NARC Rayon Replacement Program for the Space Shuttle Reusable Solid Rocket Motor Nozzle – Screening Summary

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ABSTRACT

Thiokol Corporation and NASA MSFC are jointly developing a replacement for North American Rayon Corporation (NARC) Aerospace Grade Rayon (1650/720 continuous filament), the precursor for the Carbon Cloth Phenolic (CCP) ablatives used in the Space Shuttle Reusable Solid Rocket Motor (RSRM) Nozzles. NARC discontinued production of Aerospace Grade Rayon in September 1997. NASA maintains a stockpile of NARC Rayon to support RSRM production through the summer of 2005. The program plan for selection and qualification of a replacement for NARC rayon was approved in August 1998. Screening activities began in February 1999.

The intent of this paper is to provide a summary of the data generated during the screening phase of the NARC Rayon Replacement Program. Twelve cellulose based fibers (rayon and lyocell) were evaluated. These fibers were supplied by three independent vendors. Many of these fibers were carbonized by two independent carbonizers. Each candidate was tested according to standard acceptance test methods at each step of the manufacturing process. Additional testing was performed with the candidate CCPs, including hot fire tests, process studies and mechanical and thermal characterization.

Six of the twleve fiber candidates tested were dropped at the conclusion of Phase I. The reasons for the elimination of these candidates included; difficulties in processing the material in the whitegoods, carbon and CCP forms; poor composite mechanical performance; and future availability concerns. The remaining six fibers demonstrated enough promise to merit continued evaluation and optimization of the CCP fabrication process.

Note: Certain CCP data falls under the restrictions of US export laws, (ITAR, etc.) and will not be included in this paper.

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INTRODUCTION

The Reusable Solid Rocket Motor (RSRM) nozzle uses carbon cloth phenolic (CCP) as an ablative liner to control motor pressure and thermally protect the reusable metal housings, Figure 1. The precursor material for CCP is currently a continuous filament fiber rayon. The previous supplier of RSRM nozzle rayon, North American Rayon Corporation (NARC), discontinued production in September of 1997 for financial reasons. There is no plan to resume production, thus, creating the need to find a replacement fiber. Prior to the shutdown the RSRM program stockpiled enough material to last until late 2005, assuming the current RSRM flight schedule is maintained. The program plan for selection and qualification of a replacement for NARC rayon was approved in August 1998. Candidate screening activities began in earnest in February 1999.

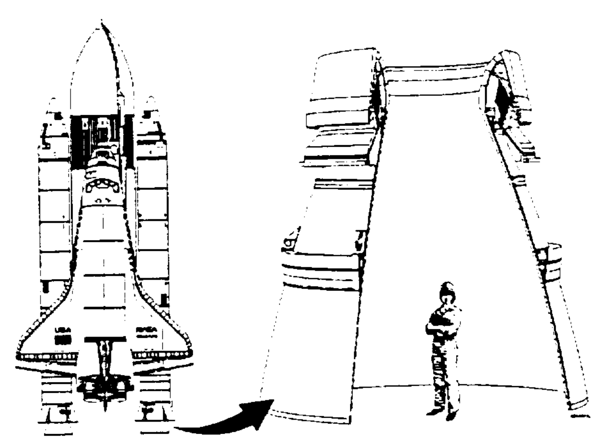
The Rayon Replacement Program has the following objectives:

- Find the best replacement fiber for NARC rayon used in the RSRM nozzle CCP considering performance, processability, variability and long term availability.
- Replace NARC rayon with a goal to not reduce performance or structural margins of safety in the RSRM nozzle CCP.
- Incorporate knowledge gained in Advanced Solid Rocket Motor (ASRM) Improved Ablatives Program, Solid Propulsion Integrity Program (SPIP), STS-79 Unexpected Unexplained Event or Condition (UUEC), and Engineering Enhancement Program to reduce CCP material variability, and ensure predictable performance.

