Development of a Convergent Spray Technologies™ Spray Process for a Solventless Sprayable Coating, MCC-1

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ABSTRACT

This paper discusses the application of Convergent Spray Technologies™ Spray Process to the development and successful implementation of Marshall Convergent Coating (MCC-1) as a primary Thermal Protection System (TPS) for the Space Shuttle Solid Rocket Boosters (SRBs). This paper discusses the environmental and process benefits of the MCC-1 technology, shows the systematic steps taken in developing the technology, including statistical sensitivity studies of about 35 variables. Based on the process and post-flight successes on the SRB, it will be seen that the technology is "field-proven". Application of this technology to other aerospace and commercial programs is summarized to illustrate the wide range of possibilities.

INTRODUCTION

The CST™ spray process eliminates the use of solvents, often used for viscosity control, by introducing filler material outside the spray gun, as illustrated in the figure 1 below.

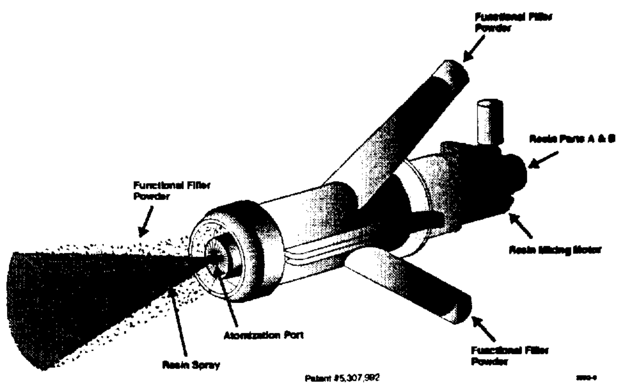


Figure 1. Schematic of the MCC-1 Spray Gun

The filler is injected into the binder material (typically two part resin) as the binder is ejected from the spray gun. The mixing of binder and filler occurs outside the nozzle, in air, because of the localized fluid dynamics. The MCC-1 coating is a specific sprayable TPS material developed for use on the SRBs. The material contains epoxy adhesive as a binder material and ground cork and hollow glass eccospheres as fillers.

DISCUSSION

Environmental Advantages

The CST™ process for MCC-1 was developed to meet the ever tightening Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) requirements. MCC-1 replaced the MSA-2 (Marshall Sprayable Ablator, 2nd generation), which contained methylene chloride and perchloroethylene, making it number 1 air pollutant and number 2 hazardous waste generator for SRB operations at NASA/KSC. Since implementation of the solventless MCC-1, air emission, hazardous waste stream, and OSHA issues have been virtually eliminated.

Process Advantages

Besides the environmental advantages, there are several process related advantages that have made MCC-1 a favorite with production personnel. Unlike MSA-2, MCC-1 spray involves no premixing of constituents, has eliminated the pot life restrictions and is very easy to start/stop - i.e. on-demand spray technology. These and other process advantages (e.g. no batch size limitations, reduced cleaning, ease of cure, fewer constituents) have earned MCC-1 its reputation of being user-friendly on the production floor. Also noteworthy is the fact that the process is so simple that we developed and successfully implemented this novel technology in a record time of less than three years.

