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P120C SOLID ROCKET MOTOR SYNTHESIS OF THE DEVELOPMENT OF THE COMMON PROPULSIVE SRM FOR ARIANE 6 AND VEGA-C AND P160C WAY FORWARD

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Abstract

The Ground Qualification of the P120C SRM, designed to be the Common Solid Propulsive Module as strap-on booster on Ariane 6 Launch Vehicle for both 62 and 64 versions and as first stage for Vega Consolidation and Vega Evolution vehicles, was successfully achieved in 2021 in the time frame scheduled despite a design to cost approach driven by a very ambitious low recurring cost objective. Following this ground qualification, the P120C SRM successfully flew on Vega-C VV21 (maiden flight) and Vega-C VV22. It is now waiting for its first flight on Ariane 6 Launch Vehicle.

The Design Definition Authority of the P120C SRM was entrusted by the Launcher System Prime Contractors to Europropulsion who has been responsible for the motor development and is in charge of production exploitation of the P120C SRM with the support of Avio and ArianeGroup.

Feedbacks from the satellites market in this phase of preparation to the first Ariane 6 commercial flights, showed that a very promising opportunity is represented by the launch of satellite constellations in Low Earth Orbit (LEO).
The first analyses performed at Ariane 6 System level indicated however the need to increase the A64 payload capability in LEO to be competitive in this interesting but very challenging market.

Among the potential Launcher performance improvement options, the increase of SRM length by one meter and of the propellant mass up to about 156T, resulting in a Launcher performance enhancement

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by 10%, has been identified as the best compromise to reinforce Ariane 6 attractiveness for Constellations customers with reasonable development duration and affordable investments on already existing facilities and MGSE.

With maiden flight expected end of 2025, the development and qualification of this P120C design evolution, called P160C, is driven by the following set of constraints:

- To preserve the product commonality for both families of European Launch Systems, Vega and Ariane, allowing a 30 years life time for the operational product;
- To make feasible the P160C development in parallel of present P120C production exploitation to satisfy the needs of both Ariane 6 (A64 and A62) and Vega C;
- To comply with the strict requirements of time to market, recurring cost, production rate still respecting the Non-Recurring Cost and assuring robust technical compliance.

To this end, the decision on the development of the P160C SRM was confirmed at the ESA Council at Ministerial level in November 2022. The P160C SRM development will be taking advantage of the industrial organization and of the technologies, facilities and hardware developed and used in the Ariane 6 and Vega C programs, in particular through the heritage of P120C SRM qualification and exploitation.

Considering the very challenging objective of achieving ground qualification in Q1 2025 for delivery of the first flight units in 2025, the P160C development activities have started beginning of 2022. The SRM Preliminary Design Review (PDR) was successfully held in June/July 2022 and the subcomponents (Nozzle, Insulated Motor Case and Loaded Motor Case) Preliminary Design Reviews were successfully held within October 2022. To be noted that it is considered possible to justify the use of P120C Igniter on P160C SRM without design modifications.

Using the huge experience gained through the P120C development and from beginning of its exploitation phase, only one ground Static Firing Test (SFT), called QM3, will be performed to achieve the ground qualification of the P160C SRM.

After a quick recall of the P120C SRM development achievements, this paper reports a description of the selected P160C SRM configuration and the current status of its justification as well as the main objectives and the logic / schedule for P160C development.

1. P120C SRM DEVELOPMENT AND QUALIFICATION

The Ariane A62/A64 launcher system architecture is derived from the Ariane 5 one (lateral solid boosters, main and upper cryogenic stages) already mastered. The same building blocks are used for A62 and A64 to address two markets (institutional and commercial) which minimizes NRC.