The plan to achieve these objectives is segmented into five phases. This paper is limited only to the results of Phase I allowed by US export laws. A brief description of the phases is as follows:

- Phase I - Initial Candidate Screening and Down-Select: Perform testing on several candidate materials and gather sufficient data to screen/down-select to a minimum of three best fibers. Additionally, a "least change" fiber candidate will be carried forward to the next phase, if none of the three best candidates constitutes a "least change" material.
- Phase IA - Process Optimization Pathfinder: Conduct pathfinder testing to understand processing parameters for incorporation into the process optimization phase. This testing will provide information needed to define processes for Phase II.
- Phase II - Process Optimization: Demonstrate that the optimized processes developed in Phase IA satisfy the program objectives and improve the performance and/or processability when compared to the baseline (or similar) RSRM process. This data will be used to select production processing parameters for each of the candidates selected in Phase I.
- Phase III – Variability Study: Each candidate material and process will be manufactured in several lots to establish the inherent lot to lot variability.
- Phase IV – Certification: Based on results from all previous phases, a single replacement material will be chosen. Phase IV accomplishes all the necessary testing to certify the replacement fiber for flight.

Figure 1
Space Shuttle Reusable Solid Rocket Motor Nozzle



DISCUSSION

Phase I covers the initial candidate material screening and down-selection process. Figure 2 summarizes the logic and tests performed in Phase I. Twelve candidates were selected from available fibers found in industry (Table 1). The fiber selection was limited to cellulose based fibers (rayons and lyocells) to remain within the RSRM program experience base. Candidate fibers were chosen based on commercial availability, technical evaluation of their method of manufacture and raw materials used. The construction of each candidate yarn used in Phase I was selected or tailored to be similar to the NARC construction. NARC yarn has a yarn denier of 1650 and is comprised of 720 continuous rayon filaments. Staple fibers were also included in Phase I. Staple fibers comprise the majority of the cellulose fiber market and therefore have the advantages of better long-term availability prospects and a wider range of available products. Only "off the shelf" fibers were considered in Phase I, with one exception; a continuous filament lyocell fiber. Currently, continuous lyocell is not commercially available, however, some material was manufactured specifically for this application.

The weaving, carbonization, and resin impregnation processes used on these Phase I candidates were similar to those used for NARC. The weaving was performed by Highland Industries. Candidate materials were carbonized at both SGL Technic, Polycarbon Div. and National Specialty Products (NSP). SGL Technic is the current qualified RSRM carbonizer. NSP has been qualified in the past for RSRM CCP carbonization. Cytec Fiberite performed the resin impregnation. An evaluation of each material was made at each step of the process. Any materials that clearly were unsuitable for this application or were too difficult to process were dropped from contention. The CCP materials were evaluated at Thiokol for handling during tape slitting operations as well as handling during a partial sub-scale wrapping operation. Ambient and elevated temperature testing of the composite material was performed at Southern Research Institute (SRI). Hot fire performance testing was performed at Thiokol, MSFC and Wright Patterson AFB. Following the completion of all processing and testing, each candidate was evaluated for processing/handling, mechanical property and motor operational performance. The more promising candidates were selected for further evaluation and for process and construction optimization in Phase IA.

