THE USE OF ZYLON FIBERS IN ULDB TENDONS

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ABSTRACT

Early in the development of the Ultra Long Duration Balloon (ULDB), Zylon was selected as the tendon material due to its favorable stress-strain properties. It is a next generation fiber whose strength and modulus are almost double those of the Kevlar fibers. In addition there are two versions of the Zylon, As Spun (AS) and High Modulus (HM). Data will be presented on why HM was chosen. Early in the development process, it was learned that this material exhibited an unusual sensitivity to degradation by ambient light. This is in addition to the expected sensitivity to UV radiation (Ultraviolet). The fiber manufacturer reported all of these properties in their literature. Due to the operating environment of the ULDB it is necessary to protect the tendons from both visible and UV radiation. Methods to protect the tendons will be discussed. In addition, information on the long term exposure of the braided tendon over a thirty-two month period in a controlled manufacturing plant will be provided. Special testing methods will be noted.

TENDON TYPES CONSIDERED FOR THE ULDB PROJECT

The ULDB tendon material had many criteria for selection. These included but were not limited to endurance in high and low temperature environments, high tenacity, low elongation, high strength to weight ratio and UV resistance. Several fibers were initially investigated by Raven Industries. These included, Zylon, Kevlar and Vectran.

A major criteria for the ULDB tendon material was the strength to weight ratio. The material has to be strong enough to withstand the pressures of an inflated balloon and support the balloon payload

Table 1. Comparison of mechanical properties of considered fibers

TYPE OF FIBER	TENSILE STRENGTH (gpd)	ELONGATION AT BREAK (%)	TENSILE MODULUS (gpd)
Kevlar	22	2.4	850
Carbon	23	1.5	1480
Zylon	42	2.5	2000
Vectran	23	3.3	525

Comparison of the mechanical and physical properties of the fibers, indicated that the Toyobo Co., Ltd Zylon High Modulus fibers was the preferred material for evaluation. As shown in Table 1 and Figure 1, the comparison of Zylon, Vectran, Carbon and Kevlar indicated that the Zylon material had strength and modulus properties double that of Kevlar and significantly greater than Vectran.

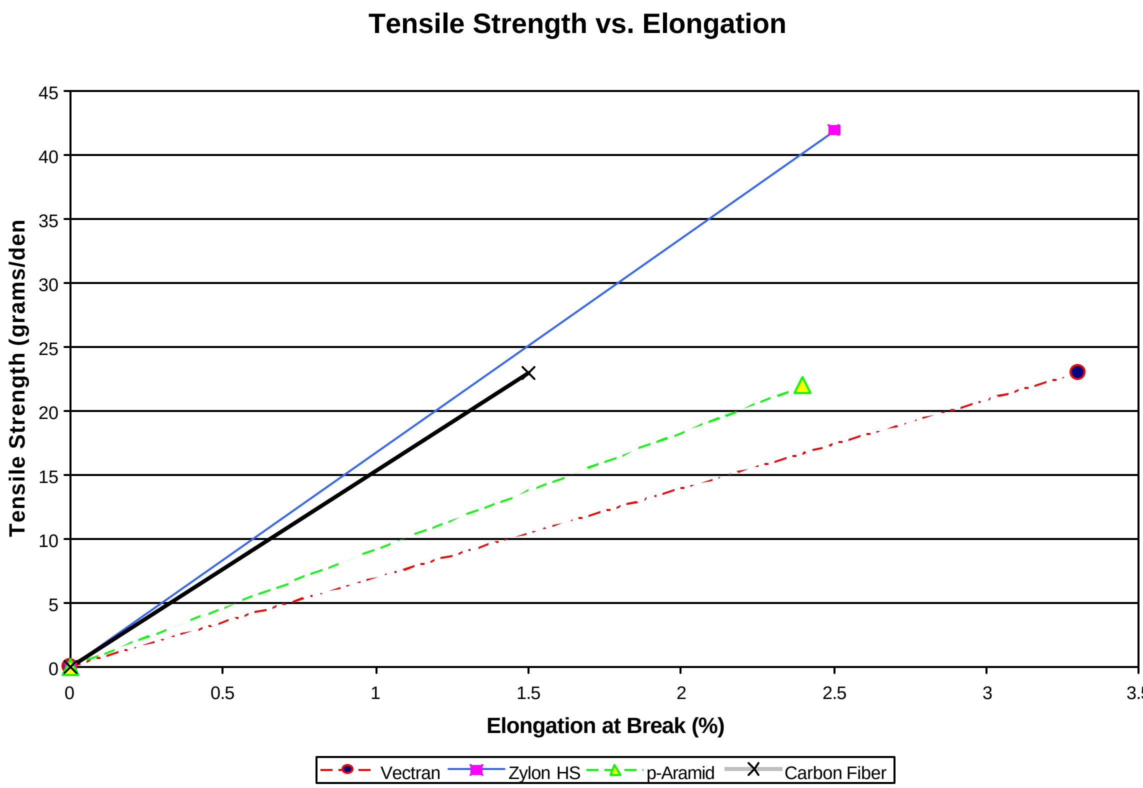

Figure 1 - Tensile strength of considered tendon fibers

ULDB TENDON SELECTION

Tendon Configuration

Once it was determined that Zylon was the fiber of choice, braided cord and Zylon tape were the two configurations considered for the ULDB balloon tendons.

