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Scalability analysis of additively manufactured grain for 4 kN High Test Peroxide Hybrid Rocket Motor

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Abstract

This paper describes the work done under RD3D project (**R**esearch & **D**evelopment of **3D** Printing Technology) in Institute of Aviation (IoA), Lukasiewicz Research Network - Center of Space Technologies in Warsaw. The paper focuses on research done with 3D printed grain for a sub-scale hybrid motor utilizing 98% Hydrogen Peroxide with main intent of scaling it into 4 kN main motor grain of ILR-33 Amber rocket. Project roadmap and experiments along with data are presented and discussed.

1. Introduction

Hybrid rocket propulsion and HTP (High Test Peroxide) constitute a significant part of research at Institute of Aviation (IoA) from Warsaw. HTP is investigated by IoA since 2009 and several liquid and hybrid motors have been designed and tested using it as oxidizer. As the leading Polish research & development facility in terms of rocket propulsion, IoA is determined to investigate any new accessible technology that allow to achieve better performance in the field of hydrogen peroxide applications. One of this technology is additive manufacturing.

2. ILR-33 Amber Project

In the beginning of 2015 ILR-33 "Amber" project started with main object was to launch world's first rocket with hybrid motor utilizing HTP 98%+. In 2017 engineering team from IoA launched ILR-33 at 15 km altitude (altitude was constrained by launch area and Polish law) and successfully recovered it. Amber rocket is still under development as a rocket technology demonstrator. Second launch was in May of 2019, main object was to test several improvements and new solutions such as steering system, it also succeed. ILR-33 serves as development platform for many new projects and technologies. One of this is RD3D (**R**esearch & **D**evelopment of **3D** Printing Technology) that is focused on studding and utilizing additive manufacturing technology in aerospace industry. Examples of parts used in ILR-33 Amber project that are 3D printed and were used in flight:

- Payload bay – electronics mountings
- Recovery systems – camera mounts
- Feeding system – over 0,4 m length cable cover rails
- Boosters – over 0,3 m in height carbon composite boosters head

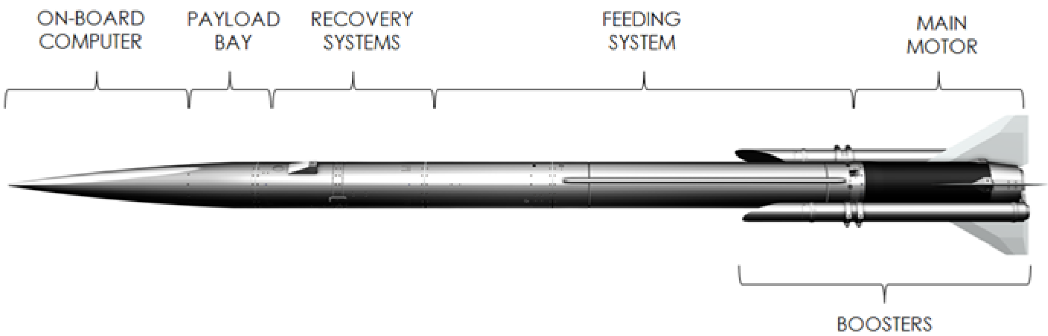

Figure 1 - ILR-33 functional sections

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3. Main motor of ILR-33 Amber Project

ILR 33 rocket utilizes High Density Polyethylene (HDPE) multiport grain as fuel and 98%+ HTP as oxidizer, this combination provides about 4 kN of thrust. Multiple test fairings and test flights proven performance and reliability. As ILR-33 rocket is a research platform, there is always space for improvements, one of planed innovation is additively manufactured fuel grain.

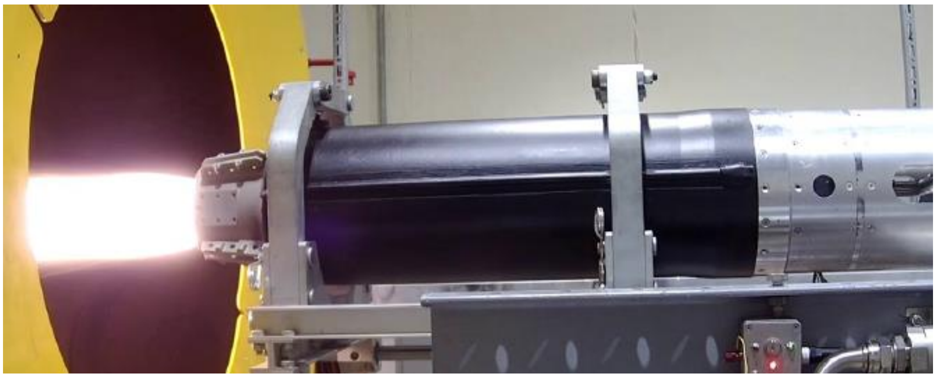

Figure 2 - ILR-33 Main motor during test.

