REPLACEMENT FOR A FLEX HOSE COATING AT THE SPACE SHUTTLE LAUNCH PAD

Mary Whitten
University of Central Florida
Mailstop: ASRC-24
Kennedy Space Center, FL 32899

Rubiela Vinje, Jerome Curran, and Barry Meneghelli
ASRC Aerospace
Mailstop: ASRC-24
Kennedy Space Center, FL 32899

Luz Marina-Calle
National Aeronautics and Space Administration
Mailstop: KT-E-3
Kennedy Space Center, FL 32899

ABSTRACT

Aerocoat AR-7 is a coating that has been used to protect stainless steel flex hoses at NASA's Kennedy Space Center launch complex and hydraulic lines of the mobile launch platform (MLP). This coating has great corrosion control performance and low temperature application. AR-7 was developed by NASA and produced exclusively for NASA but its production has been discontinued due to its high content of volatile organic compounds (VOC) and significant environmental impact. The purpose of this project was to select and evaluate candidate coatings to find a replacement coating that is more environmentally friendly, with similar properties to AR-7. No coatings were identified that perform the same as AR-7 in all areas. Candidate coatings failed in comparison to AR-7 in salt fog, beachside atmospheric exposure, pencil hardness, Mandrel bend, chemical compatibility, adhesion, and ease of application tests. However, two coatings were selected for further evaluation.

Keywords: flex hose coatings

INTRODUCTION

Aerocoat AR-7 is a coating that has been used to protect stainless steel flex hoses at launch complex (LC) 39 and hydraulic lines of the mobile launch platform (MLP). AR-7 was developed in 1969 by the Materials Testing Branch at NASA in association with B.F. Goodrich Company, in Akron, OH. The coating is a nitrile rubber base in methyl ethyl ketone solvent with phenolic resins for improved adhesion and aluminum powder for sacrificial protection against corrosion and added film strength. This coating has great corrosion control performance and low temperature application. AR-7 was produce exclusively for NASA but the production of the coating has been discontinued due to its high content of volatile organic compounds (VOC) and significant environmental impact. Therefore, companies were contacted and candidate coatings were selected for evaluation to find a replacement coating with similar properties to AR-7 that is more environmentally friendly.

Figure 1 shows an AR-7 coated flex hose cut into pieces. The interior portion of the flex hose is called the convoluted inner liner (CIL). The first braid around the CIL is called the inner reinforcement braid (IRB). The outer braid is called the outer reinforcement braid (ORB). Not all flex hoses have two reinforcement braids, some only have one. The figure shows an intact flex hose and the flex hose after being cut open.