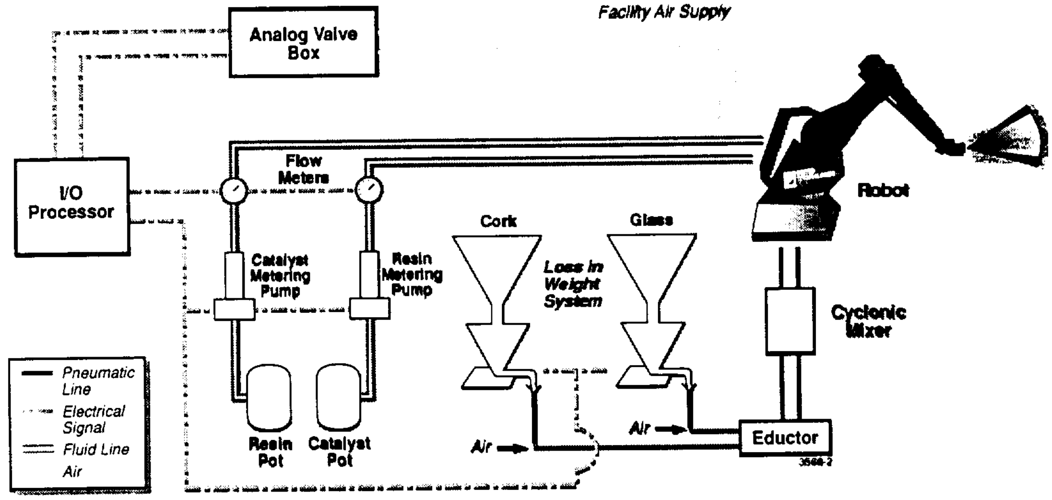


Figure 2. Schematic of MCC-1 Spray System

Figure 2 above shows a schematic of an MCC-1 spray system. Conceptually, the MCC-1 spray system shown in figure 2 can be best understood in terms of its two main component delivery systems, i.e. the liquid (resin and catalyst) delivery system and the solids (cork and glass) delivery system. In the case of MCC-1, the liquid portion is the 3M's 2216 epoxy adhesive that is comprised of 2216B, DGEBA type epoxy, and 2216A, the amine curing agent. As shown in the schematic, the resin and catalyst are delivered from their pressure pots to the spray gun using metering pumps. The metering pumps, with their associated controls, allow the accurate flow of 2216 A&B to produce the desired MCC-1 density. The solids delivery system is comprised of loss-in-weight type feeder systems that control the cork and glass eccosphere flow rates. Both of theses solids are delivered to the spray gun using an eductor-based pneumatic delivery system. As shown in the schematic, the cork and glass eccospheres are pre-mixed in the cyclonic mixer prior to delivery to the spray gun. In the case of MCC-1 application to the SRB, a robot and turn table are used to achieve the desired MCC-1 thickness, overlap pattern, and the gun stand-off distances for each structure type (e.g. nose cap, frustum, Forward skirt, Aft Skirt, and tunnel covers). These basic components of the MCC-1 spray system would remain the same for almost any CST application, although the performance requirements of the system can be greatly simplified depending upon the geometry of the part to be sprayed, and the required accuracy of the sprayed MCC-1 properties (e.g. density, thickness, strength). USBI has over six years of experience developing variations of the CST system to cater to individual needs for a given application, balancing the cost and performance requirements.

Proven Technology

The MCC-1 process and material have been extensively tested to meet the demanding requirements of the manned space flight program. For example, the material must pass more than 20 separate tests. Table 1 below lists examples of the various tests that MCC-1 must pass to be used on the SRB. Table 2 lists the key properties of MCC-1.

Table 1. Examples of MCC-1 Tests for SRB Qualification

• Flatwise Tensile Strength	• Ascent Heating (aeroheating and radiation)
- Reproducibility over painted aluminum	• Plume Impingement Heating
- Elevated Temperatures, up to 300°F	• Reentry Heating
• Density (establish reproducibility)	• Structural Integrity in Combined Environments (vibration, acoustics)

• Thickness (establish reproducibility)	• On-Pad Abort
• Strain Compatibility	• Closeout Material Compatibility
• Flatwise Tensile Strength over Polysulfide (PR 1422) Sealant	• Performance over Protuberances
• Flatwise Tensile Strength of BTA and K5NA over bare and painted MCC-1	• Lightning Strike
• Flatwise Tensile Strength of TPS Sealcoat over MCC-1	• Pyrotechnic Shock
• Flammability	• Ablation Temperature
• Effect of Outdoor Weathering	• Thermal Conductivity
• Flatwise Tensile Strength of MCC-1 over BTA, Cork and K5NA	• Specific Heat
• TPS Sealcoat to MCC-1 bond Strength	• Verification of MCC-1 as applied to each structure type
• Sensitivity studies for process parameter limits	• Qualification of the production facility