Table 1 - ILR-33 Main Motor Parameters [1]

Grain type	multiport
Grain diameter [m]	~0,2
Grain height [m]	~0,5
Burn time [s]	40
Max thrust [kN]	4
Fuel type	HDPE
Mass of fuel [kg]	~12
Chamber pressure [bar]	20
Isp [N*s/kg]	>=2000

The manufacturing method for hybrid motor fuel grains was developed by IoA specially for ILR-33 project purposes. It is a robust but complex, time-consuming and requiring experienced staff process. Nevertheless it allows to manufacture large fuel grains with various straight or curved channels geometries without complicated extrusion or casting process from HDPE or other material (utilizes only off the shelf materials and processes). The method is currently patent pending.

Additive manufacturing can simplify this process, it eliminates cutting, joining and welding process. Additionally it allows designing more advanced geometry of the grain, for example with helical or tapered channels. Concept of swirl channels were earlier investigated [2] and proved to be increasing the regression and performance.

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Figure 3 - Multiport HDPE Fuel grains manufactured in IoA.

4. RD3D – Research & Development of 3D printing technology

Additive manufacturing is not a new technology, it has its beginnings at least in 1980 [2] but it's rapidly growing in recent years. Better additive manufacturing devices are constantly developed and they are adopted in many industries, like space industry. NASA is experimenting with 3D printing since early nineties. In 2014 first Fussed Deposition Modeling (FDM) printer was placed in International Space Station, it was manufactured by American company Made In Space. Nowadays 3D printed parts are implemented in critical components of modern launch vehicles (i.e. injectors, combustion chambers, pumps) [3]. Additive manufacturing is giving great possibilities but nevertheless it also comes with new limitations which must be studied. IoA is also searching for new ways of implementing this technology into aerospace projects and researching occurring problems that come with it.

Scope of the RD3D project is to study applications of additive manufacturing that are usable in terms of aerospace and to learn more about this technology. At the beginning of the project it was assumed that is possible to print full scale HDPE fuel grain for ILR-33 motor but later studies showed that printability of this material is very weak which is described below. Other studies proved that there are other materials that can be utilized as fuel for hybrid with similar performance [4]. Road to develop full scale grain for ILR-33 Rocket motor was planned from material selection through sub-scale hybrid motor testing and it is ending at manufacturing and testing it at full scale. At the time of creating this article project is after first phase of sub-scale tests which are described below. Scaling remains an interesting problem for hybrids, issues are still not well understood and there is a need for experimental data for different motor sizes. [5]

First phase of tests assumes to investigate how chosen materials will act as grain for sub-scale rocket motor. Second phase will investigate more advanced ideas like helical or variable channel geometry to improve regression rate and performance. The test of the grain that is manufactured from two different materials in radial direction, which should result in interesting thrust profiles and can improve ignition phase, is also considered. There is also possibility to use materials with preadded metal particles which can improve regression rate which was described in earlier studies [7], [8].

5. Materials selection

During first phase of the project specific materials where chosen for testing. Main aspects of selection were theoretical performance combined with HTP oxidizer, accessibility on the market (in terms of raw materials for 3D printers) and printability. Fuel regression rate, as it can be (more or less easily) overcome by grain geometry, was not considered here. Printability is a wide term, in considered aspect it is a indicator how many problems pose printing from specific material. Printability pose a small problem during sub-scale tests because it is matter of relatively short time to overcome them. Unfortunately problems with printability from specific material scale "exponentially" in 3d printing during scaling object of interest and that leads to problems that solving can take unacceptable time.

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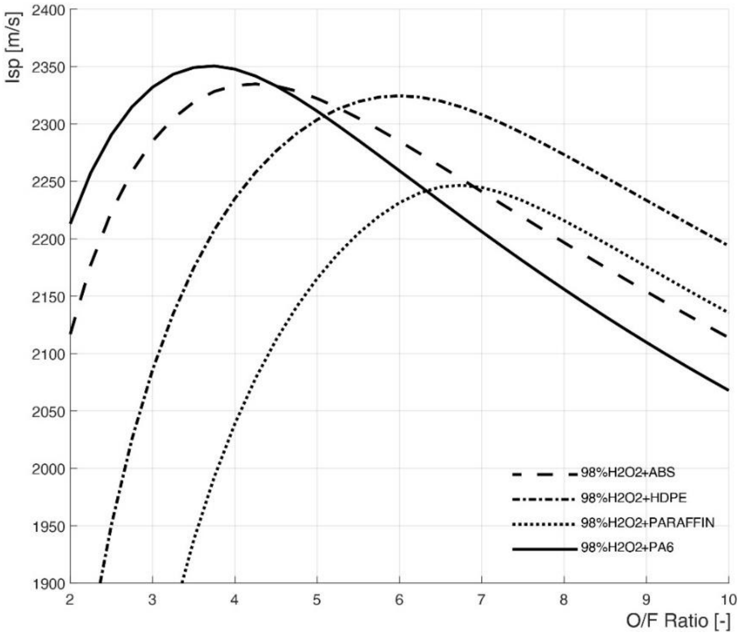