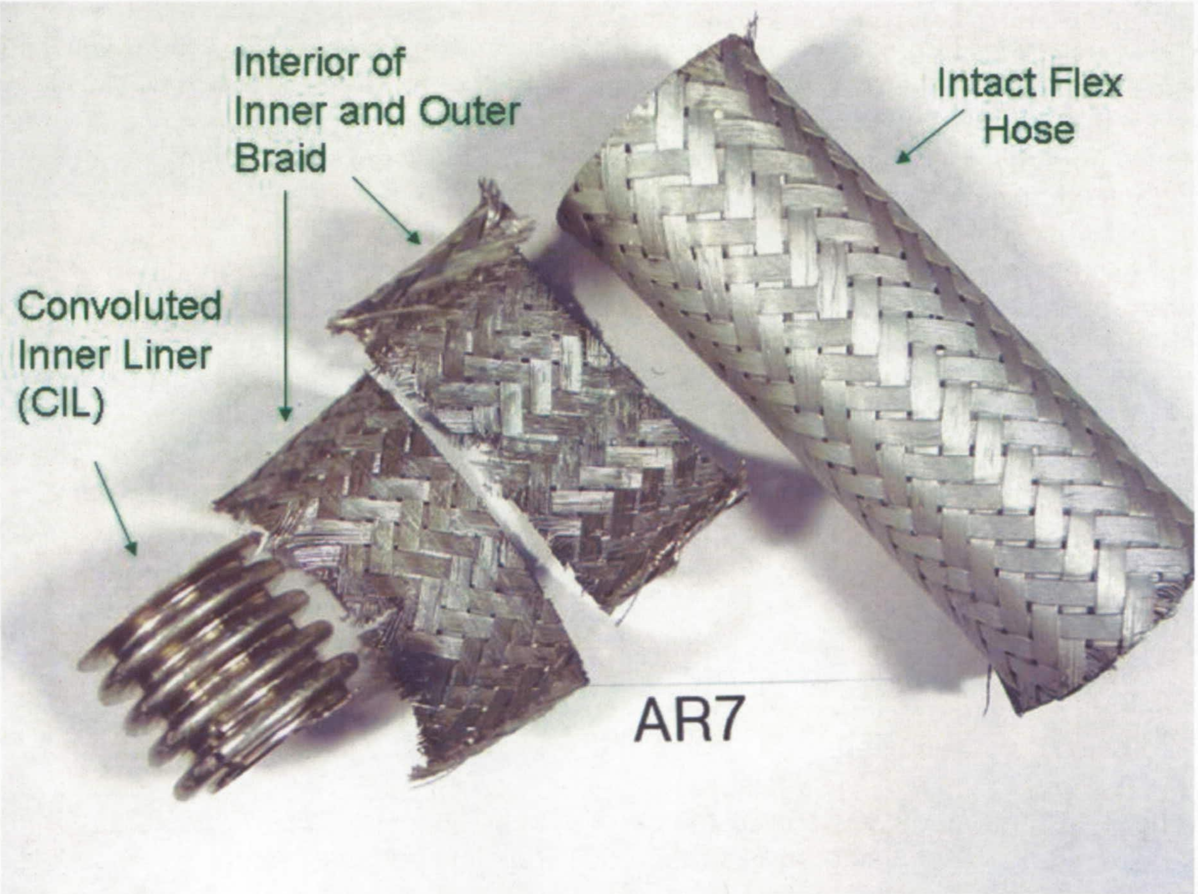

FIGURE 1 – AR-7 Coated on a Flex Hose

An ideal coating is very fluid and capable of penetrating the outer braids of a stainless steel flex hose to coat the metal hose with no more than 3 mils dry film thickness (DFT) and flexible enough to withstand the movement of the flex hose as well as the metal expansion and contraction due to changes in temperature. Ease of application and minimal sample preparation is desirable, along with durability and chemical resistance of the coating. A single component coating that could be applied by brush, spray or dipped is favorable.

After contacting numerous coating companies and explaining the unique application for the replacement coating desired, sixteen candidate coatings were selected for evaluation and comparison to AR-7.

EXPERIMENTAL PROCEDURE

Carbon steel coupons were purchased in the clean and blasted form ready for coating application.. Stainless steel coupons (304) were procured with mill finish and solvent cleaned with methyl ethyl ketone prior to coating application. The coatings were prepared following the manufacturer's specifications and applied to the metal coupons by brushing.

Several physical and chemical properties of the candidate coatings were measured and compared to AR-7. The first comparison was the ease of application. The ease of application was evaluated by the pot life of the coating and the length of time needed for the coating to dry. Ideally the coating should easily be applied to the substrate with a brush. A pot life of 45 minutes or more was practical, along with taking less than 30 minutes to dry after application.

ASTM B117 *Standard Practice for Operating Salt Spray Apparatus*[1] was used as an accelerated corrosion test. A Q-fog Cyclic Corrosion Chamber manufactured by Q-Lab was utilized for this study. Some coated samples were scribed, while others were not. The samples were subjected to a salt fog for 2000 hours. The coated panels were inspected intermittently during the 2000 hour time frame.

