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RAMJET PROPULSION FOR PROJECTILES—AN OVERVIEW OF WORLDWIDE ACHIEVEMENTS AND FUTURE OPPORTUNITIES

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Ramjet propulsion for gun-launched projectiles has received substantial attention since the invention of the ramjet engine concept in 1913. After the second World War, projectiles using solid fuel gained interest due to their inherent simplicity and robustness. Throughout the world, research and development programs have been and still are being executed on the topic of solid-fuel ramjet projectiles. In this paper the authors intend to give an overview of the worldwide activities in this field. To this end an extensive literature review is executed, which gives a clear view on the activities performed over the years by the research institutes and companies of different countries. The paper is concluded by a summary of the main achievements of all the work on solid-fuel ramjet projectiles as well as of the remaining challenges. In addition, an outlook of this technology field into the future is given by indicating some opportunities that may be within reach with the present state-of-the-art of solid-fuel ramjet projectile technology.

KEY WORDS: *literature review, solid-fuel ramjet, gun-launched projectiles*

1. INTRODUCTION

A ramjet engine is a form of an airbreathing jet engine that uses its forward motion to compress the incoming air. In contrast to a normal jet engine, the ramjet engine does not have a rotating compressor and is not able to generate thrust at zero speed. Soon after the invention of the ramjet engine cycle in 1913, people started to look at applying this engine cycle to gun-launched projectiles in order to increase range. Since then, numerous studies have been performed on ramjet projectiles. Due to the absence of a fuel feed system and associated complexity, the solid-fuel ramjet (SFRJ) has received significant attention the past few decades. Attempts to progress the SFRJ technology were undertaken, amongst others, in the United States of America, Israel, Sweden, South Africa, South Korea, and the Netherlands.

The SFRJ propulsion system combines high propulsive performance with a very low degree of mechanical complexity. As such, it is a very attractive propulsion system for gun-launched projectiles. The propulsive force generated by this propulsion system can serve to reduce time-to-target and/or increase the kinetic energy on the target or to increase the range of projectiles. The functioning of an SFRJ projectile is, however, dictated by complex physical phenomena with strong interactions. A successful design of such a projectile thus requires detailed knowledge of the performance at subsystem level as well as at the projectile's system level.

Figure 1 shows a schematic representation of a generic fin-stabilized SFRJ projectile. The axisymmetric air intake is located at the nose of the projectile. On the inner wall of the projectile body, a layer of solid fuel [e.g., a fuel based on hydroxyl-terminated polybutadiene (HTPB)] is cast. The conical exhaust nozzle is mounted on the downstream side of the tubular projectile body, where the fins to stabilize the projectile are also located. These fins are absent in the case of a spin-stabilized projectile. To transfer the gas pressure of the gun propellant to the projectile during gun launch, a pusher plate is applied, which fits in the exhaust nozzle of the projectile. Sabots segments are used to guide the projectile within the gun barrel. The pusher plate and sabots segments are not shown in Fig. 1.

After ignition of the gun propellant, the projectile is accelerated within the gun to the required muzzle velocity (e.g., Mach 4.0 = 1360 m/s at sea level for a typical direct-hit application). Directly after leaving the gun barrel, the pusher plate as well as the sabots segments separate from the projectile, and air starts to flow through the projectile. In the intake the air is compressed by shock waves, hereby reducing the flow velocity to subsonic speed. Due to the compression process, the pressure and temperature of the air rises. The hot, compressed air enters the combustion chamber over a backward-facing step acting as a flame stabilizer during combustion. The convective heat transfer causes the solid fuel to evaporate and mix with the air. Provided that the stagnation temperature of the air is high enough (roughly > 1000 K), automatic ignition of this air-fuel mixture occurs. The combustion gases leave the projectile through the exhaust nozzle, in which the flow speed is increased from subsonic to supersonic speeds, thus generating a thrust that counteracts the aerodynamic drag of the projectile. By maintaining a high supersonic flight speed, ramjet propulsion increases the projectile's range and considerably reduces the time-to-target, resulting in a higher probability of hitting the target. In addition, the higher flight speed may result in a greater impact on the target.

The present paper is an overview of worldwide achievements in the field of ramjet-propelled gun-launched projectiles, from the early activities in the beginning of the previous century up to the most recent activities concentrated on SFRJ projectiles. More-detailed descriptions will be given of the SFRJ technology development and demonstration programs executed in Sweden, the Netherlands, and South Africa.

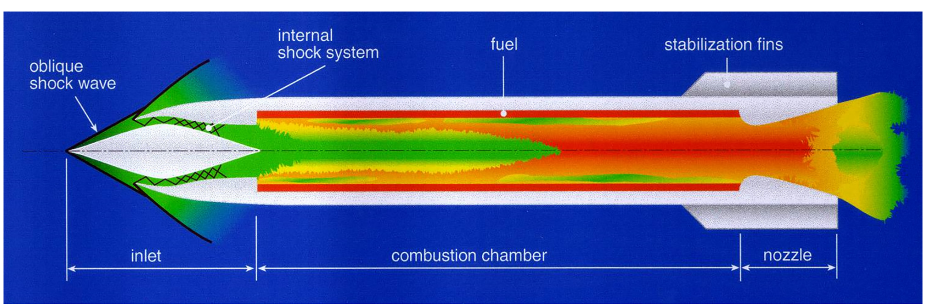

FIG. 1: Schematic cross-sectional view of a generic-fin stabilized solid-fuel ramjet projectile (Reprinted from Veraar and Mayer, 2005)

2. OVERVIEW OF WORLDWIDE ACTIVITIES ON RAMJET PROPULSION FOR PROJECTILES

The present section gives an overview of the worldwide activities in the field of solid-fuel ramjet projectiles. In the first paragraph, the literature search approach is described, as well as its statistic results. The literature forms the basis for the overview, starting with a paragraph on the "Early Years," with subsequent paragraphs describing the activities on the subject in each of the countries active in the field, starting with the countries showing the earliest publications.

2.1 Literature Review

A search was performed to identify open international literature in the following scientific publication sources:

- Proceedings of the International Symposium on Ballistics
- AIAA.org
- Scopus.com
- DITC.mil
- NASA.gov

Initially these sources were scanned for scientific publications containing the phrase "solid fuel ramjet projectile" or "ramjet projectile." This revealed a substantial amount of publications but did not include the publications that describe the more fundamental type of work that usually precedes the technology application and demonstration phase. Therefore, it was decided to also scan the publication sources for the phrase "solid fuel ramjet." Some of the thus found publications were related to ducted rocket applications instead of solid-fuel ramjets. These publications have been rejected from the literature review. Together with some open publications on the subject available to the authors, this resulted in a total number of about 340 publications. The publications were sorted by country (and by institute or company) of the main author and listed in chronological order to get a good overview of the progress of the work made over the years. Figure 2 shows the yearly total number of publications that were found using the above search phrases beginning in 1975. From the number of publications, it can be concluded that the technology field received a lot of attention in the period of 1980–1992. After that time the number of publications clearly shows a decay. In the last decade, the number of publications seems to have increased again, indicating regained interest in the technology field in that period of time.

2.2 The Early Years

Very shortly after the invention of the ramjet engine in France by René Lorin in 1913, ideas were developed by the Hungarian inventor Albert Fonó, who proposed in 1915 to use ramjet propulsion technology to extend the range of artillery shells. He recognized that this propulsion technology could provide a long range without the need for very high muzzle velocities. This would enable the firing of heavy shells from a relatively light gun, but unfortunately the Austro-Hungarian Army rejected his proposal. In 1928 he submitted a patent application in Germany for an "air jet engine" for high-altitude supersonic aircraft, which was finally granted in 1932 after

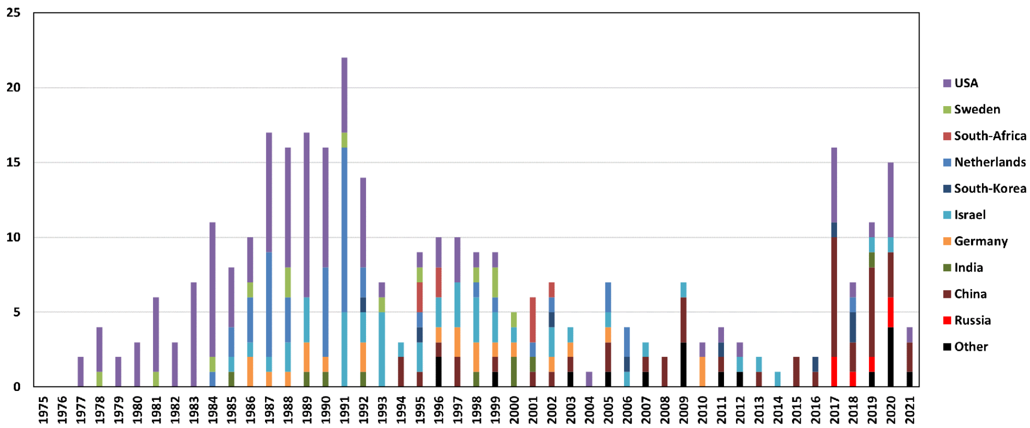

FIG. 2: Historical overview of yearly number of publications on solid fuel ramjet (projectile)

four years of examination. In Germany, Trommsdorff submitted a proposal to the Army Ordnance Office in 1936 to develop a gun-launched projectile using the ram pressure of air through a pitot intake to feed a combustion chamber with a solid propellant (see Fig. 3). Following the proposal several configurations of such projectiles were designed and manufactured in 1938 and subsequently fired from an 8.8-cm anti-aircraft gun. The projectile was fired at Mach 2.5 and carried a compressed propellant charge with longitudinal holes drilled through it. The propellant composition was oxygen deficient and was designed such that it burned slowly to generate fuel-rich gases, which subsequently could be burned with the air flowing through the projectile. The test firings were not successful due to mechanical failure of the propellant grains during gun launch. From that time on, the work of Trommsdorff was directed to develop high-velocity liquid-fuel ramjet projectiles. By the end of World War II, a large number of such ramjet projectiles were developed and flight tested, of which some had considerable success (Trommsdorff, 1956).

A comprehensive description of the early work on solid-fuel ramjet in the United States mentions the first successful flight tests of a rocket-launched solid-fuel ramjet–propelled test vehicle in the flight speed range from Mach 1.8 to 2.1 in January 1952. Following a general description of the characteristics of a solid-fuel ramjet, a detailed discussion is given with the following performance aspects (Wolf and Mullen, 1952):

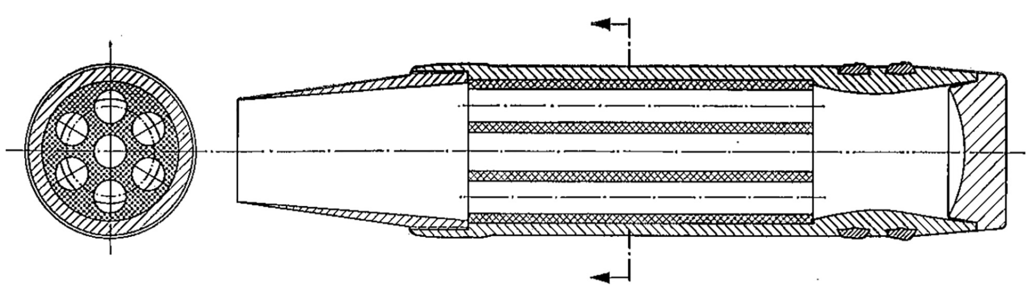

FIG. 3: Trommsdorff's 8.8-cm solid-propellant air-breathing projectile (Reprinted from Trommsdorff, 1956)

- Different solid-fuel configurations (radially burning hollow cylinder with or without bypass flow and end-burning)
  - fuel regression rate of different fuels
  - thrust control
  - flammability limits

Flight tests of a rocket-launched end-burning solid-fuel ramjet are reported by the National Advisory Committee for Aeronautics (NACA) to have demonstrated sustained combustion and a clear capability of the test vehicle to accelerate (from Mach 1.9 to 2.5) in spite of rocket booster separation problems (Bartlett, 1954). Subsequent flight tests of a similar test vehicle with a radially burning magnesium-based fuel grain with bypass airflow (to reduce combustor wall heat load) demonstrated an acceleration capability form Mach 1.9 to 2.9 (Bartlett, 1956).

2.3 United States of America

The publication statistics are summarized in Fig. 4, with publications from the U.S. Naval Postgraduate School (NPS), U.S. Army Ballistic Research Laboratory (BRL), Georgia Institute of Technology (GIT), Atlantic Research Corporation (ARC), Pennsylvania State University (PSU), U.S. Naval Weapons Center (NWC), U.S. Naval Air Warfare Center (NAWC), U.S. Naval Surface Warfare Center (NSWC), U.S. Army Research, Development and Engineering Command (RDECOM), Purdue University (PU), and other publications (Other).

2.3.1 U.S. Naval Postgraduate School

From 1977 to 1995, a large number of Master's theses have been published by the Naval Postgraduate School under supervision of David Netzer. These theses cover a wide range of topics related to solid-fuel ramjet propulsion and its applications. Initial studies cover the dependency of the solid-fuel ramjet performance as a function of its geometrical design parameters (Jones, 1973; Mady, 1977, 1978). Subsequently the work was focused more on the development of models to better predict the performance of solid-fuel ramjets (Netzer, 1977, 1978; Stevenson, 1979; Stevenson and Netzer, 1981). More detailed studies were started to increase the understanding of flow and combustion processes in a solid-fuel ramjet, using both experimental and theoretical tools that were continuously developed further. From the early 1980s onward, a substantial amount of experimental studies were conducted concerning various performance aspects

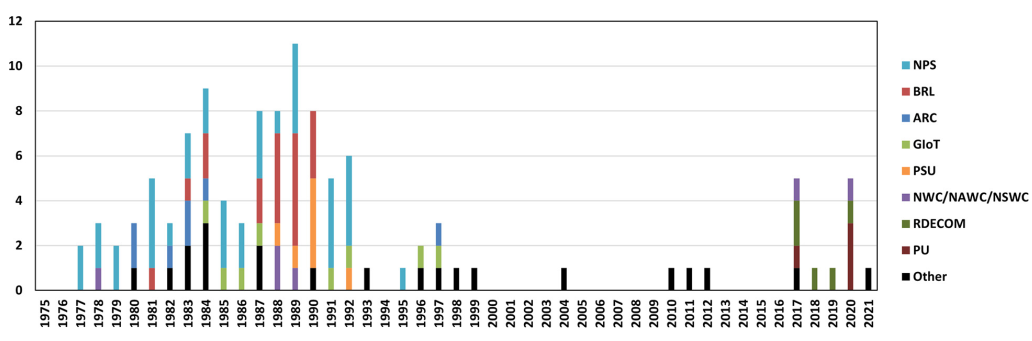

FIG. 4: Number of publications per year by the United States of America

of solid-fuel ramjets, such as the effect of swirling flow for spinning applications (Campbell, 1985), pressure oscillations (Rigterink, 1985), combustion modulation techniques (Ko, 1984; Lowe, 1986), plume infrared signature (Leuhrsen, 1991; Cheng, 1992), ignition and flammability limits (Wooldridge, 1987), performance of metalized fuels (Charles, 1986; Karamiditris et al., 1989; Netzer, 1991), and fuel thermal cycling effects (Lee and Netzer, 1992). More-detailed experimental work was also done to determine the particle size distribution in the reacting boundary layer in relation to ignition and combustion of metalized solid fuels (Powers and Netzer, 1987; Paty, 1988; Nabity, 1989).

