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Evaluation of 'Design for Assembly' Performance of Undercut Finocyl Grain Casting Mandrels

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ABSTRACT

Advanced space launch vehicles that employ solid rocket boosters are found to use undercut finocyl-shaped propellant grains. The undercut features, however, cannot be easily manufactured using conventional methods of casting propellant around rigid monolith mandrels or by machining the fin slots. To solve the problem, many non-rigid type mandrels were experimented with without wide acceptance due to functional, performance, or safety issues. Alternatively, in recent times, a few types of rigid undercut finocyl grain mandrels have been developed by different space agencies. While each claims superior performance, there has been no study measuring or quantifying their relative performance. The purpose of this study was to evaluate and compare the assembly performance of a new mandrel called 'NEX' using Design for Assembly (DFA) tools against state-of-the-art Vega mandrels employed in the making of some of the largest and highest-performing solid boosters worldwide. Mandrel parts and their assembly sequences were reconstructed using patent literature and published data. Boothroyd-Dewhurst DFA Product Simplification software was used for analyzing both mandrels and quantifying the difficulty of total assembly and disassembly. It is found that in comparison with Vega, NEX has 60 % fewer part counts, 80 % fewer fastener activities, and 41 % reduced assembly man-hours. The estimated DFA index for Vega is 3.57 and NEX is 5.78. Using the newer and safer mandrel, space launch vehicle booster manufacturing costs can be lowered.

Keywords: Design for Assembly; DFA index; Product simplification; Undercut finocyl grain; Undercut casting mandrel

1. INTRODUCTION

Many modern space solid rocket propellant grains[1-4] have undercuts as submerged longitudinal slots or fin cavities circular-patterned around a central cylindrical cavity in their internal geometry. The said grain configuration is called fin-o-cyl and when its fin cavities are submerged, it is called Undercut Finocyl Grain (UFG, hereafter). Different additive and subtractive methods of manufacturing the UFGs exist. However, considering inherent explosive hazard and processing time, molding the undercut features (additive manufacturing) is preferred over machining the propellant grain (subtractive manufacturing)[5]. In other words, net shape casting of the grains to their final shape can be safer, cheaper, and faster than casting them to intermediate geometries followed by secondary machining operations[6].

1.1 What is Still Problematic

As is known, commonly used rigid monolith casting mandrels are not suitable for molding the undercut features as they need to be extracted in one piece after propellant curing. A literature survey revealed the development of different types of non-rigid mandrels for undercut casting. Mandrels that can be deflated[7], dissolved[8-9], melted[10-11], consumed[12], or collapsed[13] have been experimented with over the past eight decades worldwide. However, they were found to have issues preventing their wide adoption. Some non-rigid mandrels could not maintain shape stability throughout the casting-curing cycle. Some like Eutectic alloy-based melting mandrels left some residue behind, contaminating the propellant grain surface and deteriorating booster ignition characteristics. They needed secondary operations to clean the grain surfaces. Hydraulically inflated and dissolving mandrels risked wetting the propellant grain. Some non-rigid mandrels could neither be scaled up nor show repeatable performance. Many had long turnaround times and were not reusable. Some mandrels that collapsed under pressure or vibration exerted large local loads on propellant grain during decoring. To remove these deficiencies, rigid undercut mandrel assemblies that disassemble into smaller parts were developed. There are two basic types:

Externally Assembled, when assembled mandrel is smaller than the motor case aperture but bigger than the grain port. They are suitable for annular slotted grains in monolith motors and UFGs in segmented motors.

Internally Assembled, when assembled mandrel is bigger than the motor case aperture and the grain port. Suitable for UFGs in monolith motors.

Casting mandrel types shown in Fig. 1 were found to be customised for specific applications. While some did not cross the experimental stage, some found limited application for some time. Stringent explosive safety requirements of

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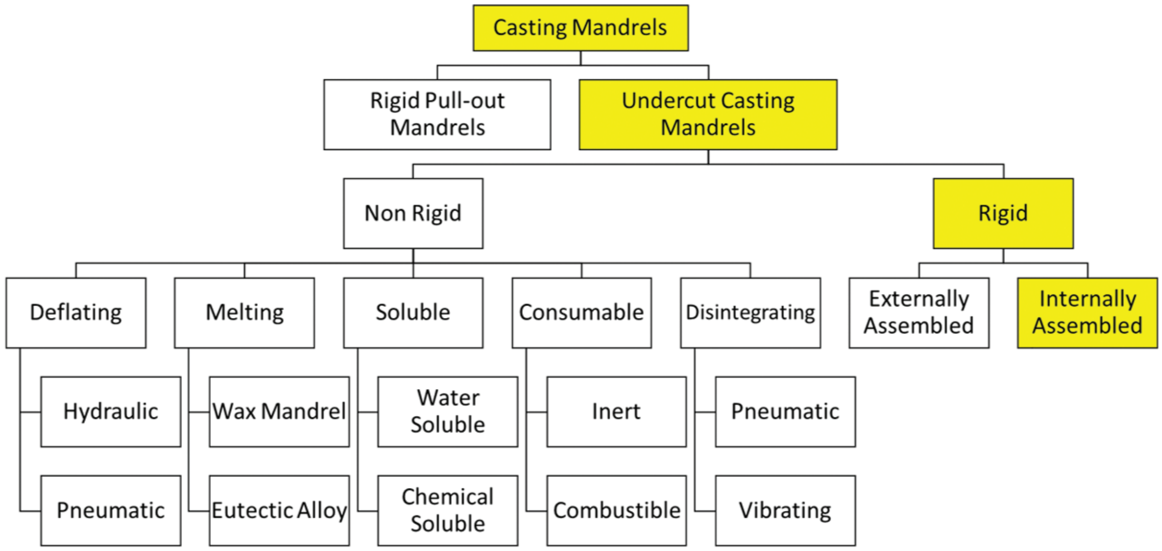


Figure 1. Classification of solid rocket propellant grain casting mandrels.

propellant processing discouraged the introduction and adoption of manufacturing methods that are not foolproof.