Atmospheric exposure of coated carbon and stainless steel panels was conducted at the Kennedy Space Center's atmospheric corrosion test site which is part of the NASA Corrosion Technology Laboratory. The atmospheric exposure test site is located approximately 100 feet from the median high tide line of the Atlantic Ocean. Ten stainless steel panels (304) and ten carbon steel panels were prepared with candidate coatings and AR-7. Half the panels remained in the marine atmosphere with no further stresses applied to the system. The other half were rinsed with simulated solid rocket booster slurry every two weeks. The slurry consisted of 28.5 grams of alumina diluted to a total volume of 500 mL with a 10% hydrochloric acid solution.

The pull-off strength of the candidate coatings and AR-7 was tested using ASTM D 4541-02, *Standard Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers.*[2] A self-alignment adhesion tester type IV was used. The brand and model was Patti 110. Size F-4 with a half inch dolly was used.

The pencil hardness study was completed per ASTM D3363 *Standard Test Method for Film Hardness by Pencil Test*[3] using an Elcometer 501 Pencil Hardness Tester.

The mandrel bend test was conducted using ASTM D 522-93a, *Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings*[4], as a guideline. Test method A was employed which utilizes the conical mandrel test apparatus. For the elongation test, the lever was moved 180 degrees over a duration time of 15 seconds. The elongation was computed using the measured distance from the farthest end of the crack to the small end of the mandrel.

Candidate coatings and AR-7 were applied on aluminum and tested for hypergol compatibility. Upon exposure to the hypergol, a similar or better reactivity than AR-7 was considered passing. A temperature increase greater than 2.8 °C after exposure to the chemical was considered a failure. Three chemicals were tested: monomethylhydrazine (MMH), hydrazine (N_2H_2), and dinitrogen tetroxide (N_2O_4).

Since the flex hoses are used with cryogenic liquids, flex hoses were coated and arranged as a flex hose manifold. Figure 2 shows the assembly. The flex hose manifold was propped up to provide for positive elevation change during liquid nitrogen flow. A 10-12" stainless steel tube (1/2" o.d.) was attached to the top (outlet) of the manifold to direct the vent stream from the manifold away from the personnel that conducted the testing. The input from the 900 gallon liquid nitrogen tank was attached to the bottom (inlet) of the manifold.

A total of five chilldown, liquid nitrogen flow and warming cycles were completed on the flex hose manifold. During each cycle, the chilldown time was 5 minutes and the liquid nitrogen flow time was 10 minutes. Each warming cycle was approximately 30 minutes in duration. Prior to the start of each cycle, all coated flex lines were inspected for signs of wear.

A liquid nitrogen bath was used to simulate cryogenic spillage or other direct exposure of the flex hose manifold. The manifold was tested in two sections since it could not be totally immersed in the bath at one time. Prior to immersion, the manifold was allowed to warm to ambient temperature, purged with gaseous nitrogen, and capped at both ends. The cap on the ambient end of the manifold was loosened to allow for the escape of any trapped gas inside the manifold. The submerged end of the manifold remained in the bath for 5 minutes after quenching had subsided. After the manifold was allowed to warm-up, this process was repeated by switching submerged and ambient ends of the manifold. All flex lines were inspected after direct exposure in the liquid nitrogen bath.