While most of the initial work at the Naval Postgraduate School focused on understanding the flow and combustion phenomena, later work also included studies into the application of this technology for gun-launched projectiles and tactical missiles. For high-speed tactical missile applications, experimental and theoretical studies were conducted into the dual-mode solid-fuel ramjet in which the solid fuel was burned in a subsonic combustion chamber, producing fuel-rich gases to be burned in the larger supersonic combustion chamber. The studies indicated that at Mach 6, the dual-mode solid-fuel ramjet could outperform the classical solid-fuel ramjet (Vaught et al., 1989, 1992). An initial experimental study on an SFRJ with supersonic combustion was performed, demonstrating supersonic combustion of polymethylmethacrylate (PMMA) at good combustion efficiencies (Angus et al., 1993). In addition, work was done on low-cost small tactical missiles using solid-fuel ramjet propulsion (Fruge, 1991; Woods, 1995). David Netzer contributed to a chapter on solid-fuel ramjets in the AIAA book *Tactical Missile Propulsion* (Leisch and Netzer, 1996).

2.3.2 U.S. Army Ballistic Research Laboratory

In support of the need of the U.S. Army for reliable, ballistically matched and low-cost training rounds that can be used on restricted training ranges, a program was started at the U.S. Army Ballistic Research Laboratory (BRL) to numerically predict the external and internal flow field of tubular projectiles. The SFRJ projectile was considered a suitable concept to match the ballistic behavior of large-caliber kinetic energy (KE) ammunition. The SFRJ program carried out by BRL was aiming for a full demonstration of a training round. A 75-mm subcaliber tank gun training round (see Fig. 5) was developed for the 105-mm M68 gun to replicate the flight path of a

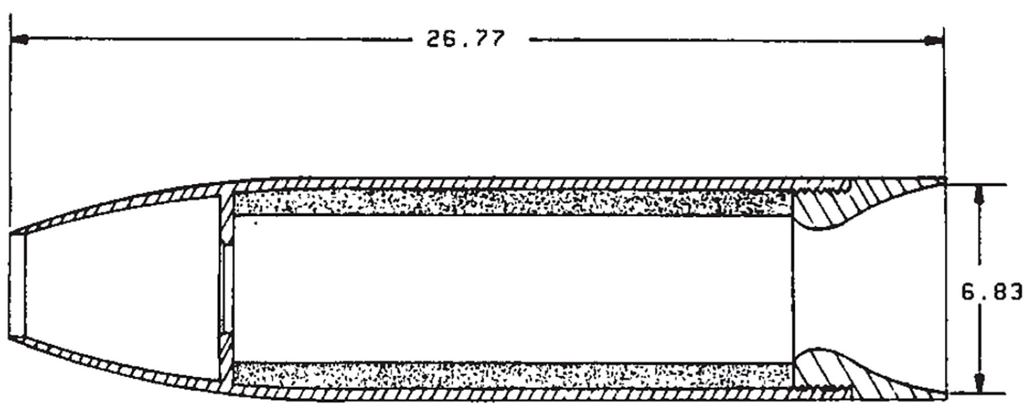

FIG. 5: BRL Prototype 75-mm tank gun training round (dimensions in cm) (Reprinted from Mermagen and Yalamanchili, 1984)

KE round without exceeding the maximum safety range of 7.5 km (Mermagen and Yalamanchili, 1984). Direct-connect ramjet tests and wind tunnel tests were performed prior to flight testing. The flight test results showed good autoignition performance but also revealed (allegedly spin-induced) combustion performance lower than that expected based on direct-connect test results. Successful flight test results (i.e., good reproduction of the flight profile of the KE round) were obtained using a more energetic fuel. Later on, a finned version of the 75-mm SFRJ projectile and a 60-mm fin- and flare-stabilized SFRJ projectile were studied based on results from wind tunnel and flight test data (Danberg and Sigal, 1987; Sigal and Danberg, 1988; von Wahlde, 1989; Guidos, 1989). Computational and wind tunnel work was also done on a 40-mm spin-stabilized projectile for an air-defense application developed in the early 1980s by the U.S. Army Chemical Research Development and Engineering Center (CRDEC) in order to find an explanation for the small differences in the flight performance of projectiles with and without fuel (Nusca et al. and Nusca, 1987–1990).

2.3.3 Georgia Institute of Technology

At the Georgia Institute of Technology, fundamental research work was done (under contract from the Air Force Office of Scientific Research) to study the flow in the recirculation zone downstream of a backward-facing step. Initially the work concentrated on a two-dimensional configuration using cold gas without and with gas blowing from the wall to simulate evaporating fuel coming from the solid-fuel wall (Walterick et al., 1984). Detailed laser velocimetry was performed in conjunction with a Navier–Stokes solver using the k-ε turbulence model (Richardson et al., 1985), and the acoustic behavior of the flow in the simulated SFRJ combustor was studied (Davis et al., 1986). Later this work was extended to include detailed nonintrusive measurements of the reacting flow field in a two-dimensional setup (Wu et al., 1992; Matta and Jagoda, 1996; Matta et al., 1997).

2.3.4 Atlantic Research Corporation

The work done by the Atlantic Research Corporation (ARC) in the early 1980s focused on boron combustion in solid-fuel ramjets for tactical missile propulsion applications under contract from the Air Force Office of Scientific Research. Boron ignition and combustion models were developed and used to predict the combustion of boron-containing fuels (Limage et al., 1980a,b; King, 1982; Komar et al., 1983). In addition, experimental programs were executed to establish the kinetics of liquid boron oxide and water vapor (crucial to ignition) to study the effect of LiF coatings on boron ignition and to characterize boron solid-fuel ramjet combustion using a windowed slab burner (King et al., 1983, 1984). Much later, an application study was performed into the combined ducted rocket and solid-fuel ramjet cycle (Limage, 1997).

2.3.5 Pennsylvania State University

Under a contract from the Office of Naval Research (ONR), a research group of the Pennsylvania State University (PSU) led by Kenneth Kuo conducted a research program to investigate the pyrolysis, ignition, and burning of HTPB-based solid fuels containing metal particles (mainly boron) to increase the volumetric impulse of the ramjet engine (Chen et al., 1988). It was shown that glowing boron particles close to the fuel surfaces acted as ignition sources, resulting in a lower autoignition temperature when compared to the pure HTPB fuel (Kuo et al., 1989). The addition of small percentages of boron particles (5% to 10% by weight) also increased the burning rate. Combustion of solid fuels under supersonic crossflows was also successfully demonstrated and resulted in higher regression rates when compared to subsonic crossflow conditions. However, to promote ignition at supersonic crossflow conditions, it was necessary to increase the backward-facing step height at the combustor entrance (Kuo et al., 1990; Jarymowycz et al., 1990a,b). Subsequent work concerned a numerical study of solid-fuel combustion under supersonic crossflows in a simple geometry, showing that both the air pressure and temperature had a strong influence on the burning rate (Jarymowycz et al., 1992).

2.3.6 U.S. Naval Weapons Center/Naval Air Warfare Center/Naval Surface Warfare Center

Various experimental studies on solid-fuel ramjets have been performed at the Naval Weapon Center. An early work by Schadow et al. investigated the combustion in an SFRJ combustor using a hydrocarbon fuel, indicating that the mixing process and combustion of soot particles are crucial for obtaining a high combustion efficiency (Schadow et al., 1978). Further experimental work was done on a single side-dump solid-fuel ramjet in a 4-inch subscale test setup (Nabity and Walls, 1988). Various combustor geometries in terms of injector-to-combustor area ratio, combustor-to-nozzle throat area ratio and side-dump injection angle were investigated using an HTPB-based fuel grain with carbon black. The results indicated that the single side-dump SFRJ combustor is a viable option to the conventional central-dump SFRJ combustor. Further research was done on both passive and active shear-flow control to suppress pressure oscillations, improve combustion efficiency, and to extend flame stability limits in solid-fuel ramjets and other high-speed airbreathing propulsion systems (Schadow and Gutmark, 1989). An experimental study was performed to establish the effects of equivalence ratio and air mass flux on combustion efficiency and particle distribution in a central-dump solid-fuel ramjet with a fuel grain highly loaded with boron carbide (Nabity et al., 1993). This study showed that combustion efficiency increased with increasing equivalence ratio (i.e., fuel grain length) and increasing air temperature. Short fuel grains resulted in lower combustion efficiency, while higher air temperatures resulted in higher combustion efficiencies.

An experimental methodology was developed at the Naval Air Warfare Center to quantify the ignitability of solid fuels using a small-scale setup featuring oxygen and nitrogen crossflow and a CO_2 laser as ignition source, with the application of an integral rocket SFRJ in mind (Hedman et al., 2017). This small-scale experimental setup was used to screen the ignitability of HTPB-based fuels with additions of carbon black, aluminum, boron, magnesium, and polytetrafluoroethylene (PTFE), indicating that magnesium and PTFE promoted the ignition and combustion of boron.

An experimental study was conducted at the Naval Surface Warfare Center using a counterflow diffusion flame setup to explore the combustion characteristics of small samples of HTPB fuel with nitrous oxide, gaseous oxygen, or heated air, with hybrid rocket and solid-fuel ramjet applications in mind. Oxygen concentration in each oxidizer was shown to play a key role in the fuel regression rate, measured using optical techniques (Young et al., 2020).

2.3.7 U.S. Army Research, Development and Engineering Command

Experimental research was done with the objective of developing a solid-fuel ramjet formulation with thermal decomposition onset temperatures lower than conventional ramjet fuels while maintaining a Shore-A hardness of at least 30. The results show that polysulfide-based formulations decompose at temperatures approximately 120°C lower than HTPB-based fuels. Additionally, the results demonstrate that the decomposition onset temperature and the heat of decomposition can be further reduced with the addition of elemental sulfur (McDonald et al., 2017a). In addition, copolymers consisting of the combination of the LP-33 polysulfide and HTPB were investigated with the objective of combining the low-decomposition and autoignition characteristics of the sulfur-based LP-33 with the high heat of combustion per unit mass of the HTPB. The copolymer showed improved mechanical properties and similar onset of decomposition as the LP-33 formulation. Simple small-scale combustion under hot air crossflow in an open tube indicated improved performance over the LP-33 monopolymer at high inlet momentum values (McDonald et al., 2017b). In follow-up work, equations were developed for thrust to drag, net specific impulse, impulse density, and a newly defined performance parameter, the momentum density as a function of the ratio of the intake area to the aerodynamic reference area (McDonald and Rice, 2018). Thermochemical analyses were conducted for a range of common polymers and solid particulate additives. This method was extended with a method to obtain relative fuel regression rates from the maximum reaction rates obtained from differential thermal analysis curves with the objective of developing a method for optimizing and screening potential fuel polymers at the laboratory scale level (McDonald and Rice, 2018). The results of the analyses showed that fuels with the combination of low stoichiometric air-fuel (AF) ratios, lower regression rates, and high densities tend toward the highest values of total impulse within a given geometry. In subsequent work, a fuel is made from the combination of the highest-performing materials, which are 1,6-hexanediol diglycidyl ether (epoxy polymer) and methyltetrahydrophthalic anhydride (curative). The material is further characterized by conducting thermogravimetric and differential scanning calorimeter analyses, bomb calorimetry, pyrolizer gas chromatography mass spectroscopy, and direct-connect fuel grain testing. An examination of the collected data suggests that this material represents an excellent candidate for SFRJ applications, showing low-decomposition and autoignition temperatures, stable combustion, and acceptable regression rates (McDonald et al., 2020).

2.3.8 Purdue University

In the 2016–2017 time frame, under the leadership of Scott Meyer, a high-pressure combustion laboratory was designed and developed at the Purdue University, which included a nonvitiated direct-connect SFRJ test capability at relevant operational conditions for missile and projectile applications (Meyer et al., 2017). This SFRJ test facility was subsequently used to experimentally investigate the performance of SFRJ combustors using HTPB-based fuels, including the effect of air injector geometry and air bypass on combustion efficiency (Evans et al., 2020, 2021). The SFRJ test facility also includes an optically accessible 2-D slab burner, allowing for more fundamental studies into the highly turbulent reacting flow field of the SFRJ by using advanced, nonintrusive measurement techniques. These techniques include OH-, HCHO-, and acetone- planar laser-induced fluorescence (PLIF) and OH*- and CH*-chemiluminescence to perform nonintrusive measurements of combustion species, planar, and stereoscopic particle imaging velocimetry (PIV), laser doppler velocimetry (LDV), and phase doppler particle anemometry (PDPA) to measure velocity fields, dual-pump coherent anti-Stokes Raman spectroscopy (CARS) to measure temperature, and Schlieren to visualize density gradients in high-speed flows (Meyer et al., 2017; Senior et al., 2021).

As part of a student design course, a design of a solid-fuel ramjet ground launch demonstrator was conceived (Kubicki et al., 2019). The work describes the design and simulated performance of the chin inlet, combustor with an internal bypass system, which also provides the flame-holding capability, nozzle, airframe, and fins of the SFRJ demonstrator, indicating that the internal bypass system results in a 43% increase in ground range.

2.3.9 Recent Other Publications

In a cooperative effort with the US Naval Air Warfare Center, the Southern Utah University studied several HTPB-boron-magnesium fuels on a small scale to evaluate the performance for ramjet application (Sandall et al., 2017). Particle behavior just above the fuel surface is studied by performing holography experiments and laser ignition tests. In addition, small-scale direct-connect tests have been performed to establish ignition temperatures (in transient temperature tests) and combustor performance at an air mass flow rate of about 120 g/s, air temperatures from 500 to 660 K, and a combustor pressure between 5 and 6 bar. The results indicate that the addition of magnesium is only beneficial to HTPB–boron mixtures if added in appropriate quantities.

Recently, scientists from the department of mechanical engineering and the department of chemistry of Stanford University conducted a study to enhance the mechanical properties and the combustion performance of boron-loaded HTPB fuels (Jiang et al., 2021). The work was supported by the Office of Naval Research and demonstrated that surface functionalization of the boron particles greatly enhanced the dispersion of boron particles in the HTPB, up to a boron weight percentage of 40. This resulted in largely improved mechanical properties of the boron-loaded fuel and a substantially higher heat of combustion compared to the same fuel composition without surface functionalization of the boron particles.

2.3.10 Gun-Launched Projectile Application Studies

On the gun-launched projectile application, an interesting study was performed concerning the “Performance of Solid Fuel Ramjet Guided Projectile for USN 5″/54 Gun System” (Amichai, 1982). Another study of a ramjet-propelled indirect fire application is the 8″ Advanced Indirect Fire System Projectile, for which wind tunnel tests were done by Norden Systems, Inc., to determine the aerodynamic characteristics of such a round (Fink, 1982; Simpson, 1983; Simpson et al., 1983).

2.3.11 Ramjet Missile Propulsion Overviews

Several comprehensive overview papers have been published on the United States’s work on ramjet propulsion for missiles, which also describe solid-fuel ramjet missile development activities (Waltrup et al., 1996, 1997; Wilson et al., 1996; Hewitt et al., 2002; Chase, 2010; Fry, 2004, 2011). In spite of these missile development activities, no solid-fuel ramjet missile has entered service, as far as is known to the authors.

2.3.12 U.S. Army Long-Range Artillery Development Program

In their 2019 Army Modernization Strategy, the U.S. Army defined "long-range precision fires" to be one of the six army modernization priorities, in which extended-range cannon artillery (ERCA) was identified as one of the three signature efforts (Anonymous, 2019a). The XM1155 Extended-Range Artillery Projectile (ERAP) program, initiated in 2019, aims to develop a prototype GPS independent guided artillery round to be fired from the ERCA gun with a range in excess of 100 km (Anonymous, 2018). Within the XM1155 program, several concurrent teams are reported to be active, either on an SFRJ solution or on an unpropelled glider solution. For the SFRJ solution, Boeing teamed up with Nammo in Norway for their expertise on SFRJ propulsion (Anonymous, 2019b). Likewise, Raytheon teamed up with TNO in the Netherlands (Anonymous, 2020a), and Northrop Grumman teamed up with SPARC Research (Anonymous, 2020b).

2.4 Sweden

The publication statistics are shown in Fig. 6. All publications are from the Swedish National Defence Research Institute FOA (after merging with the Swedish National Aeronautical Research Institute FFA in 2001 called FOI).