1.2 Findings of Relevant Studies

Pros and cons of different types of casting mandrels for a given combination of motor case and propellant grain have been evaluated and reported in the literature. For instance[9], in the early 1990s, for casting Space Shuttle's φ3.71 m ASRM grains, employing conventional rigid metal mandrels was found to have safety issues due to the huge breaking force needed for decoring. A water-soluble mandrel, on the other hand, with a conductive rubber barrier enveloping the soluble material, provided an easier and safer solution. Also, for the undercut finocyl configuration in its forward end segment, soluble mandrel allowed joint-free and thus crevice-free interfaces between fins and core of the mandrel. Other reported advantages were the flexibility it provided in grain design and the lack of need for an exclusive remote decoring facility. However, in the recent 5-segmented NASA SLS SRBs, derived from the 4-segmented Shuttle SRBs, segmented metal UFG casting mandrel has been used[14], possibly to avoid the risk of water contamination during decoring soluble mandrel.

Another paper[6] emphasized the need for "one-step molding" using "a removable mechanical core which does not require a finishing operation (e.g. machining)". It was advocating for net-shape casting using rigid undercut mandrels.

While past studies have focused on establishing the suitability of a casting mandrel type for realizing a particular size and shape of grain configuration, no attempts seem to have been made to evaluate different mandrels of the same type and quantify their performance. More than one type of rigid UFG mandrels is available today. But no study rating their relative performance towards achieving the same end product seems to have been carried out.

1.3 Importance of the Topic

The space launch vehicle market is fast expanding. Liquid and semi-cryogenic rocket-based launchers have the advantage of higher specific impulse. For upcoming solid-fueled launch vehicles to stay competitive, safer, quicker, and more cost-effective manufacturing methods are needed, especially for realizing the high-performance UFGs. In that context, it is important to measure the performance of any newly developed UFG casting mandrel in comparison with existing state-of-the-art. The presented method using DFA tools can be used for benchmarking existing and future designs. It can also be used to identify areas with further scope for improvement in terms of parts consolidation and assembly duration.

1.4 Statement of the Research Question

This study was undertaken to evaluate using DFA methods the difficulty of assembly and disassembly of a newly developed rigid undercut finocyl grain casting mandrel called NEX vis-à-vis a state-of-the-art (SOTA, hereafter) mandrel called Vega used in many advanced space boosters.

2. METHODOLOGY

The objective of the research study was to benchmark the assembly performance of a new UFG casting mandrel against a SOTA mandrel using Design for Assembly (DFA) methods. Various assembly-related design aspects of both mandrels are also analysed for compliance with DFA guidelines. The outline of the study design follows:

2.1 Selection of Candidates

In line with the objective, for comparison with rigid UFG mandrel NEX, recent space solid rocket boosters employing undercut finocyl grains along with their reported method of manufacturing were identified after a survey.

Necessary technical details of the mandrels and methods were sourced from patent literature, peer-reviewed journals, conference proceedings, official reports, and video clippings that show their operations. Due attention was given to ensuring the reliability of the publicly available data. Patent claims were cross-verified with working details from other independent and authentic sources. Data with incomplete or speculative technical details were ignored.

From among the surveyed mandrels, one SOTA mandrel with maximum available details and widely reported usage was chosen for DFA evaluation and comparative study with the newly developed UFG casting mandrel NEX.

2.2 Research Methodology

The procedures used for conducting the study follow:

DFA evaluation started with careful reconstruction of NEX and the identified SOTA mandrel. All parts were solid modeled and assembled in the exact sequence as published/ reported.

For parity, the geometry of the end product, that is the cast grain, was made the same in both.

Three equispaced screws were assumed for all removable joints where actual number of fasteners is not known. Therefore, the estimates on total number of screws are conservative.

Boothroyd-Dewhurst DFMA® Software's DFA Product Simplification module was used to analyze the efficiency of the mandrel assemblies. Difficulty of assembly and/or disassembly is estimated and quantified as DFA Index[15].

$$\text{DFA Index, } E_{ma} = \frac{N_{\min} \times t_a}{t_{ma}} \times 100 \tag{1}$$

where, N_{min} is the theoretical minimum number of parts, t_a is the basic assembly time for one part and t_{ma} is the estimated time to complete the assembly of the product.

Basic assembly time t_a is the average time for a part without difficulties in handling, insertion, or fastening. Its value is about 3 s. Estimated total assembly time t_{ma} is determined by the software using inputs in terms of the physical properties of the parts and how every part is acquired, oriented, inserted, and secured. Relevant DFMA databases were created by Boothroyd and team after decades of time studies and the same are embedded in the software[15].

The DFA Product Simplification software uses "an intuitive question and answer interface that identifies opportunities for substantial cost reduction in a product"[16]. It can also be used to identify parts that can be eliminated or consolidated without losing functionality. The reported total cost reduction from over 100 published case studies that used the DFA software is about 50 %. This includes savings in part count, number of separate fasteners, weight, assembly tools, cost, and time.

DFA analysis steps in Boothroyd Dewhurst DFA Product Simplification software[17] follow:

- Starting from the base part, all parts and subassemblies were sequentially added to create the final assembly while defining the product structure. Any intermediate operation was inserted at the appropriate spot
- The overall dimensional envelope of every item was defined as that of a cylinder or cuboid
- Item function was chosen as to fasten, connect, or other. When the other was chosen, its functionality was checked. As per minimum part criteria of DFA principles, in an assembly, a part is deemed to be essential only if it (a) is the base part, (b) moves relative to others during operation, (c) must be of different material, or (d) will prevent previous part assembly otherwise. All other parts including fasteners and connectors can be eliminated or merged
- Depending on the size, shape, and mass of a part, its mode of handling requirements and difficulties were selected
- The securing process for each part was then selected with branching finer details
- Insertion depth and difficulties including restricted access to and obstructed sight of mating locations were finally defined.