Figure 4 - Theoretical performance of selected fuels with 98% hydrogen peroxide (throat frozen, pi=20bar, pi/pe=20).

Based on the theoretical analysis (made with modified CEA script [7]) of Specific impulses ABS, PA6 and HDPE was chosen for first phase of the test studies. In Figure 4 there was also added paraffin for comparison as commonly hybrid rocket motor fuel.

1) **ABS (Acrylonitrile butadiene styrene)** – one of the most popular material for FDM additive manufacturing process, with very good printability results.
2) **PA6 (Polyamide 6)** – type of nylon, with high temperature resistance and medium printability performance. Absorbs moisture which require low humidity storage conditions. Moisture in the raw material implicates very poor print quality. Drying in vacuum oven before using is highly recommended. Printing time is also longer in comparison to ABS.
3) **HDPE (High Density Polyethylene)** – Original proposition for fuel grain. Printability performance is very poor. Additive manufacturing require specific printing conditions for different phases of the manufacturing process, heated bed and heated printing chamber are required.

Figure 5 -Failed attempts of HDPE grains

Project involved thorough investigation printing properties of HDPE. Special preparation of build plate is required for printing from this material. High thermal expansion coefficient vastly affects prints and impacts more if object are scaled up. Due to properties of this material it is important to maintain equal temperature distribution in build direction as each layer prints because internal thermal stresses can cause large deformation or even separation between layers. As one can notice this problems are more serious when designed object must be fully filled as it needs be for this application. In this project challenges of HDPE printability were addressed at very beginning, different types of HDPE were tested with shapes resembling scaled grain (Figure 5).

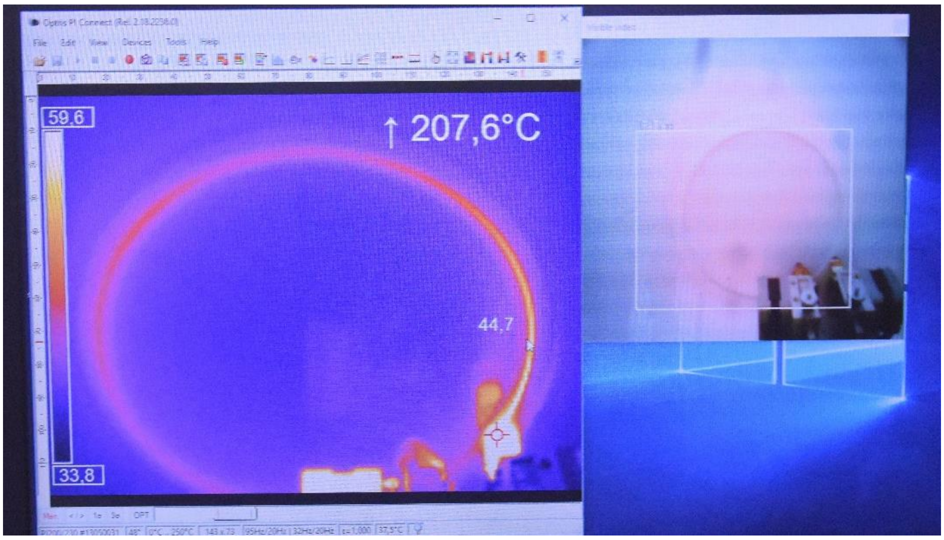

Figure 6 - Image from thermographic camera during HDPE printing process.