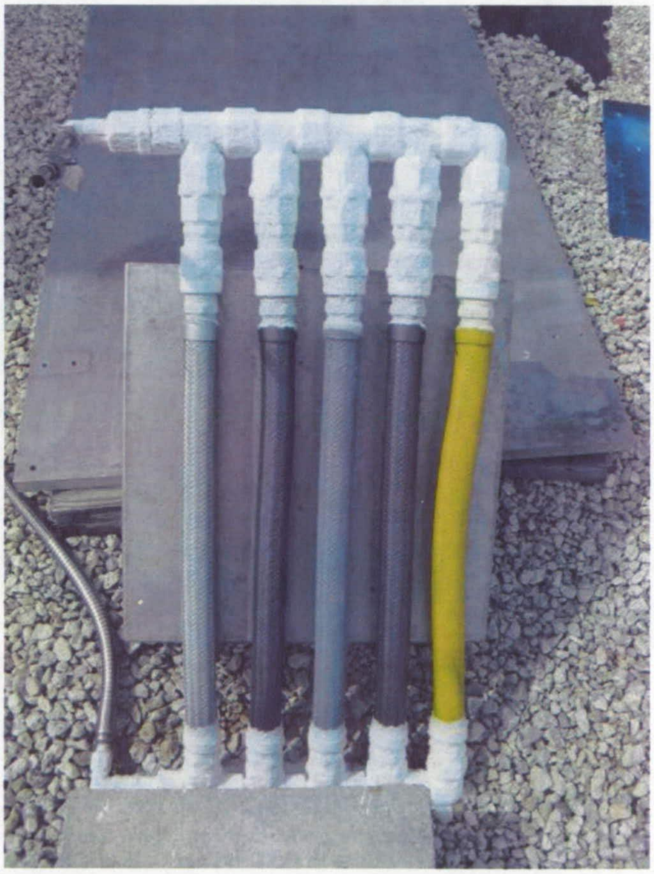

FIGURE 2 – Flex hose manifold.

RESULTS

The candidate coatings were compared to AR-7 in physical and chemical tests. If the candidate coating performed similarly or better than AR-7, the coating passed the test. Table 1 summarizes the results.

For ease of application, AR-7 has a pot-life of 45 to 60 minutes. The paint had to be constantly agitated to keep the paint uniformly mixed. Two coating applications were necessary to obtain 3 mils for the required dry film thickness. AR-7 was thoroughly dried after 30 minutes. In comparison to AR-7 as seen in Table 1, Candidates 1, 3, 4, 5, 8, 11, 12, 13, 15 and 16 were not easily applied to the substrate. More specifically, Candidates 1, 11, 12, 13, 15, and 16 had curing issues. They were still wet or tacky after 336 hours. Candidates 3 and 8 had too short of a pot-life. Candidate 4 was too thick for easy application, and Candidate 5 caused flash rust on the panels prior to drying.

TABLE 1
SUMMARY OF PHYSICAL AND CHEMICAL TESTS OF CANDIDATE COATINGS

Product	**Application**	**Salt Fog**	**Atmospheric Beach Exposure**	**Adhesion**	**Pencil Hardness**	**Mandrel Bend**	**MMH**	**Hydrazine**	**Dinitrogen tetroxide**	**Cryogenic Tests**
AR-7	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control
Candidate 1	Fail	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Candidate 2	Pass	Fail	N/A	Pass	Fail	Pass	Fail	Fail	Fail	N/A
Candidate 3	Fail	Fail	Fail	Pass	Pass	Fail	Fail	Pass	Fail	N/A
Candidate 4	Fail	Fail	Fail	Pass	Pass	Fail	Pass	Pass	Fail	N/A
Candidate 5	Fail	Fail	Pass	Pass	Pass	Pass	Fail	Pass	Fail	N/A
Candidate 6	Pass	Pass	Pass	Pass	Fail	Pass	Pass	Pass	Fail	Pass
Candidate 7	Pass	Fail	Fail	Pass	Pass	Pass	Pass	Pass	Pass	N/A
Candidate 8	Fail	Pass	Pass	Pass	Pass	Pass	Fail	Pass	Fail	N/A
Candidate 9	Pass	Pass	Pass	??	Fail	Pass	Pass	Pass	Fail	Pass
Candidate 10	Pass	Pass	Fail	Pass	Pass	Fail	Fail	Pass	Fail	Pass
Candidate 11	Fail	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Candidate 12	Fail	Fail	Pass	Fail	Fail	Fail	Fail	Pass	Fail	N/A
Candidate 13	Fail	Fail	Fail	Fail	Fail	Fail	N/A	N/A	N/A	N/A
Candidate 14	Pass	Fail	N/A	Pass	Fail	Pass	Fail	Fail	Fail	N/A
Candidate 15	Fail	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Candidate 16	Fail	Fail	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

