbach equation

$$\Delta p = f \frac{l_f}{D_h} \frac{\rho_c u_c^2}{2} \tag{29}$$

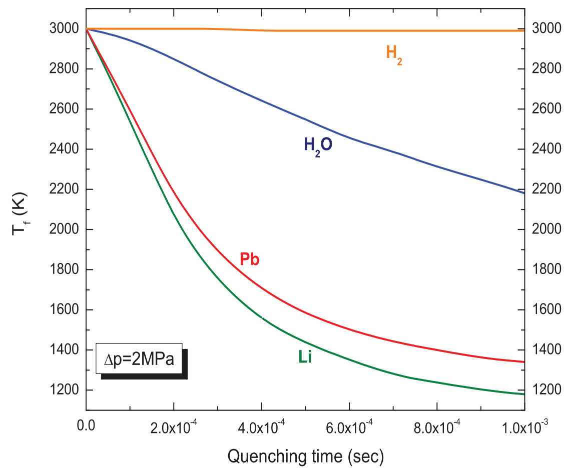

FIG. 5: Quenching times for several coolants. The pressure was fixed to Δp=2 MPa, and specific properties of coolants and inlet temperature are depicted in Table I.

where Δp is the pressure drop over coolant channel, f the Darcy-Weisbach friction factor, l_f the length of fuel -which is the same length of the coolant channel, and D_h the hydraulic diameter equal to $\frac{4A_c}{P_w}$ where A_c is the coolant flow area and P_w the wetted perimeter., ρ_c is the density of coolant, and u_c its velocity. Rearranging Eq.(29) one obtains

$$D_h = f\frac{l_f}{\Delta p}\frac{\rho_c u_c^2}{2} \tag{30}$$

On the other hand, for a given pin power, this heat production must be removed according to the relationship:

$$c_f m_f \Delta T_f = \rho_c u_c A_c c_c \Delta T_c t \tag{31}$$

where c_f, m_f and ΔT_f are the fuel heat capacity, mass and temperature drop after a quenching time t, respectively. Likewise, ρ_c, c_c and ΔT_c are the coolant density, heat capacity, and the axial difference between outlet and inlet temperature, respectively.

Considering our cylindrical geometry with a fuel diameter D_f and length l_f, the mass of fuel is given by $m_f = \rho_f \pi \frac{D_f^2}{4} l_f$, and likewise, for the coolant channel $A_c = \pi\frac{D_h^2}{4}$. Thus, Eq.(31) becomes

$$u_c = \frac{c_f}{c_c}\frac{\rho_f}{\rho_c}\frac{\Delta T_f}{\Delta T_c}\frac{l_f}{t}\left[\frac{D_f}{D_h}\right]^2 \tag{32}$$

which inserted into Eq.(30) leads to

$$D_h = \left[f\frac{l_f}{\Delta p}\frac{\rho_c}{2}\right]^{\frac{1}{5}}\left[\frac{c_f}{c_c}\frac{\rho_f}{\rho_c}\frac{\Delta T_f}{\Delta T_c}\frac{l_f}{t}\right]^{\frac{2}{5}} D_f^{\frac{4}{5}} \tag{33}$$

and by the definition of hydraulic diameter, the volume ratio between coolant-gap and fuel follows the same relationship than the hydraulic diameter to diameter of fuel, i.e., $\frac{V_c}{V_f} = \frac{D_h}{D_f}$, and then

$$\frac{V_c}{V_f} = \left[f\frac{l_f}{\Delta p}\frac{\rho_c}{2}\right]^{\frac{1}{5}}\left[\frac{c_f}{c_c}\frac{\rho_f}{\rho_c}\frac{\Delta T_f}{\Delta T_c}\frac{l_f}{t}\right]^{\frac{2}{5}}\left[\frac{1}{D_f}\right]^{\frac{1}{5}} \tag{34}$$