In details, the A6 Launcher architecture consists of:

- Common central core:
  - ✓ lower composite = H140 class, equipped with Vulcain 2.1 engine
  - ✓ upper composite = H28 class equipped with Vinci engine
- Common SRM with VEGA program used as lateral solid propellant boosters (P120 class) with:
  - ✓ 2 SRM for A62 configuration
  - ✓ 4 SRM for A64 configuration

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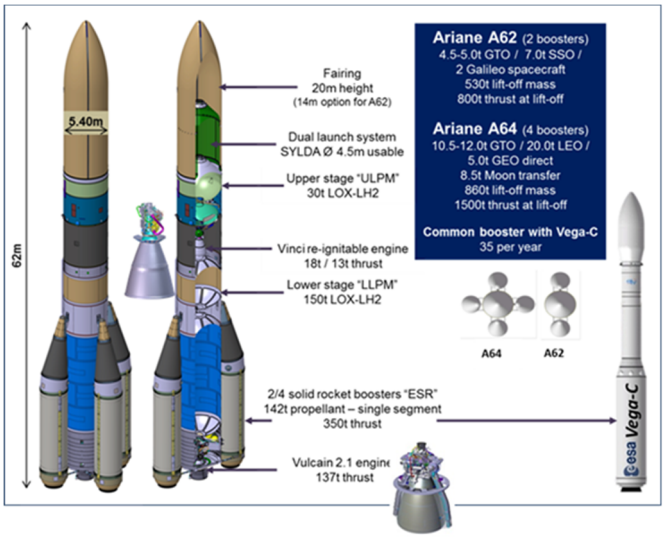

Fig. 1: Ariane 6 Launcher: A62 and A64 versions – Vega C Launcher

The Vega C launcher system is based on the common SRM used as first stage motor, with the Zefiro 40 and Zefiro 9 motors in the second and third stage, and an upgrade AVUM+ module.

The P120C SRM has been developed as a European "building block" motor with a design and manufacturing low-cost orientation target followed all along the time schedule of the development. It is currently one of the largest monolithic SRM ever built in the world.

P120C Solid Rocket Motor Development and Qualification logic was characterised by several milestones adapted to two different programs (Ariane 6 and Vega C).

Three full scale SRM Static Firing Tests (SFT) namely DM, QM1 and QM2, were performed respectively mid-2018, beginning 2019 and fall-2020.

The Qualification phase was split into two separate steps:

- a first Ground Qualification Review (GQR1), achieved in October 2019 following the QM1 Static Firing Test performed in January 2019, that allowed a timely Vega C System GQR and the preparation of relevant Maiden Flight, by verification and validation at least of the P120C requirement subset related to Vega C;
- a complement of Ground Qualification Review (GQR2), held in 2021 following the QM2 Static Firing Test performed in October 2020, that allowed Ariane 6 Launcher System GQR and enable the relevant Maiden Flight.

Since this last development milestone, P120C mass production is ongoing to face launch production manifest. The first two flights of the VEGA-C launcher occurred in 2022 both with a successful behaviour of the P120C SRM. The maiden flight of Ariane 6 (A62) will allow to fully achieve the development phase initiated in 2015.

2. P120C Solid Rocket Motor Overview

The P120C Solid Rocket Motor is one of the largest monolithic SRM ever built in the world. Main characteristics are reported here after:

Total length	13.5 m
External diameter	3.4 m
Total mass	153 t
Structural coefficient	~7.5 %
MEOP	10.5 MPa
Maximal thrust (in vacuum)	~4500 kN
Combustion time	~134 s

Table 1 - P120C SRM main characteristics.

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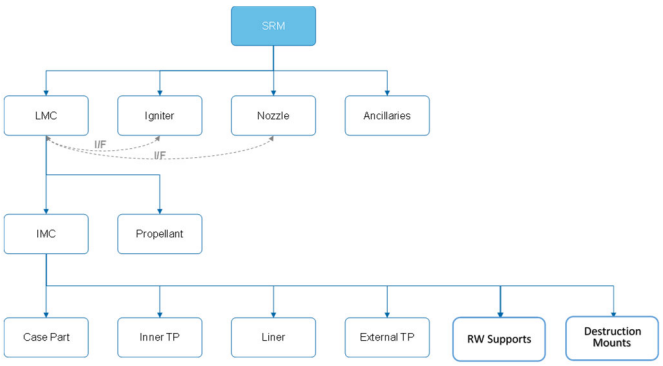
P120C SRM design qualified configuration is constituted of the subsystems shown in the product tree hereafter reported.