The software, from its inbuilt elaborate database, estimated the processing time for each part. Analysis results were summarised as the number of parts, separate operations, theoretical minimum items, and finally, the metric of assembly efficiency 'DFA Index'. The higher the DFA index, the more efficient the design for assembly.

The new mandrel was benchmarked against the SOTA by comparing the following DFA parameters:

- Analysis of equivalent subassemblies and their mechanisms in both mandrels
- DFA index
- Total and theoretical minimum part count
- Unique part count and repeatedly assembled parts
- Fasteners count and type
- Field assembly sequence plots
- Number of steps and process time in field assembly

Areas for further improvements in NEX were also discovered using the results from DFA analysis.

3. RESULTS AND DISCUSSIONS

The survey of space solid rockets with undercut finocyl grains revealed that only those manufacturers catering to commercial or civilian launch vehicle market published propellant grain processing details. Even among them, details of casting mandrels were revealed in only a few cases. The surveyed mandrels are listed in Table 1. Some old patents disclosed concepts for deploying, securing, and retracting

Table 1. List of surveyed rigid undercut finocyl grain casting mandrels

Rocket booster	Space agency	Mandrel type	Source of details
SLS booster forward segment	NASA - ATK	Externally assembled	NASA paper[14] Official youtube video[20]
Not known	Ariane group	Internally assembled	French patent[21]
Not known	FR&PC Altai		Russian patent[22]
Vega P80	ESA-Ariane group		Conference paper[23,24] Official youtube video[25] European patent[26]
Vega Z23			
Vega Z9			
Vega-C P120C			
Vega-C Z40			

the undercut fin mandrels using mechanical linkages[18] or permanent magnets[19]. They were not considered for this study as no products still using them could be found. Manufacturing details of advanced boosters with UFGs like those of Minotaur-IV[1], H-3[2], and Epsilon-S[2] could not be found in the public domain.

3.1 Selection of SOTA UFG Mandrel

3.1.1 SLS Booster Mandrel

Twin boosters of NASA’s SLS are the largest solid rockets ever flown. Each booster carries 640 tons of propellant in five near-equal-sized segments. The forward segment features an undercut finocyl grain[27]. The aft-end aperture of the forward segment is almost as big as the case diameter. That allows a fully assembled UFG casting mandrel with deep fins to be directly inserted inside the case. However, after casting and curing, the mandrel is taken out in parts – the core is pulled out first and the fins are taken out next, as shown in video clip[20].

There are advantages to an externally assembled UFG mandrel. The integrity of mandrel part joints can be better assured while outside the lined rocket case. With very large solid rockets, this method allows for near-equal distribution of propellant volume among segments. Recently retired Ariane-5 P238 booster could have benefited by eliminating one segment joint from its two[28]. The P238 segments were split 23:107:107 where 23-ton star grain was cast using a monolith mandrel. With undercut mandrels, it could have been two segments with 120-ton grain in each. Similar is the case with LMV3 S200 with its 29:97:83 segments[29] and PSLV S139 with its 18:30:30:30:30 segments[30]. Although SOTA in its type, this UFG mandrel could not be considered for the study as it cannot be used inside cases having small apertures.

3.1.2 French Patent FR3090751A1

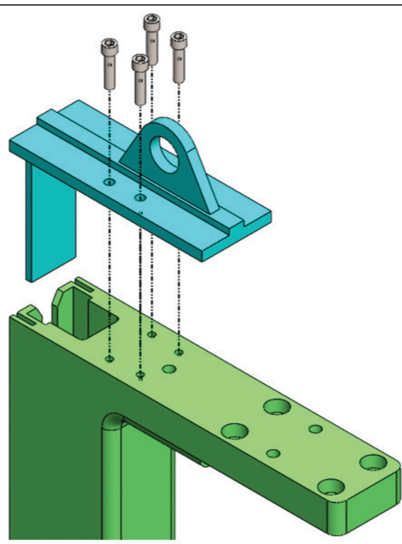
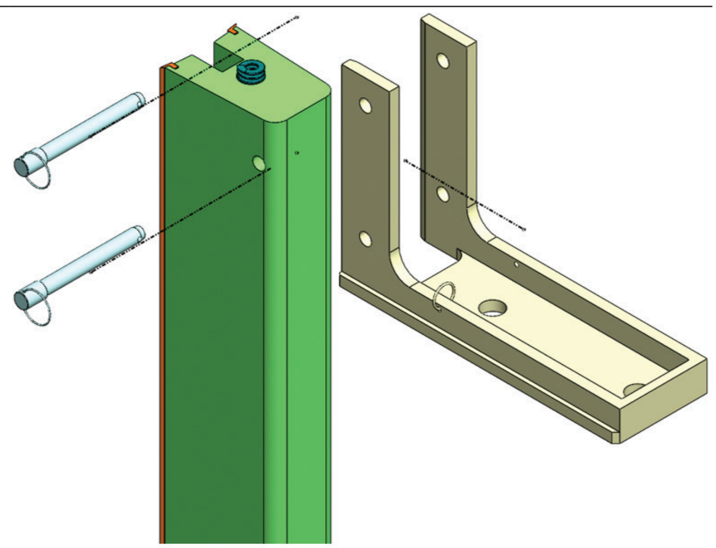
Ariane Group’s recent patent[21] teaches a UFG mandrel where tapered fins are pushed out radially from inside a hollow and slotted core that is already positioned inside the case. A shoulder at the base of the fin stops further radial movement once the fin is fully engaged. Finally, a central stopper is axially inserted inside the core to prevent the fins from moving back.

The reported advantage of the scheme is the prevention of accidental fall of the fin mandrel to the bottom of the case as the fins are negotiated from inside the core slots. Another is the potential protection the core mandrel provides propellant grain surface during fins decoring. However, the type of fins-core joint is not securely and reliably sealable to prevent propellant ingress.