2.4.1 Initial Work

At the Swedish National Defence Research Institute FOA, design and construction of a direct-connect test facility was undertaken in the late 1970s. Tests were performed using polyethylene and HTPB fuel grains with an internal diameter of 100 mm (for missile applications) prior to scaling down the test facility to a fuel grain internal diameter of 46 mm. This early work at FOA, in which a wide variety of fuels and fuel additives were tested, is described in internal FOA reports (Eliasson, 1978–1988, in Swedish).

2.4.2 40-mm Anti-Aircraft SFRJ Projectile Development Program

Based on the more exploratory research done in the previous decade (as described above), in the late 1980s FOA started a research and development program of a 40-mm anti-aircraft SFRJ projectile. The goal was to investigate the possibilities and limitations of the SFRJ engine concept for this application. To this end an experimental 40-mm spin-stabilized SFRJ projectile was designed (see Fig. 7) to produce thrust equal to drag after being gun-launched at 1450 m/s (= Mach 4.3). The projectile had a length-to-diameter ratio of roughly 5 and featured a single-cone axisymmetric air intake. Work was done on the design and performance prediction of the air intake using simple engineering relations and assuming a certain viscous loss factor. The external

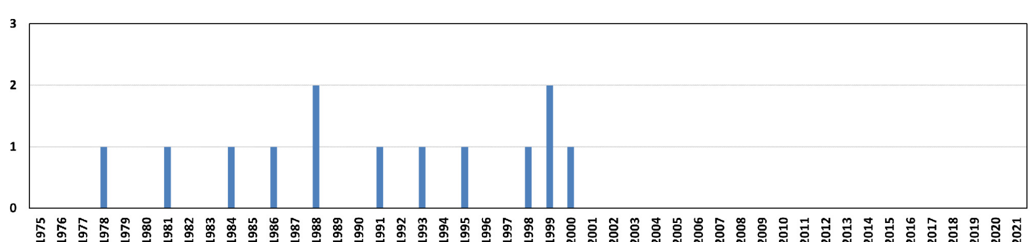

FIG. 6: Number of publications per year by Sweden

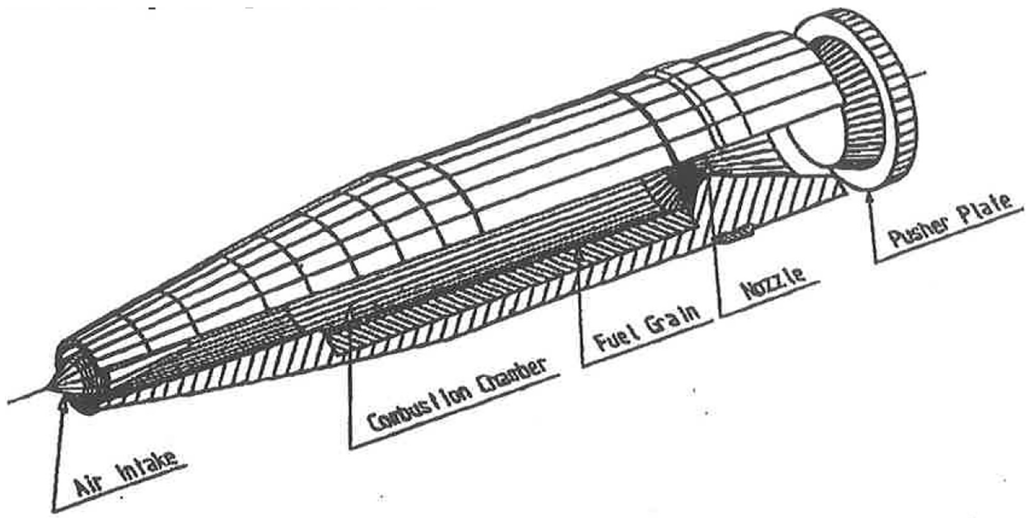

FIG. 7: Experimental spin-stabilized 40-mm anti-aircraft projectile (Reprinted from Wimmerström et al., 1993)

drag components of the projectile were calculated using a tool based on the method of characteristics. A one-dimensional chemical equilibrium code was used to predict the thrust performance. Direct-connect tests were performed at pressures and air temperatures significantly lower than those during a Mach 4.3 flight. Extrapolation of the test data to the real flight conditions indicated that the fuel regression rate would be sufficient to generate a thrust equal to drag. Acceleration tests performed to verify fuel strength and bonding stress showed that a pure HTPB fuel did not survive a 60,000-g launch load. Actual gun firings on very short test ranges (70 and 200 m) with improved fuel compositions demonstrated structural integrity and stable initial flight of the projectile. Using suitable fuels, self-ignition and sustained combustion were also demonstrated (Wimmerström et al., 1991, 1993).

However, long-range test firings, which were performed subsequently, showed that the thrust performance of the projectile was insufficient to maintain its flight speed. To better understand the complex internal flow and combustion phenomena, a test rig was designed and commissioned to perform direct-connect spinning tests of a solid-fuel ramjet engine. The results of the experimental work with this setup indicated that spin resulted in better flame-holding characteristics and reduced fuel regression rate and thrust (Wimmerström et al., 1995).

2.4.3 FOA–TNO Technology Demonstration Program

Between July 1995 and December 1999, a cooperative study program on SFRJ propulsion for projectiles was performed by the FOA Defence Research Establishment, Weapons and Protection Division, in Sweden, and the Netherlands Organisation for Applied Scientific Research (TNO). The cooperation program was extended to prepare and perform an additional flight test series in 2000. The study program aimed at demonstrating the technology of SFRJ propulsion for gun-launched projectiles by means of designing, manufacturing, and flight testing a generic 61-mm fin-stabilized SFRJ-propelled projectile with a body diameter of 40 mm (see Fig. 8).

FIG. 8: One of the versions of the FOA-TNO generic fin-stabilized projectile (Reprinted from Veraar et al., 2006)

To direct the technology development effort, a so-called baseline design of the SFRJ projectile was defined early in the study program based on requirements for typical anticipated applications. Using this baseline design as a guideline, a large number of activities has been performed during the Swedish–Dutch SFRJ projectile program in the following areas (Andersson, and Andersson and Veraar, 1998–2000):

- *Aerodynamics*

  The external drag components and projectile stability characteristics were predicted for different projectile designs. Detailed air intake performance calculations were performed using computational fluid dynamics (CFD) tools (see Fig. 9). In addition, aerodynamic heating analyses of the most critical projectile components were performed.

- *Combustor and nozzle performance*

  Several fuels were developed from which one fuel with sufficient mechanical and combustion performance was selected. Mechanical tests of the fuel were performed to verify the mechanical properties, and acceleration tests were performed to verify structural integrity and bonding of the fuel. Nozzle performance calculations were performed, including a nozzle performance sensitivity analysis. The TNO SFRJ test facility was improved to

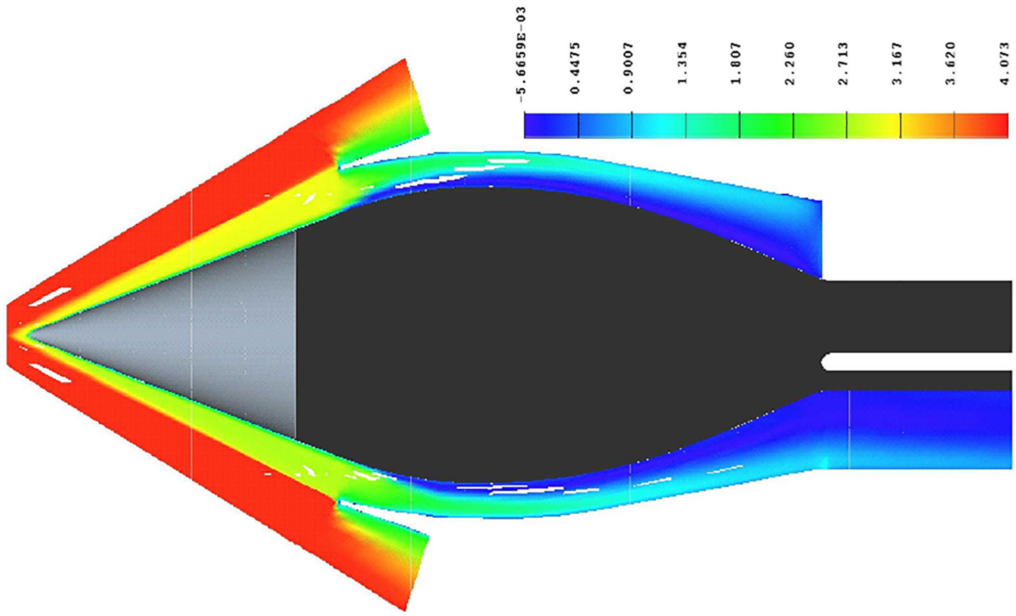

FIG. 9: Example of 3-D air intake CFD calculated Mach number distribution at 2° angle of attack (Reprinted from Andersson and Veraar, 2000)

better simulate the in-flight combustor entrance conditions, and subsequently numerous combustor performance tests were executed.

- *Projectile system performance*

  A projectile baseline design was defined, which was updated throughout the technology demonstration effort. The TNO-developed Ramjet Propelled Projectile Performance Prediction Program RP^5 (Netherlands; Veraar, 1995) was modified to predict the projectile flight performance more accurately. The RP^5 code was subsequently used for baseline projectile performance prediction and projectile performance sensitivity calculations in order to direct the activities in all other technology areas and to enable design trade-offs.

- *Mechanical design*

  The mechanical design of the projectile was established including a pusher plate and sabot segments. Acceleration tests of the projectile components and sub-assemblies were performed to verify structural integrity. The mechanical design and the acceleration tests were supported by finite element calculations.

- *Gun system*

  Gun firings with dummy projectiles of different masses and using several different types and amounts of gun propellant were performed to characterize the gun and to select a suitable gun propellant.

Prior to the flight test series with the final projectile design, several short-range flight tests were performed with a simplified projectile intake configuration. Three final test series were done at Bofors Test Centre in Sweden during the last quarter of 1999 and during the last quarter of 2000. These flight test series, performed at 600 m to 10 km test range at muzzle velocities ranging from 1292 to 1382 m/s, demonstrated the following (Andersson and Veraar, 2000):

- Structural integrity of the projectile
- Clean separation of pusher plate and sabot segments (see Fig. 10)
- Stable flight in the initial flight phase
- Severe ignition problems

Attempts to solve the ignition problems were only partly successful. Some of the projectiles showed a clearly lower drag coefficient than the reference round without fuel. Full ignition was only achieved for one projectile, which clearly demonstrated the capability to generate a thrust equal to the drag, resulting in a short but clear constant-velocity flight phase. After completion of this cooperation program, FOI decided not to continue the work on solid-fuel ramjet projectiles.

2.5 Netherlands

The publication statistics are shown in Fig. 11. All publications were generated by the Delft University of Technology (DUT) and/or the Netherlands Organisation for Applied Scientific Research (TNO).

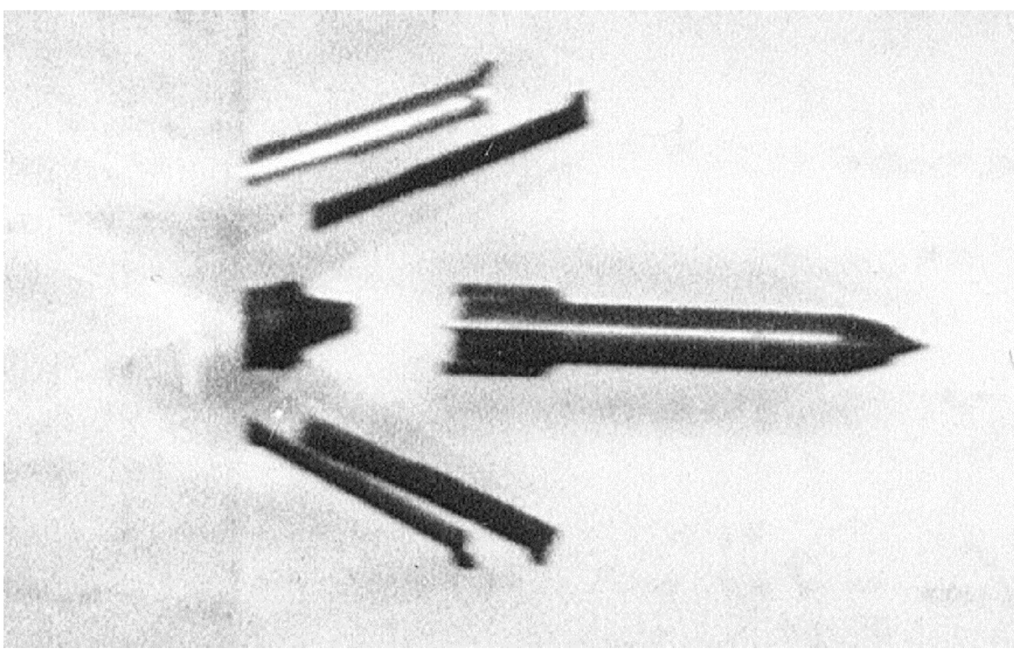

FIG. 10: High-speed video frame showing clean separation of pusher plate and sabots (Reprinted from Veraar et al., 2006)

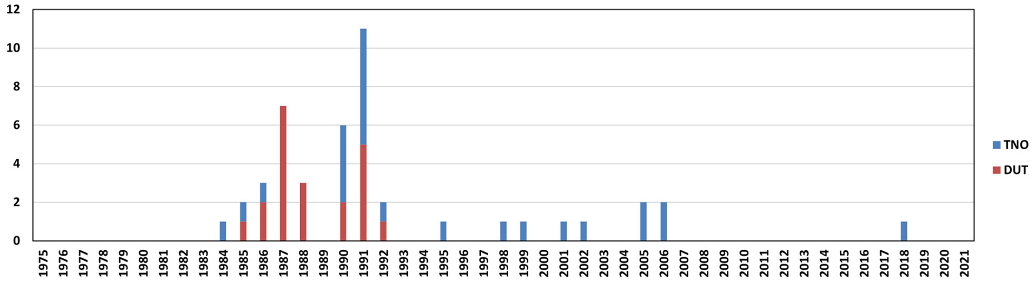

FIG. 11: Number of publications per year by the Netherlands

2.5.1 Fundamental Research Program by TNO and Delft University of Technology

In the time period from 1982 to 1990, the Netherlands Organisation for Applied Scientific Research (TNO) and the Faculty of Aerospace Engineering of the Delft University of Technology (DUT) conducted a cooperative research program with the aim to gain experience in designing and testing of solid-fuel combustion chambers for future applications, with an emphasis on air-breathing aerospace propulsion. During this research program, a direct-connect solid-fuel ramjet test facility (see Fig. 12) was developed (Korting and Schöyer, 1984). This test facility was used extensively to study the combustion behavior using diagnostic techniques like spectroscopy and ultrasonic techniques for measurement of the solid-fuel regression rate (Korting and Schöyer, 1985; van der Geld et al., 1986; Dijkstra and Korting, 1990). Furthermore, a Navier–Stokes solver was developed to predict the flow and combustion processes in a solid-fuel combustion chamber for comparison with experimental results (Vos, 1986–1988; Elands and Vos, 1987; Elands, 1987–1991). Furthermore, time-dependent numerical simulations were performed on

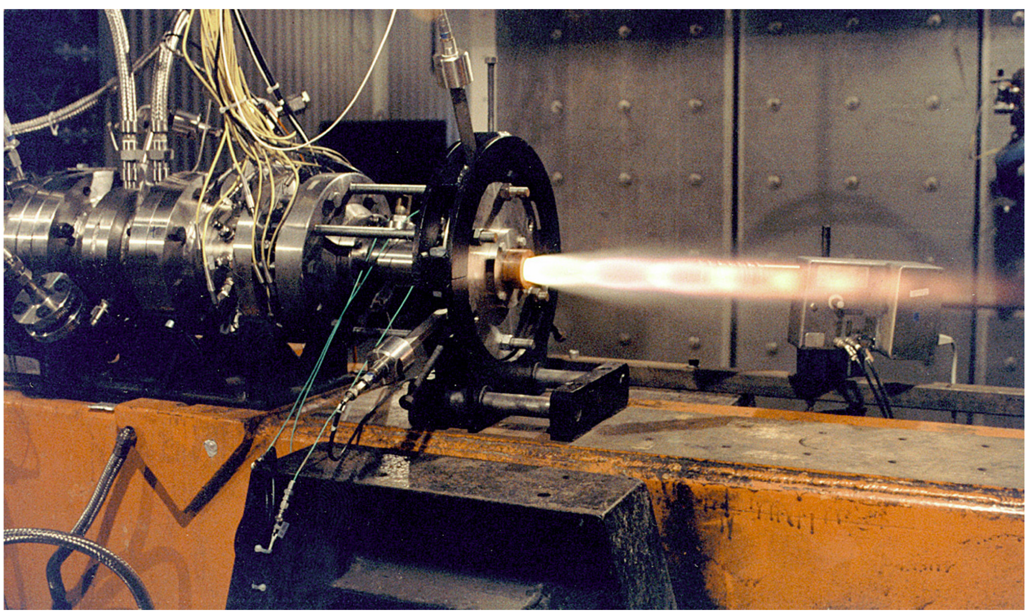

FIG. 12: The TNO direct-connect test setup during an SFRJ test (Reprinted from Veraar and Mayer, 2005)

vortex shedding in solid-fuel combustors (van der Geld, 1987). Extensive work was done to compare the results of the experimental and numerical work (Elands et al., 1988–1990; Zandbergen, 1991). The fuel pyrolysis process was found to be a very important aspect in the functioning of both hybrid rocket motors and solid-fuel ramjets and consequently received significant attention (de Wilde, 1991; de Wilde and Elands, 1991).

