

Yurii V. Frolov – Leader in the Russian Combustion Community and beyond

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Professor Yurii V. Frolov passed away from coronavirus related complications in Moscow on 30 January 2021. His research concerned propellants, pyrotechnic formulations, and combustion. He is particularly renowned for his insights into the enhancing performance of compositions including aluminum and other metals. Prof. Frolov served as a head of laboratory of energetic materials and a vice-director at the Semenov Institute of Chemical Physics, Russian Academy of Sciences (Moscow). He was a Russian Federation State Prize Laureate (1986) and an Honored Scientist of Russia (2004). Professor Frolov was also firmly committed to strengthen scientific cooperation. He had spent many years actively working as a leader in the International Pyrotechnics Society.

Scientific Background

Yuri Vasilevich Frolov was born on February 22, 1937, in Moscow, USSR in a family of four children. In perfect accord with the Soviet Space Program, he enrolled in the Moscow Engineering Physical Institute (MEPHI) in 1957, and graduated in 1961. He was then employed as a junior researcher at the Semenov Institute of Chemical Physics in 1961 (Figure 1). In 1965 he defended his PhD thesis devoted to ignition and combustion of metal particles. Yuri was fortunate to be mentored by first-class renowned physicists Yakov B. Zeldovich and Alexander Belyaev. His first paper “Combustion and ignition of particles of finely dispersed aluminum”



Figure 1. Just hired by Semenov Institute, Yurii Frolov (right) welcomes Gagarin’s first flight into space.

[1] appeared in 1968. His bright ideas resulted in novel experimental setups to study metal particle combustion and brought him wide recognition even early in his career. He leaves behind a large family including the children Dmitry and Elena, two granddaughters, and one great-granddaughter. His main hobbies were skiing, yachting, and jogging.

His Advancements in Combustion

A list of selected publications of Yurii Frolov in Combustion, Explosion and Shock Waves (*Fizika Gorniya i Vzryva* in Russian) and some others is listed in the Reference section.

Yurii’s interests in the field of combustion were very broad: including the ignition and combustion of metal particles and metalized solid propellants, the nanosized components for solid propellants, the microstructure of reactive solid heterogeneous systems, amongst many others [1,3–20].

The pioneering results obtained by Prof. Frolov under the supervision of his thesis advisor A. F. Belyaev on the ignition and combustion of aluminum particles appeared in 1968 [1]. These results had a long-term impact on combustion theory and applications. About forty years later in 2005, M. W. Beckstead summarized over ten different sources with almost 400 combustion characteristics of aluminum particles [2]. The correctness of Prof. Frolov’s experimental approach and interpretation of the data has been confirmed by recent works: viz., the aluminum combustion is controlled by the D^n law (n varies from 1.5 to 1.8), and the effects of pressure and initial temperature are minor, by [1]. Yurii described the aluminum agglomeration phenomena and proposed the most important equations

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obtained with the use of a smart experimental technique for collecting condensed combustion products at the combustion surface, i.e., the “rotating drum” method [3,4]. This method is still of wide use worldwide. Apart from many journal papers, he summarized these results in the well-known monograph *Combustion of Powdered Metals in Active Media* [5]. This famous handbook is familiar literally to anyone who ever worked on the combustion of metals.

He was one of the pioneers in the research of nanoscale components of solid fuels. Starting from the nano- and ultra-dispersed aluminum [6], he continued with deposited-in-vacuum nano-RDX, nano-AN/RDX composites, nano-TNT, and many other compositions [7–9]. The rich theoretical and experimental insights obtained by Yurii and co-workers facilitated the development of the industrial-scale production of nano-sized components. While investigating the nanoscale components of solid fuels, Prof. Frolov proposed new relations interconnecting the microstructure of heterogeneous condensed systems and the energy release. Using a wide range of experimental techniques, Prof. Frolov and his colleagues obtained deeper insights into the nature of these processes [10–12]. He described the boron combustion and shed light on the nature of the boron particles oxidation under different media [13,14]. These results reported at the international conferences received wide recognition among the community (Figure 2).

It is also important to note Yurii’s firm commitment to use combustion as a source of energy for civilian purposes. Together with the colleagues from USA, he developed pyrotechnic compositions useful for “terrestrial” neutralizing

landmines [15]. For “space” purposes, in collaboration with French colleagues, he worked on the destroying of space debris [16].

His International Outreach to the Scientific Community

In 1970, he was invited by Prof. Martin Summerfield as a Visiting Scientist in his Combustion and Propulsion Laboratory at Princeton University. From January to March 1971, he gave lectures and worked experimentally on the influence of aluminum powders on solid-propellant combustion and burning rates. During the 1970s, he had visited Princeton University three more times to give talks at seminars and to discuss new research with his American colleagues.