After 2000 hours in the salt fog chamber per ASTM B117, AR-7 and the candidate coatings were evaluated. Three different ASTM methods were used to evaluate the panels. The first was ASTM D 1654-05 *Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments.*[5] This method is used as a basis to evaluate corrosion, blistering and adhesion in the area of a scribe on a panel. A rating number of 10 is the best evaluation a panel can receive, with zero being the worst. AR-7 received a rating of 7 after 2000 hours in the salt fog. The second method used was ASTM D 610 -01 *Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces.*[6] A panel with no rusting would receive the highest rating of 10. The percent of rusting of a panel increased with a decreasing rating number. The letter after the number for this method designated the type of corrosion present, spot (S), general (G), or pinpoint (P). After 2000 hours in the salt fog, AR-7 had a rating of 8G. The third ASTM method used for the evaluation of the coatings was ASTM D 714-02, *Standard Test Method for Evaluating Degree of Blistering of Paints.*[7] AR-7 received a rating of Size 6 Medium. Figure 3 shows carbon steel panels coated with AR-7 after 2000 hours in the salt fog chamber. Three panels were not scribed, and two panels were.

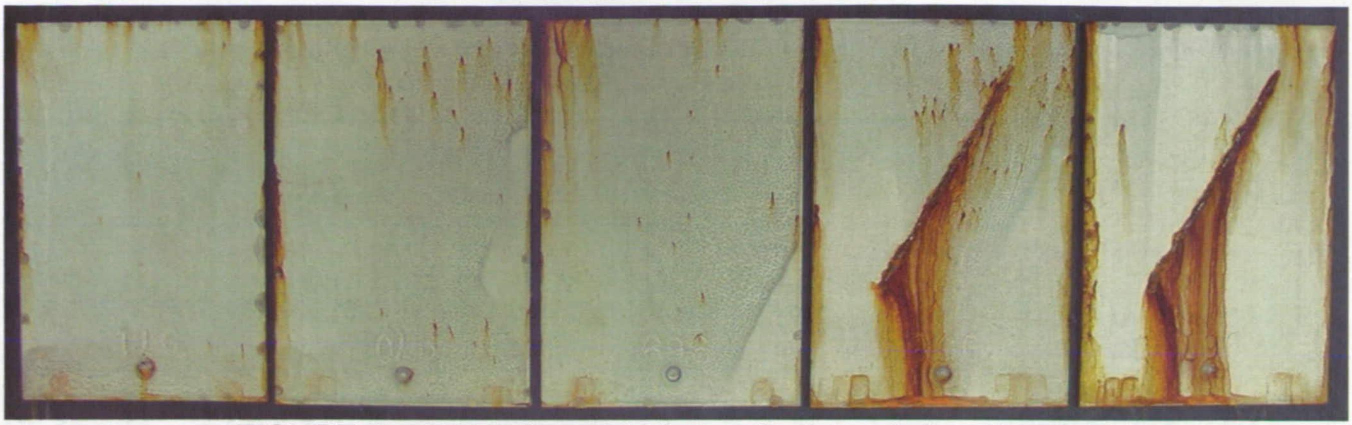

FIGURE 3 – AR-7 after 2000 hours in the salt fog chamber.

As seen in Table 1, Candidates 6, 8, 9, and 10 performed the same or better than AR-7 after being in the salt fog chamber for 2000 hours. Candidate coatings with an 'N/A' were not placed in the chamber because they never cured properly. Candidate coatings which failed performed worse than AR-7.

