Failure Analysis of In-Flight Refueling System of Super Sonic Aircraft's Hose

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Abstract— In the pursuit of attaining cutting technologies it is a prudent and efficient way to have an airborne fuel station and in-fight refuelling feature added to the advanced generation of aircraft. The 'in-flight' refuelling system essentially consists of hose (flexible pipe), drogue chute, receptacle and the winding cage. The hose is integrated with the mother aircraft refueling system on the air platform structure which is kept in a rolled condition over a roller with guiding mechanism for uniform winding of the hose all over the roller width. The end of hose is connected to the mother aircraft refueling tank while the other end which comes out of the aircraft through a drogue chute. This drogue chute uses its aerodynamic drag in a moving air platform to the receiving which flies at little lower altitude so as to allow the hose in being unrolled to come in contact with to receiving ATF (aviation turbine fuel) through the mid air refuelling port. After the refuelling is complete the mother aircraft pulls back the mid air refueling hose to once again pack it on the roller through the guide mechanism. An operator of one of advanced generation aircraft having the feature of mid air refueling hose was stationed at DMSRDE Kanpur for a major defect / failure, making the hose unserviceable which occurred during one refueling exercise wherein the top most portion of the Elastomeric layer had given way to cleavage with exposed helical and braided reinforcement provided for avoiding formation of kink which was deformed and damaged. The assigned objective was to determine the cause of this failure and suggest design modification in hose construction to avoid recurrence of this kind of failure which has a very critical rolled to play from strategic angles . The aerodynamic assessment was done and the material was put to various test such as DSC, TGA, SEM, EDAX and we analysis. Based on the aerodynamic assessment it indicated that the maximum splashing of the hose occurred during rolled backed of the hose in view of roll back tendency against the G-effect (Gravitational effect) and the aerodynamic drag. The elastomeric covering also was studied in detail with the most advanced instrumental techniques having the likely hood of ageing phenomena. Although the elastomeric layer was found to be chemically in good compositional condition still the permanent set in the rubber lining which is under maximum stress during winding being the outer most lining was found to be significant and thus the permanently stressed zone leading to reduction in resilience of the elastomer . Further the compression set is a temperature dependent phenomenon, which is high in tropical country and thus is the most likely cause of failure. Also as the drag is proportional to the square of relative air speed therefore a reduction of the fuel transfer IAS (Indicative air speed) can prevent such a phenomenon. Therefore an improved rubber lining with lower drag coefficient and suiting Indian conditions where the average temperature are high as compared with the temperate conditions with lower platform cruise speed till the refueling hose winding is complete can prevent recurrence of such a phenomenon.

Key words: re-fuelling, in-flight, air platform, aerodynamic drag, winding, resilience, indicated air speed, DSC, TGA, SEM, EDAX

I. INTRODUCTION

Air-to-Air refuelling (AAR) or tanking, is the process of transferring fuel from one aircraft (the tanker) to another (the receiver) during flight. Aerial refuelling, also called air refuelling, or in-flight refuelling (IFR)[1], The aviation pioneer Alan Cobham bought a patent from David Nicolson and John Lord for £480 each and then started development of the Grappled-line looped-hose air to air refueling system, which while complex in operation, was the world's first practical air-to-air refueling system and gave public demonstrations of the system[2,3], FRL realized that their looped-hose system left a lot to be desired and began work on an improved system that is now commonly called the probe-and-drogue air-to-air refuelling system and today is one of the two systems chosen by air forces for air-to-air refueling[4], The first non-stop circumnavigation of the globe proved that, because of aerial refuelling, vast distances and geographical barriers were no longer an obstacle to military air power. Normally two planes are used for in-flight refueling[5,6],In 1949 four additional ARS units were organized by the USAF and both the 43d and 509th ARS became fully operational. The first use of aerial refuelling in combat took place during the Korean War, involving F-84 fighter-bombers flying missions from Japanese airfields refuelling from converted B-29s using the drogue-and-probe in-flight refuelling system with the probe located in one of the F-84's wing tip fuel tanks.[7].

II. OBJECTIVE

To carry out failure analysis of in-flight refuelling hose which failed in air while in use during transfer of fuel from the mother aircraft to the receiving aircraft while in flight at around 750 km/hr IAS and 300 meters altitude.

Fig. 1: Close –up photograph of the damaged - area of the mid-air refuelling hose.