Finally, the power required to move the coolant through the flow area channel -or pumping power, P_c, is given by

$$P_c = \Delta p \cdot A_c \cdot u_c \tag{35}$$

To obtain some idea of the minimum thickness of the coolant gap, we assume some typical values of the parameters: friction factor from the Moody chart for suitable Reynolds number $\sim 10^3$ of $f \sim 0.05$ (depending of the pipe roughness); length of fuel $l_f \sim 0.5$m; fuel density $\rho_f \sim 10^4$ kg/m^3; lithium density $\rho_c \sim 400$ kg/m^3; a maximum permissible coolant pressure across the channel as 1.0 MPa, IAEA, 2006,[13]; fuel heat capacity $c_f \sim 400$J/(kg)(K); lithium heat capacity $c_c = 4169$J/(kg)(K); $\Delta T_f \sim 2000$ K; $\Delta T_c \sim 2500$ K (assuming pressurized gap without boiling of lithium); $t \approx 10^{-3}$ sec; and $D_f \sim 150\mu m$ for the required fast cooling derived from our previous calculations. With these assumed parameters we get: $D_h \sim 1$ mm, $\frac{V_c}{V_f} \sim 6.67$, a coolant velocity $u_c = 21.5$ m/s^2 and a pumping power 21.5 MW/m^2, which considering a 1 meter diameter core, results in a total pumping power $\simeq 16.8$ MWt. For comparison, the high-pressure fuel turbopump (HPFTP) (a three-stage centrifugal pump driven by a two-stage hot-gas turbine) boosts the pressure of the liquid hydrogen from 1.9 to 45 MPa. Therefore, all the hydraulic requirements for

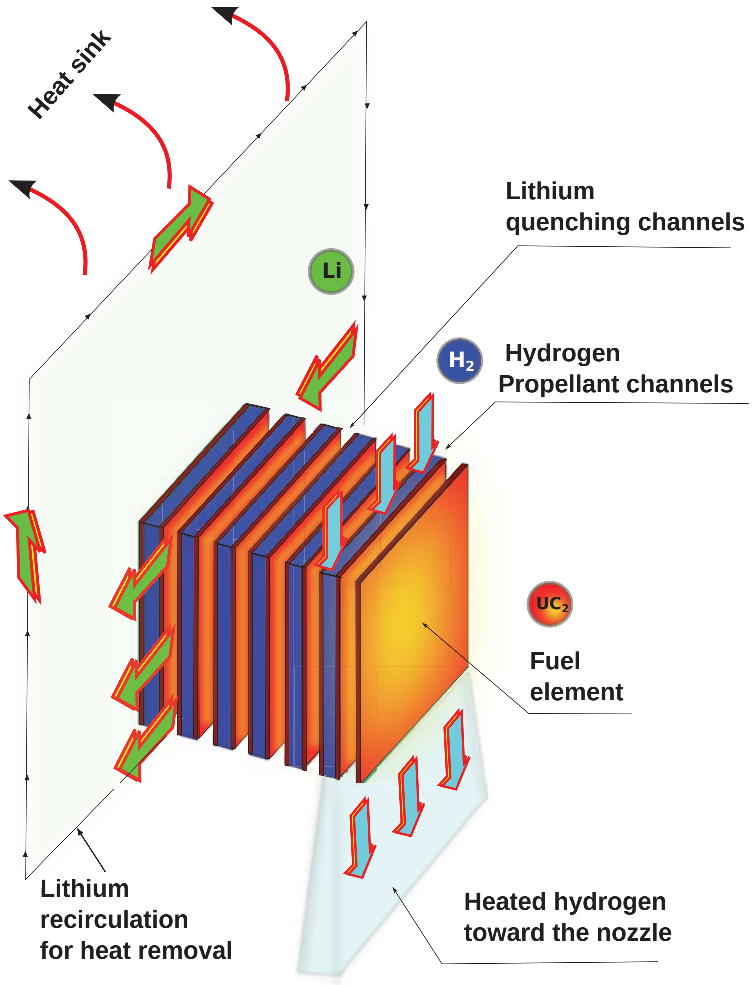

FIG. 6: Illustrative sketch of a possible unit cell for a pulsed thermal nuclear rocket.

the concept are in the ranges of real applicability.