3.1.3 Russian Patent RU2508464C2

FR&PC Altai’s patent[22] describes a UFG mandrel where each assembled fin is bigger than the nearest case aperture. The insertion/removal problem is solved by splitting the fin mandrels and assembling them with screws while inside the case. Sealing between the fin joints becomes more critical due to the presence of threaded fasteners in propellant-wetted space.

Table 2. Comparison of fin handling method

 **Figure 2. Vega fin lifting.**	 **Figure 3. NEX fin with its holder.**
4 tapped holes in the fin to fasten the lifting bracket (2 screws on either side for symmetry & redundancy)	No screws (fin holder fastened with 2 ball lock pins for a snap fit joint)
The center of gravity of the fin is not below its surface resting on the support plate. So, the fin needs to be held down with four screws. Fin verticality is ensured with two additional screws	Stable configuration with fin lifting/supporting points in line with the center of gravity
Screws take more time	With quick-release fasteners, it takes less time
Risk of loose screws slipping inside the case	Pins are tethered to a fin holder and they can be inserted from either side (insertion symmetry)
Thread damage could junk costly fin mold	NA

There are some similarities between mandrel assemblies in sections 3.1.2 and 3.1.3: the core is inserted first and the fins last. Fins are deployed radially from inside the core. Apart from the minimal details in the patent literature, no other details of their workings or application could be found. Therefore, the mandrel assemblies could not be analyzed for DFA performance.

3.1.4 Vega Mandrel

From the survey, at least five different space rocket motors were found to be using the Vega series of UFG casting mandrels. The basic mandrel assembly[25-26] consists of fins with extended arms for supporting and securing them to the core mandrel outside the case. Inside the case, spring-loaded mushroom-shaped bodies on the core mandrel releasably connect fins to the core. The core mandrel itself is a complex subassembly with three coaxial bodies – outer tubular body, middle actuating device, and inner sliding cam. The propellant slurry is charged through annular gaps between the core and fins. Finally, the excess propellant in the annular gaps is squeesed into plugs that are pushed into the gaps.

For complete reconstruction and analysis, sufficient technical details were available for the Vega mandrel in patent literature[26] and conference proceedings[23-24]. Parts of its actual working details could be found in a video clip[25] showing the making of the world's largest monolith rocket P120C (first flown as first stage booster of Vega-C in 2022). Therefore, Vega mandrel was selected as the SOTA for a comparative DFA study with NEX.

3.2 DFA Analysis of Vega & NEX Mandrels

3.2.1 NEX Mandrel

NEX is a recently developed UFG mandrel. In it, a set of fins are temporarily fastened to the central core using screw-actuated mating wedge pairs. While the core wedges protrude, fin wedges are submerged. The actuating screw also axially fastens the core to the fins. Rubber seals sandwiched between fins and core get compressed during the screw action. Each fin is handled using a multi-functional fin holder fastened to the fin with a tethered ball-lock-pin (a non-threaded, quick-release fastener). The fin holder sits on a two-piece fin assembly jig mounted on height-adjustable screws. For the DFA analysis,

Table 3. Comparison of fin-core mandrel fastening mechanism

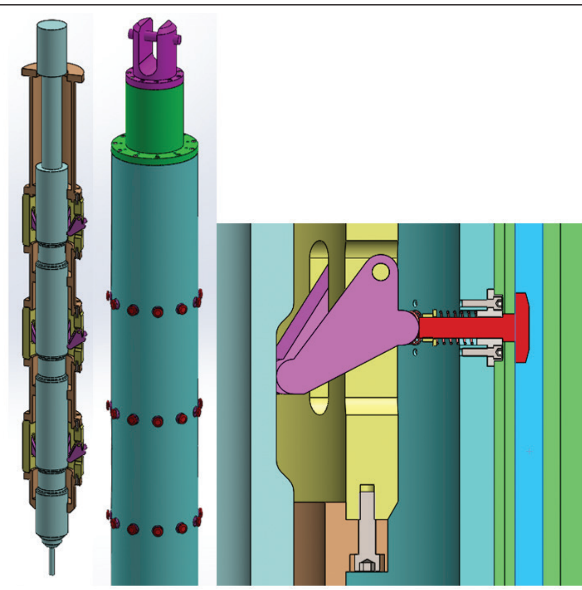


Figure 4. Vega core subassembly showing cam-based fin fastening mechanism.

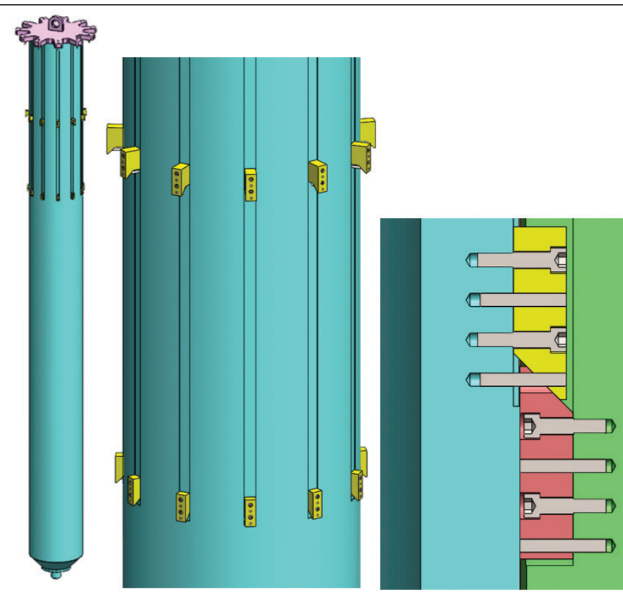


Figure 5. NEX core subassembly showing fixed wedges around and top flange.