2.1. Insulated Motor Case (IMC)

The motor case is, at the same time, the combustion chamber of the SRM and the structure subjected to the mechanical loads of the vehicle. Lightweight structures are necessary in order to obtain the optimized mass ratio (MR) requested for the stage, so due to the high pressure experienced in the combustion chamber, materials with high ultimate stress are needed.
An additional important characteristic required to the case is the stiffness, in order to fulfil the system requirements and to limit the stress induced on the propellant.

The IMC is divided in:

- Case Part whose composition is the following:
  - ✓ A cylindrical vessel, closed with the forward and aft domes, manufactured by prepreg carbon epoxy roving wound onto a metallic mandrel covered by the internal insulation and thermally cured;
  - ✓ High strength aluminium alloy polar bosses reinforcing the domes opening and interfacing igniter and nozzle;
  - ✓ Forward and aft skirts interfaces realized in prepreg carbon epoxy plies ending with high strength aluminium alloy rings providing interface towards the Fwd/Aft Skirts or interstage;
- An Inner Thermal Protection part made by low density thermal protection, wound onto the mandrel. Stress relief flaps are foreseen in the forward and aft regions of the motor in order to reduce propellant shrinkage induced loads after propellant grain curing and cooling.
- An External Thermal Protection, applied on the external cylindrical surface of the case part
- Raceways Supports and Destruction Mounts, bonded on the external cylindrical surface of IMC and providing mechanical interface with raceways and cutting charges
- A Liner, sprayed on the inner surface of the IMC, able to provide mechanical interface with propellant grain.

2.2. Loaded Motor Case (LMC)

The propellant grain is the motor component devoted to generate, after ignition, the pressure necessary to produce the required thrust. The Propellant grain configuration retained is a finocyl (i.e. fins-on-cylinder) shaped grain selected (as in P80, Zefiro 9, Zefiro 23 and Zefiro 40) in order to comply with the thrust requirements and at the same time to reach a high-volume fraction.

A new propellant HTPB formulation has been selected, characterized by high Aluminium percentage providing high specific impulse, high density and low binder content. It has been chosen to fit the burning rate targets defined for P120C, to provide proper mechanical performances and to be in line with the safety constraints related to casting activities in Guyana (CSG-European Space Center in Kourou) plants (Regulus).

Of course, one of the important drivers in the definition of the propellant formulation was the recurring costs reduction with respect to Ariane 5 MPS and Vega P80 propellants. In order to achieve this objective, all the raw materials have been analysed to find out possible solutions and improvements for cost saving. In addition, certain materials used in the past were replaced in order to be in line with the latest REACH standards and avoiding short term obsolescence.

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2.3. Igniter

The Igniter is composed of two stages (pyrotechnic igniter and main igniter) equipped with pressure transducers and IFOCs.

The main igniter structure is a carbon composite wound vessel without thermal protection connected to igniter flange by steel pins. The flange is connected to the forward polar boss by a snap ring. The functions of thermal barrier and tightness are assured by a carbon rope and two O-rings.

2.4. Nozzle

The P120C Nozzle configuration baseline took advantage of P80 Nozzle return of experience [6] [7]. The general design of this nozzle is a classical one, with a submerged architecture and a downstream pivot point articulation (Fig. 2).