VI. NEUTRONICS CONSIDERATIONS

For the neutronic aspects of this concept, two topics were preliminary investigated, namely: **(1)**-the feasibility to obtain criticality conditions for a self-sustainable core., and **(2)**-the fuel temperature coefficient of reactivity (FTC).

To begin with, it is necessary to define the most general and illustrative geometry for the unit cell to be used in the neutronic code, and this is, perhaps, the geometry schematically depicted in Fig. 6. In this figure, an array of fuel slabs are interspersed by lithium gaps and propellant (hydrogen) channels. The lithium is recirculating and continuously removing the unwanted energy (the *delayed-heat* from fission fragments) generated between pulsations. This unwanted energy will be transferred to the empty space by heat transfer radiation if the pulsed mode is used in space transfer maneuvers, or can be used to generate additional thrust by using the planetary atmosphere if the pulsed mode is used during the lift off of planetary bodies. At the same time, hydrogen is continuously being heated partially by the fuel and partially by the instantaneous neutronics bursts from pulsations. With this idea in mind, we will proceed with the computational modeling.

A. Computer code used

The calculations presented in this section were performed with the SCALE-VI code system, and the KENO-VI, ([14]), applied to a single 3-D unit cell configuration using the V7-238-energy-group libraries generated using the BONAMI and CENTRM modules for the unresolved and resolved resonances, respectively. The MULTIGROUP cell treatment was found appropriated for the reference unit cell composed for a large array of interspersed fuel-lithium gaps slabs.

The reference unit cell is composed of a fuel central region consisting of parallel slab elements of UC_2 and lithium-gaps interspersed each other and surrounded by hydrogen as moderator. The density of UC_2 was 12g/cm^3, for the lithium 0.4 g/cm^3 and density of hydrogen of 0.4 g/cm^3. Each fuel slab has dimensions of 150μm thick by 40 cm long by 40 cm high. Each lithium-gap has dimensions 900μm thick by 40 cm long by 40 cm high. Fuel slabs and lithium-gaps were interspersed in parallel until a square of 1.05 cm long was filled.
The square was surrounded by hydrogen slabs at both sides of 1 cm thick by 40 cm long by 40 cm high, resulting in a volume of fuel region (including lithium gaps) to volume moderator of ~ 2. Reflective condition were considered for the unit cell and then calculations of criticality are on κ_∞. For this preliminary assessment, no burnup calculations were performed, and therefore all the results are at Beginning Of Life of fuel (BOL). The reference unit cell is shown in Figure 7.

Fig. 8 shows the required enrichment of ^{235}U as function of the depletion of ^{6}Li in order to obtain a criticality $\kappa_\infty = 1 \pm 70$ pcm. Referring to this figure, it is seen that, ^{6}Li has a very strong influence in the required enrichment. Because we are relying on the prompt negative fuel temperature coefficient of reactivity (FTC) to limit the power peak and because the FTC in oxide-fueled cores the main phenomenon affecting the FTC is the Doppler broadening of the fuel resonances mainly from ^{238}U, then we must to pursue as much as possible a low enrichment of ^{235}U, and then depletion of ^{6}Li seems necessary. Fig. 9 shows the FTC for different ^{6}Li