Figure 2
Phase I Flowchart - Initial Candidate Screening

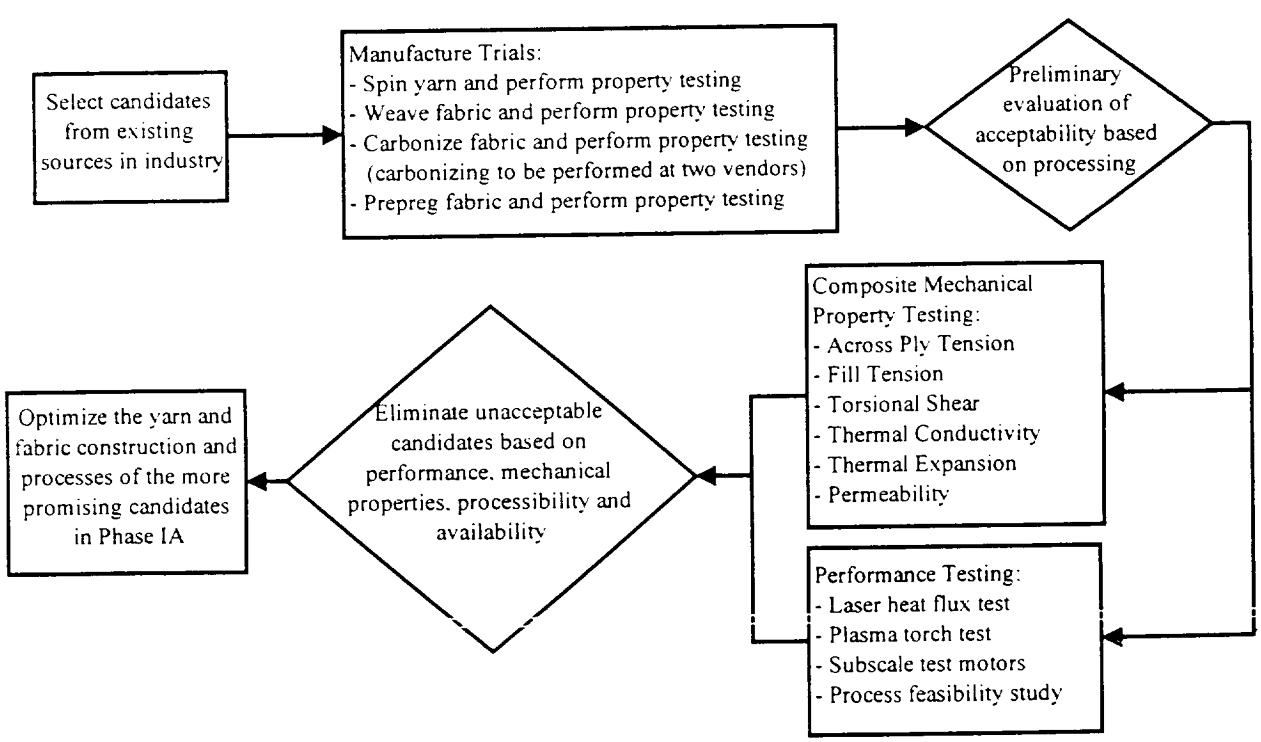


Table 1 - Phase I Fiber Candidates

Fiber Description	Physical Properties		Vendor	Most Common Use
NARC – Current Precursor	1650 yarn denier 720 filament	2.3 fiber denier Continuous filament	NARC	Designed for carbonization
Candidate A - Staple Lyocell (Tencel)	1650 yarn denier 550 filament	3.0 fiber denier 2.0 inch length	Acordis	Textiles
Candidate B - Staple Lyocell (Tencel)	1650 yarn denier 550 filament	3.0 fiber denier 4.0 inch length	Acordis	Medical gauze and textiles
Candidate C - Staple Lyocell (Tencel)	1650 yarn denier 550 filament	3.0 fiber denier 2.0 inch length	Lenzing	Textiles, non-wovens
Candidate D - Continuous Filament Lyocell	1650 yarn denier 540 filament	3.3 fiber denier Continuous filament	Acordis	New fiber,
Candidate E - Staple Rayon	1650 yarn denier 300 filament	5.5 fiber denier 6.0 inch length	Acordis	Textiles, felts, medical, hygiene products
Candidate F - Staple Rayon	1650 yarn denier 550 filament	3.0 fiber denier 2.0 inch length	Acordis	Textiles, felts, medical, hygiene products
Candidate G - Tire Cord Rayon (Cordenka)	1650 yarn denier 1000 filament	1.65 fiber denier Continuous filament	Acordis	Tire cord, mechanical rubber goods
Candidate H - 6 Ply Textile Rayon (Enka)	1800 yarn denier 360 filament	5.0 fiber denier Continuous filament	Acordis	Textiles
Candidate K - 3 Ply Textile Rayon	1800 yarn denier 336 filament	5.4 fiber denier Continuous filament	Cydsa	Trimmings, embroideries, linings
Candidate L - 480/1650 Rayon	1650 yarn denier 480 filament	3.4 fiber denier Continuous filament	Cydsa	Upholstery
Candidate M - Aerospace Grade Rayon	1650 yarn denier 720 filament	2.3 fiber denier Continuous filament	Cydsa	Designed for carbonization
Candidate V - Staple Lyocell (Tencel)	1650 yarn denier 550 filament	3.0 fiber denier 3.0 inch length	Acordis	Textiles

RESULTS

US export laws prevent the public release of certain CCP tests results. Consequently this paper will be limited to a discussion of yarns, weaving and carbonization processes and data. Prepreg, composite and thermal performance data was intentionally left out of this discussion.