Since 1989, TNO has been working on SFRJ propulsion for gun-launched projectiles (Veraar, 1991; Elands et al., 1992; Veraar and Elands, 1998). In this period, the application of SFRJ propulsion technology to several types of projectiles was studied using in-flight performance predictions based on direct-connect SFRJ combustor test results using a large variety of fuel types and additives.

2.5.2 TNO-FOA Cooperative Technology Demonstration Program

From 1995 through 2000, a cooperative study program on SFRJ propulsion for projectiles was performed by TNO and FOA. The study program aimed at demonstrating the technology of SFRJ propulsion for gun-launched projectiles by means of designing, manufacturing, and flight testing a generic fin-stabilized SFRJ-propelled projectile. The level of knowledge reached within this program on technology areas like aerodynamics, combustor and nozzle performance, projectile performance prediction, and mechanical design enabled the detailed design of a fin-stabilized SFRJ projectile. A more extensive description of the activities performed is given in Section 2.4.3. The mechanical functioning, including clean separation of the pusher plate and sabot segments, was demonstrated in actual gun firings. Although the free-flight tests revealed serious ignition problems, it was demonstrated that the SFRJ propulsion system was capable of generating a thrust that cancels the drag of the projectile, resulting in an essentially constant flight velocity (Veraar et al., 1999; Veraar and Andersson, 2001).

2.5.3 TNO-RWMS Cooperative Technology Demonstration Program

Subsequently, TNO executed a technology demonstration program in cooperation with Rheinmetall Waffe Munition Schweiz AG (RWMS, formerly Oerlikon Contraves Pyrotec AG) on the application of solid-fuel ramjet propulsion technology to a 35-mm spin-stabilized air-defense projectile (Veraar and Giusti, 2005; Veraar et al., 2006). From 2000 to 2004, a complete and integrated structural and aero-thermodynamic projectile design was conceived, satisfying the requirements on projectile mass and length following from the use of a standard gun. To support the design of the intake, computational fluid dynamics calculations have been performed by CFS Engineering SA under contract from TNO (see Fig. 13). The structural integrity during gun launch of this projectile, including fuel, was verified in test firings (see Fig. 14).

A new free-jet test facility was developed at TNO as part of this demonstration program (Veraar and Mayer, 2005), which was used for aerodynamic heating experiments on projectile parts, for intake performance verification, and for on-ground verification of the functioning of complete projectiles (see Fig. 15).

In May 2004 the TNO-RWMS technology demonstration program was concluded by flight demonstration tests at the Ochsenboden test range in Switzerland. The flight tests on a 1000-m test range demonstrated a very short ignition delay (see Fig. 16) and a clear capability to maintain a flight speed of 1400 m/s. The limited length of the test range did not allow for demonstration of sustained propulsive performance over the design-propelled flight range of 3000 m. Based on

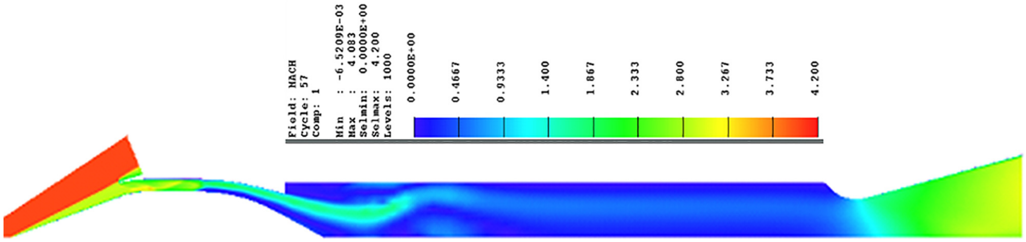

FIG. 13: CFD-predicted Mach number distribution within the TNO/RWMS SFRJ projectile (Reprinted from Veraar and Mayer, 2005)

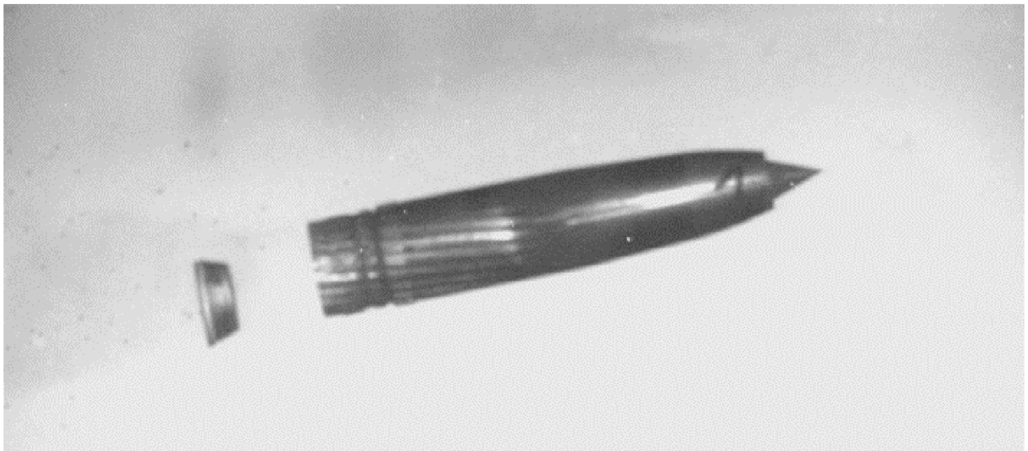

FIG. 14: The structural integrity of the TNO/RWMS SFRJ projectile was verified in gun firings (Reprinted from Veraar et al., 2006).

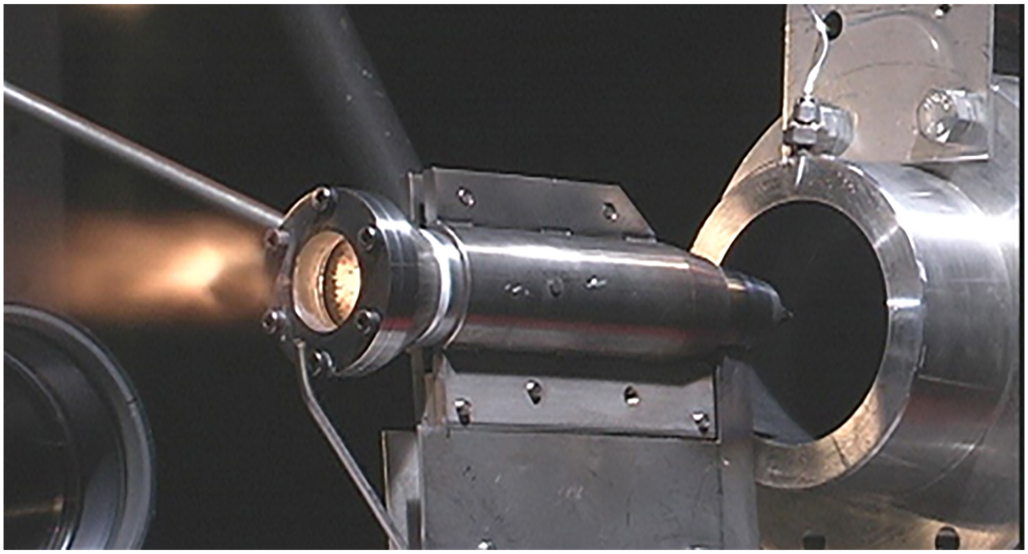

FIG. 15: Burning ramjet projectile during a Mach 4 free jet experiment at TNO (Reprinted from Veraar and Mayer, 2005)

FIG. 16: The exhaust trail on the right of this video frame demonstrates fast ignition (Reprinted from Veraar and Mayer, 2006)

the results of the work executed within the TNO-RWMS cooperation, the application of solid-fuel ramjet propulsion technology for medium-caliber air-defense projectiles was considered feasible. The successful demonstration of the thrust equal to drag capability of a spin-stabilized solid-fuel ramjet-propelled projectile at Mach 4 flight speed was a first for Europe and, as far as is known, also for the world.

To obtain a first impression of the terminal ballistic performance of ramjet projectiles, gun firings with the ramjet projectile flight demonstrator were performed in November 2005 on range targets (plate arrays) representing a fighter aircraft and an armored helicopter (Veraar et al., 2006). Although the ramjet projectile was not designed for optimal terminal ballistic performance, both targets were perforated and damaged significantly (see Fig. 17).

The results of the work executed clearly show the benefit of using solid-fuel ramjet propulsion technology for gun-launched projectiles. Specifically, the results demonstrate the flight and terminal ballistic performance of this technology for medium-caliber air-defense projectiles. These results open the way for application of this technology in future munitions for both direct and indirect fire applications ranging from medium to large caliber.

2.5.4 Integration of SFRJ Technology in Large-Caliber Guided Ammunition

In spite of the successful flight demonstration, the development of the medium-caliber SFRJ air-defense projectile was not pursued further by RWMS, and the cooperation between TNO and RWMS on this topic was ended. Instead, the focus of the SFRJ work at TNO shifted to scaling up the flight-demonstrated SFRJ technology to enable integration in large-caliber guided artillery ammunition. Under contract from the Office of Naval Research-Global, a study was performed on the sustained combustion limits of a central-dump solid-fuel ramjet combustor at

FIG. 17: Impact damage on a range target representing a fighter aircraft (Reprinted from Veraar et al., 2006)

high-altitude operational conditions (Veraar and Wieling, 2018). A flame-holding model previously developed by the Delft University of Technology within the framework of their cooperation with TNO (Calzone, 1992) has been reviewed, modified, and applied to predict the flame-holding limits of a gun-hardened high-performance HTPB-fueled SFRJ combustor at high-altitude operational conditions. In addition, dedicated SFRJ experiments using the TNO SFRJ direct-connect test setup have been performed using HTPB fuel grains casted in PMMA casings to validate the predicted flame-holding limits. Aside from flame-out and sustained combustion, these tests also revealed a partially sustained combustion mode (see Fig. 18). Comparison of model and experimental results showed that the flame-holding model allows for accurate prediction of the sustained combustion limit at the operational conditions currently investigated (see Fig. 19). Subsequently, TNO teamed up with Raytheon Missiles and Defense for the U.S. Army XM1155 program (United States of America; Anonymous, 2020a); see Section 2.3.12.

2.6 Israel

The publication statics are shown in Fig. 20. All publications have been generated by the Technion—Israel Institute of Technology at the research groups led by Prof. Alon Gany and Prof. Benny Natan.

From the mid-1980s, extensive research work on solid-fuel ramjet and scramjet has been done at Technion—Israel Institute of Technology. The combustion phenomena of highly metallized boron-containing fuels were studied in a 2-D combustor, allowing for high-speed photography through side windows (Gany and Netzer, 1985, 1986). This work was supported by numerical studies into the ignition and combustion of boron particles in the flow field of an SFRJ combustor, including the effect of an air bypass (Natan and Gany, 1987, 1989, 1991; Gany, 1991a, 1993).

The feasibility and performance of gun-launched SFRJ-propelled projectiles was studied, indicating that this technology could result in twice the range of conventional rounds with base bleed, much higher kinetic energy, and strongly reduced time-to-target, making this technology potentially attractive for air-defense applications (Gany, 1988, 1991b).

With small-caliber projectiles as the projected application, work was done on a small SFRJ with an internal diameter of 5–10 mm (Netzer and Gany, 1988, 1991; Zvuloni et al., 1989a,b).

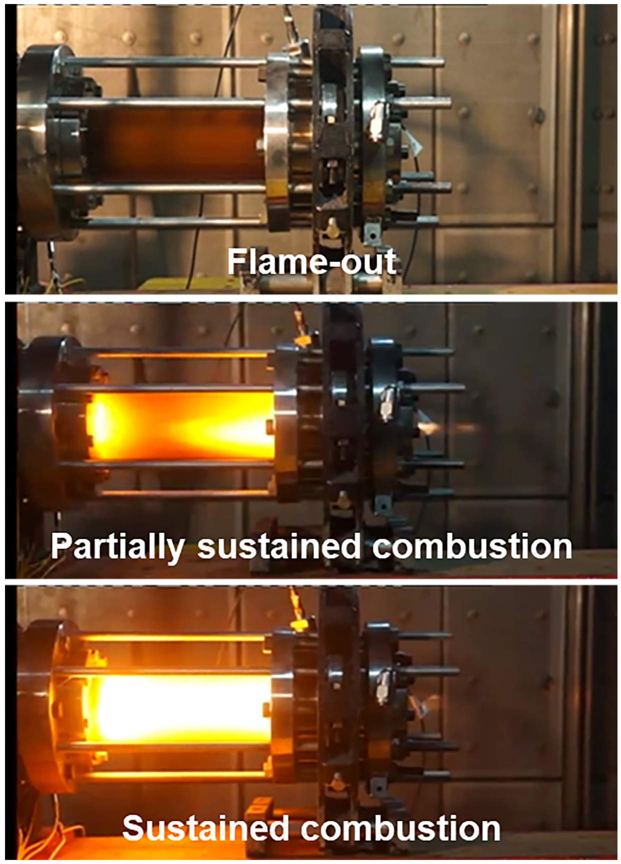

FIG. 18: Three combustor operating modes observed during the flame-holding model validation tests (Reprinted from Veraar and Wieling, 2018)

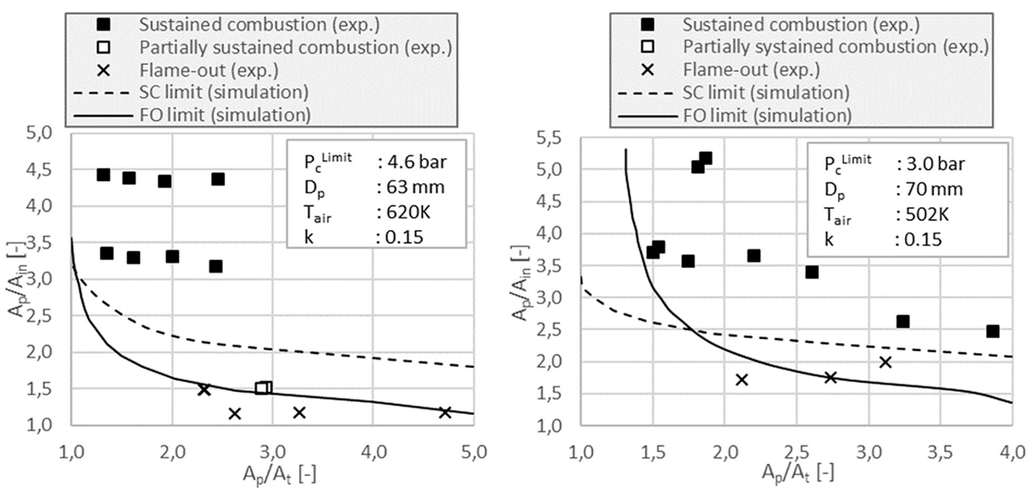

FIG. 19: Flame-holding limits at two different sets of simulated flight condition; left: Mach 3 at altitude of 10 km; right: Mach 2.5 at altitude of 10 km (Reprinted from Veraar and Wieling, 2018)

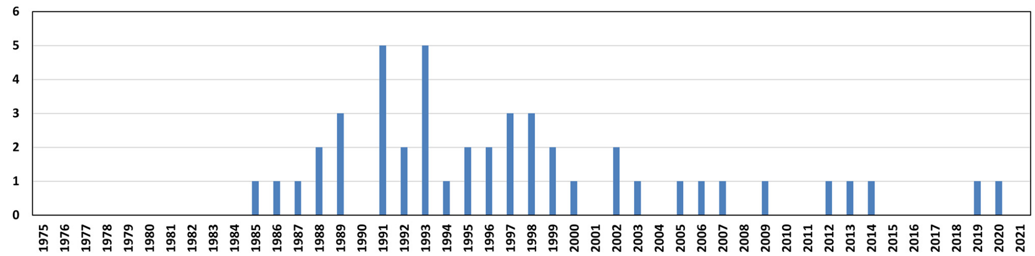

FIG. 20: Number of publications per year by Israel

Using an electrical air heater to simulate the Mach 3 in-flight air temperature, experiments were done in a direct-connect test setup. The results demonstrated high combustion efficiencies ($>$ 90%) and a larger dependency on the backward-facing step size than is found for larger combustor dimensions.