After 3 months at the beachside atmospheric exposure test site, Candidates 3, 4, 7, 10, and 13 did not perform as well as AR-7 as seen in Table 1. Candidates 3, 4, 7, and 13 showed corrosion in the center of the coated carbon steel panels. The corrosion was evident on the panels rinsed with the solid rocket booster slurry simulant and the non-rinsed panels. The Candidate 10 coating on the stainless panels which was rinsed with the solid rocket booster slurry simulant started to delaminate from the bottom, as seen in Figure 4. Candidate 2 was not placed at the beach, since it corroded too easily in the salt fog chamber. Candidate 16 was still tacky, so it did not cure very well and was not included in the atmospheric exposure test.

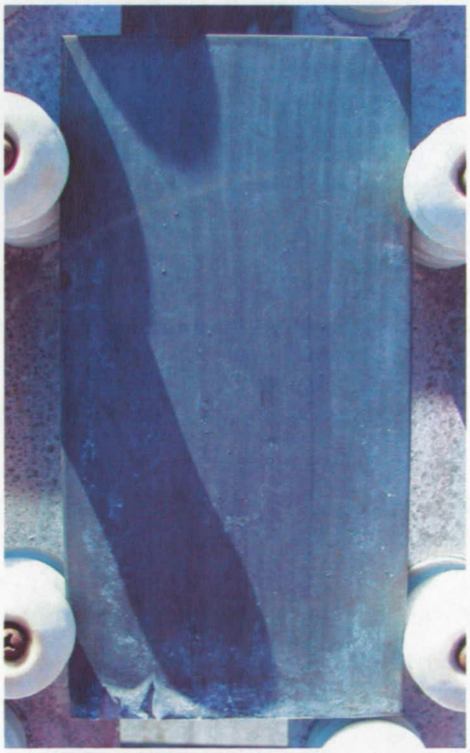

FIGURE 4 - Candidate 10 Delaminating from Bottom of Panel

The pull off tensile strength calculated using the results from the adhesion tester for AR-7 was 26 psia. Candidates 12 and 13 failed; because the calculated pull off tensile strength was lower than that of AR-7. The dolly used for the adhesion tester did not adhere to Candidate 9. Several epoxies and glues were utilized but the adhesive would not adhere to the surface. Therefore, the pull off tensile strength could not be determined for Candidate 9.

AR-7 has a moderate pencil hardness of 2H. Candidates 9, 12, and 13 were extremely soft with a rating of less than 6B. Candidates 2 and 6 had a rating of 3B. Candidate 14 had a rating of F. Since these coatings were softer than AR-7, they did not perform as well as AR-7 in the pencil hardness test. The remaining Candidate coatings tested were as hard as or harder than AR-7 as seen in Table 1.

To show an example of the extent a panel was bent, Figure 5 shows a Candidate 6 three by five panel after the Mandrel Bend test. The coating did not crack or peel as a result of being elongated. AR-7 performed very well in the Mandrel Bend test also. There were no cracks evident in the coating after the coated panel was bent over a conical apparatus. AR-7 is very flexible. Candidates 3, 4, 10, 12, and 13 cracked upon being bent. Since the coatings are being tested for use on a flex hose, flexibility of the coating was important. Candidates 2, 5, 6, 7, 8, 9, and 14 showed no signs of cracks after being elongated as seen in Table 1.