He also assumed leadership roles in the International Pyrotechnics Society (IPS). For many years, Yurii had been a session organizer and a chairman (Figure 3). For decades, his service had taken him to the United States on even-numbered years and all over the world in odd-numbered years. Altogether, he served as a co-chairman and international scientific committee member for about 20 IPS meetings. During his tenure, the society itself and its journal *Propellants, Explosives, Pyrotechnics* (PEP) notably expanded their impact. A few of his contributions to PEP can be found at the end of this article.

Remembrances by his International Colleagues

A Few of Len Caveny’s Good Memories of Yurii

Yurii V. Frolov arrived at Martin Summerfield’s lab at Princeton in January 1971 as a part of an agreement Summerfield made in 1969 with his peers at the USSR and US Academies



Figure 2. Professor Frolov giving a talk at a scientific conference in 1982.



Figure 3. Allen Tulis and Yurii discussing the IPS business at the 2002 IPS meeting (Colorado, USA).

of Sciences. Yurii was already known to a few of us for his pioneering “rotating drum” innovation for collecting particles at various stages of combustion. Summerfield’s initiatives stemmed from his deep respect for leading scientists at the Soviet institutes such as the Semenov Institute, Kapitsa Institute, and the Institute for Problems of Mechanics. Yurii was among the first three Soviet ambassadors of *science and goodwill* to spend several months interacting directly with the U.S. combustion scientists. Yurii shared an office with me, a post-doctoral researcher at that time, and immediately helped to establish a new series of aluminum combustion in composite propellant experiments. Yurii’s congenial manner and his willingness to explain his publications won him rapid acceptance as a colleague of us. I recall him sitting at my desk and explaining to me his Cyrillic graphs and tables. Indeed, very soon some of us learned enough Russian to understand figure captions. Yurii quickly made friends with our technicians by introducing a Russian lunch-time game of pitching coins at a line on the floor. Soon Yurii was visiting our homes, joining poker games (Figure 4), enjoying restaurants, and Roy Crosby was teaching him how to hit a golf ball.

Yurii’s classic article on ignition and burning of powdered aluminum in high-temperature reactive gases [3] demonstrates his high proficiency of the topic. No one in the U.S. (exception for Andre Macek) had a practical knowledge that included the scope of Yurii’s article. Importantly, his article foretold the importance of ultrafine metal powders.

By March 1971, Yurii’s combustion experiments were completed and the data analyses began. Yurii used the Russian approach and I attempted our traditional approach of using computerized models. I had a sense of why and how the Russian’s more empirical techniques were more expedient while including the essential physics. As an example of East meeting West, Yurii and I worked on a paper explaining our data during his visits to Princeton over the next several years.

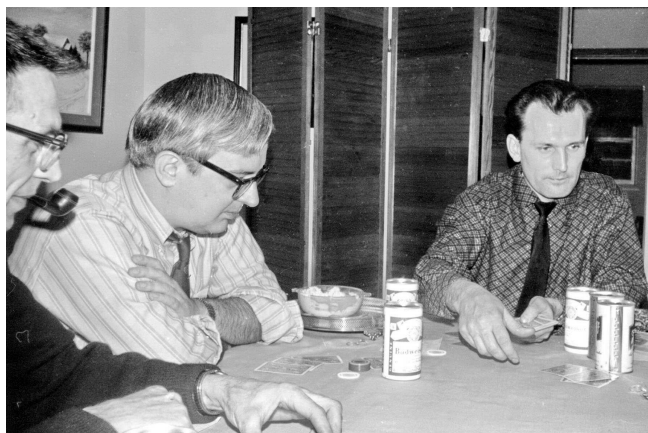


Figure 4. Yurii Frolov playing poker with Summerfield’s staff Chris Felsheim and Sam Morris in Caveny home. 1971.

Yurii was devoted to the International Pyrotechnics Society as an international scientific community; he vigorously interacted with participants to strengthening scientific cooperation between countries. Quoting Ruth M. Doherty, “The intersection of chemistry, physics, materials science, and engineering is at the heart of its journal *Propellants, Explosives, Pyrotechnics* (PEP).”

Yurii continued to visit Princeton every two years (in conjunction with his IPS participation), often with George B. Manelis. As illustrated in Figure 5, our discussions continued over the next decades. Our family enjoys a collection of post and Christmas cards and greetings from Yurii. Yurii very generously gave me silver coins commemorating Soviet science and space events. In the 1990s, I made one or two visits each year to Moscow. For example, during a November 1993 conference at the Hotel Uzkoye of the Russian Academy of Sciences, I was less than a kilometer from Yurii’s home. One night, Yurii greeted me and we walked in ankle-deep snow through the woods to his home for an enjoyable supper. Meeting his teenage son, cousin and his wife, and Collie dog Emir was fun and memorable.

Sorting through my Russian papers and books on Yurii’s research and contributions is to tour just a small part of his full and satisfying career in a field rapidly advancing from simple strand burners to X-Ray Photoelectron Spectroscopy.

When our daughters learned the sad news about Yurii, they immediately recited their pleasant and enduring memories of his visits with them. I miss Yurii.