Experimental investigations have been carried out to establish the regression rate of different polymeric fuels like polyethylene (PE), polypropylene (PP), PMMA, and HTPB to support development and validation of a fuel regression rate model (Hadar and Gany, 1991, 1992). A theoretical analysis into the similarity and scale effects in SFRJ combustors showed that the so-called pD scaling (i.e., keeping the product of combustor pressure and diameter constant) is appropriate for SFRJ combustors as well. The developed scaling model enables prediction of parameters like fuel regression rate, fuel–air ratio, thrust, and combustion efficiency of larger SFRJ based on small-scale laboratory test results (Ben-Arosh and Gany, 1992).

The studies on fuels with additives like boron and boron carbide were continued, and solutions to the problem of low combustion efficiency due to the incomplete combustion of boron were investigated. Among the suggested solutions are the use of bypass air and an afterburner and applying coating to the boron particles. The results of the developed theoretical models revealed that good combustion efficiencies and high combustion temperatures can be achieved (Natan and Gany, 1993a,b; Povitsky and Goldman, 1993; Rosenband et al., 1995; Natan and Netzer, 1993, 1996, 1997). Based on the work done, a comprehensive overview of characteristics of and the challenges associated with boron combustion in airbreathing propulsion systems was made, indicating that extraction of the theoretical boron combustion energy would be particularly problematic in systems operating at variable conditions (Scheuer and Gany, 2005; Gany, 2006). Further work was done on boron combustion, identifying thermodynamic conditions associated with highly boron-loaded ramjet combustors, which may lead to blockage of the reaction between boron and air (Gany, 2013, 2014).

In addition, work was done on thrust modulation by means of regulating the bypass air mass flow. Based on an SFRJ performance model, a theoretical regulation law aiming to achieve a constant fuel-to-air ratio was developed (Pelosi-Pinhas and Gany, 1999, 2000). A subsequently executed experimental program showed a very good agreement with the theory (Pelosi-Pinhas and Gany, 2002, 2003), demonstrating the feasibility of using this regulation technique over a wide range of simulated flight conditions (Mach 1.5–4.7, sea level to 13 km altitude).

A study was published on design and testing methods of high-speed air-breathing engines, including solid-fuel scramjets (Timnat, 1995). Subsequently, both theoretical and experimental work was done on supersonic combustion solid-fuel ramjets. Using a hydrogen-burning air heater, direct-connect experiments were executed simulating a Mach 5.5 flight condition at high and medium altitudes. Using PMMA as fuel, pressure measurements and video recordings of the flow and combustion processes in an axisymmetric combustor demonstrated self-ignition and solid-fuel supersonic combustion (Ben-Yakar and Gany, 1994; Ben-Yakar et al., 1998; Cohen-Zur and Natan, 1998). Theoretical and numerical studies on the fuel–air mixing and combustion in a scramjet combustor were further conducted (Ben-Arosh et al., 1997a,b, 1998, 1999). Later on, experimental studies were also performed with HTPB-based fuels with substantial amounts of ammonium perchlorate, which resulted in reduced flame-holding capability but increased fuel regression rate (Feldman and Gany, 2002).

One of the milestones of the solid-fuel ramjet work conducted at the Technion was designing and launching of an SFRJ vehicle, about 4 m long and 100 kg weight (Avital-Kaufman et al., 2007). Based on the work done on solid-fuel ramjets and scramjets at Technion and other research institutes around the world, a comprehensive overview of accomplishments and challenges in solid-fuel ramjets and scramjets was made (Gany, 2009). This work concluded, among other things, that one of the main applications for solid-fuel ramjets and scramjets may be propelling supersonic- and hypersonic-speed gun-launched projectiles.

An experimental investigation was performed into the performance of the solid-fuel ramjet with various amounts of aluminum particles added to an HTPB-based fuel (Saraf and Gany, 2012). This study indicated that the inclusion of aluminum increases the fuel mass flow rate (due to slightly increased fuel burn rate and increased fuel density), resulting in increased specific thrust and reduced specific impulse, which was in agreement with the theoretically predicted performance.

A numerical parametric investigation of the internal ballistics of a boron-containing solid-fuel ramjet was performed by applying the ANSYS FLUENT CFD to simulate the 2-D axisymmetric flow and combustion in the ramjet combustor at Mach 2.5 operating conditions. For the ignition and combustion of the boron particles, the model of King (United States of America; King, 1982) was used. The simulations performed show the feasibility of thrust regulation by means of an air bypass but also reveal decreasing specific impulse with increasing boron content, indicating low combustion efficiency (Kadosh and Natan, 2019).

An experimental study was performed into the surface processes occurring during the burning of a solid polymeric fuel containing a small fraction of expandable graphite (EG) particles or flakes with the aim to substantiate the claim that EG enhances the regression rate of hybrid rocket motors or solid-fuel ramjets. High-speed video revealed that the EG particles tend to swell and form worm-like strings extending into the gas flow with lengths up to the millimeter scale when exposed to elevated temperatures at the fuel burn surface, thus enhancing the heat conduction through the EG strings from the hot gases into the fuel material (Muller and Gany, 2020).

2.7 India

The publication statistics are shown in Fig. 21, showing the publications from the Indian Institute of Science (Inst. of Science), the Indian Institute of Technology (Inst. of Tech.), and the Indian Defence Research and Development Organisation (DRDO).

2.7.1 Indian Institute of Science

An internationally published work on SFRJ was found from the Indian Institute of Science; they conducted an experimental study with two different setups using polyester fuels with different percentages of ammonium perchlorate to promote ignition and sustained combustion (Raghunandan et al., 1985).

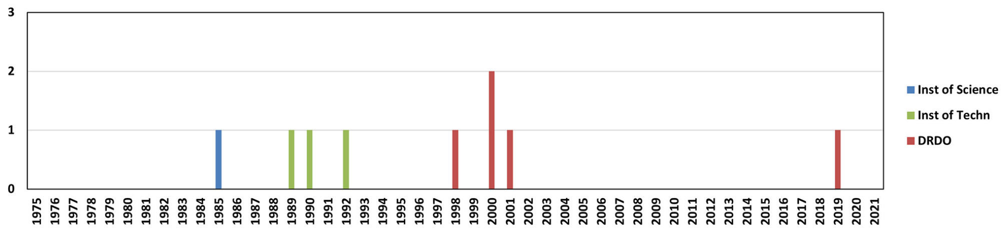

FIG. 21: Number of publications per year by India

2.7.2 Indian Institute of Technology

A very comprehensive study on solid-fuel ramjet combustor design was performed at the Indian Institute of Technology. Based on a review of open literature, the following issues are addressed: different experimental setup conditions adopted in combustor research, various suitable fuel types, flammability limits, fuel regression rate behavior, methods of achieving high efficiency in metallized fuel, and various modeling efforts. Based on the information gathered, a design procedure was developed for an SFRJ-assisted gun-launched projectile assuming a so-called pseudo-vacuum trajectory, in which the drag experienced by the projectile is always balanced by the thrust produced by its propulsion system (Krishnan and George, 1998; Krishnan et al., 2000; Rao and Krishnan, 2001). Application of the SFRJ technology is also explored for the incineration of solid waste, an application that once also was considered by TNO and DUT in the Netherlands (Paroor et al., 2000). An experimental study was performed using an opposed flow burner to characterize the burn rate of boron-loaded HTPB-based fuels (Hashim et al., 2019). Although this study is performed with the application of a hybrid gas generator for a ducted rocket in mind, the considered fuel compositions are relevant for an SFRJ as well.

2.7.3 Defence Research and Development Organisation

At the Defence Research and Development Organisation, a ramjet projectile flight performance model was developed assuming the internal flow and combustion processes to be one-dimensional. The flight performance model was subsequently extended into a six degrees of freedom model, which was applied to study SFRJ-assisted artillery rounds. Design aspects like ramjet combustor geometry, metal additives for the fuel, as well as some control aspects were discussed in several publications (Basu and Khatri, 1989; Basu, 1990, 1992).

2.8 Germany

The publication statistics are shown in Fig. 22. Most of the publications have been generated by the German Aerospace Center DLR and the University of the Federal Armed Forces Munich (UniBw).

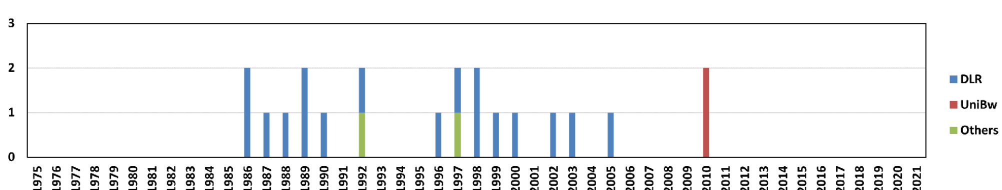

FIG. 22: Number of publications per year by Germany

2.8.1 German Aerospace Center

In Germany, most of the work done on SFRJ was performed by the German Aerospace Center DLR in the period of 1986–2003. Experimental study programs were executed to determine the fuel regression rate and flame stability limits of solid-fuel ramjets over a wide range of operational conditions in direct-connect tests using PE and HTPB as fuels. Thermocouples and gas-chromatographic techniques were applied to obtain temperature and species concentration profiles throughout the combustion chamber. This revealed incomplete mixing of the relatively cold core air flow and the combustion products closer to the solid-fuel wall (Schulte and Pein, 1986, Schulte, 1986; Schulte et al., 1987). Using roughly the same test setup, additional experiments were performed to determine the influence of swirl flow and fuel composition on boron combustion efficiency, combustion products, and specific thrust. HTPB fuels with up to 40% boron or boron carbide were tested with and without swirl using an exhaust particle sampling technique combined with chemical analysis. The results indicate that the combustion efficiency is significantly enhanced by swirl and that addition of more than 20% boron leads to reduced combustion efficiencies (Düsterhaus and Högl, 1988; Pein and Vinnemeier, 1989, 1992). Together with the Delft University of Technology, a study was performed into the heat transfer in a solid-fuel combustion chamber, resulting in a combined experimental and numerical method to determine the convective heat transfer coefficient (Vinnemeier and de Wilde, 1990).

More fundamental experimental research was conducted using a two-dimensional combustion chamber in which methane was injected as a fuel through a porous wall, thus simulating the flow field and combustion phenomena occurring in SFRJ. Quartz side walls allowed for optical access, and laser doppler velocimetry was used to measure streamwise and crosswise mean velocity and turbulence intensities. A moveable thermocouple was used to measure the temperature profiles at the centerline of the combustor at several axial locations. The measurement results performed at two different methane injection velocities showed that the higher methane injection velocity resulted in a reduced length of the recirculation zone and increased turbulence levels of the core air flow (Krametz and Schulte, 1989).

Subsequent work was done on the application of the gas and particle sampling techniques (Ciezki and Schwein, 1996) and advanced nonintrusive diagnostics [IR-spectroscopy, CARS thermometry, laser doppler velocimetry (LDV), color Schlieren, and PIV] in a planar solid-fuel ramjet combustor to further improve the understanding of the combustion behavior of boron-loaded solid fuels. These experiments indicated limited mixing of the burning boron particles with the air core flow (Blanc et al., 1997; Ciezki et al., 1997, 2000, 2003; Claus et al., 1998; Sender and Ciezki, 1998; Ciezki, 1999; Thumann and Ciezki, 2002).

A thorough overview was given on performance of energetic materials in general, including an overview of diagnostics for the combustion of particle-containing solid fuels at conditions relevant for SFRJ applications (Eisenreich et al., 2005). This overview describes both intrusive sampling probes and various advanced nonintrusive diagnostics like color Schlieren, LDV, PIV, and CARS thermometry, as well as some relevant results obtained in the planar solid-fuel ramjet combustor test setup at DLR.

2.8.2 University of the Federal Armed Forces Munich

Although developed mainly for ducted rocket applications, the work done at the Munich University of the Federal Armed Forces on boron combustion models is also worth noting. An overview was generated of particulate boron combustion modeling with the aim of identifying and describing an extended combustion model for single boron particles, which can be implemented and applied in 3-D CFD calculations with acceptable computational effort. This study identified and modified a boron combustion model from the Pennsylvania State University. A comprehensive validation and comparison of the new extended model with other models and with combustion experiments shows the applicability of the new model (Hussmann and Pfitzner, 2010a,b).

2.8.3 Technology Application Work

A solid-fuel ramjet projectile application study executed by Rheinmetall describes paper designs and corresponding predicted performance of SFRJ projectiles for artillery, air defense, and anti-armor ammunition. Wind tunnel tests on dedicated intake designs were executed at the DLR. The study showed promising performance results but concluded that especially for the hypervelocity air-defense application, considerable progress still was required in the field of heat resistant materials, aerothermodynamics, and advanced computational fluid dynamics (Mönig and Moll, 1992).

2.9 South Korea

The publication statistics are shown in Fig. 23, showing that the publications have been generated by the Korean Agency for Defense Development (ADD), the Seoul National University (Seoul Uni), and the Korea Advanced Institute of Science and Technology (KAIST).