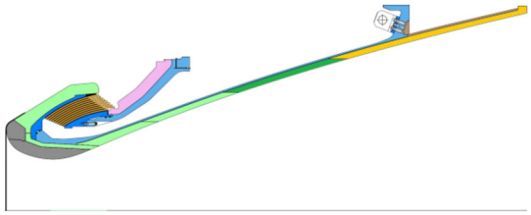

Fig. 2. P120C Nozzle Design

This general architecture is close to the P80 Nozzle, but with a component parts number reduction (3 parts suppressed), an improvement of specification, design and definition to allow cost reductions:

- Simple design of the flex-seal thermal protection, using only self-protected glass/epoxy composite shims, allowing removal of the flex-seal cowl in Naxeco-Resin®,
- Single piece exit cone insulator made of both Carbon and Silica Phenolic composite materials wounded one shot,
- Single piece Throat Insulator,
- Use of a new rubber insulation for the stationary shell, which is able to be directly wounded on the metallic shell.

The aluminium alloy carter supports the carbon-phenolic exit cone. A high strength aluminium alloy stationary shell is connected to the aft polar boss through “circlip” and a closing membrane provided with SRM pressurization port device.

As for the forward junction, the functions of thermal barrier and tightness are assured by a carbon rope and two O-rings.

3. P120C Solid Rocket Motor Qualification Status

The P120C development and qualification was supported by three SRM Static Firing Tests (SFT) performed at BEAP Test Bench (CSG) operated by CNES.

Fig. 3. P120C firing test at CNES BEAP French Guyana (Courtesy ESA/CNES)

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The ground qualification reviews have been successfully held for two SRM ballistic configurations called SP (Standard Performances) and HP (High Performances).

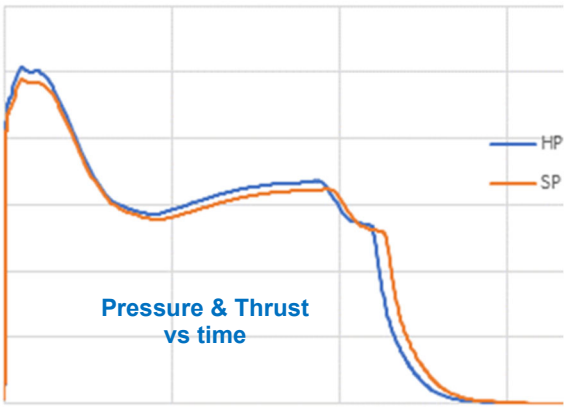


Fig. 4. P120C SP and HP ballistic curves

The only missing step for the closure of P120C SRM development phase is the Ariane 6 maiden flight.

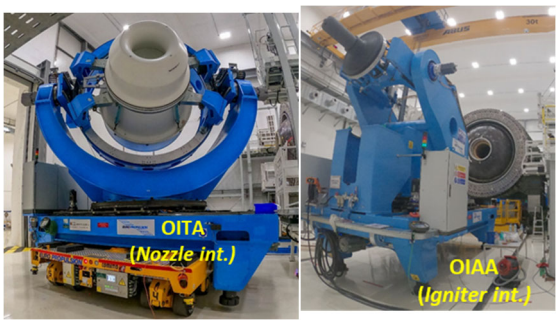
The P120C will be produced in both configurations in the first phase of P120C exploitation (transition phase) then only the HP configuration is planned to be delivered.

4. P120C SRM Integration technologies

The implementation of the SRM horizontal integration approach, best solution identified to comply with target series production costs and cadence considering applicable constraints in terms of investments and development planning, requested:

- The design and realization of new industrial facilities, the CIH (Cellules Integration Horizontale) and the BBP (Batiment Basculement Propulseurs)

- The development of new industrial means and tools:
  - the new machines for Nozzle and Igniter semi-automatic horizontal integration;



  - the AIT400/Skidder, needed for SRM/Stage horizontal integration in CIH, transfer between facilities in horizontal configuration, verticalization and delivery to Ariane 6 stage finalization facility (EFF).