Yarn

The yarns selected for potential use in RSRM nozzles were limited to cellulose-based yarns, rayons and lyocells. Polyacrylonitriles (PAN) and other commonly ued carbon precursors were not included. This ground rule was established to remain within the RSRM database. By doing so the size of the replacement effort was reduced and the need to redesign the nozzle due to a different thermal performance was avoided. Lyocells were included in the Phase I screening effort because they are more environmentally friendly than rayons and they have a growing market share whereas the market share of rayons has been dropping in recent years.

One area where an intentional deviation was made from the RSRM family was the evaluation of staple fibers. Staple fibers comprise the majority of the cellulose fiber market. They have the advantages of better long-term availability prospects compared to the continuous fibers and there is a wider range of available products. Also, all lyocell yarns currently on the market are spun from staple fibers.

Fiber microscopy was performed with each candidate. The shapes of the fibers can be grouped into three different families. The lyocell fibers (Candidates A, B, C, D, and V) were basically round with smooth surfaces. The tire cord rayon fibers (Candidate G) were kidney shaped with smooth surfaces. The other textile and industrial rayon fibers (NARC and Candidates E, F, H, K, L, and M) varied from round to oblong with crenulated surfaces.

Weaving

The weave pattern on all candidates woven in Phase I was a 5-harness satin weave, similar to the 8-harness satin weave used on the current qualified CCP. The switch to the 5-harness satin weave was made to improve the stability of the fabric. It was also the selected weave pattern for the advanced Solid Rocket

Motor Program (ASRM). Aerial weights were targeted at 17 oz per yd^2. Candidates G, H, K, and V wove well with no problems identified. Candidates A, C, E, F, and L were marginally acceptable. Candidates B and M all had significant weaving problems. Even though samples were finished for these latter two candidates, they required excessive effort by the weaver. Fortunately, both of the unacceptable candidates had problems that could be resolved through modifications at the spinner or fiber producing site. Later runs proved that the modifications were successful. Weaving of Candidate D was never attempted. Unlike the other candidates, only small quantities of Candidate D were available during the early stages of Phase I. Consequently early efforts were focused on carbonizing the un-woven yarn. A lack of success in the carbonization of Candidate D, plus concerns about its long term availability, eliminated it from contention before weaving quantities were received.

Carbonizing

There was very little experience carbonizing any of these materials prior to the start of this program, consequently the carbonization process used for NARC was selected as a starting point for all Phase I materials. The values included in this paper are averages between fabric carbonized by both SGL Technic and NSP. The tests performed on these carbon material include: carbon assay, carbon yield, ash and sodium content, electrical resistivity and break strength (Table 2).

All materials tested met the carbon assay target range of 95 – 99%. Less than 95% carbon assay would be an indication of insufficient carbonization. Greater than 99% carbon assay would be approaching graphitization, which alters the thermal characteristics of the material. Carbon yield varied between the candidates with most materials not performing as well as NARC. The results of the electrical resistivity tests also varied significantly, with most of the staple fibers having a higher resistivity than NARC and the continuous fibers with lower resistivity than NARC. Ash and sodium levels can be used as an indication of the completeness of the carbonization, but can be strongly influenced by the impurity level of the incoming materials.

The most challenging requirement to satisfy at the carbonized fabric level was carbon break strength. The objective of this requirement is to carbonize a material that is strong enough to be easily processed downstream. The target values for carbon break strength are 30 and 25 lbs./inch minimum in the warp and fill directions, respectively. The suppleness or brittleness of the fabric is generally correlated to the carbon break strength. None of the Phase I materials had carbon break strengths or suppleness that is typical of NARC. However, this was not expected since the NARC material and the carbonization process were tailor made for each other. Rayons carbonized better than the lyocells when the NARC process was used. Also continuous filament yarns had better break strength than the staple yarns.