A Few of Luigi DeLuca’s Good Memories of Yurii

When Yurii joined Prof. Summerfield’s laboratory at Princeton University, I was already there as a visiting student, arriving few months earlier from Italy. At that time, I was learning about laser (Figure 6) assisted ignition of solid propellants (continuing the work of another Russian scientist, Boris N. Kondrikov), while Yurii was already established authority in metal burning. Despite the obvious cultural gap, we quickly

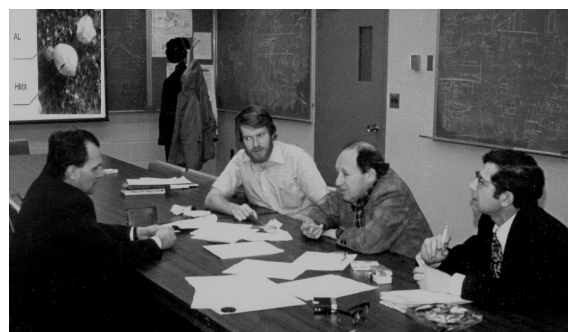


Figure 5. Yurii V. Frolov, Len Caveny, and George B. Manelis in conversation with Martin Summerfield. February 1974.



Figure 6. Luigi T. DeLuca in Summerfield's laboratory adjusting his CO₂ laser apparatus for energetic-material ignition experiments. 1971.

became good friends probably because we were both European visitors a bit "lost" in a new and magic place. Now and then I would show him my experimental results and Yurii would introduce me to the complexities of Al particle burning, but our mutual liking was more important. We would spend quite a lot of time learning about each other's personal life and background. This way I got so interested in Russian life that, at the end of the spring semester, Yurii quickly organized for me a visit to Moscow by directly accessing the Russian embassy in Washington. At the end of June 1971, I could visit his home and meet his family, see the Semenov Institute and its labs, tour various museums and the Red Square, have great Russian food and drinks, and so on. Those were also the days that Russian astronauts Georgy Dobrovolsky, Vladislav Volkov, and Viktor Patsayev died while reentering to Earth from their space mission to Space Station (29 June 1971, Soyuz-11/Salyut-1 accident). Magically, thanks to Yurii, I could bypass the huge line of people waiting to pay homage to them just next to the red walls of Kremlin and Lenin's mausoleum.

In the following years, we kept in touch, in person or remote, until recently. The last time we met Yurii, with Alon and Vladimir Zarko, was in Moscow in October 2014 for the conference Zeldovich Memorial III (honoring his 100th birthday). Meanwhile, I also met Dr. Alla Pivkina and other members of his lab both in Moscow and elsewhere for international conferences. Some of their young researchers visited our SPLab in Milan and we entertained some useful cooperative programs, i.e. wrote joint articles, e.g., for hybrid rocket propulsion [17], and offered coordinated contributions in books [18–20] or journals.

Thank you for your true friendship and valuable teaching, Yurii, we will miss you!

A Few of Alon Gany's Good Memories of Yurii

I arrived in Princeton University in the summer of 1976 for a 3-year research associateship as a post-doctoral fellow at Martin Summerfield's lab. My main research subject was combustion of aluminized solid propellants. This was the first time for me to investigate metal combustion, which further became one of my significant research subjects. A major source of scientific information and knowledge of the subject was the outstanding book (translated from Russian) "*Combustion of Powdered Metals in Active Media*" co-authored by Yurii Frolov [5]. We cited it in at least 5 of our journal publications and several more conference papers and presentations (with Len Caveny and Martin Summerfield at Princeton University, as well as later-on with my research group at the Technion in Israel). I was therefore very enthusiastic meeting Yurii in person during his bi-annual visits at Princeton (with George Manelis) when I was there, Figure 7. We had scientific discussions in the lab as well as friendly personal relations. My wife and I hosted Yurii and Manelis at our home in Princeton, and in another occasion, we enjoyed the conversations we drove them in our car for a meeting in Washington DC.

The last time that I met with Yurii was during my participation in the conference Zeldovich Memorial III (honoring his 100th birthday) that took place in Moscow in October 2014 (where Luigi and Vladimir Zarko made presentations as well). Alla arranged a meeting with Yurii in their laboratory, and we had a memorable time talking science and reminiscing about the good old days in Princeton.



Figure 7. Tom Ohlemiller and Alon Gany demonstrating an experiment in Summerfield's laboratory for George Manelis and Yurii. 1978.

I have high regard of Yurii as a scientist and warm feeling for our years of friendship. I will miss him.

Summary

Prof. Yurii Vasilevich Frolov was an outstanding scientist, a pioneer in combustion, and inventor of laboratory apparatus. He had a big success in gaining understanding and improvements in propellants and pyrotechnics. He will be remembered by his colleagues and generations of scientists and engineers for his numerous contributions, publications, and his collegial manner. We and our combustion community have lost a leader, a colleague, and a friend.

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