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5. P160C SRM Evolution

5.1. Context

After a successful achievement of P120C SRM qualification, and in parallel to the first phase of production (2 SRM have already flown on Vega C and 3 SRM were assembled and are waiting for delivery), an improvement of the P120C SRM common to Vega C and Ariane 6 is proposed at solid propulsion level to further contribute to increase the competitiveness of the European launchers.

Indeed, to meet the needs of diverse and ambitious European institutional missions in a variety of scenarios, to remain adapted to fast-moving evolutions of satellites platform technologies, and to preserve the mixed public/private exploitation model which best preserves European autonomous access to space, the competitiveness of the Ariane 6 launchers must be continuously improved.

The analyses performed at SRM and Ariane 6 system levels identified the increase of P120C SRM length (+1m) as the best compromise to reach the performance target at launcher level with development schedule in line with the need and affordable development investments.

The overall set of evolutions for Ariane 6 Launcher adaptations are addressed within Ariane 6 Block 2 program, and the associated solid motor booster new target configuration is called P160C SRM (Fig. 5).

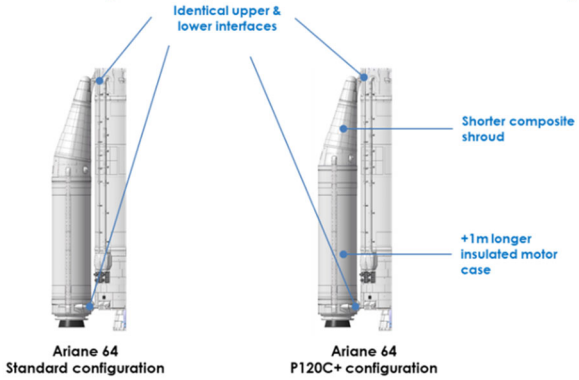

Fig. 5: P160C SRM compared to P120C SRM

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As time to market is challenging and taking into account that the first Ariane 6 missions using P160C SRM are expected end of 2025, it was necessary to start development activities early 2022.

5.2. P160C SRM Design Overview

At first, preliminary trade-off activities were performed in a closed engineering loop between motorists and systems responsible to identify the best compromise in terms of SRM/Launcher performances increase, Flight Hardware complementary development compliance with applicable constraints (budget, schedule first), impacts on existing industrial tools/means with relevant investments budget/schedule and finally the impacts on recurring cost.

These studies allowed to identify the following SRM Design Evolution hypotheses as the best solution considering the given objectives and the existing constraints. These hypotheses have been confirmed at the SRM and subcomponents CDR (Critical Design Reviews), successfully held between July and October 2022:

- Unmodified interfaces with upper and lower inter stages,
- Unmodified LMC external diameter (no geometrical impact on inter-stages and handling tools interfaces),
- Unmodified polar bosses openings (no geometrical impact on igniter and nozzle interfaces),
- Unmodified star shape profile of aft finocyl, (impact on propellant geometry limited to the cylindrical zone)
- Unmodified MEOP (set at 110 bar, as for P120C HP SRM version),
- Unmodified propellant formulation (HTPB 2013),
- Unmodified nozzle throat and exit cone diameters,
- Unmodified propellant loading factor.
- Unmodified igniter

One meter is the maximum length increase allowed by industrial constraints of the LMC production plant. This constraint yields to 14 tons of propellant mass increase per booster vs. the 142 tons of current P120C.

This solution generates limited design impacts at Nozzle, IMC and LMC level. But it will require significant modifications on production means and tools in particular at IMC/LMC levels.

With IMC length increase, the same external diameter and same casting mandrel fins, the propellant grain will maintain the same web thickness and will have a larger combustion surface for all its functioning time.

The obtained vacuum thrust curve for the P160C is represented in the next picture, in comparison with current P120C standard and HP versions. According to the main design evolutions considered for the P160C, the propellant burning rate was tuned in order to reach a combustion time between P120C SP and HP configurations and to keep the present MEOP and maximum thrust unchanged to preserve present SRM design structural margins, avoiding costly and time-consuming design evolutions as well as potential impacts at launcher level.