2.9.1 Agency for Defense Development

After having worked at the U.S. Naval Postgraduate School as an exchange scientist on SFRJ (see USA references: Lee and Netzer, 1992), Lee published his first international article on the South Korean SFRJ activities. This concerns experimental studies done at the Agency for Defense Development into the flammability limit and fuel regression rate of an SFRJ (Lee and Netzer, 1992) and into the effects on combustion efficiency and fuel properties of performing multiple tests with the same fuel grain (Lee, 1995). Between 1999 and 2002, a research program was performed, aiming at demonstration of the SFRJ technology for gun-launched projectile applications. The work concentrated on the design and flight testing of a 40-mm spin-stabilized projectile to be launched at Mach 3 from the 40 mm L/70 Navy gun system. A single-cone intake and a pitot intake were designed and tested in a wind tunnel. The ramjet combustor with an HTPB fuel was tested in a direct-connect test setup. During flight tests, the projectile with the single cone intake did not show autoignition due to adverse effects on the intake performance at the high yaw angles that occurred in the initial flight phase. The projectiles with pitot intake did

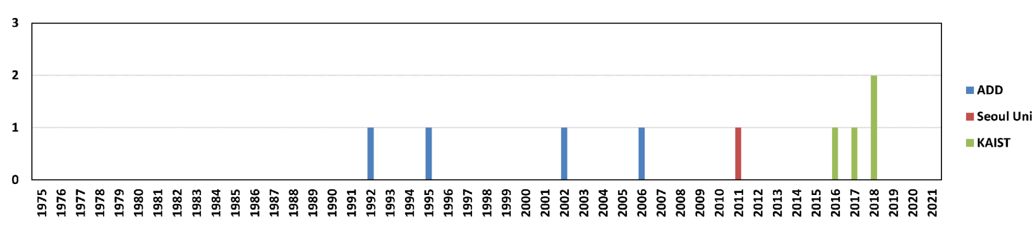

FIG. 23: Number of publications per year by South Korea

show autoignition, but the thrust generated was much lower than the drag, resulting in substantial deceleration (Hwang et al., 2002). Follow-up work included an experimental study using a 63-mm diameter axisymmetric dump combustor in a direct-connect test setup using HTPB fuels with and without boron carbide. Based on a Brayton cycle analysis, the experimental results are translated into a total efficiency parameter, which shows a maximum around simulated flight conditions of Mach 4 (Lee, 2006).

2.9.2 Seoul National University

At the Seoul National University, a very comprehensive experimental and numerical study was performed into the flow characteristics of small supersonic inlets for SFRJ applications. An axisymmetric single cone and a 2-D (rectangular) two–compression ramp intake model were tested in a wind tunnel at Mach 2.5 with varying back pressure, revealing unstable "buzz" behavior similar to large inlets (Lee et al., 2011).

2.9.3 Korea Advanced Institute of Science and Technology

An experimental study was performed on the ignition and combustion characteristics of an SFRJ combustor using a fuel-rich solid propellant with boron and aluminum additives in a small-scale test setup using an ethanol-blended hydrogen peroxide (H_2O_2) gas generator providing an air simulant mass flow rate of about 150 g/s and temperature around 550 K. Regression rate in the order of 0.5 mm/s and combustion efficiencies around 80% were reported to confirm the combustion of the boron particles (Jung et al., 2017, 2018a). To ensure fast ignition, an ignition support material consisting of $NC/BKNO_3$ was applied, and the fuel grain was coated with a composite propellant. This ignition system was developed and tested in a separate test campaign using high-density polyethylene (HDPE) fuel grains using the same test setup as for the combustion experiments described above (Jung et al., 2016, 2018b).

2.10 South Africa

The publication statistics are shown in Fig. 24, with most publications generated by Denel.

2.10.1 Background

During the early 90s, Somchem, Division of Denel developed an integral rocket ramjet propulsion system for missile applications (see Fig. 25). The project was funded by Armscor. Ramjet technology, simulation software, and test facilities were established locally as part of the project

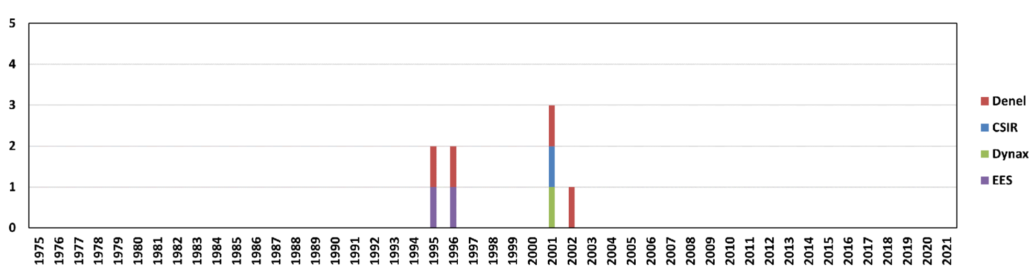

FIG. 24: Number of publications per year by South Africa

FIG. 25: Ramjet demonstrator for missile application

(Stockenström, 1995a; du Buisson, 1995). The project culminated in a successful flight test demonstration of the propulsion system at the Overberg Test Range. However, the successful demonstration test was never followed up with a development program due to the lack of a related missile development program locally. Somchem was responsible for the propulsion system and had to rely on a missile system house for applications.

2.10.2 76-mm Kinetic Energy Penetrator Round

The next logical step was to find ramjet application in gun-launched systems. In such a system, Somchem could take responsibility for the complete projectile without being dependent on large missile development programs. The initial gun-launched effort was spent on a 76-mm kinetic energy penetrator round (see Fig. 26). The burn time requirement was for 2 seconds, the projectile did not spin, and muzzle velocities were in the order of 1400 m/s (Mach 4). This was a less demanding environment for fuel ignition and the combustion process. It was possible to demonstrate that muzzle velocity could be maintained during the burn time of 2 s. Again, this successful demonstration was not followed up with a development program. The cost and complexity of the projectile did not justify the enhanced performance (Stockenström, 1995b; du Buisson et al., 1996).

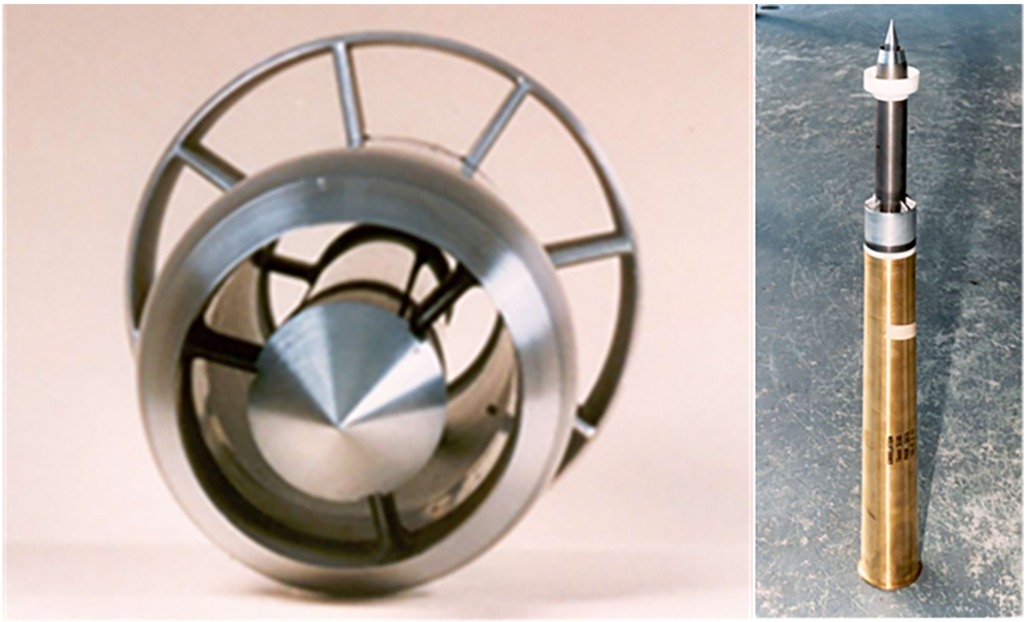

FIG. 26: 76-mm kinetic energy penetrator round

2.10.3 155-mm Application

South Africa was a leader in the field of artillery, and it was decided to shift the focus of ramjet work to 155-mm artillery projectiles with the objective to extend maximum range. The major objective of the 155-mm project was to demonstrate a range of at least 80 km from a 52-caliber weapon (muzzle velocity of 945 m/s). Two functional challenges posed to this project from the start were to allow enough volume for payload (4 kg of high explosives) and to consider options for achieving an acceptable dispersion at maximum range (Oosthuizen et al., 2001, 2002).

The project can be divided in the following subsystems:

- *Structural Layout*

  Major challenges posed to the structural designers were:

  - A sealing plug was required at the rear of the projectile to seal off the combustion chamber from the high pressure (420 MPa) in the barrel. This plug also had the purpose to transfer spin from the barrel grooves to the projectile. Furthermore, this plug should separate immediately after muzzle exit, opening the nozzle for the propulsion phase to start [see Fig. 27(a)].
  - Manufacturing of a canted fuze/payload support in the inlet [see Fig. 27(b)].
  - Design tradeoff between an annular- and center-support payload [see Fig. 27(c)].

- *Propulsion System*

  Major challenges to the propulsion engineer were:

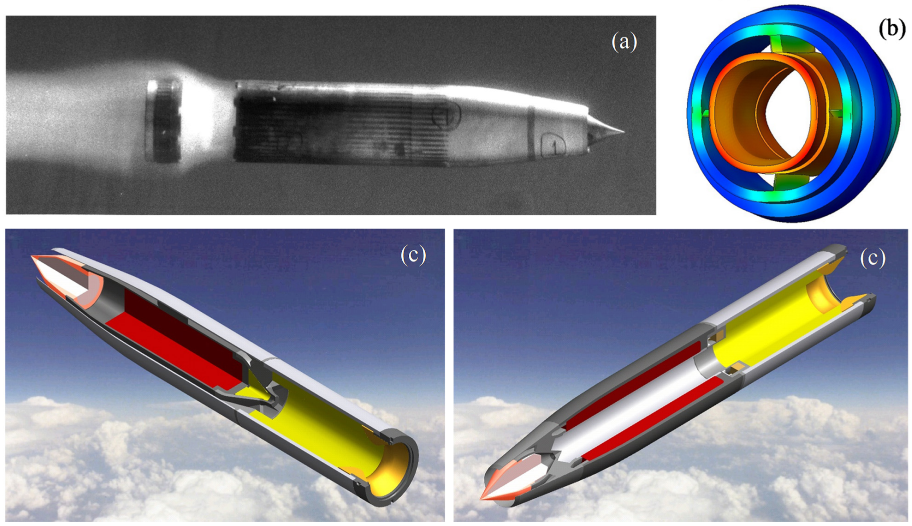

FIG. 27: (a) Drive plug separation, (b) FE simulation result showing the stress levels in the canted fuze support, and (c) payload options (Reprinted from Oosthuizen et al., 2002)

- Adapting the existing ramjet test facility to provide air at the correct conditions over the full burn time of 20 s, considering changes in air density according to the ballistic flight path.
- Tradeoff between different grain compositions. Finding a grain composition that can ignite under prevailing conditions vs. optimum combustion energy. It was necessary to add oxidizer components to the grain composition to achieve this. Experiments were done with different igniter designs to get the combustion process going.
- Spin has a major influence on the combustion process, and it was necessary to commission a full-scale spin jig in the blow-down test facility (see Fig. 28).
- The assumed combustion efficiency, which was used in trajectory simulations, could not be demonstrated up to the date when the project was stopped at RDM. Two major reasons for this could be the small mixing chamber before the nozzle and the influence of spin on combustion.

• *Inlet/Aero*

Challenges posed to the Inlet/Aero engineer were:

- Establishment of a trajectory simulation code and equations to closely represent physical conditions through the inlet, combustion chamber, and nozzle in a measurable way (Stockenström, 2001).
- Obtaining aerodynamic coefficients in the wind tunnel over the flight envelope and at different angles of incidence. All the measuring equipment had to be developed at the South-African Council for Scientific and Industrial Research (CSIR) wind tunnels for these measurements (Dionisio and Stockenström, 2001).
- Tradeoff between different inlet designs for maximum pressure recovery and also to match the inlet with combustion conditions and outlet nozzle (see Fig. 29).

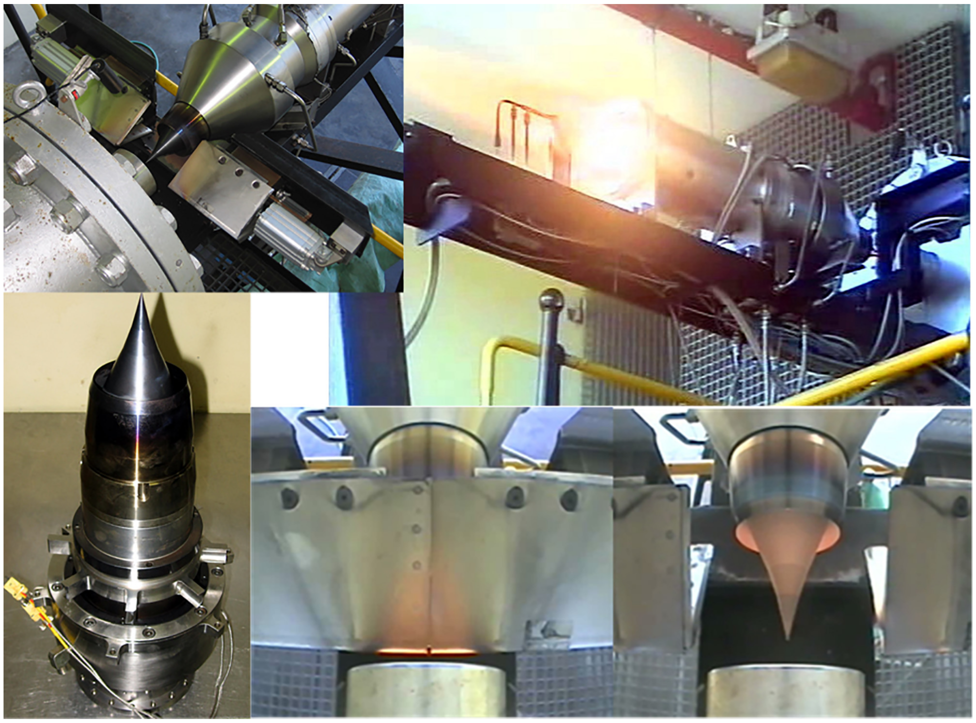

FIG. 28: Test facility and spin jig

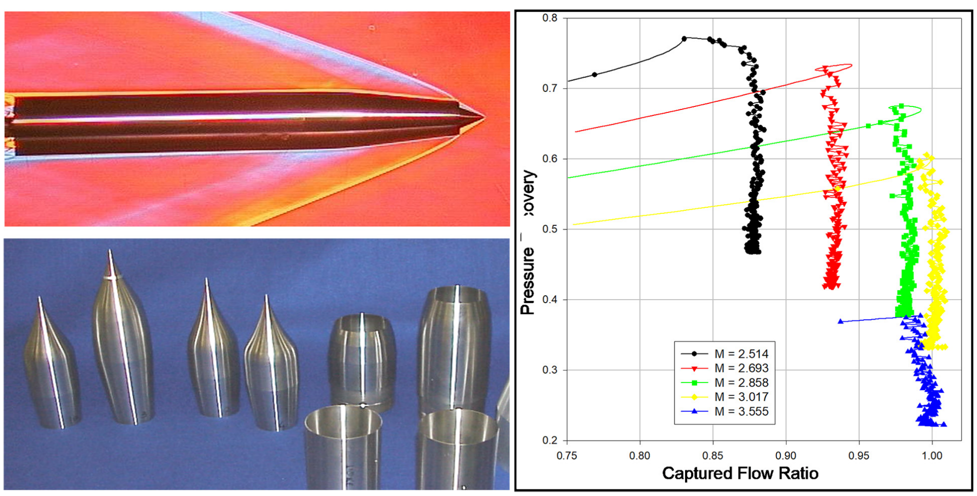

FIG. 29: Wind tunnel models with pressure recovery results (Reprinted from Dionisio and Stockenström, 2001)

- *Dynamic Flight Tests*

  Charges had to be adjusted to obtain the required muzzle velocities, but the rest of the infrastructure existed at the Alkantpan test range. The initial focus of flight tests was to verify structural integrity of the design under top charge launch conditions. When this was achieved, the focus shifted to tracking radar information to determine propulsion system performance and duration of sustained thrust (Oosthuizen et al., 2002), as shown in Fig. 30. The initial objective was to maintain the muzzle velocity for 20 s, but this has never been achieved due to challenges mentioned above.