Table 2. Typical MCC-1 Properties

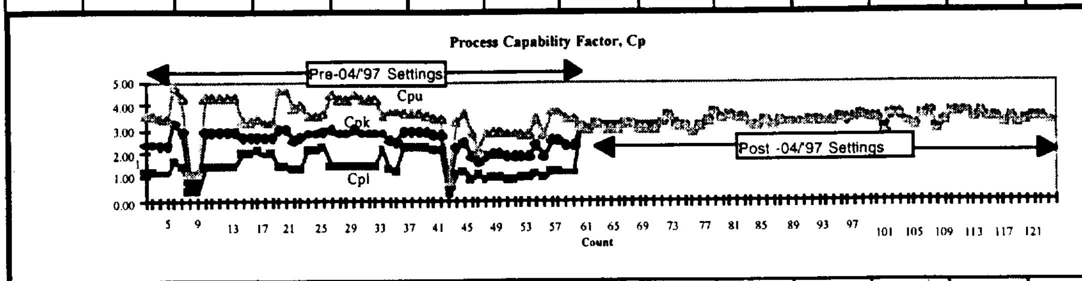
Density Range	30-41 pcf	Thermal Conductivity	0.60 Btu-in/hr-°F-ft^2 (at RT)
Flatwise Tensile Strength :		Specific Heat	0.42 Btu/lb$_m$-°F (at RT)
at RT	540 psi	Ablation temperature	540 °F
at 150 °F	90 psi		
at 300 °F	40 psi	Flammability	Meets NASA Acceptance Criteria
		Recession Characteristics	Recession equation as a function of heating rate developed for SRB heating environment
Spray Thickness	Up to 1/2" *	Thermal (Flight related loads : aerodynamic, radiant, reentry, vibration, pyroshock, etc.)	Qualified to SRB requirements
Materials Compatibility	Qualified for SRB materials	Outdoor Weathering	Qualified to SRB requirements

* Recent studies are extending the qualification limit to 3".

Furthermore, to ensure that the process is robust for production implementation, approximately 35 material and process variables were identified to characterize their effects on MCC-1 physical and thermal properties. The approach involved application of statistical design of experiments for phase 1 and 2, assessing the effects of the variables on MCC-1 physical properties (density, strength, thickness). In the phase 3 of the sensitivity study, more expensive thermal responses were characterized for a selected number of variables. Table 3 below lists the materials and process variables evaluated.

Table 3. MCC-1 Process Parameters for Sensitivity Study

Flow Parameters	Application Parameters	Cure Parameters
1. Resin flow rate (2216B)	1. Stand-off distance	1. Precure temperature
2. Catalyst flow rate (2216A)	2. Eductor air pressure	2. Precure time
3. Resin to catalyst ratio	3. Atomizing air pressure	3. Cure ramp rate
4. Glass eccospheres flow rate	4. 2216 A/B mixer air pressure	4. Cure temperature