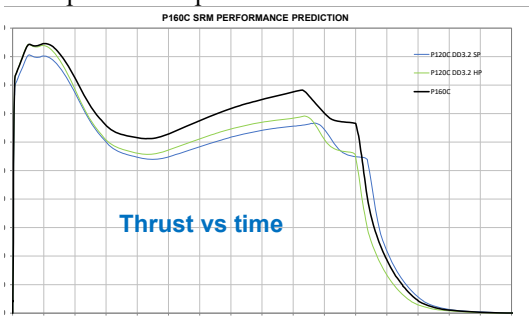

Fig. 6: P120C SP, HP and P160C thrust profile comparison

Impacts on the pressure oscillations have also been estimated in the frame of the P160C SRM CDR, mainly based on engineering general know-how and simulations results. The main expected impact is that due to increased SRM length the duration of the hydrodynamic instabilities will be longer than for P120C. Thus, the envelope range shall evolve as showed in the following figure for the amplitude of the first acoustic mode.

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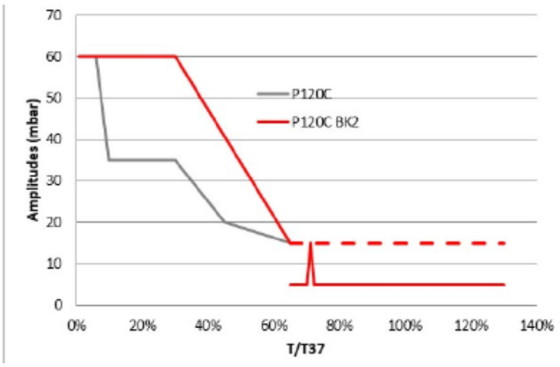

Fig. 7. P120C vs P160C 1st acoustic mode pressure oscillations envelopes

The development logic main hypothesis is to qualify the P160C SRM with a single static firing test. This approach is considered robust enough considering the significant experience (both at SRM and components level) collected in the frame of P120C development as well as the know-how coming from past Ariane 5 MPS and P80 developments.

P160C SRM bench firing test (QM3) is currently scheduled end of 2024.

The QM3 Static Firing Test will be performed as much as possible using stage parts of A6 ESR (Equipped Solid Rocket).
It shall allow to confirm the compliance of P160C design with applicable technical specifications, performances objectives and applicable system specifications (ignition transient, thrust imbalance, thrust oscillations, dynamic loads etc.).

The QM3 test campaign shall also support the validation/qualification of adapted SRM integration/handling tools/means.

5.3. P160C subcomponents development assumptions

5.3.1 Igniter

Being that the MEOP (110bar) is not increased and that all mechanical interfaces of the Igniter with the LMC remain the same, the only new design dimensioning requirement for the Igniter are the thermal fluxes.
Considering the design thermal margins demonstrated at the end of P120C development phase, it is assumed that it will be possible to justify and qualify the present Igniter design for P160C, accepting the small impact on SRM ignition transient behaviour due to larger chamber volume with respect to P120C (to be consolidated).

5.3.2 IMC

Considering that the same sizing loads of the P120C will be kept for the P160C, the structural sizing of the component will not change, assuring the same margins with respect to P120C. In fact, the elongation of the cylindrical area does not impact the stress field of the component. Impacts in terms of buckling loads have been considered acceptable at IMC PDR.

A preliminary design of the internal thermal protection was completed, allowing to start the design loop for the long lead items (IMC winding mandrel). Confirmation of design margins (inner thermal protections) will be achieved through the QM3 firing test.

As far as raceway mounts and cutting charge mounts are concerned, configuration loops between System Authorities and subcomponent Technical Responsible allowed to freeze the configuration.