2.10.4 Future of Ramjet in South Africa

The future of gun-launched solid-fuel ramjet projectiles in South Africa should be seen against the following background:

- *Development Environment*

  The development environment in the defense industry has changed in the following ways since the start of this project (PRO-RAM) in the late 90s:

  - Most defense companies have changed their focus from a strategic view to a commercial view to survive.
  - This change of focus has led to complexities like IP ownership and multinational ownership of defense companies.
  - It became difficult for a technology-related project like PRO-RAM to compete for scarce human resources; keeping in mind that Rheinmetall Denel Munition has a long-range projectile in VLAP (very long-range artillery projectile; 60-km range), with a less complex design.

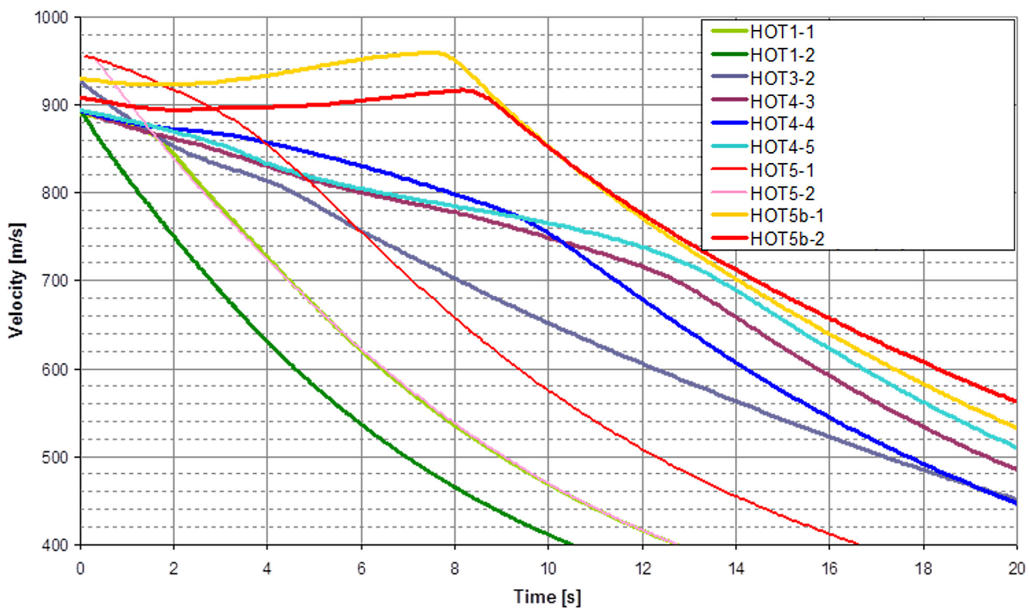

FIG. 30: Alkantpan test range tracking radar data of gun firings with different 155-mm SFRJ projectile configurations showing that roughly constant flight velocity was achieved for some configurations (Reprinted from Oosthuizen et al., 2002)

- Technology budget from Armscor has shrunk over the last few years in real terms.
- A potential solution against this background was that the PRO-RAM project could be continued by Flamengro, which is part of Armscor. The focus of Flamengro is more toward simulation technology establishment.

- *Technical Focus*

  Future focus should be to solve the one unproven technical goal, which is to achieve the initially assumed combustion efficiency in a real-life environment.

2.11 China

The publication statistics are shown in Fig. 31, with publications from the National Tsing Hua University, the Beijing Institute of Technology, the Nanjing University, the Beijing Institute of Testing Technology, the National University of Defense Technology, and the Xi'an Jiaotong University.

2.11.1 National Tsing Hua University

The first international publication found on the subject describes an experimental study into solid-fuel regression during ignition transient in an SFRJ. Using a continuous flow setup with an LPG-fueled air heater, slabs of PMMA were tested in a 2-D ramjet combustor with a backward-facing step. Flow velocity, temperature, and oxygen content of the air flow were varied, as well as the step height. The experiments revealed two different modes of ignition: diffusion-controlled ignition, with first ignition spots close to the re-attachment point, and kinetics-controlled ignition, with first ignition spots at the dividing streamline between the core flow and the recirculation zone (Yang and Wu, 1994, 1995; Yang et al., 1994). Follow-up work has investigated the effects of different step configurations on the ignition and fuel regression behavior. In cold flow tests, the velocity flow field was measured using a laser Doppler anemometer. It was concluded that, in order to achieve good ignition and flame stabilization properties, a large reverse flow speed in the recirculation zone is required, without increasing the turbulence intensity too much (Wu and Yang, 1997). Complementary to the experimental work, numerical studies were done simulating an axisymmetric solid-fuel ramjet combustor with gas radially injected at different velocities through a porous wall (Liou and Hwang, 1996; Liou et al., 1997, 2002; Yang et al., 2003). In later work the particle image velocimetry (PIV) technique was applied to investigate in detail the ignition transient in a 2-D solid-fuel ramjet combustor using PMMA as fuel (Yang et al., 2008; Hsiao et al., 2009).

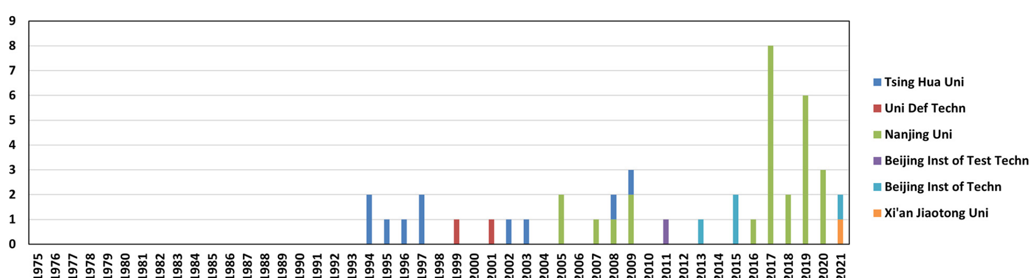

FIG. 31: Number of publications per year by China

2.11.2 National University of Defense Technology

At the National University of Defense Technology, numerical simulations of the flow and combustion in a solid-fuel ramjet are combined with a flight performance model to determine the benefits of SFRJ over a solid-propellant rocket motor (SRM) for missile propulsion. The predicted results indicate a two to three times range improvement of the SFRJ missile when compared to the SRM missile (Chen et al., 1999; Tan et al., 2001).

2.11.3 Nanjing University of Science and Technology

Acknowledging the importance of the inlet of a ramjet-assisted projectile, experimental and numerical work was done at the Nanjing University of Science and Technology to improve the understanding of the inlet flow. Numerical studies were performed into the effect of inlet cowl lip shape on the inlet flow field and performance. An axisymmetric bi-cone inlet with a design Mach number of 2.2 was tested in a wind tunnel at Mach 2.0 at 0, 4, and 8 degree angles of attack. A Navier–Stokes solver was used to yield predictions of the external and internal flow of the wind tunnel model, showing good agreement with the test results (Chen et al., 2005a,b, 2007). Follow-up work concentrated on development and validation of a numerical technique to optimize single- and double-cone inlet designs (Wang et al., 2008). Additional work was done using FLUENT to predict the internal and external flow of the 75-mm tank training round, as developed by BRL in the mid-1980s (see Section 2.3.2). Comparison shows reasonable agreement between numerical results and wind tunnel data (Sun et al., 2009). Also using FLUENT, the influence of angle of attack was studied of an axisymmetric mixed-compression intake with struts having a design Mach number of 2.94 (Xia et al., 2009).

A numerical coupled multi-physics model was developed for simulating swirling reacting unsteady flow in a solid-fuel ramjet engine by solving the axisymmetric unsteady Reynolds-averaged Navier–Stokes equations of the turbulent swirling compressible flow field with chemical reactions combined with prediction of heat transfer to and in the solid-fuel grain (Musa et al., 2016). This model was verified by comparing the results with SFRJ test results without swirl using polyethylene (PE) as fuel. Simulations were carried out to investigate the effect of turbulence models, indicating that the proposed modified curvature-correction shear stress transport turbulence model provides slightly better results. Further numerical and experimental investigation on the solid-fuel ramjet was carried out to study the effect of combustor geometry on combustion characteristics (Gong et al., 2017a,b). Relations were established describing the effect of combustor geometry on the air–fuel ratio and combustor performance using PE as fuel, with the accuracy of the model reported to be 5% on the predicted average fuel regression rate and characteristic velocity. This model was subsequently extended to solve the 3-D unsteady Reynolds-averaged Navier–Stokes equations (Gong et al., 2017c). The ignition and flame stability was studied numerically and experimentally for different swirl intensities using high-density polyethylene (HDPE) as fuel, indicating that swirl reduces ignition time delay and increases the residence time, heat transfer, regression rate, and mixing degree, thus improving the combustion efficiency and stability (Musa et al., 2017a). A comprehensive overview is given of work on the solid-fuel ramjet engine and difficulties associated with the numerical modeling of turbulence in swirling flows with combustible gases (Musa et al., 2017b). Further simulations and experiments were done to investigate (and establish relations describing) the effect of combustor entrance conditions in terms of swirl intensity, mass flow rate, and air inlet temperature on

SFRJ performance, and to validate the numerical model (Musa et al., 2017c,d,e, 2018; Li et al., 2021). Furthermore, the effect of combustor geometry on the performance of an SFRJ combustor with swirling flow was investigated both numerically and experimentally using HDPE as fuel (Li et al., 2018, 2019, 2020a). An experimental study was performed into the performance of an SFRJ combustor using a blend of paraffin and HDPE as fuel, indicating that the fuel regression rate increased but the overall performance of the SFRJ combustor decreased (Li et al., 2020b). The work was extended to include an experimental investigation on the performance of HTPB fuels with additions of ammonium perchlorate, aluminum, and magnesium, and on the specific challenges related to agglomeration of the metal particles during the combustion process (Li et al., 2020, 2021).

The work was extended to include more applied numerical investigations of the external flow and internal flow, self-ignition, and combustion of a PE-fueled SFRJ-propelled kinetic energy projectile using a separate in house–developed CFD model, originally developed to predict projectile drag reduction due to base bleed (Zhuo et al., 2019a,b). This work was supported by dedicated direct-connect PE-fueled SFRJ experiments at high total temperature, roughly corresponding to Mach 4 at sea level, focusing on identifying the effect of nozzle throat diameter and air mass flow rate on ignition characteristics and fuel regression rate (Zhuo et al., 2019c).

A novel design of an SFRJ engine was proposed to enhance its performance by introducing a second cylindrical HDPE fuel grain at the centerline of the combustor (Musa et al., 2019a,b). Simulations carried out to identify the effect of the second fuel grain with and without swirl showed decreased ignition delay, increased fuel regression rate, and mixing, resulting in increased combustor performance.

2.11.4 Beijing Institute of Aerospace Testing Technology

A CFD study was performed at the Being Institute of Aerospace Testing Technology to explore the aerodynamic characteristics of ramjet projectiles having different geometries and at various flight Mach numbers (Zhang et al., 2011).

2.11.5 Beijing Institute of Technology

A numerical investigation is performed into the combustion process and its change in time due solid-fuel regression in a solid-fuel scramjet using an HTPB-based fuel (Pei et al., 2013) using the combustor geometry and experimental data of work done at Technion—Israel Institute of Technology (Ben-Yakar and Gany, 1994; Ben-Yakar et al., 1998). The simulation results are reported to be generally in agreement with the experimental data. The same experimental data was used to verify a quasi-one-dimensional model that was developed to predict the performance of a solid-fuel scramjet to enable design of such an engine (Wang et al., 2015a,b). An experimental and numerical investigation was performed into the effect of magnetic fields on the regression rate of a PMMA solid fuel (Zhang and Wei, 2021). The experimental results indicated that the regression rate could be regulated over a range of -32% to $+11\%$ by varying the magnetic field gradients, making this, in theory, a useable technique to throttle a solid-fuel ramjet. The numerical simulations were reported to be in good agreement with the experiment. The magnetic force affects the flame shape and temperature distribution, which subsequently affects the heat transfer between the gas and the fuel surface.

2.11.6 Xi'an Jiaotong University

An experimental investigation was performed into the dynamic ignition and combustion characteristics of agglomerated boron-magnesium particles in order to enable the realization of the full potential of boron additives in solid-fuel ramjet and scramjet. The results of experiments using an electrical heating furnace indicated that the combustion process of agglomerated boron-magnesium particles can be divided into agglomerated combustion and micro-explosion combustion. The addition of magnesium reduced the critical ignition temperature and the ignition delay substantially (Li et al., 2021b).

2.12 Russia

The publication statistics are shown in Fig. 32, with publications from the Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences (RAS Mech) and the Institute of Problems of Chemical Physics of the Russian Academy of Sciences (RAS Chem).

2.12.1 Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences

A numerical investigation was performed into the combustion stability within a solid-fuel ramjet, in which the fuel grain head end has a larger port diameter as the remainder of the fuel grain, thus creating a cavity which serves as flame holder. The Reynolds-averaged Navier–Stokes equations are solved with finite-rate chemistry in the turbulent gas phase flame taken into account, assuming PMMA as fuel using a simple model describing the decomposition mass flow rate as a function of the convective heat flux. Unsteady simulations were performed for various combustor entrance conditions in terms of pressure, velocities, and fixed fuel boundaries (Rashkovskiy et al., 2017). In subsequent work, a broader range of combustor entrance conditions is considered, and the combustor geometrical parameters are varied to numerically identify the flammability limits of the solid-fuel ramjet combustor with a head-end cavity in the fuel grain (Rashkovskiy et al., 2018). In follow-up work, an analytical model was developed describing the combustion stability in a solid-fuel ramjet combustor with a head-end cavity in the fuel grain, allowing for quick parametric design studies without the need to perform time-consuming CFD simulations (Rashkovskiy et al., 2020).

2.12.2 Institute of Problems of Chemical Physics of the Russian Academy of Sciences

A quasi-one-dimensional model of describing the processes inside the solid-fuel ramjet combustor was developed based on mass, energy, species, and momentum conservation equations

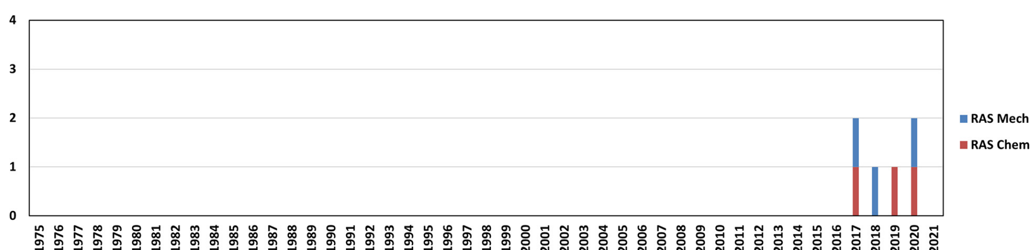

FIG. 32: Number of publications per year by Russia

and taking thermochemical processes into account (Razmyslov et al., 2017). The model allows for calculation of the solid-fuel regression rate and gas flow parameters at the combustor outlet at fixed combustor entrance conditions. The model is verified by comparison of the numerical results with previous (not internationally published) experimental data. Subsequently, a model solving the 2-D axisymmetric Reynolds-averaged Navier–Stokes equations was developed, including modeling of turbulence, solid-fuel pyrolysis, and combustion, using PMMA, PE, and HTPB as solid fuels (Razmyslov and Sultanov, 2019). The numerical model was verified by comparing with experimental results from the Nanjing University of Science and Technology (Musa et al., 2017c). Using this model for a given combustor geometry and combustor entrance air temperature and pressure of 500 K and 5 atm, respectively, the dependencies of the fuel mass flow rate, equivalence ratio, and combustion efficiency on the air mass flow rate were predicted for PMMA, PE, and HTPB fuels. The results showed only weak dependency of the equivalence ratio and combustion efficiency on the air mass flow rate for all three fuels considered, and the lowest combustion efficiency for the HTPB fuel. Follow-up work included the effect of radiation into the model (Razmyslov and Sultanov, 2020). The results indicated that radiative heat transfer does not influence solid-fuel regression rate significantly within wide range of airflow rates for a PE fuel grain.