III. LITERATURE REVIEW

During the past half century the world has made seemingly smaller progress as compared to the progress of travel by flying. Commercial airports are very busy places and offer a vast choice of destinations for the business and pleasure travel, such operations are partly attributable to the advanced state of technology of the aircraft in that plane may land after a long distance flight and be ready to disembark on another in couple of hours. Helping to achieve this efficiency is the speedy refuelling of the aircraft whilst other operations are carried out, not only is this task required to be quick, since an average 747 requires at least 1 hours per side for fuel refuelling, but it also needs to be safe to both the refuelling technician and other airport users, including arriving/departing passengers, also the aircraft operates from cold to hot and hot to cold climates so it is essential that the fuel conveying equipment is just as efficient under these temperature extremes. The refuelling operation requires fuel to be transferred from a tanker or bowser to an aircraft as quickly and safely as possible. This is usually achieved by a flexible conduit to transfer the fuel under pressure therefore a hose is employed for this purpose. The aircraft, as stated earlier, may be being refuelled in any part of the world therefore the hose is expected to provide the same function under various weather conditions. It was inevitable that eventually specifications would be required for the hoses used in aircraft refuelling applications and the current specification, BS3158:1985(specification for rubber hose and hose assemblies for aircraft ground fuelling and defuelling), covers the hose requirements used in commercial aircrafts, and was based on an old ministry of defence specification, Another specification is AP11528 (American petroleum institute) but a European standard is soon to be issued, namely EN1361, which combines both BS3158 and AP1529. The current specifications were developed from the need to satisfy a certain operational and safety criteria and were based on years of accumulated knowledge of aircraft fuels, hose design, environmental conditions and service requirements. It is therefore logical that the finished hose design would reflect these aspects in its construction.

In 1929, a group of U.S. Army Air Corps fliers, led by then Major Carl Spaatz, set an endurance record of over 150 hours with the Question Mark over Los Angeles. Between June 11 and July 4, 1930, the brothers John, Kenneth, Albert, and Walter Hunter set a new record of 553 hours 40 minutes over Chicago using two Stinson SM-1 Detroiters as refueller and receiver. Aerial refuelling remained a very dangerous process until 1935 when brothers Fred and Al Key demonstrated a spill-free refueling nozzle, designed by A. D. Hunter. They exceeded the Hunters' record by nearly 100 hours in a Curtiss Robin monoplane, staying aloft for more than 27 days .

The US was mainly concerned about Trans-Atlantic flight for the faster postal service between Europe and America. In 1931 W. Irving Glover, the second assistant postmaster, wrote an extensive article for Popular Mechanics concerning the challenges and the need for such a regular service. In his article he even mentioned the use of Aerial refueling after takeoff as a possible solution. There were parallel experiments conducted in Europe; at Le Bourget the Aero-Club de France and the 34th Aviation Regiment of the French Air Force were able to demonstrate passing fuel between machines at the annual aviation fete at Vincennes in 1928. The UK's Royal Aircraft Establishment was also trialing refueling-in-mid-air, with the aim to use this technique to extend the range of the long-distance flying boats that serviced the British Empire. By 1931 they had demonstrated refueling between two Vickers Virginias, with fuel flow controlled by an automatic valve on the hose which would cut off if contact was lost.

IV. DETAILS OF INSTRUMENTAL EXPERIMENTATION AND APPARATUS

In the present study the following techniques for the characterization of the air refuelling hoses.

A. *Thermal Analysis:*

- Differential scanning calorimetry (DSC)
- Thermogravimetric analysis (TGA)

B. *Energy Dispersive X-ray (EDX) Elemental analysis*

C. *Scanning Electron Microscope (SEM)*

1) *Differential Scanning Calorimetry (DSC):*

Differential scanning calorimetry or DSC is a thermo analytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature. Both the sample and reference are maintained at nearly the same temperature throughout the experiment. Generally, the temperature program for a DSC analysis is designed such that the sample holder temperature increases linearly as a function of time. The reference sample should have a well-defined heat capacity over the range of temperatures to be scanned.

The technique was developed by E.S. Watson and M.J. O'Neill in 1960, and introduced commercially at the 1963 Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy. The term DSC was coined to describe this instrument which measures energy directly and allows precise measurements of heat capacity.