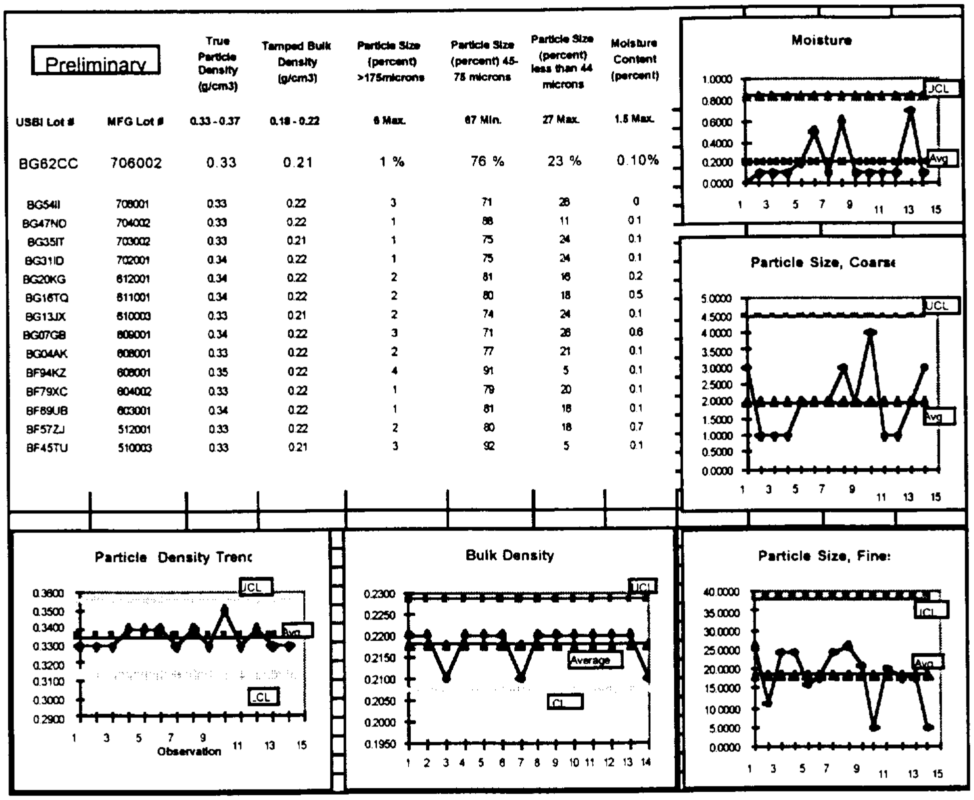


Footnote : Cp values greater than 1.3 are desired, between 1.0-1.3 are marginally satisfactory, and less than 1.0 are unacceptable.

Figure 5. MCC-1 Resin Flow Rate Data Trending

<u>Other Applications</u>

The success of this technology has been extended beyond the Shuttle SRB production system. For example, MCC-1 is being used by the Air Force for the Titan IV program, a similar material called USI has been selected for the Boeing Sea Launch program, and USBI has demonstrated application of the CST technology to skid resistant road coatings, and to roof coatings. The inherent flexibility of this spray technology allows use with a range of fillers and liquid resins. The technology can also be applied to acoustic insulation, light weight concrete, fire barrier coatings, asphalt repair, and protective primers and coatings, among other things.



USBI Lot #	MFG Lot #	True Particle Density (g/cm3)	Tamped Bulk Density (g/cm3)	Particle Size (percent) >175microns	Particle Size (percent) 45-75 microns	Particle Size (percent) less than 44 microns	Moisture Content (percent)
		0.33 - 0.37	0.18 - 0.22	6 Max.	67 Min.	27 Max.	1.5 Max.
BG62CC	706002	0.33	0.21	1 %	76 %	23 %	0.10%
BG54II	708001	0.33	0.22	3	71	28	0
BG47NO	704002	0.33	0.22	1	88	11	0.1
BG35IT	703002	0.33	0.21	1	75	24	0.1
BG31ID	702001	0.34	0.22	1	75	24	0.1
BG20KG	612001	0.34	0.22	2	81	16	0.2
BG16TQ	611001	0.34	0.22	2	80	18	0.5
BG13JX	610003	0.33	0.21	2	74	24	0.1
BG07GB	609001	0.34	0.22	3	71	28	0.6
BG04AK	608001	0.33	0.22	2	77	21	0.1
BF94KZ	606001	0.35	0.22	4	91	5	0.1
BF79XC	604002	0.33	0.22	1	79	20	0.1
BF69UB	603001	0.34	0.22	1	81	18	0.1
BF57ZJ	512001	0.33	0.22	2	80	18	0.7
BF45TU	510003	0.33	0.21	3	92	5	0.1