Consists of three coaxial bodies, field assembled and moving relative to each other. The outer body has 33 spring-loaded, field-adjustable, mushroom bodies. The middle body has pivoted cam followers. The inner body is a sliding cam, whose reciprocating motion engages or disengages fins.	The top flange and 22 core wedges are factory-assembled. The core is a single subassembly in the field. Top flange screw operated mating wedge-pairs axially as well as radially fasten fin to the core while compressing a sandwiched rubber seal and spring
Axial fastening of fins to the core is independent of radial fastening with mushroom bodies	The top flange screw is multi-functional
The spring force in each mushroom body can be adjusted using a nut. Needs verification before every field assembly	No field adjustments
The actuating mechanism could be mechanical or hydraulic (prone to leak)	Simple mechanical system
All fins are held or released simultaneously by common cam action	Each fin is separately fastened to the core
The core is repeatedly inserted and removed in the assembly sequence	The core is inserted only once
Fins are held close to the core using only friction grip during the intermediate stages of mandrel assembly	Fins are firmly supported by the fin holder on jigs during the intermediate stages

Table 4. Comparison of product structure and part count of NEX vs Vega mandrel assemblies

Vega		NEX	
Part activity sequence	**Part count**	**Part activity sequence**	**Part count**
Add harnessed motor case	1	Add harnessed motor case	1
Add frame	1		
Screw frame to case	3		
Add NEPO adapter ring	1		
Screw NEPO adapter ring to case	3		
Add connect plate	1		
Screw connect plate to frame	3		
Add telescopic collar	1	Add center cylinder	1
Screw telescopic collar to connect plate	3	Screw center cylinder to case	3
Add position device	1	Add fin jig 1	1
Screw position device to connect plate	3	Add fin jig 2	1
Add support plate	1		
Screw support plate to position device	3		
Add fin	11	Add fin	11
Add fin seal	11	Add fin seal	11
Add fin lifting bracket	11	Add fin holder	11
Screw fins to lifting brackets	44	Add ball lock pins	22
Screw fins to support plate	66	Add fin springs	11
Unscrew fins from lifting brackets	44	Remove fin jig 2	1
Remove fin lifting bracket	11		
Add actuating device to tubular body	1		
Add tubular body with actuating device to case	1	Add core	1
Add top cap	1	Screw core to fins	11
Screw top cap to tubular body	3	Remove ball lock pins	22
Add top lifting bracket	1	Remove fin holder	11
Screw top lifting bracket to top cap	3	Remove fin jig 1	1
Add star body	1		
Screw star body to tubular body	3		
Screw star body to fins	11		
Unscrew fins from support plate	66		
Unscrew support plate from position device	3		
Remove support plate	1		
Unscrew star body from fins	11		
Unscrew star body from tubular body	3		
Remove star body	1		
Unscrew top cap from tubular body	3		
Remove top cap with lifting bracket	5		
Remove actuating device from tubular body	1		
Add top cap with lifting bracket	5		
Screw top cap to tubular body	3		

Vega		NEX	
Part activity sequence	**Part count**	**Part activity sequence**	**Part count**
Add star body	1		
Screw star body to fins	11	Add center ring	1
Screw star body to tubular body	3	Add hopper	1
Add center device	1	Screw hopper to center cyl	3
Screw center device to position device	3	Add distributor	1
Propellant slurry casting		Propellant slurry casting	
Screw center device to position device	3	Remove distributor	1
Remove center device	1	Unscrew hopper from center cyl	3
Add annular plugs	11	Remove hopper	1
Add center device	1	Remove center ring	1
Screw center device to position device	3	Add annular plugs	11
Propellant curing		Add center ring	1
Screw center device to position device	3	Screw center ring to center cyl	3
Remove center device	1	Propellant curing	
Remove annular plugs	11	Unscrew center ring from center cyl	3
Unscrew star body from tubular body	3	Remove center ring	1
Unscrew star body from fins	11	Remove annular plugs	11
Remove star body	1		
Unscrew top cap to tubular body	3		
Remove top cap with lifting bracket	5		
Add actuating device to tubular body	1		
Add top cap with lifting bracket	5		
Screw top cap to tubular body	3		
Add support plate	1	Add fin jig 1	1
Screw support plate to position device	3	Screw fin jig 1 to case	3
Screw fins to support plate	66	Add fin holder	11
Add fin lifting bracket	11	Add ball lock pins	22
Screw fins to lifting brackets	44	Unscrew core from fins	11
Remove tubular body, actuating device, top cap	10	Remove core	1
Unscrew fins from support plate	66	Add fin jig 2	1
Remove fins with seals, lifting brackets & screws	77	Remove fins sub assembly	66
Unscrew position device from connect plate	3	Remove fin jig 2	1
Remove position device, support plate & screws	5	Unscrew fin jig 1 from case	3
Unscrew telescopic collar from connect plate	3	Remove fin jig 1	1
Remove telescopic collar	1	Unscrew center cylinder from case	3
Unscrew connect plate to frame	3	Remove center cylinder	1
Remove connect plate	1		
Unscrew NEPO adapter ring to case	3		
Remove NEPO adapter ring	1		
Unscrew frame to case	3		
Remove frame	1		

the NEX mandrel was configured with the major dimensions of the SOTA mandrel of P120C booster[25].

The total mandrel along with the motor case, assembly tools, and casting accessories were reconstructed in CAD software. Important and equivalent parts, subassemblies, and mechanisms of the two mandrels were then compared and contrasted to check for compliance with DFA guidelines as shown in Table 2 and Table 3.

3.2.2 DFA Analysis Data

Reconstructed assembly-disassembly sequences for both mandrels are in Table 4. Major subassemblies like that of Vega tubular body or NEX core were added to the product structure without further analysis (DFA software had the option to add subassemblies with or without analysis).

Mandrel product structure was fed to DFA software in Table 4 sequence. Then each part was defined in detail. To show an example, the NEX core subassembly was defined thus:

- Repeat count: 1
- Item weight: more than 13.6 kg (30 lb)
- Envelope dimensions, mm: φ1500 x 12000 mm
- Item function: Item has other function
- Minimum part criteria: Item must be separate from all other items assembled, because: Separate to allow assembly
- Handling or insertion difficulties: Two persons needed, overhead crane needed, multi-insertion points, minor vision restrictions, large insertion depth
- Insertion depth: 12000 mm

Fasteners and connectors do not meet minimum part criteria. For fin jigs, movement was defined as item function, as the jigs are height adjustable and they facilitate sliding of fin holders over them. An examination of Table 4 would show details of how and where each item fits in the assembly. In NEX columns, consolidation of parts and consequent reduction in part count can also be seen.