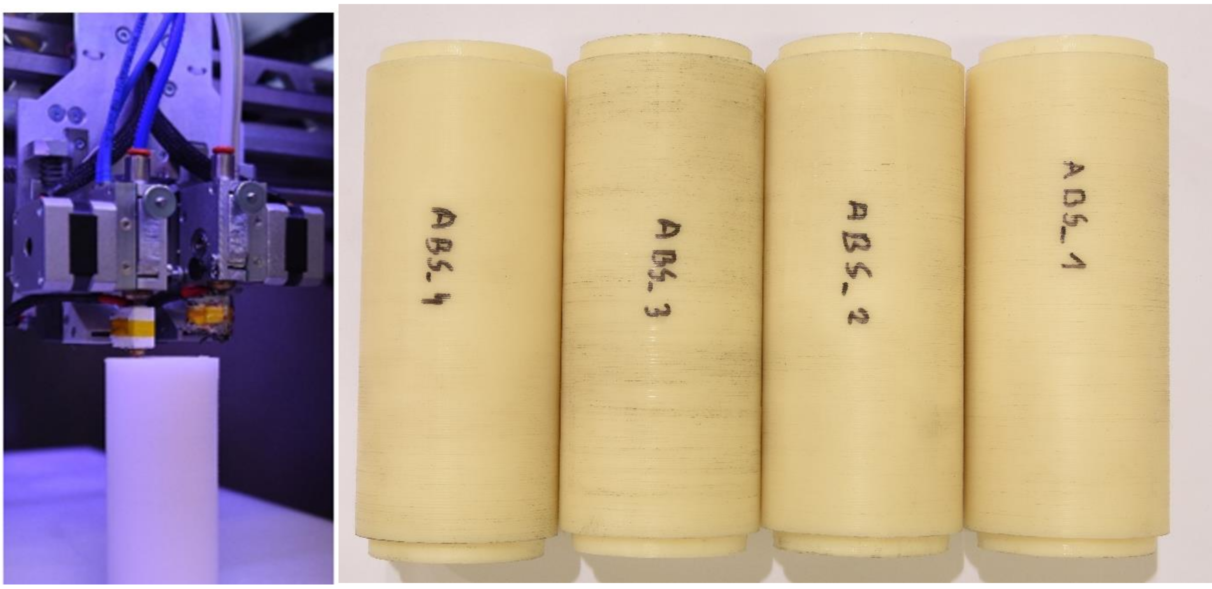

Figure 7 - Succeed attempt of printing from HDPE and ABS

For achieving satisfying results thermographic camera was used to monitor temperature field across printed object and adjust specific parameters of manufacturing process. After succeed attempts of final grain was designed and printed. Print time is significantly longer comparing to ABS, nevertheless it is possible to achieve satisfying quality of the object at the end.

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6. Grain manufacturing hardware

Due to the project specify, volume and materials accessibility one of the most popular method for additive manufacturing was chosen – Fused Deposition Modeling (FDM). In this method plastic rod is melted in printers head and material is extruded layer by layer along programmed path.

Taking into account main interest of the project (Full scale grain for ILR-33 Rocket), FDM 3D printer was acquired with specified requirements :

1) Print volume with minimum size of 0,5 x 0,5 x 0,5 m (X,Y,Z)
2) Heated Bed up to 100ºC
3) Heated chamber up to 50ºC
4) Heads temperature up to 315ºC
5) Water cooling system for heads
6) Double printing heads to have possibility of printing with two different materials
7) Open material base (with software that allows for specified parameters)
8) Extrusion nozzle applicable from size 0.4 mm up to 1 mm

Figure 8 - Acquired 3D printer for RD3D project [3].

7. Sub-scale rocket motor

For sub-scale testing a test bench motor utilizing 98%+ HTP was designed. It is using the same catalyst as ILR-33 Amber main motor – Mn_xO_y on Al_2O_3 spherical pellets.

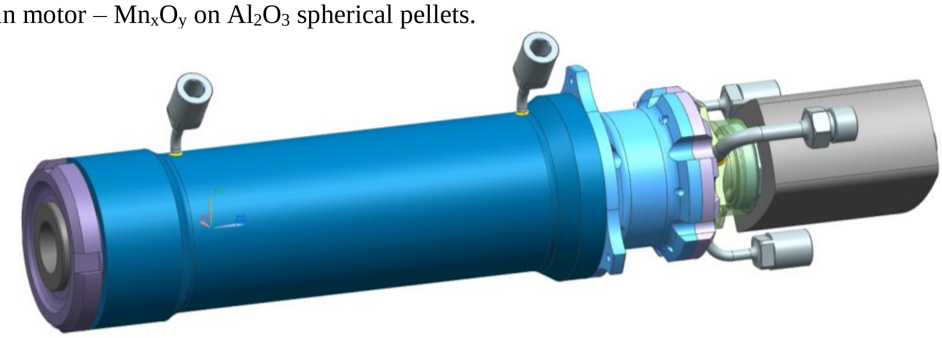

Figure 9 - CAD model of designed sub-scale RD3D hybrid motor

DOI: 10.13009/EUCASS2019-979

For simplicity main oxidizer valve has been integrated into injector module, which also enables fast response of the motor (in case of pulse mode firing). Whole motor have been designed to enable easy access to combustion chamber for fast grain and insulation replacement between tests. It can also be easily adjusted to different fuel needs by changing pre- and post- combustion chambers lengths. Whole motor is mainly manufactured from stainless steel to withstand multiple hot fires with different fuels.