Figure 4. Glass Eccospheres Properties Data Trending

Table 5. MCC-1 Thickness Data

Structure	Avg.	Std. Dev.	Lowest	Highest	n =	N =	Std. Dev. of Avg.	Requirement Min	Requirement Max	Reqmt. Mean	k - Factors : A-Basis :	k - Factors : B-Basis :	Minimum thickness : A-Basis :	Minimum thickness : B-Basis :	Maximum thickness : A-Basis :	Maximum thickness : B-Basis :
Nosecap :																
Acerage [1]	179	9.8	**158**	228	544	8	6.6	150	250	200	2.717	1.735	**152**	162	205	196
Dome :	228	50.4	**161**	393	124	8	24.7	150	410	280	2.905	1.846	**82**	135	375	321
Frustum[2]	172	13.1	**142**	209	3812	11	11.6	100	210	155	2.676	1.709	**137**	150	207	195
F-Skirt[3]	147	11.7	122	183*	2911	9	15.0	90	200	145	2.676	1.709	**116**	127	178	167
Aft Skirt[4]																
High Heating Region	312	22.5	**240**	396	1640	8	15.0	250	500	375	2.676	1.709	**252**	274	372	351
Low Heating Region :	252	23.4	**211**	369	423	8	17.3	160	400	280	2.745	1.753	**188**	211	316	293
Tunnel Covers[5]	181	14.5	**136**	229	3357	10	6.2	130	220	175	2.676	1.709	**142**	156	220	206

Notes about Target Thickness :

1. Nosecap target thickness is purposefully kept below the mean value of the requirement due to the concern related to slump.
2. Frustum target thickness is purposefully kept above the mean value of the requirement because of the concern relating to maintaining proper thickness over the fastener areas.
   thickness over the fastener areas.
3. F-Skirt target thickness is closely matched to the mean value of the requirement. Separately, note that the absolute highest value for these F-skirts were 357 mils.
4. Aft Skirt target thicknesses are based on values that would satisfy requirements for the thick/thin areas during one simultaneous spray operation.
5. Tunnel Covers target thickness is closely matched to the mean value of the requirement.

* The absolute highest value for these F-skirts was 357 mils, which occurred due extra pass on just one structure.

5. Cork flow rate	5. Cyclonic air pressure	5. Cure time
	6. Spray booth temperature	6. Post cure cool down time
	7. 2216 B&A temperature at gun	
	8. Atomizing air temperature	
	9. Eductor air temperature	**Raw Materials Properties**
	10. Number of coats	
	11. Delay time between coats	1. 2216 B&A activator concentration
	12. Overlap increment	2. Cork particle size distribution
	13. Application speed	3. Cork moisture
	14. Spray booth humidity	4. Glass Eccospheres density
	15. Solids feed line height	
	16. Vertical spray pattern	
	17. Nozzle types	
	18. Test delay time effect	
	19. Brush down time	
	20. MCC-1 Repair for spray interruption	

The optimum levels and upper/lower limits for the MCC-1 variables were selected using statistical analysis of the responses (density, strength, thickness, and thermal). The table 4a and 4b lists these allowable limits and optimum set points as applied to the SRB. In applications where the final MCC-1 properties are not required to be controlled as accurately as for the SRB application, the allowable range can be expanded and the cost of the MCC-1 application can be further reduced.