In the DFA software, after questions for all items in the product structure were carefully answered, all input data could be seen and verified in the worksheet tab. Process time for individual items and total assembly were also shown. In the redesign tab, items fit for elimination, merger, or redesign were highlighted under three categories in decreasing order of impact: (a) those that were neither fastener nor connector nor fit the minimum part criteria, (b) fasteners, connectors, and separate operations and (c) handling or insertion difficulties.

When parts are merged, essential dimensional tolerances can be consistently achieved from the manufacturing process itself, instead of relying on the outcome of assembling the parts every time, which can differ from assembly to assembly.

A summary of the DFA analysis results is shown in Fig. 6. P120C is Vega and NEX1 is NEX in the Table. Significant differences can be seen in part count, assembly time, and design efficiency. DFA index of NEX is 62 % better than Vega's.

3.2.3 DFA Analysis Plots

From Fig. 7, it can be observed that the total number of parts that need to be field assembled in NEX is only about 60 %

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Design for Assembly
Assembly Totals for Design for Assembly

Tuesday, January 30, 2024

Entries including repeats	P120C	NEX1
Parts meet minimum part criteria	121	115
Parts are candidates for elimination	455	117
Analyzed subassemblies	0	0
Separate assembly operations	2	2
Total entries	578	234
Assembly labor time, s		
Parts meet minimum part criteria	41337.62	26387.34
Parts are candidates for elimination	8363	2756
Insertion of analyzed subassemblies	0	0
Separate assembly operations	13.10	13.10
Total assembly labor time	49714	29156
Design efficiency		
DFA Index	3.57	5.78

Figure 6. Screenshot of DFA product simplification software analysis results.

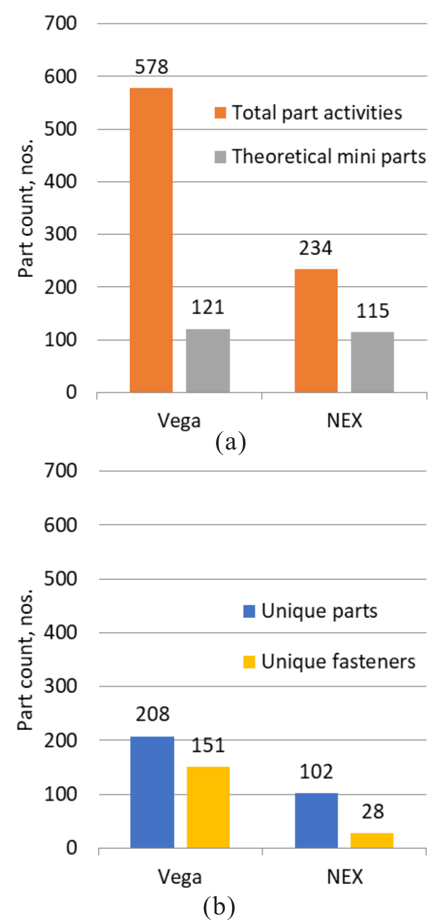

Figure 7. (a) Vega vs. (b) NEX: Summary of part counts in field assembly

of Vega's. As per estimates of the DFA software, in Vega, only 121 parts out of 578 parts are essential, the rest 79 % qualify for elimination or merger. The corresponding figure for NEX is 51%. In terms of unique parts, Vega has about twice that of NEX. But within Vega, unique part activities constitute 36 % of total part activities, whereas for NEX it is 44 %. The rest of the activities are repetitions.

One of the main objectives of DFA is to minimize fasteners. It reduces assembly time and recurring costs. The number of unique fasteners in the field assembly of Vega is 151, constituting about 26 % of the total parts in the assembly. In NEX, only 12 % of total parts are unique fasteners. Even though fasteners do not meet the minimum part criteria, the significant reduction of 81 % in NEX unique part count shows the more efficient mandrel design. It may be noted that estimates on screw count are conservative as only three per joint were assumed.

Even among fasteners, the highest to lowest order of preference goes from snap-fit to press-fit to riveting to screw fastening[15]. Figure 8 shows the distribution of fastener numbers and types among Vega and NEX. Total fastener activities in NEX are 80 % less than in Vega (444 vs. 87). There is a 95 % reduction in screw activities from Vega to NEX. As a rule, in mandrel design, threaded fasteners are strongly discouraged, especially in propellant-wetted areas. Wherever possible, snap-fit type of ball lock pins have been used in NEX. Also, none of the ball lock pins are loose. Two are tethered to each fin holder as seen in Figure 3. This one feature in NEX drastically reduces the risk of damaging lined motor cases with dropped foreign objects.

Another important cause for the increase in the number of assembly steps and duration is when some parts are assembled, disassembled, and reassembled. Also, repeat activities increase the scope for errors and wear and tear. NEX fares better with 64 % less overall repeat-activities and 80 % less fastener repeat-activities.

Further, from the DFA analysis results, plots showing the addition and subtraction of parts at every step along with the time taken (except for propellant casting and curing activities) are shown for Vega and NEX in Fig. 9 & Fig. 10 respectively.