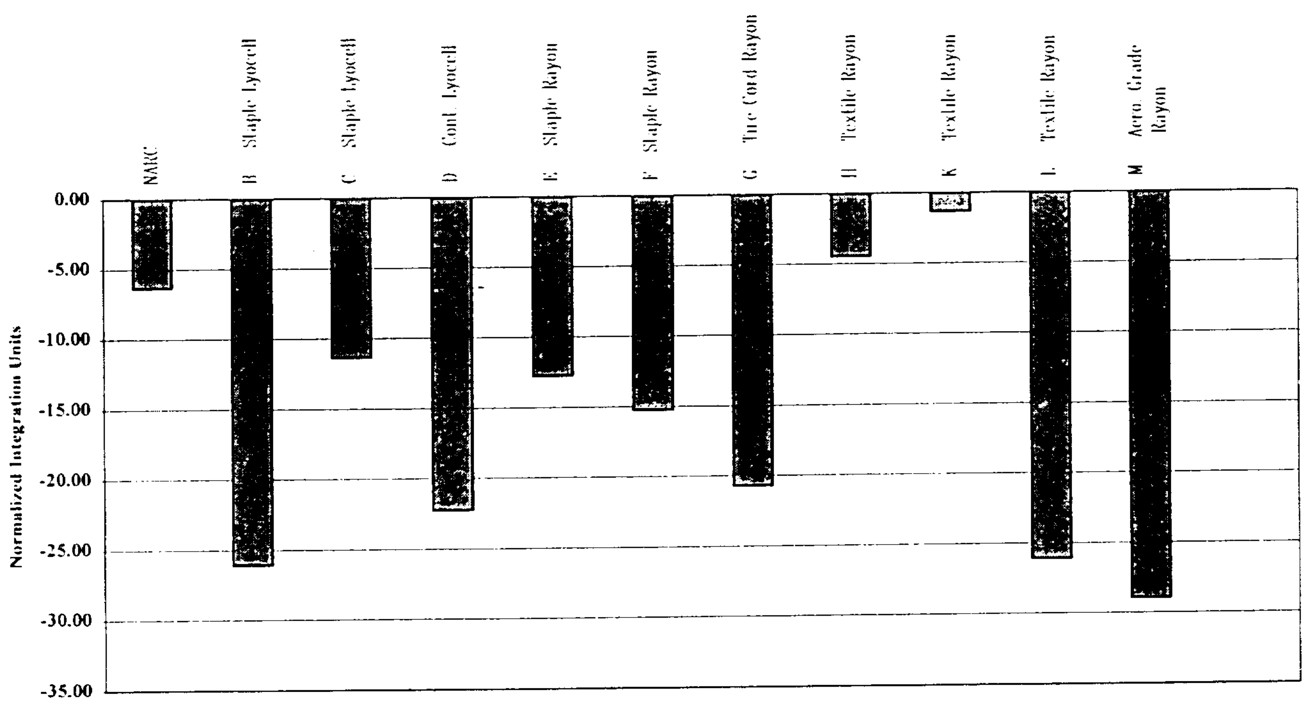
Table 2
Carbonization Data Summary

Fiber Description	Carbon Assay (%)	Carbon Yield (%)	Ash/ Sodium (ppm)	Electrical Resistivity Warp (ohms)	Break Strength (lbs/in)	
					Warp	Fill
NARC Typical Values	97.8	22	2600/593	5.6	64	74
Candidate A – Acordis Staple Lyocell	95.6		1600/202	6.4	4.2	2.7
Candidate B – Acordis Staple Lyocell	96.3	17.8	5100/1493		5.6	7.3
Candidate C – Lenzing Staple Lyocell	97.1	20.4	4500/1328	4.9	6.7	3.3
Candidate D – Acordis Continuous Lyocell		17.8			4.5*	4.5*
Candidate E – Acordis Staple Rayon	95.7	20.3	3100/585	5.9	15.2	10.1
Candidate F – Acordis Staple Rayon	95.7	19.5	2800/565	5.6	9.1	4.3
Candidate G – Acordis Tire Cord Rayon	98.6	18.4	800/190	3.2	29.2	23.8
Candidate H – Acordis 6 Ply Textile Rayon	97.7	22.8	3700/833	4.8	49.3	38.1
Candidate K – Cydsa 3 Ply Textile Rayon	97.0	23.1	4500/1203	4.8	16.2	11.5
Candidate L – Cydsa 480/1650 Rayon	98.0	16.0	4700/121	3.6	14.9	8.6
Candidate M - Cydsa Aerospace Grd Rayon	97.1	14.8	920/125	3.4	20.7	19.5
Candidate V – Acordis Staple Lyocell	96.5				14.5	11.0

* 10 ply yarn tested in place of fabric.