Table 4a. MCC-1 Process Variables - Limits for Shuttle-SRB

Flow Parameters	**Shuttle-SRB Specification (set point)**
Resin flow rate	228-244 g/min (236 g/min)
Catalyst flow rate	228-244 g/min (236 g/min)
Cork flow rate	228-244 g/min (236 g/min)
Glass eccospheres flow rate	228-244 g/min (236 g/min)
Activator concentration	0.8-1.2 wt.% of 2216A (1 wt.%)

Table 4b. MCC-1 Process Variables - Limits for Shuttle-SRB

Process Parameters	Shuttle-SRB Specification (set point)
Eductor air pressure	29-35 psi (32 psi)
2216 B/A mixer air pressure	82 psi minimum
2216 B/A temperature at gun	103-127 °F (115 °F)
Atomizing air pressure	34-48 psi (42 psi)
Cyclonic air pressure	3-9 psi (6 psi)
Stand-off distance	7" - 8.7" (8")
Spray booth temperature	73-93°F
Spray booth humidity	20%-55%
Over lap increment	0.4" - 1.3"
Table speed	N/A / 1 rpm for 160-170 mils coat
Delay between coats as follows :	
For 1/4 inch MCC-1	30 minutes minimum
Precure temperature	68-92°F
Precure time	4 hrs minimum
Cure ramp rate	5 °F per minute maximum
Cure temperature	112-200 °F
Cure time	9 hours minimum

MCC-1 process optimization is an on-going activity that has continued since the MCC-1 system installation at the production site. Figure 3 (MCC-1 density), figure 4 (Glass eccospheres properties), table 5 (MCC-1 thickness control) and figure 5 (resin flow rate) are examples of the statistical process control charts used for continuing improvement of the MCC-1 application process. Needless to say, CST™ based MCC-1 is well characterized and a proven product. By now, we have over 12 flight histories and detailed evaluation of over 62 SRB post-flight structures that all have proven performance without even a single failure or a close-call. This is a remarkable improvement over the previous sprayable materials utilized, and we believe that is so because of the depth of the evaluations carried out to guarantee a high level of success.

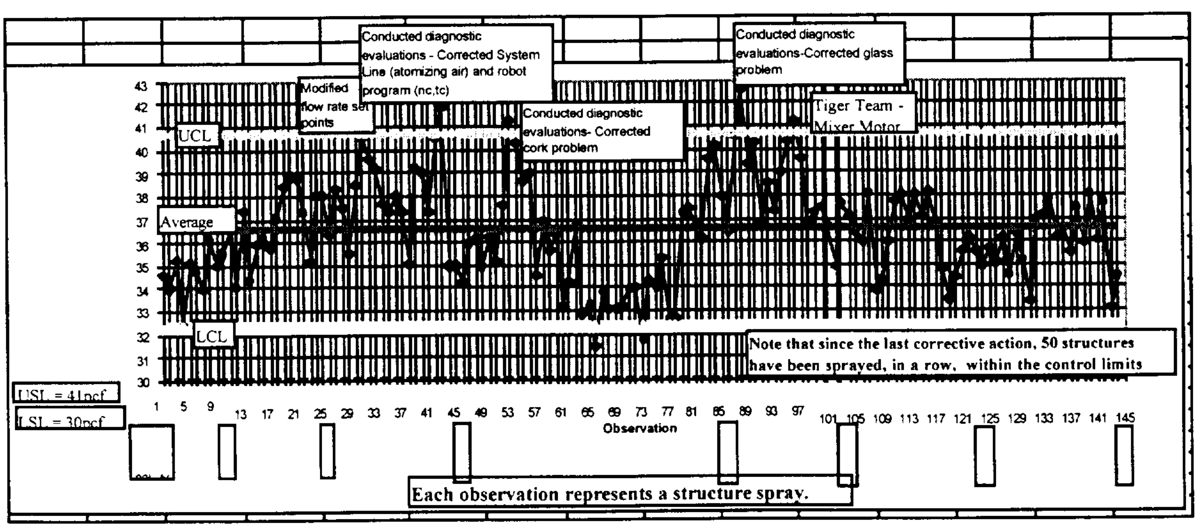


Figure 3. MCC-1 Density Control Chart