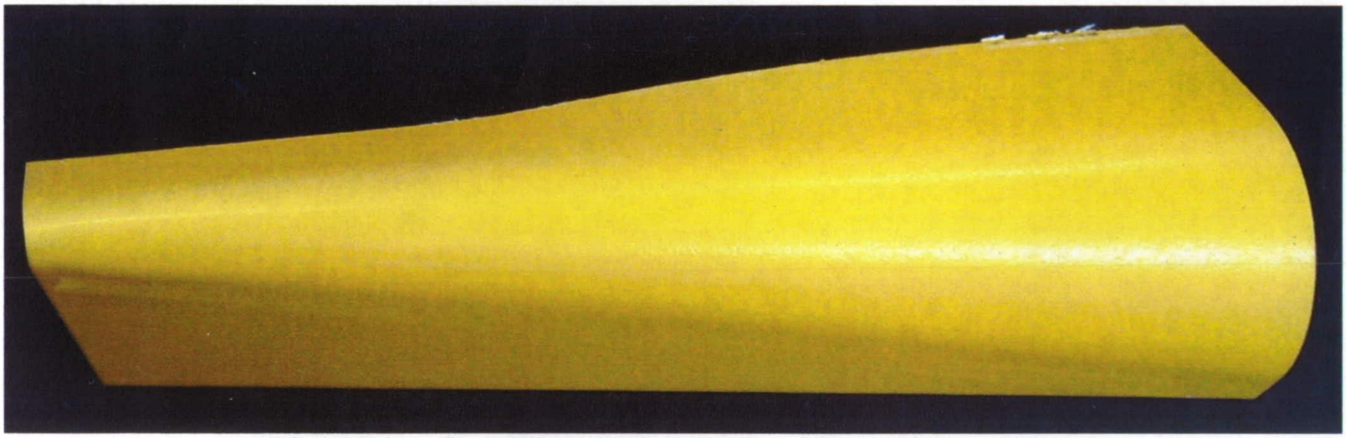

FIGURE 5 – Candidate 6 Panel after Mandrel Bend Test.

When AR-7 was exposed to the chemicals monomethylhydrazine, hydrazine, and dinitrogentetroxide, the coating roughened and bubbled. Therefore, if candidate coatings had a similar or less of a reaction to the reactive species, it passed the test. Many of the candidate coatings failed when exposed to monomethylhydrazine and dinitrogentetroxide due to the coating delaminating from the metal surface.

Candidates 6, 7, and 9 had the passed the higher number of tests that compared the coatings to AR-7. Candidates 6 and 9 were chosen to be tested under cryogenic conditions. Candidate 7 was not chosen due to the poor performance at the atmospheric beach corrosion test site. The durability of a coating to protect the base metal in the hot, humid conditions at the Kennedy Space Center is paramount for a successful replacement to AR-7. Candidate 10 was also subjected to cryogenic tests, since it was currently being used at non-launch facilities at the space center.

Figure 6 shows the manifold after both cryogenic tests were completed. In the first test, cryogenic liquid nitrogen was pumped through the manifold. In the second test, the manifold was dipped in liquid nitrogen. Figure 6 shows from left to right: AR-7, Candidate 10, Candidate 9, Candidate 10 (diluted), and Candidate 6.

FIGURE 6 - Flex Hose Manifold Post-Immersion Warm-Up

None of the coatings showed any observable signs of wear during either the flow-thru or immersion testing using liquid nitrogen. No cracking or peeling of the coatings was observed on any of the flex lines.

CONCLUSIONS

AR-7 outperformed all the coatings included in the study to find a coating for its replacement. Of the coatings tested, Candidate 6 performed the best, being softer than AR-7 and partially delaminating upon exposure to dinitrogen tetroxide as the only failures. Candidate 9 performed similarly to Candidate 6. However, the test for adhesion for this coating could not be completed due to the inability of the epoxy glue to adhere to the coating. Candidate 10 is currently used in some applications at the space center. However, it failed in comparison to AR-7 during the mandrel bend test, upon subjection to a solid rocket booster slurry simulant at the beach on stainless steel, and upon exposure to MMH and dinitrogen tetroxide.

The performance of the candidate coatings at the atmospheric corrosion test site is vital for the coating to be considered as an alternative coating for use in place of AR-7. The results for three months exposure were presented, but a lengthier stay at the beach site is necessary for a full evaluation of Candidate 6 and Candidate 9 for use on NASA's Kennedy Space Center launch complex and hydraulic lines of the mobile launch platform.

ACKNOWLEDGEMENTS

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