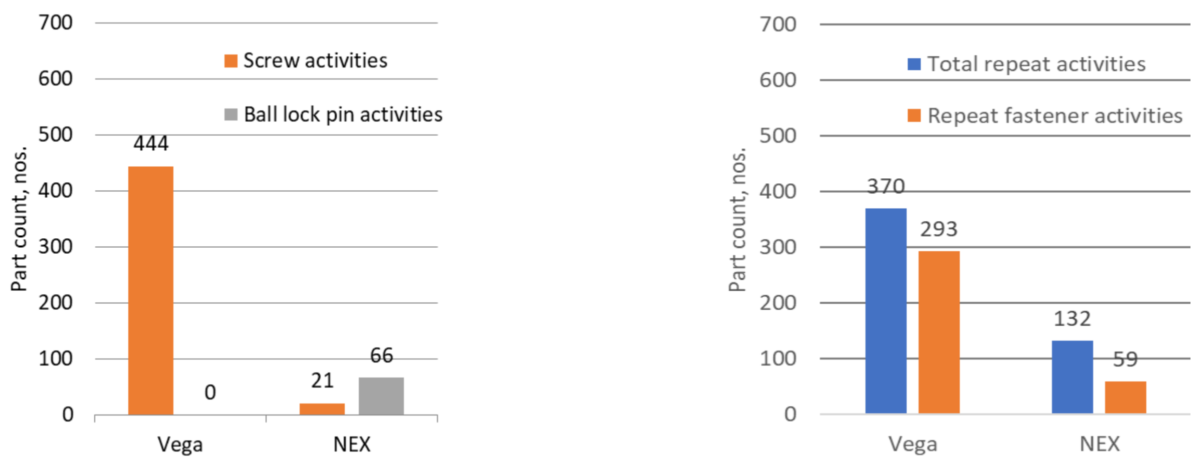

Figure 8. (a) Vega vs. (b) NEX: Fasteners and repeat activities.

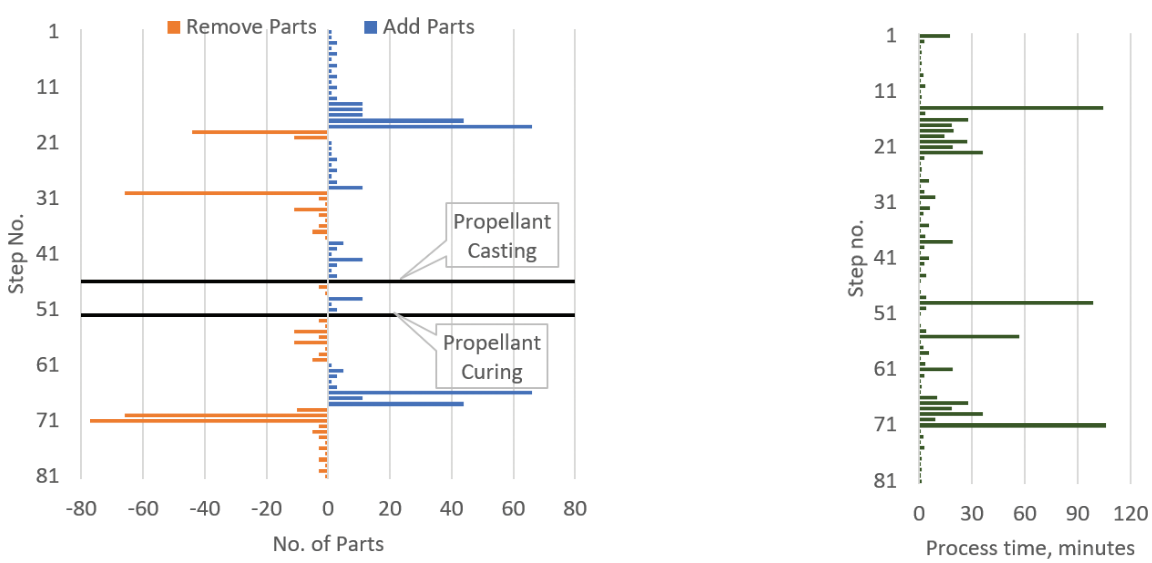

Figure 9. Field assembly-disassembly sequence of Vega mandrel showing addition & removal of parts & sub-assemblies along with time taken.

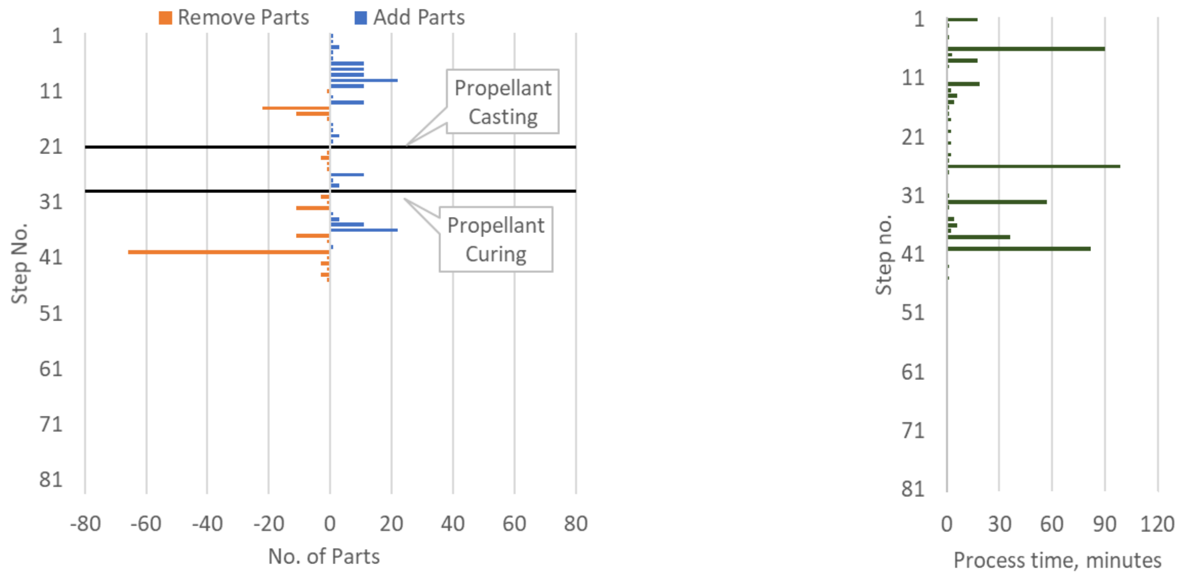

Figure 10. Field assembly-disassembly sequence of NEX mandrel showing addition & removal of parts and sub-assemblies along with time taken.