2) *Thermo gravimetric Analysis (TGA):*

Thermo gravimetric analysis (TGA) is the most widely used thermal method. It is based on the measurement of mass loss of material as a function of temperature. In Thermo gravimetric a continuous graph of mass change against temperature is obtained when a substance is heated at a uniform rate or kept at constant temperature. A plot of mass change versus temp (T) is referred to as the Thermo gravimetric curve (TG curve) TG curve help in revealing the extent purity of analytical sample and in determining the mode of their transformation within specified range of temperature.

Energy Dispersive X-ray (EDX) Elemental Analysis: Energy-dispersive X-ray spectroscopy (EDX) is an analytical technique used for the element analysis or chemical characterization of a sample. It is one of the variants of x-ray fluorescence spectroscopy which relies on the investigation of a sample through interactions between electromagnetic radiation and matter, analyzing x-rays emitted by the matter in response to being hit with charged particles.

EDX characterization capabilities are due in large part to the fundamental principle that each element has a unique atomic structure allowing X-rays that are characteristic of an element's atomic structure to be identified uniquely from one another.

3) Scanning Electron Microscope (SEM):

The SEM produces three principal images: secondary electron images, backscattered electron images, and elemental x-ray maps. Secondary and backscattered electrons are conventionally separated according to their energies. They are produced by different mechanisms. When a high-energy primary electron interacts with an atom, it undergoes either inelastic scattering with the atomic electrons or elastic scattering with the atomic nucleus. In an inelastic collision with an electron some amount of energy is transferred to the other electron.

V. EXPERIMENTALS OUTCOME DATA AND TRACES

A. Discussion of DSC traces:

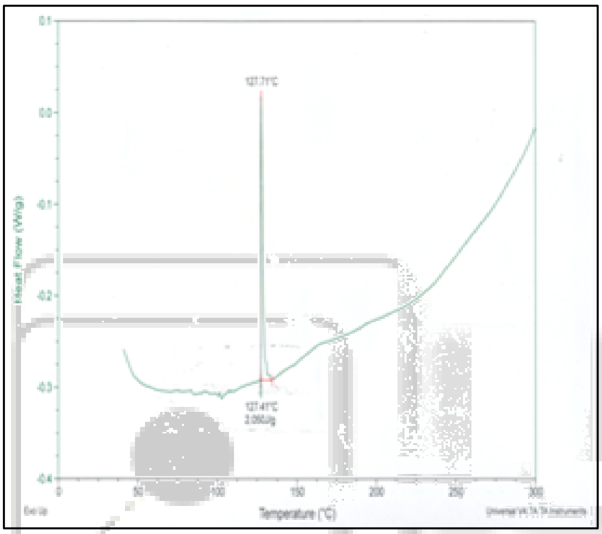

Fig. 2:

The DSC traces indicate that transitions occurring at 77 and 127 C in the given sample. This accounts for the mild variance in the chemical composition in as far as the macromolecular weight is concerned, nevertheless the phenomenon can be explained in terms of residual curing which is deliberately built in the material to provide the desired long range elasticity in the material.

The exotherms at 77 and 127 are thus the transitions for the curing of the material. The shift in the points of exotherms indicate the compositional difference as explained above and the extent of degradation in terms of compression set as also is evident from the SEM of the damaged area accounting for the variance in the extent of release of energy in the two different cases shown as peaks in the traces.