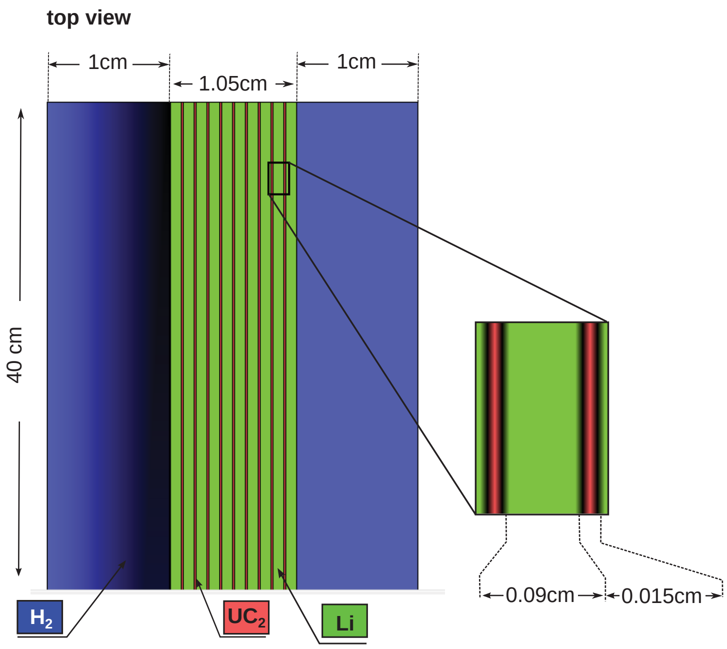

FIG. 7: Reference unit cell.

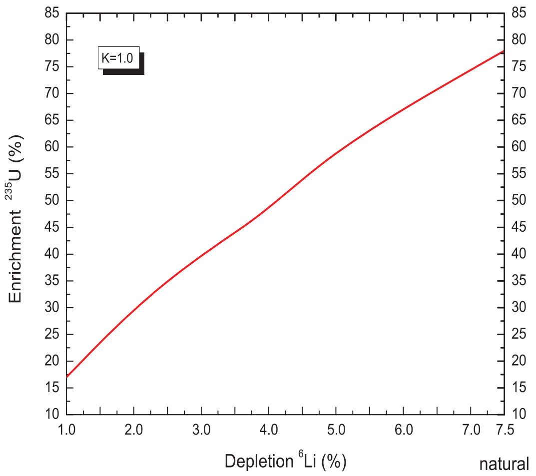

FIG. 8: The required ^{235}U enrichment for $\kappa_\infty = 1 \pm 100$ pcm, as function of depletion ^{6} Li.

depletions starting from a criticality $\kappa_\infty = 1$ (and then from different enrichments of ^{235}U). For FTC calculations, two sets of simulations were performed: First considering a fuel temperature increase of $\Delta T_f = 100$K and another considering an abrupt instantaneous temperature increase of $\Delta T_f = 1500$K. For both calculations it was assumed an initial temperature of fuel $T_f = 1300$ K. At was mentioned before, ^{6}Li has an strong effect on the FTC because the reduction of ^{238}U, and even the FTC is becoming positive for $\Delta T_f = 100$K at $\simeq 4\%^6$Li. This means that depletion on $\leq 4\%^6$Li, at least, seems mandatory.

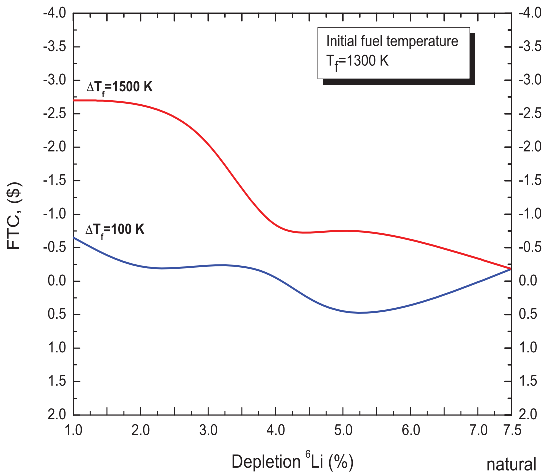

FIG. 9: FTC as function of depletion of ^{6} Li, after an instantaneous fuel temperature increase of 1500 K.