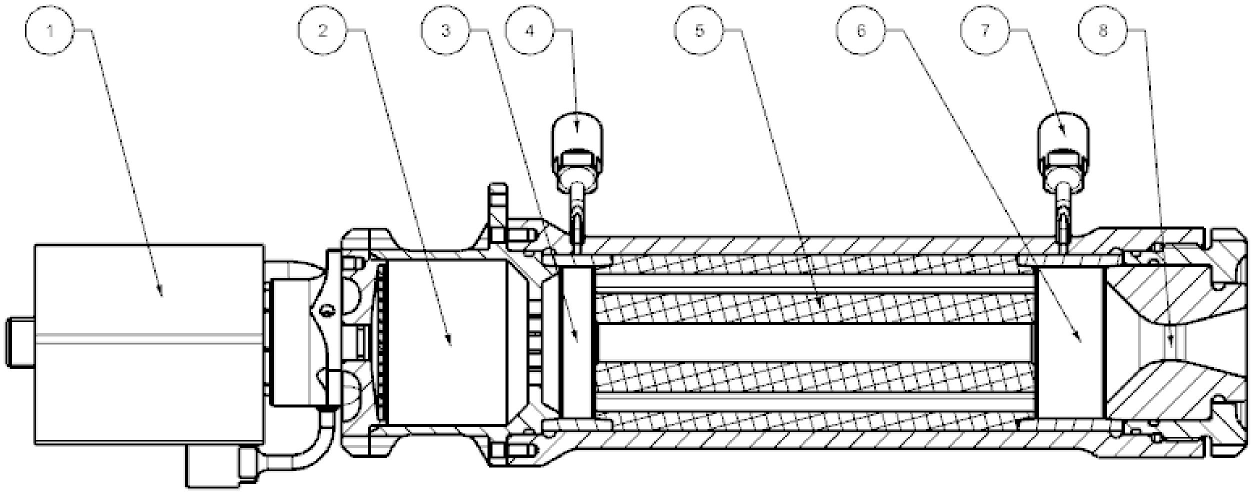

Figure 10 - Section view of a RD3D sub-scale rocket motor

1) Main oxidizer solenoid valve
2) Catalyst chamber
3) Pre combustion chamber
4) Pre combustion chamber pressure port
5) Fuel grain
6) Post combustion chamber
7) Post combustion chamber pressure port
8) Graphite nozzle

Table 2- Theoretical performance of base RD3D motor

Grain type	6-port
Grain diameter [m]	0,05
Grain height [m]	0,125
Burn time [s]	10
Designed thrust [N]	200
Designed chamber pressure [bar]	20

8. Experiment Methodology

Each test described in this paper was conducted in Institute of Aviation by experienced personnel on specially prepared test stand. Using highly concentrated hydrogen peroxide requires high cleanness standards, especially in oxidizer supply installation.

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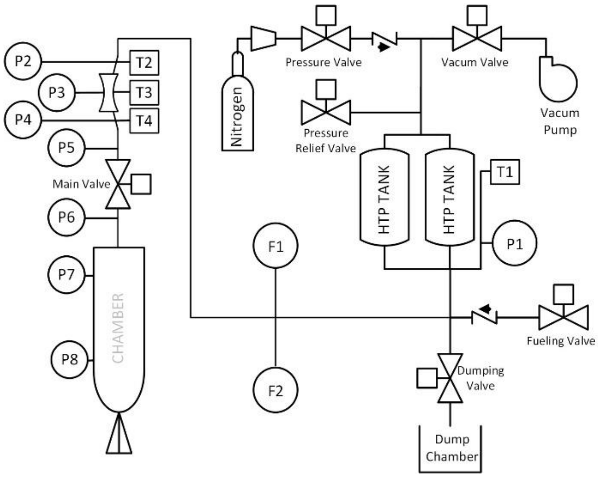

Figure 11 - Test RD3D installation

Installation utilizing H2O2 with Pressure transducers (Px), Flow meters (F1 – turbine type, F2 – Coriolis type) and temperature sensors (Tx) has been developed for this and other test subjects, simple schema of it is presented on Figure 11. HTP delivery system is equipped with orifice (before Main Valve) to reduce instabilities and to achieve calculated oxidizer flow.