According to the previous hypotheses, no structural qualification will be performed for the IMC. In fact, the strong similarity with the P120C allows considering fully applicable the P120C qualification tests (mechanical tests, pressure tests, burst test). Matching between design goals and manufactured unit will be guaranteed by a reinforced monitoring during acceptance tests on the qualification unit devoted to the QM3 firing test. An additional pressure test at 1.16*MEOP will also be performed to increase the confidence for the first and only P160C SFT.

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P160C liner profile will be 100% equivalent to the previous configuration.

Development activities are focused on the adaptation of existing tools and means and the relative technological delta qualification. The first manufacturing activities for QM3 specimen are foreseen after the summer in order to comply with the QM3 Static Firing Test schedule.

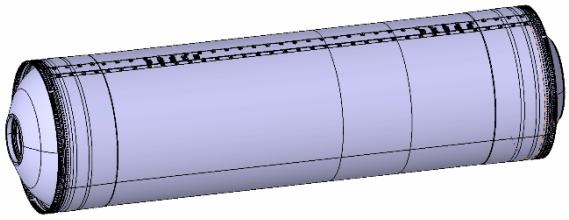

Fig. 8 P160C IMC

5.3.3 LMC

Following the successful qualification of P120C Loaded Motor Case, and the wide experience collected in the frame of development and first production phase, the P160C development is based on a lean approach aimed to minimize the time and cost.
In particular, no inert model will be manufactured, considering the limited evolutions foreseen in casting tools and manufacturing processes:

- The casting mandrel will maintain the same fins number and profile, while just an increase of core length will be implemented (+1 m) respecting the same inner bore conicity.

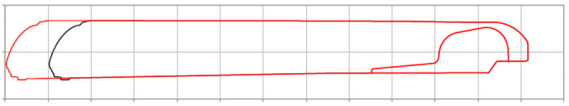

Fig. 9. P160C propellant grain evolution

- The increase of total propellant mass will be achieved adding a single MV1800 gallons batch in the casting sequence.
- No new technology will be introduced, as well as no additional building, just adaptation of present tools to cope with LMC length increase.

Special attention will be devoted to propellant grain and interfaces structural justification to ensure the correct margins despite the increase of loaded mass.
Finally, no propellant formulation change is foreseen even if opportunities will be evaluated for what concerns future obsolescence.

5.3.4 Nozzle

Based on the achievement of P120C Nozzle Qualification and Manufacturing Transition Phase [4], the evolutions concerning P160C Nozzle development will cover all the activities up to the qualification of the new improved SRM.

This includes in particular at Nozzle Level:

- Re-design and justification activities,
- Process and industrial tool adaptations.

The main assumptions for these activities are the following, as shown in Fig. 10:

- No evolution of Nozzle requirements except the ones related to pressure law evolution (but same MEOP),
- No increase of the throat inner diameter
- Flexible joint design frozen with only potential adjustment of shim length, and no modification of pivot point, allowing to keep the P120C thrust vector activation system (TVAS) unchanged,
- No need of exit cone length adjustment.

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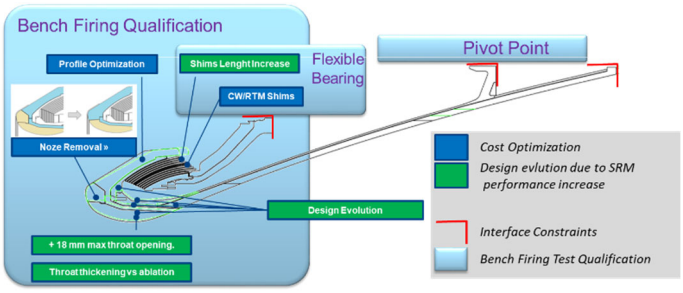

Fig. 10. P160C Nozzle Evolution

Two mains axes of evolutions are proposed for cost reductions purposes:

- Shims manufactured with contour weaving process (partially introduced on QM3 specimen),
- Removal of the C/C nose part, replaced by a carbon phenolic nose cap in a single piece.