B. The pulse

The most important parameters of the pulse are the total energy release, the maximum power, an the power width at half maximum. The interested reader can find a complete theory about critical excursions in the excellent classical book of Lewis,[7] (1977) (chapter 5).

According with the theory, the energy at any time after the pulse is given by,

$$Q(t) = \frac{\Lambda}{|\mu|}\left(R + \frac{\rho_o - \beta}{\Lambda}\right)\frac{(1 - \exp^{-Rt})}{(1 + B\exp^{-Rt})} \tag{36}$$

where Λ is the prompt neutron generation time, β the delayed neutron fraction, ρ_o the reactivity insertion at $t = 0$ and μ is often referred to as the prompt reactivity coefficient as

$$\mu = \frac{1}{m_f c_f}\frac{1}{\kappa}\frac{\partial \kappa}{\partial T_f} \tag{37}$$

and R is given by

$$R \simeq \frac{\rho_o - \beta}{\Lambda} \tag{38}$$

and

$$B \simeq \frac{2(\rho_o - \beta)^2}{\Lambda|\mu|P(0)} \tag{39}$$

being $P(0)$ the initial power before excursion.

The time-dependent power is obtained by differentiation of Eq.(36) and yields

$$P(t) = \frac{2\Lambda R^2}{|\mu|}\frac{B\exp^{-Rt}}{(1 + B\exp^{-Rt})^2} \tag{40}$$

With these set of equations, we obtain for the total energy release

$$Q(\infty) \simeq \frac{2(\rho_o - \beta)}{|\mu|} \tag{41}$$

and the maximum power

$$P_{max} \simeq \frac{(\rho_o - \beta)^2}{2\Lambda|\mu|} \tag{42}$$

and the burst width at half maximum yields

$$\Gamma \simeq \frac{3.52\Lambda}{\rho_o - \beta} \tag{43}$$

With the above expressions, we can do some specific calculations for our referenced unit cell.

First, the total energy given by the pulse, i.e., by Eq.(41) must be equal to the sensible energy stored into the fuel by the instantaneous temperature increase ΔT_f. Thus, by equating $Q(\infty) = c_f m_f \Delta T_f$ and inserting Eq.(37), we obtain for the required positive reactivity insertion ρ_o the following expression

$$\rho_o \simeq \frac{1}{\kappa}\frac{\partial\kappa}{\partial T_f}\frac{\Delta T_f}{2} + \beta \tag{44}$$

with an initial core $\kappa = 1$, $\Delta T_f = 1500$K, $\beta = 600$ pcm., and our previous calculated FTC of

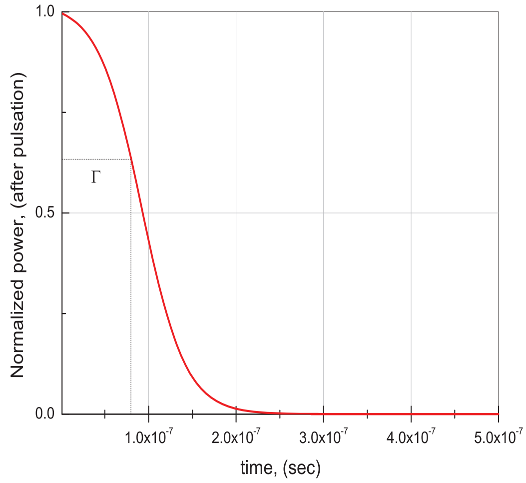

FIG. 10: Energy pulse profile as a function of time.

$\left|\frac{\partial\kappa}{\partial T_f}\right| \sim \frac{1626}{1500}$pcm/K (assuming an instantaneous temperature rise), one obtains $\rho_o \simeq 1413$ pcm.