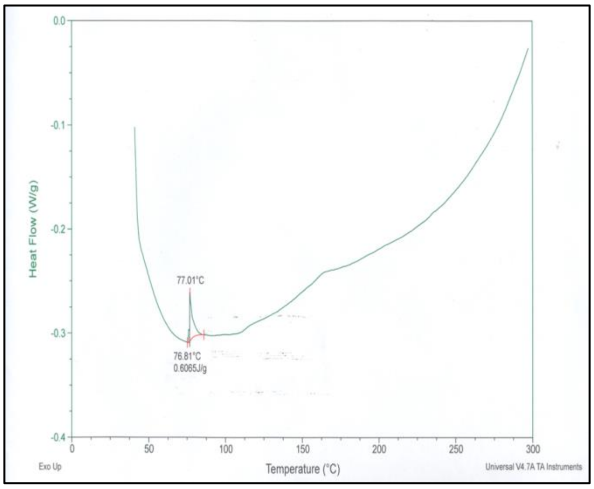

Fig. 3: DSC Trace 2

B. Discussion of TGA traces:

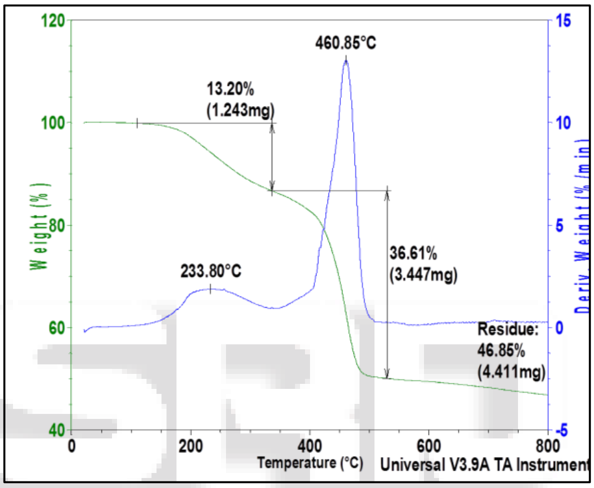

Fig. 4: TGA Trace 1

The two Thermo gravimetric traces indicate that the samples have shown degradation pattern in terms of weight loss with increasing temperature of 20^0 C per minute, the first step indicates the condition of polymer part, the second phase indicates the presence of reinforcing filler as carbon and the residual step indicates presence if inorganic fillers and the char of polymer matrix. The similarity indicates uniformity of the material in as far as the composition is concerned.

The point of interest is that the degradation in terms of weight loss is around 100^0 C which has been the temperature of the exotherms in DSC traces. This indicates in general that the temperature of degradation is reasonably safe from the end use conditions where the maximum expected temperature is likely to be below 100^0 C and also ensures that the external environmental degradation due UV radiation, ozone etc. is ruled out. Only the permanent set in tropical conditions has been the mode of degradation from the inner side which also shown in SEM pictures.

The blue trace indicates the first derivative of the weight loss with temperature and the peaks arte the characteristic of the given material also known as maximum decomposition temperature. In both the cases these T (max) is similar hence proving the material uniformity.