Figure 12 - Control room in IoA

During each test every parameter is measured with 10 kHz frequency and most significant are presented in control room as shown on Figure 12. Measurement hardware is mainly produced by National Instrument but software is internally written and adjusted to every test subject. Each test is executed with preprogrammed sequence which increases repeatability and monitored with live cameras from different angles for safety reasons and later examination. Before and after each test most important components are weighted and inspected.

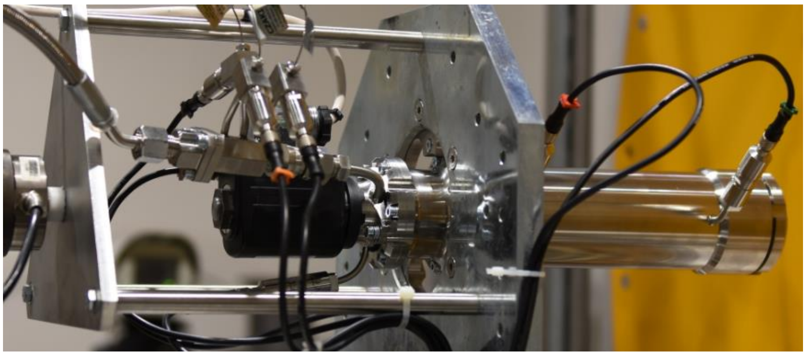

Figure 13 - RD3D motor assembled on the test stand.

DOI: 10.13009/EUCASS2019-979

9. Experiments Results

In first phase of the testing multiple hot fire in sub-scale motor using chosen grains have been done. Sub-scale motor have been designed based on the ILR-33 Amber main motor and should give best results with HDPE although even without changing geometry of the motor and grains results are comparable and giving overview on performance of each fuel. Each test was planned for 8 seconds of burning which also contains monopropellant phase at the beginning.