2.13 Other Countries

The publication statistics of the following countries are summarized in Fig. 33: Brazil, Portugal, Iran, Italy, and Spain.

2.13.1 Brazil

Experimental studies on the combustion of a polyethylene fuel in a solid-fuel ramjet were conducted at the Instituto Nacional de Pesquisas Espaciais. Using a direct-connect test setup, the combustor entrance conditions and the combustor geometry (including the introduction of intermediate and aft mixing chambers) were varied to establish basic relations for the fuel regression rate as a function of these parameters (Ferreira et al., 1996, 1999).

At the Army Institute of Research and Development in conjunction with the University of Rio de Janeiro, numerical analyses have been performed of the flow field inside the ramjet combustor of an SFRJ-assisted projectile, including predictions of the fuel regression rate. The results show qualitative agreement with experimental results obtained at the U.S. Naval Postgraduate School (see Section 2.3.1) in the early 1970s (Cordeiro and Nieckele, 2003). An experimental study was performed by the University of Brazil to investigate the performance of paraffin-based fuels in a small solid-fuel ramjet test setup (Azevedo et al., 2019). At the Chemical Propulsion

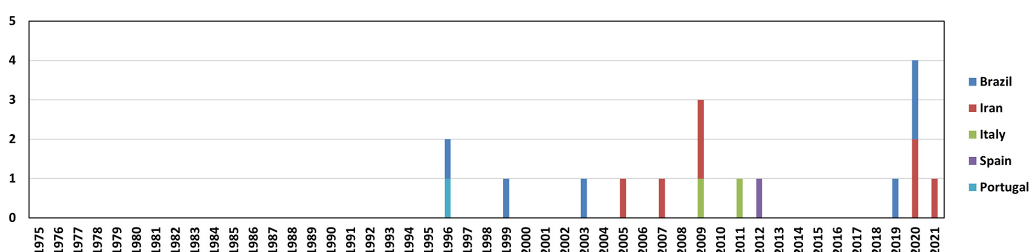

FIG. 33: Number of publications per year by Brazil, Portugal, Iran, Italy, and Spain

Laboratory (CPL) of the University of Brazil, a direct-connect ramjet test setup was developed within the framework of the research project "design and development of a high-maneuverability supersonic missile with ramjet engine," and cold flow experiments were performed to confirm the functionality of the test setup (Freitas and Shynkarenko, 2020). Subsequent work was done on the development of a thrust control system, which was applied successfully during tests with hybrid rocket motors and SFRJs (Shynkarenko and Gontijo, 2020).

2.13.2 Portugal

Following contract work for TNO in the Netherlands on further improvements of the Navier–Stokes solver developed by Vos in the early 1980s to predict the flow and combustion inside an SFRJ (see Section 2.5.1), the University of Lisbon executed numerical studies to verify and validate the improved numerical techniques (Coelho at al., 1996).

2.13.3 Iran

At the Sharif University of Technology, a numerical model predicting the internal ballistics of a solid-fuel ramjet propulsion system was developed, including a concept description and (neural network) control characteristics of a mechanism to regulate the thrust (Durali and Alemohammad, 2005). In addition, numerical studies were initiated to gain insight into the dynamics of the igniter flow field in solid-fuel ramjets. A steady-state simulation of a planar cold wall jet in a solid-fuel ramjet geometry was performed, showing that the recirculation flow field is drastically affected by the supersonic jet flow of the simulated igniter (Tahsini, 2007; Tahsini and Farshchi, 2009). Subsequently, an experimental setup was designed and commissioned to do combined theoretical and experimental studies into the functioning of a ramjet engine with swirling flow, with the aim of reducing the wall heat load in liquid-fuel ramjets and increasing the fuel burning rate in solid-fuel ramjets (Shafiei et al., 2009). A numerical study was performed into the coupled flow through the complete solid-fuel ramjet engine, including the inlet, the combustor, and the nozzle, by solving the 3-D Navier–Stokes equations coupled with heat transfer into the solid phase to predict the fuel regression rate and subsequent combustion of the PMMA fuel (Tahsini, 2020a). The results indicated that the combustor performance clearly depends on the flow field delivered by the inlet subsystem, suggesting that an integral modeling approach is required, and a thrust increase of 15% was reported due to swirl. Additional work resulted in an optimized swirler design for increased fuel regression rate and low pressure loss (Tahsini, 2021). Further numerical studies were performed to investigate the effect of spin on the PMMA fuel regression rate, showing that the spin augmented the fuel regression rate by approximately 10% due to an increase in convective heat flux at the fuel surface (Tahsini, 2020b).

2.13.4 Italy

At the University of Rome, studies were undertaken into the use of lithium hydride (LiH) as fuel for solid-fuel scramjets. The theoretical study using numerical tools indicated that LiH is an ideal candidate for solid-fueled scramjet applications due to its characteristics as a high–energy density bi-fuel system but also as a safe and compact hydrogen carrier (Simone and Bruno, 2009; Bruno and Simone, 2011).

2.13.5 Spain

Around the year 2012, a research program was initiated by the Instituto Tecnológico de la Marañosa (ITM) and the Instituto Nacional de Técnica Aeroespacial (INTA), with a four-year target to develop a prototype of a 30-mm SFRJ-propelled projectile for a Mach 3.85 sea level flight. The already-existing direct-connect test facility at the ITM is being modified to allow for testing at the correct total temperature conditions and for free-jet testing. Preliminary designs of intake and ramjet combustor were presented, and computational fluid dynamic calculations have been performed to study the flow in the intake and subsonic diffuser (Garcia et al., 2012).

3. CONCLUDING REMARKS ON MAIN ACHIEVEMENTS, CHALLENGES, AND OPPORTUNITIES

3.1 Main Achievements

From the literature overview in Section 2, it can be concluded that the amount of work performed on solid-fuel ramjets is very substantial. In many countries, fundamental studies have been or are being performed into the flow and combustion processes that occur inside a solid-fuel ramjet. In the past five decades, extensive experimental studies have been performed to establish the influence of combustor geometry, inflow conditions, and solid-fuel type and additives. The development of advanced nonintrusive measurement techniques like laser doppler velocimetry (LDV), coherent anti-Stokes Raman scattering (CARS), and particle image velocimetry (PIV) enabled to measure these effects in a more direct way, thus contributing substantially to the understanding of the complex physics of turbulent mixing and combustion. The increasing computing power enabled the development of numerical tools that were no longer limited to the prediction of nonreacting flows. In the early 1980s, numerical tool developments were initiated to solve the Navier–Stokes equations fully coupled with a finite-rate chemical kinetic model (Vos, 1986). These tools and their modern descendants enabled numerical studies that contributed significantly to the understanding of the physical phenomena involved.

A very significant amount of work has been done on the combustion of boron as additive to solid fuels because of its very high energy content, resulting in a thorough insight in the characteristics of combustion of boron particles. Progress made both in theoretical and experimental studies seems to indicate that ignition and combustion of boron particles in solid fuels can be promoted by adding magnesium or by applying surface functionalization of the boron particles. Recently, a substantial amount of work has been reported on new fuel formulations like polysulfide-based fuels for SFRJ projectile and missile applications. Another noteworthy development is the work done on solid-fuel scramjets, which seems to have received increased attention in the last 10 years.

When looking into the application of this solid-fuel (sc)ramjet technology to gun-launched projectiles, the functioning of the solid-fuel (sc)ramjet combustor is not the only concern. The combustor needs to be designed for proper functioning in conjunction with the air intake and integrated in a projectile design capable of surviving the harsh gun-launch environment. These problems are being faced only when progressing the technology development beyond the fundamental research in technology demonstration or prototype development programs. According to the open literature found on the subject, to date, the following solid-fuel ramjet projectile development programs have been executed, including a brief description of their main results:

- United States of America in the 1980s by the U.S. Army Chemical Research Development and Engineering Center (CRDEC) and the U.S. Army Ballistic Research Laboratory:
  - 40-mm spin-stabilized anti-aircraft projectile (not successful)
  - 60-mm fin- and flare-stabilized projectile (not successful)
  - 75-mm spin-stabilized tank training round (flight trajectory of the KE round fired from the105-mm M68 gun was successfully matched)
- Sweden in the period from the late 1980s to 1995 by the Swedish Defence Research Agency FOA:
  - 40-mm spin-stabilized anti-aircraft projectile (not successful due to insufficient thrust)
- South Africa in the period from 1993 to 1996 by Denel:
  - 76-mm fin-stabilized KE projectile (successful demonstration of thrust equal to drag capability)
- Sweden/the Netherlands in the period from 1995 to 2000 in a cooperative technology demonstration program by FOA and TNO:
  - 61-mm generic fin-stabilized projectile (successful demonstration of thrust equal to drag capability but only for short duration)
- South Africa in the period from 1998 to 2002 by Denel:
  - 155-mm spin-stabilized artillery round (successful demonstration of thrust equal to drag capability, but sustained propulsion performance beyond roughly 8 s not demonstrated due to insufficient combustion efficiency)
- South Korea in the period from 1999 to 2002 by the Agency for Defense Development:
  - 40-mm spin-stabilized air-defense projectile (pitot intake version unsuccessful due to insufficient thrust; cone intake version unsuccessful due to lack of autoignition)
- The Netherlands/Switzerland in the period from 2000–2005 by TNO and RWMS:
  - 35-mm spin-stabilized air-defense projectile (successful demonstration of thrust equal to drag capability at a 1000-m test range)
- United States of America, in the period from 2019 to 2023 by the U.S. Army in the XM1155 program:
  - Development of a fully integrated TRL6 GPS independent guided artillery round capable of achieving ranges beyond 100 km, with SFRJ propulsion being one of the options to reach this range objective.

In conclusion, it can be stated that several solid-fuel ramjet projectiles have been developed and tested in actual gun firings with different gradations of success. However, the main achievements listed above in chronological order do show progress is being made. Thrust equal to drag capability of fin-stabilized projectiles has been demonstrated by Denel in South Africa and by

FOA/TNO in Sweden/the Netherlands. Following earlier attempts that failed to demonstrate the same for spin-stabilized projectiles, Denel in South Africa has successfully demonstrated a thrust equal to drag capability for a 155-mm projectile, while TNO in the Netherlands, together with RWMS in Switzerland, demonstrated the same for their 35-mm projectile.

The introduction of large-caliber precision-guided munitions has renewed interest in solid-fuel ramjet technology, with the objective of achieving ranges beyond 100 km, which recently has resulted in the start of the U.S. Army XM1155 program. This program represents a milestone in transferring decades of technology development into an actual solid-fuel ramjet artillery round, of which a TRL6 prototype demonstration is expected to be performed in 2023.

Furthermore, it can be concluded that during the last 10 to 15 years, the solid-fuel ramjet technology, and more specifically, the application of this technology to gun-launched projectiles has drawn the attention of countries in the far-east. While the number of publications of the western countries on this technology field have been reduced significantly since the period between 1985 and 1995, these countries are generating an increasing number of publications. For instance, a substantial amount of publications have been generated recently on the subject by China and Russia. The nature of the work published suggests that actual flight tests are in preparation.

3.2 Remaining Challenges

From a mechanical point of view, the solid-fuel ramjet is an extremely simple propulsion system. It is this mechanical simplicity that allows us to devise the robust projectile designs that are required when being fired from a gun. In contrast to its mechanical simplicity, the functioning of the fully passive propulsion system is dictated by the following highly interactive complex physical processes, which would require a fully coupled multi-physics model to predict the integral performance of the SFRJ propulsion system:

- Aerodynamic flow phenomena, which are dominated by shock-shock and shock-wave boundary layer interactions in the air intake
- Convective (and radiative) heat transfer to the solid fuel and subsequent vaporization, which largely depends on the flow characteristics (e.g., velocity profile and turbulence level) delivered by the air intake
    - Turbulent fuel air mixing and combustion of fuel including:
        - two-phase effects on flow and chemical kinetics in case the fuel contains (metal) particles
        - air swirl and rotational force effects in case of a spin-stabilized projectile
    - Highly dynamic intake combustor interaction

Integrating the SFRJ technology into projectiles (and missiles) is always a volume-limited problem. In other words, due to the limited volume available within the projectile for all of its subsystems (i.e., warhead, guidance, navigation and control, and propulsion), the ultimate challenge is to generate sufficient propulsive performance within the limited volume allocated for the propulsion subsystem. This in turn leads to the technological challenge to maximize the amount of energy added to the air flow per unit of system volume. Solution directions for this challenge are ways to increase:

- The (volumetric) energy content of the fuel (e.g., by addition of high volumetric energy components to the fuel)
- The fuel burn rate (e.g., by adding burn rate–enhancing constituents to the fuel)
- The combustion efficiency (e.g., by enhancing the mixing of the fuel with the air)

It should be noted that modifications to the fuel composition can be implemented only for gun-launched projectiles under the prerequisite that the mechanical properties are sufficient for the fuel grain to survive the gun launch.

Another technological challenge is related to the passive nature of the SFRJ propulsion system. The amount of fuel added to and burned within the air flow depends on the characteristics of the air flow delivered by the air intake to the combustor, which in turn depend heavily on the flight conditions of the projectile or missile. This results in a build-in passive throttleability of the SFRJ, of which the characteristics are fully determined by the propulsion system design in combination with the flight profile of the vehicle. To have a higher degree of freedom in terms of flight profiles that can be flown by the projectile or missile and/or to widen the operability limits of its flight envelope, it would be very attractive to have an option for active throttle control. For missile applications, a substantial amount of work has already been done on the use of air bypass channels in combination with valves that actively control the amount of air that is bypassed around the fuel grain and injected in the aft mixing chamber. Since this solution seems to be less suitable for gun-launch projectile applications, finding alternative ways to achieve active throttle control can be identified as an important technological challenge as well.

The successful design of a solid-fuel ramjet projectile requires that all of the above aspects are carefully balanced. The major challenge may therefore not be in the isolated optimization of all of the above aspects and related subsystem performances, but more in the integrated approach to arrive at a projectile design that shows optimum overall performance. This can be achieved by tradeoff studies using results of in-depth design, development, and verification activities on the following performance aspects:

- Internal ballistic performance
- Intermediate ballistic performance (behavior of the projectile upon and immediately after exiting the muzzle of the gun)
- Structural performance during gun launch (including structural behaviour of the fuel grain)
- In-flight aerodynamic and aerothermodynamic performance (including aerodynamic heating of the airframe)
- In-flight propulsive and kinematic performance (including guidance and control)
- Terminal ballistic performance

3.3 Future Application Opportunities

Due to the demonstrated progress made over the past few decades, SFRJ projectiles still hold a great promise for future applications. The following gun-launched applications are considered to be most attractive for the SFRJ technology:

- By providing increased range and reduced time-to-target by sustained propulsion, large-caliber SFRJ artillery projectiles could be a solution:
  - to accommodate to the increasing size of the battle space and to strive for optimum operational flexibility for land-based artillery
  - to fulfil the range requirements for Naval Surface Fire Support applications
- To counter high-speed anti-ship missiles, medium- and large-caliber SFRJ air-defense projectiles could be a solution by providing:
  - high-initial and high–mean flight velocity to maintain sufficient keep-out range
  - increased level of kinetic energy by maintaining a very high flight velocity
  - increased range by sustained highly efficient propulsion

At the same time, the SFRJ technology holds a great promise for application in missiles as well. Especially in combination with throttle control, the SFRJ might be a cost-effective solution to achieve a dramatic increase in range compared to solid-propellant rocket motor-propelled missiles.

The technology readiness level of solid-fuel scramjet engines is still rather low at this moment. But given the amount of work currently being done on this subject, breakthroughs may be expected in the coming years, opening the possibility of applying this promising technology to propel projectiles and missiles well into the hypersonic-speed regime.

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