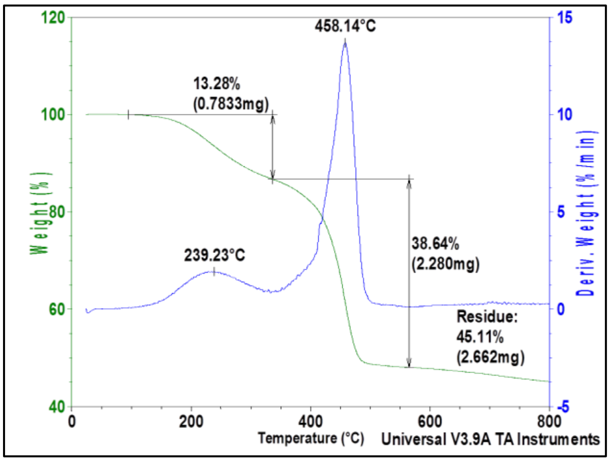

Fig. 5: TGA

Sl. No.	Temperature (^{0}C)	Weight (%)	Deriv. Weight (%min)	Sl. No.	Temperature (^{0}C)	Weight (%)	Deriv. Weight (%min)
1	30.00	100.0	−0.03515	34	360.00	85.57	1.069
2	40.00	100.0	0.02805	35	370.00	85.00	1.237
3	50.00	100.0	0.03308	36	380.00	84.34	1.400
4	60.00	100.0	0.03042	37	390.00	83.59	1.573
5	70.00	100.0	0.04161	38	400.00	82.76	1.771
6	80.00	100.0	0.05010	39	410.00	81.77	2.512
7	90.00	99.99	0.06985	40	420.00	80.06	4.267
8	100.00	99.95	0.08761	41	430.00	77.47	6.128
9	110.00	99.90	0.1138	42	440.00	73.96	7.919
10	120.00	99.84	0.1433	43	450.00	69.39	10.63
11	130.00	99.75	0.1971	44	460.00	63.30	13.04
12	140.00	99.64	0.2649	45	470.00	57.05	11.10
13	150.00	99.48	0.3624	46	480.00	52.75	5.798
14	160.00	99.26	0.5365	47	490.00	51.04	1.677
15	170.00	98.96	0.7092	48	500.00	50.56	0.5416
16	180.00	98.54	0.9345	49	510.00	50.36	0.2686
17	190.00	97.99	1.290	50	520.00	50.22	0.2662
18	200.00	97.24	1.646	51	530.00	50.09	0.2603
19	210.00	96.38	1.790	52	540.00	49.97	0.2704
20	220.00	95.48	1.833	53	550.00	49.85	0.2116
21	230.00	94.55	1.870	54	560.00	49.75	0.1837
22	240.00	93.61	1.886	55	570.00	49.68	0.1463
23	250.00	92.68	1.845	56	580.00	49.61	0.1216
24	260.00	91.76	1.784	57	590.00	49.55	0.1351
25	270.00	90.89	1.684	58	600.00	49.47	0.1720
26	280.00	90.08	1.554	59	610.00	49.39	0.1907
27	290.00	89.34	1.409	60	620.00	49.29	0.2095
28	300.00	88.67	1.284	61	630.00	49.18	0.2128
29	310.00	88.06	1.134	62	640.00	49.06	0.2211
30	320.00	87.51	1.049	63	650.00	48.94	0.2343
31	330.00	87.02	0.9539	64	660.00	48.82	0.2213
32	340.00	86.54	0.9151	65	670.00	48.69	0.2285
33	350.00	86.08	0.9621	66	680.00	48.56	0.2640
Sl. No.	Temperature (^{0}C)	Weight (%)	Deriv. Weight (%min)	Sl. No.	Temperature (^{0}C)	Weight (%)	Deriv. Weight (%min)
67	690.00	48.44	0.2518	73	750.00	47.53	0.2707
68	700.00	48.30	0.2922	74	760.00	47.38	0.2700
69	710.00	48.14	0.3874	75	770.00	47.25	0.2552
70	720.00	47.97	0.3147	76	780.00	47.12	0.2774
71	730.00	47.81	0.2819	77	790.00	46.99	0.2444
72	740.00	47.66	0.3086	78	800.00	46.85	0.2642

Table 1: Data Of Tga Trace 1

Sl. No.	Temperature (^0C)	Weight (%)	Deriv. Weight (%min)	Sl. No.	Temperature (^0C)	Weight (%)	Deriv. Weight (%min)
1	30.00	100.0	−0.01376	10	120.00	99.84	0.1581
2	40.00	100.0	0.02607	11	130.00	99.74	0.2069
3	50.00	100.0	0.02443	12	140.00	99.61	0.2951
4	60.00	100.0	0.03596	13	150.00	99.43	0.4249
5	70.00	100.0	0.04234	14	160.00	99.17	0.6145
6	80.00	100.0	0.04365	15	170.00	98.81	0.8137
7	90.00	100.0	0.05901	16	180.00	98.34	1.061
8	100.00	99.96	0.08432	17	190.00	97.74	1.302
9	110.00	99.91	0.1204	18	200.00	97.03	1.563

Table 2: Data Of Tga Trace 2

Sl. No.	Temperature (^0C)	Weight (%)	Deriv. Weight (%min)	Sl. No.	Temperature (^0C)	Weight (%)	Deriv. Weight (%min)
19	210.00	96.21	1.744	49	510.00	48.60	0.2894
20	220.00	95.31	1.861	50	520.00	48.47	0.2304
21	230.00	94.36	1.928	51	530.00	48.35	0.2205
22	240.00	93.40	1.911	52	540.00	48.25	0.2017
23	250.00	92.45	1.838	53	550.00	48.16	0.1642
24	260.00	91.55	1.739	54	560.00	48.09	0.1179
25	270.00	90.70	1.621	55	570.00	48.03	0.1136
26	280.00	89.92	1.483	56	580.00	47.97	0.1274
27	290.00	89.21	1.330	57	590.00	47.89	0.1648
28	300.00	88.57	1.188	58	600.00	47.80	0.1854
29	310.00	87.99	1.044	59	610.00	47.70	0.2075
30	320.00	87.47	0.9764	60	620.00	47.60	0.2104
31	330.00	87.01	0.9985	61	630.00	47.49	0.2114
32	340.00	86.56	0.9349	62	640.00	47.38	0.2373
33	350.00	86.09	0.9729	63	650.00	47.26	0.2261
34	360.00	85.55	1.157	64	660.00	47.14	0.2693
35	370.00	84.90	1.457	65	670.00	47.01	0.2408
36	380.00	84.10	1.762	66	680.00	46.89	0.2508
37	390.00	83.17	2.062	67	690.00	46.75	0.2714
38	400.00	82.09	2.354	68	700.00	46.59	0.3539
39	410.00	80.77	2.920	69	710.00	46.42	0.3584
40	420.00	78.80	4.700	70	720.00	46.26	0.2861
41	430.00	75.92	6.764	71	730.00	46.11	0.2914
42	440.00	72.02	8.893	72	740.00	45.95	0.3142
43	450.00	66.84	12.23	73	750.00	45.81	0.2551
44	460.00	60.19	13.57	74	760.00	45.67	0.3003
45	470.00	54.10	10.18	75	770.00	45.53	0.2573
46.	480.00	50.39	4.608	76	780.00	45.39	0.2963
47	490.00	49.11	1.179	77	790.00	45.25	0.2755
48	500.00	48.77	0.4247	78	800.00	45.11	0.2829