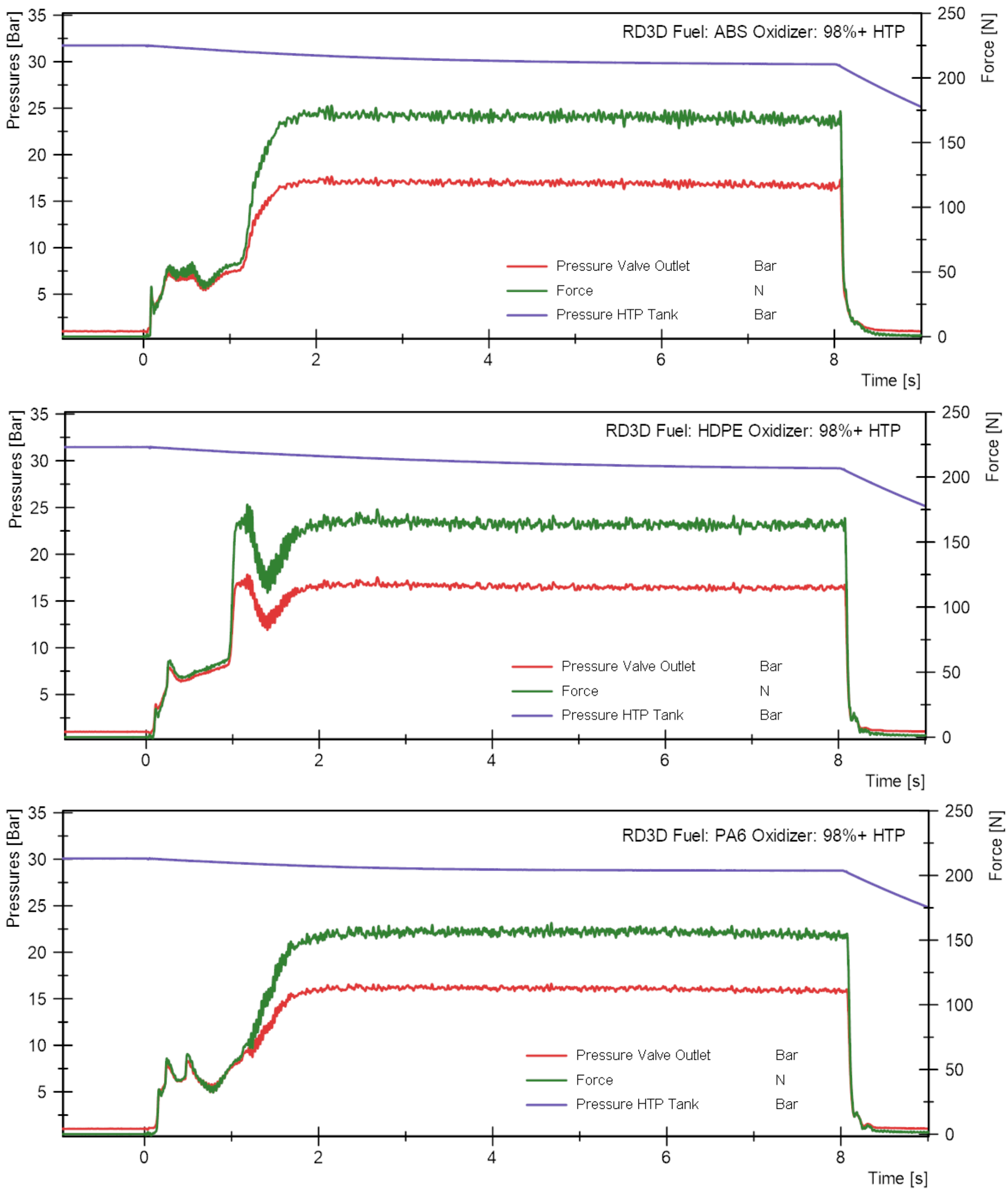

Figure 14 Test results with different grain fuels.

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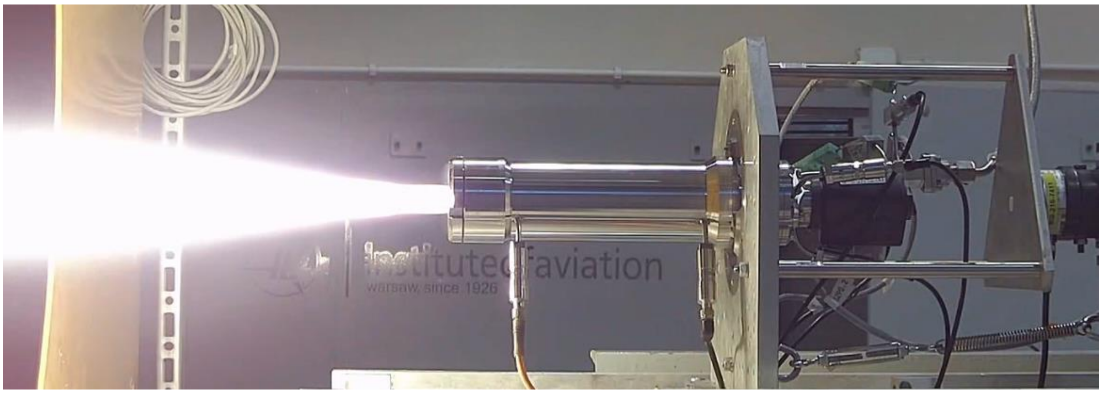

Figure 15 - RD3D hybrid motor with ABS grain, 4'th second of the hot fire test.

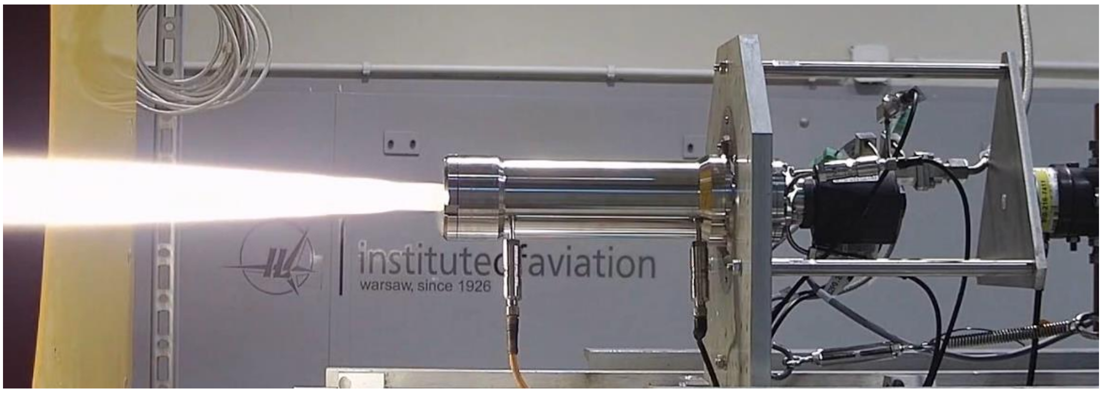

Figure 16 - RD3D hybrid motor with HDPE grain, 4'th second of the hot fire test.