Now, considering a typical prompt generation time for thermal reactors above $\Lambda \simeq 2 \times 10^{-5}$ sec., and using Eq.(43), the burst width at half maximum yields $\Gamma \simeq 8 \times 10^{-2}\mu$sec, meaning that the pulse will have a very high resolution, and predictably a very small tail. This tail may be inferred by plotting Eq.(40). For this purpose, we need to know the parameter B, and then, a certain estimation of $P(0)$. This power may be roughly assumed as the residual heat decay accumulated (as a background) between pulses. With this assumption, the Wigner-Way formula, (Wigner-Way formulae, [15]) gives us a value less than a 10% of the initial power as much, and then, by taking the initial power as the maximum power from Eq.(42), this results in $B \simeq 40$, and $R \simeq 4 \times 10^{-7}$ sec^{-1}. Fig. 10 is a normalized plot of Eq.(40). It is seen, that the pulse has a very narrow tail meaning that there will be no overlapping between pulses for frequencies of pulsations of 1 kHz or thereabouts.

VII. SUMMARY OF RESULTS AND CONCLUSIONS

A novel idea has been proposed for thrust and Isp augmentation based on the use of a bimodal pulsed-stationary nuclear thermal rocket. Some interesting results are raised by this preliminary study as follows:

(a) It is possible to obtain important amplifications in energy from a pulsed core in comparison with the stationary mode by fast quenching of thin fuel geometries and the at low Fourier numbers.

(b) Direct thrust enhancement is possible by increasing proportionally the propellant mass flow rate.

(c) I_{sp} augmentation is possible by harnessing the huge neutronic flux from the burst. However, for this goal to be achieved there must be an auxiliary cooling system which provides the required fast quenching of the fuel and the heat removal of the heat from fission fragments which in this concept is an unwanted energy . Liquid metals gaps are the feasible -and possible unique solution, with lithium as main candidate.

VIII. APPENDIX

A. Total heat transfer for plates and spheres

• for spheres, we have,[4]

$$Q = Q_o \left[1 - 3 \sum_{n=1}^{\infty} \frac{\theta_n^*}{\zeta_n^3} \left\{ \sin(\zeta_n) - \zeta_n \cos(\zeta_n) \right\} \right] \tag{45}$$

where

$$\theta_n^* = C_n \exp\left(-\zeta_n^2 \mathbf{Fo}\right) \tag{46}$$

and

$$C_n = \frac{4\left[\sin(\zeta_n) - \zeta_n \cos(\zeta_n)\right]}{2\zeta_n - \sin(2\zeta_n)} \tag{47}$$

and the discrete values of ζ_n are positive roots of the transcendental equation

$$1 - \zeta_n \cot \zeta_n = \mathbf{Bi} \tag{48}$$

- for infinite plates, we have,[4]

$$Q = Q_o\left[1 - \sum_{n=1}^{\infty}\frac{\sin\zeta_n}{\zeta_n}\theta_n^*\right] \tag{49}$$

where

$$\theta_n^* = C_n \exp\left(-\zeta_n^2 \mathbf{Fo}\right) \tag{50}$$

and

$$C_n = \frac{4\sin\zeta_n}{2\zeta_n + \sin(2\zeta_n)} \tag{51}$$

and the discrete values (eigenvalues) of ζ_n are positive roots of the transcendental equation

$$\zeta_n \tan\zeta_n = \mathbf{Bi} \tag{52}$$

NOMENCLATURE

A_s = surface area of the fuel

B = parameter defined by Eq.(39)