Table 3:

VI. DISCUSSION OF EDAX TRACES

The EDAX analysis indicates that the sample contained nitrogen and chlorine apart from carbon and other commonly found elements in a cured rubber. This is a clear indication from the established literature that the rubber is a homogenous blend of Nitrile and neoprene rubber both these rubbers have separate role to play. On one hand Nitrile provides fuel resistance and the neoprene rubber provides the resistance towards environmental degradation. The presence of sulphur indicates the rubber is sulphur cured. The other elements present are due to the accelerator activators etc.

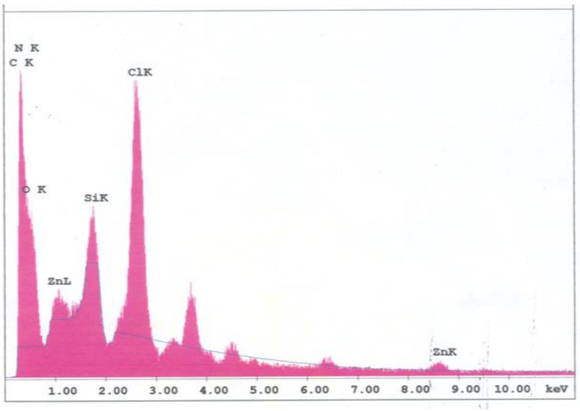

Fig. 6: Edx Trace 1

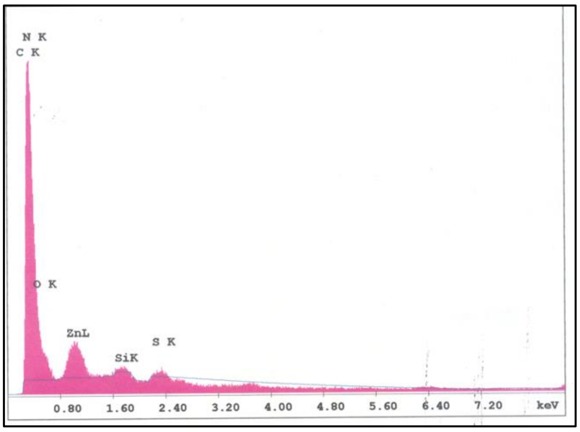

Fig. 7: Edx Trace 2

VII. CONCLUSION

At the outset the digital photographs of the damaged hose it appears that failure has taken place only at certain localized areas as the cleavage of rubber lining and little reinforcement eruption is seen only at two places.

The aircraft fuel transfer is a microprocessor controlled phenomenon with flight data recording which has not shown any anomaly hence excessive internal pressure were never achieved.

The TGA indicated that the rubber was only reasonably stable in the air environment and decomposition started around 130 0C.

The two DSC traces are indicating different transition temperatures widely at variance.

SEM micrographs indicate the crescents of permanent sets indicated two zones of degraded and not degraded outer most stressed linings.

EDAX trace shows presence of a polymer blend giving opportunity for going in for better weathering resistant material for tropical conditions.

The hardness data taken on the different locations by Durometer, shore 'A' also variance, which varied from 70-85 shore 'A'.

Hence excessive bending of the hose whose outer lining has already aged must have undergone excessive compression load during the bending while re-winding operation leading to the reported failure.

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