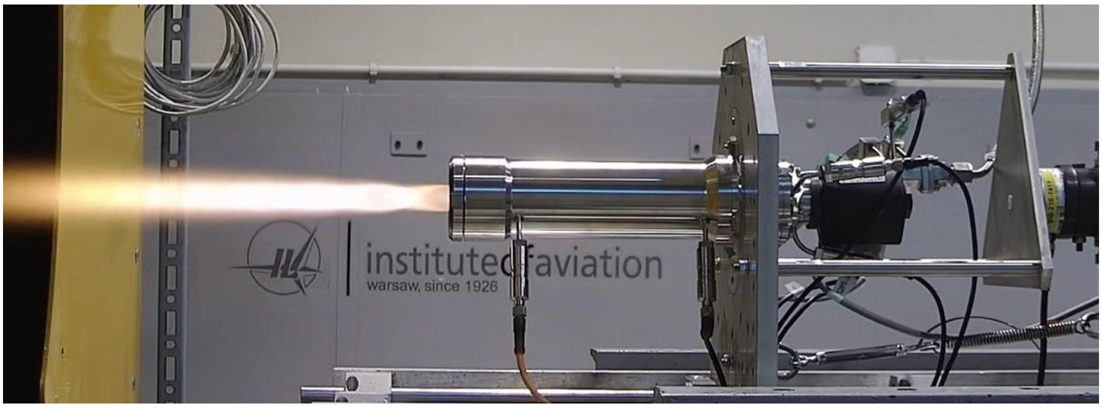

Figure 17 - RD3D hybrid motor with PA6 grain, 4'th second of the hot fire test.

Several tests with same grain geometry but different materials had been performed. Based on camera footage and results first conclusion is that for different materials engine can be optimized. Large flame behind the nozzle in ABS test can be indication that post combustion chamber is too short. PA6 burns with nice flame, shock diamonds are visible throughout whole burn.

Different HTP Tank pressure is mainly due to mechanical regulator in feeding system. Regulator is set manually, hence the pressure slightly varies in each test. Although pressures were still in a designed range of venturi nozzle which assures right oxidizer flow in next phase of test electronic pressure regulator will be implemented. In the tests PA6 had very stable combustion throughout all burn time which was also visible in post inspection of the grain, inside walls of unburned grain were straight without noticeable roughness.

Table 3 - Performance of selected materials

	ABS	HDPE	PA6
Mean Thrust [N]	170,3	165,1	156,5
Oxidizer flow [g/s]	68,06	67,83	66,88
Mean Combustion Pressure [Bar]	16,12	16,07	15,60
Mean fuel mass flow [g/s]	17,39	12,80	12,79
O/F Ratio	3,91	5,30	5,23
I_{sp} [m/s]	1993,07	2047,63	1964,17
c* [m/s]	1481,71	1565,35	1537,73
Real Infill material [%]	97%	93%	94%
Raw material density [g/cm^3]	1,04	0,95	1,12

$$I_{sp} = \frac{\int F\,dt}{\int (\dot{m}_f + \dot{m}_o)\,dt} \tag{1}$$

$$c^* = \frac{A_t \int Pc\,dt}{\int (\dot{m}_f + \dot{m}_o)} \tag{2}$$

Characteristic velocity and specific impulse was calculated accordingly to eq. 1 and 2, where F is Force, $\dot{m}_f$ and $\dot{m}_o$ stands for fuel and oxidizer flow. P_c is combustion chamber pressure measured in post combustion chamber, A_t is area of nozzle throat. All performance numbers in Table 3 relate to hybrid mode, not monopropellant mode of the test, since that was main interest of this experiments.

As expected HDPE performed best in terms of Isp (specific impulse) or c* (characteristic velocity). It is safe to assume that after optimizing geometry of combustion chamber and grain it is possible to achieve same or better performance for ABS or PA-6. In addition PA6 is 18% more dense and burns more stable than HDPE. Regression of PA6 is lower but can be improved in further studies by advancing in geometry or implementing additives into material. Test subjects achieved efficiencies around 85%-90% in first phase which is close to efficiency of ILR-33 Amber main motor.

In RD3D project there were also tests with materials with aluminium particles as additive, it introduced large instability to the combustion chamber but also highly increased regression rate and combustion chamber pressure.

10. Conclusions

First phase proved that Additively manufactured grain can be a substitute for conventionally manufactured grain if manufacturing difficulties are solved.
HDPE FDM printing is harder than expected and a trade-off studies must be performed to choose a final design, including material selection, of the full scale 3D printed grain for the ILR-33 main motor.
Ignition transient phase should be taken under investigation to understand different fuel behavior. Augmented ignition should be considered to minimize burn/ignition delay.
There is still need for investigating more advanced grain geometries and improve test installation.

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