BOL = Beginning Of Life of fuel

D = diameter

D_f = diameter of fuel

D_h = coolant hydraulic diameter

$\mathbf{Bi}$ = Biot number

C_n = parameter defined by Eq.(11)

c = heat capacity

f = Darcy-Weisbach friction factor

f_n = fraction of prompt heat

f_t = number of pulsations during propellant remains in the chamber

F = thrust

FTC = fuel temperature coefficient reactivity

Fo = Fourier number

$HTGR$ = high temperature gas reactor

h = heat transfer coefficient of coolant

I_{sp} = specific impulse

J_o = Bessel function of the first kind

J_1 = Bessel function of the first kind

l_f = length of the fuel

m_f = mass of the fuel

$\dot{m}_c$ = propellant mass flow rate

NTR = nuclear thermal rocket (stationary)

n = *n-times*

Δp = pressure drop over core

P = power

P_c = coolant pumping power

P_s = power in the stationary mode

Pr = Prandtl number

Q = total heat transfer in the pulsed mode

Q_s = total heat transfer in the stationary mode

R = parameter defined by Eq.(38)

r = radius

t = quenching time ,time of residence of propellant

ΔT_c = axial temperature increase of coolant

ΔT_f = temperature increase of fuel

T = temperature of cold fuel

T_c = average coolant/propellant temperature

T_m = maximum fuel temperature

T_i = inlet temperature of the propellant

T_o = outlet temperature of the propellant

T_p = propellant temperature before expansion

u_c = coolant velocity

V = volume

v_c = velocity of the propellant

v_e = exhaust velocity

\$ = Dollar reactivity, equal to 600 pcm

Greek symbols

β = delayed neutron fraction

τ = thermal time constant

ρ = density

Λ = prompt neutron generation

μ = prompt reactivity coefficient

κ_∞ = infinite multiplication

ρ_o = step positive reactivity insertion

Γ = burst width at half maximum

θ_n^* = parameter defined by Eq.(6)

ζ = eigenvalues from resolving heat transfer transient equation

κ_f = thermal conductivity of the fuel

Subscripts, Superscripts

c = coolant, propellant

f = fuel

o = reference, initial value

s = stationary, surface

ACKNOWLEDGEMENTS

This research was supported by the Spanish Ministry of Economy and Competitiveness under fellowship grant Ramon y Cajal: RYC-2013-13459.

IX. REFERENCES

[1] Whittemore. W.L. A continuously Pulsed Triga Reactor: An Intense Source for Neutron Scattering Experimments. XAD41687

[2] Breakthrough in Ricardo Kinergy "second generation" high-speed flywheel technology; Press release date: 22 August 2011. retrieved 2012-07-03

[3] Bowman C.D. Prospects for Reactor Reactivity Control Using Lasers. Transactions of American Nuclear societ, Atlant, June 4-8, 1989, Vol 59, p 340.

[4] Incropera F.P., DeWitt D.P., 1996. Introduction to Heat Transfer. Thrid edition. John Wiley & Son

[5] Schneider P.J., 1955. Conduction Heat Transfer. Addison-WEsley, Reading, MA.

[6] Waltar A.E., Reynolds A.B., 1981. Fast Breeder Reactors. Pergamon Press.

[7] Lewis E.E. 1977. Nuclear Power Reactor Safety. John Wiley & Son.

[8] Bellon M. 1973. Thermal and Hydraulic Time Constants for Diferrent Types of Reactors. Unpublished M.S. project report, Nuclear Engineering Program, Northwestern University.

[9] Turner J.L M. Rocket and Spacecraft Propulsion. Principles, Practice and New developmentss. Third edition. Springer-Praxis Publishing. Chichester, UK.

[10] Dudestadt J.J., Hamilton L.J. 1976. Nuclear Reactor Analysis. John Wiley & Sons. ISBN 0-471-22363-8.

[11] Davison. H.W. Compilation of Thermophysical Properties of Liquid Lithium. NASA technical note, NASA TN D-4650. 1968.

[12] Cahn R.W. Physical Metallurgy, Third edition, Elsevier Science Publishers B.V., 1983

[13] Fast Reactor Database 2006 updated, in IAEEA TECDOC series, 2006. IAEA, p.450

[14] SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, ORNL/TM-2005/39, Version 6.1, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.

[15] Way K., Wigner E.P. The Rate of decay Fission Products. Phys.Rev, 73, 1318-1330. 1948