Indeed, due to the insufficient maturity level at the time of P120C PDR in 2015, those solutions were not included in the P120C Nozzle development.

The removal of the nose in C/C has been approved in the frame of the nozzle CDR held in June 2022. The QM3 SFT will allow to confirm the soundness of this new design.

6. P160C SRM Integration MGSE Impacts

The impacts of P160C design evolution on already existing integration/handling installations and tools can be summarized as follows:

- Impact on SRM Integration configuration in the horizontal integration room (CIH): adaptation of ground interfaces for Nozzle & Igniter integration machines, platforms geometry/position…
- P120C AIT400 Skidder (adaptation to the increased length) and relevant P120C Mock Up for AIT 400/Skidder initial qualification and yearly revalidation.

In order to limit the modifications of the test BEAP test bench structure and interfaces, it was decided to reduce the forward skirt height, as shown in the following figure.

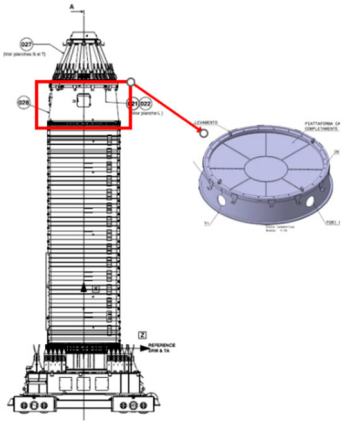

Fig. 11. P160C test article adaptation

7. P160C SRM Overall Development Master Schedule

In accordance with the calendar objectives of the program pulled by Mega constellation customer needs, the P160C SRM development logic has been established, involving main components and generating the following milestones:

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- P160C SRM PDR successfully held in July 2022, allowing the approval of the technical specification (ST) by both Launcher Systems, Ariane 6 and Vega C
- P160C Components PDR successfully held in Q3 2022
- P160C Components CDR (and Igniter Suitability KP) planned between June and October 2023 (on-going)
- P160C SRM CDR before end of 2023
- P160C QM3 static firing test and Exploitation L 0+ (& expertise in Kourou) in Q4 2024
- P160C SRM GQR foreseen in Q2 2025

8. Conclusions

The development and qualification of the P120C SRM, Common Solid Propulsive Module to be used as strap-on booster on Ariane 6 Launch Vehicle for both 62 and 64 versions and as first stage for Vega Consolidation and Vega Evolution vehicles has been successfully achieved. New integration technologies have been successfully tested on development models and on Vega-C maiden flight SRM.
The final steps of SRM Ground Qualification, devoted to the release of manufacturing of flight items in 2020 for Vega C launcher and in 2021 for Ariane 6 launchers, have been completed.
The SRM subcomponents are already in the production phase to guarantee the availability of SRMs on production ramp up phase.
The industrialization activities were also completed in 2021 and SRM integration technologies are now qualified for both launchers.
Vega-C maiden flight, which occurred in July 2022 allowed to complete the P120C SRM qualification for Vega-C launcher. The first pair of SRM devoted to Ariane 6 maiden flight is foreseen to be delivered in September 2023.

Despite the challenging objectives of the P120C development, as well as its very tight schedule, the well proven industrial organization demonstrated to be a key factor for the success of the program.

In parallel, in order to improve European launchers performance, and in particular Ariane 6 performance for constellations market, an increase of the SRM length by 1 m leading to an upgraded version of the P120C, called P160C, was identified as an opportunity. With limited design and process modifications, this upgraded P120C version is expected to be qualified in 2025 following a static firing test to be performed in 2024. This motor evolution will also benefit to the overall competitiveness of Vega C.

Development activities for this improved P120C configuration were initiated beginning 2022, the PDRs were successfully held in 2022 and the CDR are expected to be closed by end 2023.

ESA support for the development of the P160C was confirmed at the ESA Council at Ministerial level held in November 2022.

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