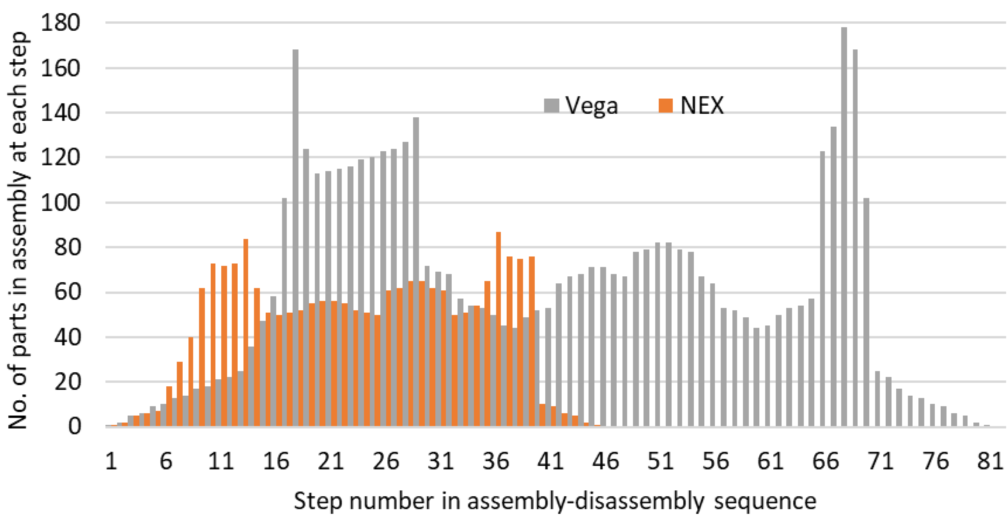

Figure 11. Comparative plot showing part count at each assembly-disassembly step.

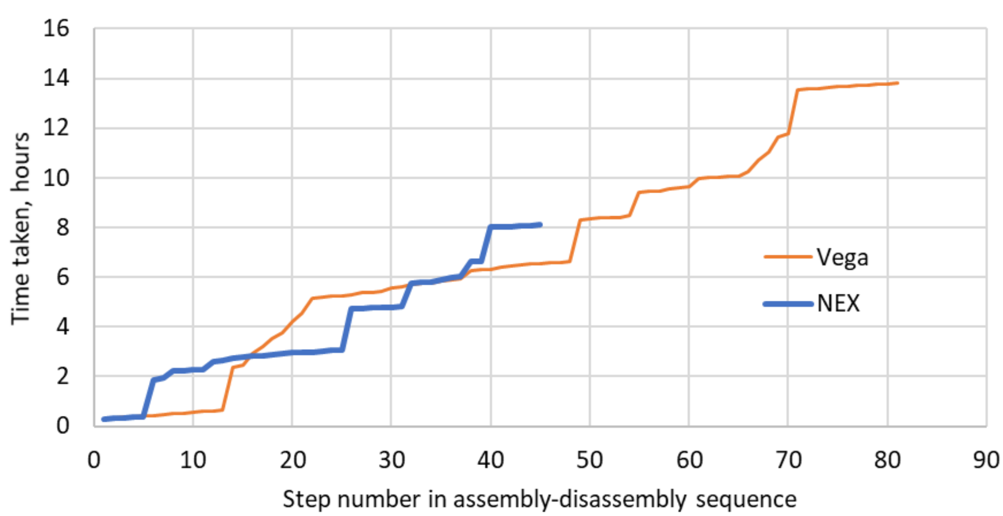

Figure 12. Comparative plot showing the time taken for assembly & disassembly.

When read with Table 4, they illustrate mandrel assembly/ disassembly efficiency. Time differences seen in post-curing activities have a direct bearing on the safety rating of the processes.

The relative complexity of the mandrel assembly activities is shown in Fig. 11, where step-wise instantaneous part count is plotted. The area under each plot can be another measure of assembly efficiency. Values for Vega and NEX are 4944 and 2056 sq. units respectively. Accordingly, NEX is about 58 % more efficient than Vega.

The data plotted in Fig. 12 is the summary of the DFA analysis results. It is significant for the following reasons. Whenever an activity involves a large number of steps, the chances of missing a step or deviating from the sequence go up. Vega mandrel assembly-disassembly activity stretches for almost 14 man-hours, excluding the time for casting, curing, and other activities. Fatigue can lead to human error in such safety-critical activities. With almost half the number of steps and time taken, NEX achieves the same results as Vega, showing its better 'Design for Assembly' performance.

3.3 Future Works

Continuing the work, it can be attempted to further simplify the NEX mandrel by merging a few more parts while retaining functionality. For instance, can the fin-lifting feature be configured without fasteners?

Squeeze casting operation is unsuitable for high-viscosity propellant slurries. In actual cases, gaps between the squeeze cast plug mandrels, necessary for smooth assembly, are seen to be filled with propellant slivers which could ignite during relative motion between said mandrels (decoring). Safer methods without squeeze casting need to be developed.

4. CONCLUSION

A propellant grain casting mandrel is a tooling that is repeatedly used to form or shape necessary grain geometry inside a solid rocket case. It is therefore configured to give safe, reliable, and consistent performance over the mandrel's service life. In this study, a newly patent-filed undercut finocyl grain casting mandrel called NEX has been benchmarked against a state-of-the-art Vega mandrel, using Boothroyd-Dewhurst DFA product simplification software. Cam-actuated fin-core joining mechanism of Vega is found to be complex and time-consuming when compared to the screw-actuated wedge-pairs mechanism of NEX. With improvements like merged functions, important DFA parameters for NEX mandrel are found to be significantly better than Vega's. The estimated efficiency of assembling and disassembling (DFA index) of NEX is about 62 % better than Vega's. This comes from lesser field assembly part count, reduced safety critical fastener activities, and faster turnaround time. The new method will help reduce the manufacturing cost of high-performance space solid boosters.

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In the present study he guided the research work and reviewed and formatted the manuscript.