The amount of energy expended to carbonize the materials can be determined by integrating the endotherm curve measured using Dynamic Thermal Analysis (DTA) (Figure 4). Many of the same trends that were observed in the TGA data can be observed in the DTA data. Candidate H had a similar endotherm to NARC. The lyocells (Candidates A, B, C, D, and V), the tire cord (Candidate G) and two Cydsa rayons (Candidates L and M) all had substantially larger endotherms than NARC, again suggesting a strong potential for improvement through carbonization optimization. The staple rayons (Candidates E and F) also had relatively high endotherms. Candidate K had the smallest endotherm of all materials tested.

Figure 4
Integrated Peak Values for Carbonization Endotherm by DTA
(normalized to initial sample weight)



CONCLUSIONS

Six of the twelve fiber candidates tested in Phase I showed promising enough results to be further evaluated in Phase IA. The objective of Phase IA is to optimize the yarn and fabric construction and fabrication process at all levels. Table 3 contains a summary of the rationale for keeping or dropping each Phase I candidate.

Table 3
Phase I Candidate Summary

Fiber Description	Phase I Result	Summary
Candidate A Acordis Staple Lyocell (Tencel)	Dropped	This candidate was dropped because the carbon fabric was too difficult to process (carbonize, resin impregnate, etc.) due to low carbon break strengths. Other staple lyocells are more promising (Candidate V)
Candidate B Acordis Staple Lyocell (Tencel)	Selected for Phase IA	This candidate showed some potential for improvement through Phase IA optimization, plus the future availability is promising.
Candidate C Lenzing Staple Lyocell (Tencel)	Dropped	This candidate was dropped because the yarn was difficult to process (weave) due to low fiber strength. Downstream processing (carbonize, resin impregnate, etc.) was also difficult. Other staple lyocells are more promising (Candidate V)
Candidate D Acordis Continuous Filament Lyocell	Dropped	This candidate was dropped because the yarn had poor carbon break strengths. Also the long term availability of the yarn was in question. It was never woven
Candidate E Acordis Staple Rayon	Selected for Phase IA	The fabric was strong enough to be processed (weave, carbonize, resin impregnate, etc.), but not as strong as NARC. Additional effort required to process.
Candidate F Acordis Staple Rayon	Dropped	This candidate was dropped because the carbon fabric was too difficult to process (carbonize, resin impregnate, etc.) due to low carbon break strengths. The other staple rayon is more promising (Candidate E)
Candidate G Acordis Tire Cord Rayon (Cordenka)	Selected for Phase IA	The carbon fabric break strengths were low, but within the NARC family. The yarn processed reasonably well.
Candidate H Acordis 6 Ply Textile Rayon (Enka)	Selected for Phase IA	Processability and performance of this fiber is the closest to NARC of any fiber tested in Phase I. It was the only fiber to meet all carbon requirements while using the NARC processes.
Candidate K Cydsa 3 Ply Textile Rayon	Dropped	This candidate was dropped because the carbon break strengths were low and the fabric was too difficult to process (too brittle). Analytical studies showed little potential for improvement through carbonization optimization.
Candidate L Cydsa 480/1650 Rayon	Dropped	Carbon break strengths were low, but mostly within the NARC family. This candidate was dropped because the fabrication process, equipment and raw materials are similar to Candidate M, which had better performance.
Candidate M Cydsa Aerospace Grade Rayon	Selected for Phase IA	The carbon fabric break strengths were within the NARC family. The yarn processed reasonably well. This candidate showed potential for improvement through Phase IA optimization.
Candidate V Acordis Staple Lyocell (Tencel)	Selected for Phase IA	This candidate was the best staple yarn tested in Phase I. The fabric was strong enough to be processed (weave, carbonize, resin impregnate, etc.), but not as strong as NARC.