1. Tape, unidirectional: The Zylon fibers were adhered to a plastic backing with a pressure sensitive adhesive as the mechanism for adherence to the balloon.

2. Tape, twisted and untwisted fiber: Zylon 1500 denier fibers were twisted, fabricated and adhered to Arclad 7876 silicone adhesive tape.

3. Braided cord: The Zylon 1500 denier fibers were braided into a 48000 denier chord. This allowed for the termination of the braided chords with a Brummel Splice.

Tests were performed on the unidirectional and twisted fiber Zylon tape. Figure 2 is a graph of the attachment method test results. As can be seen on the graph, the braided cord (test method #9) has the highest repeatability in the theoretical strength measurement. Please note, there are 5 specimens within the tight grouping shown in method number nine. Once the superiority of the braided cord with the Brummel Splice was proven, it was chosen as the tendon configuration for the ULDB balloons.

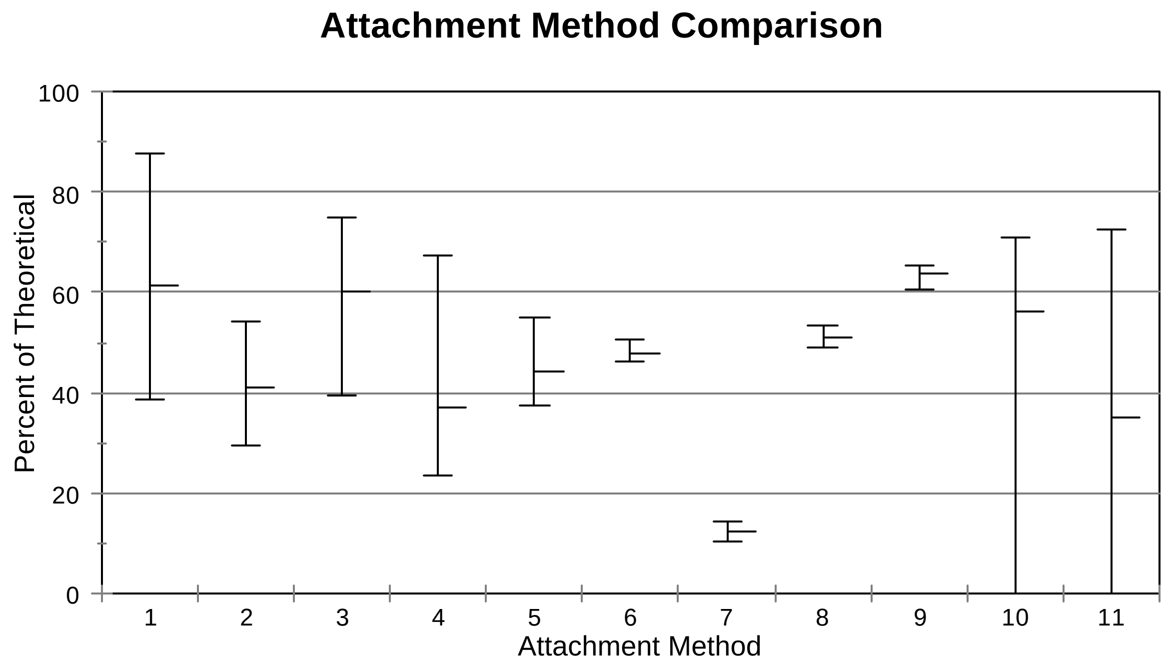

Figure 2 - Tendon attachment method comparison

Attachment of the Tendon to the Balloon Shell

In the 51500 cubic meter Phase II balloon, SSA-10 tape was used to adhere the tendons to the balloon shell. Due to the inward pressure on the balloon shell in sub-pressure areas of the balloon the tendons separated from the balloon shell. This condition caused tendons to re-align on top of neighboring tendons in a cascading failure. Once enough tendons were displaced, the stresses in the shell material became great enough to rupture the material. Following this failure, a new method of attaching the tendons to the balloon shell had to be determined. The tacking of the tendon to the protective tendon sheath with a simple double overhand clove hitch knot had no adverse effects upon the tensile parameters of the tendon as can be seen in Figure 3.

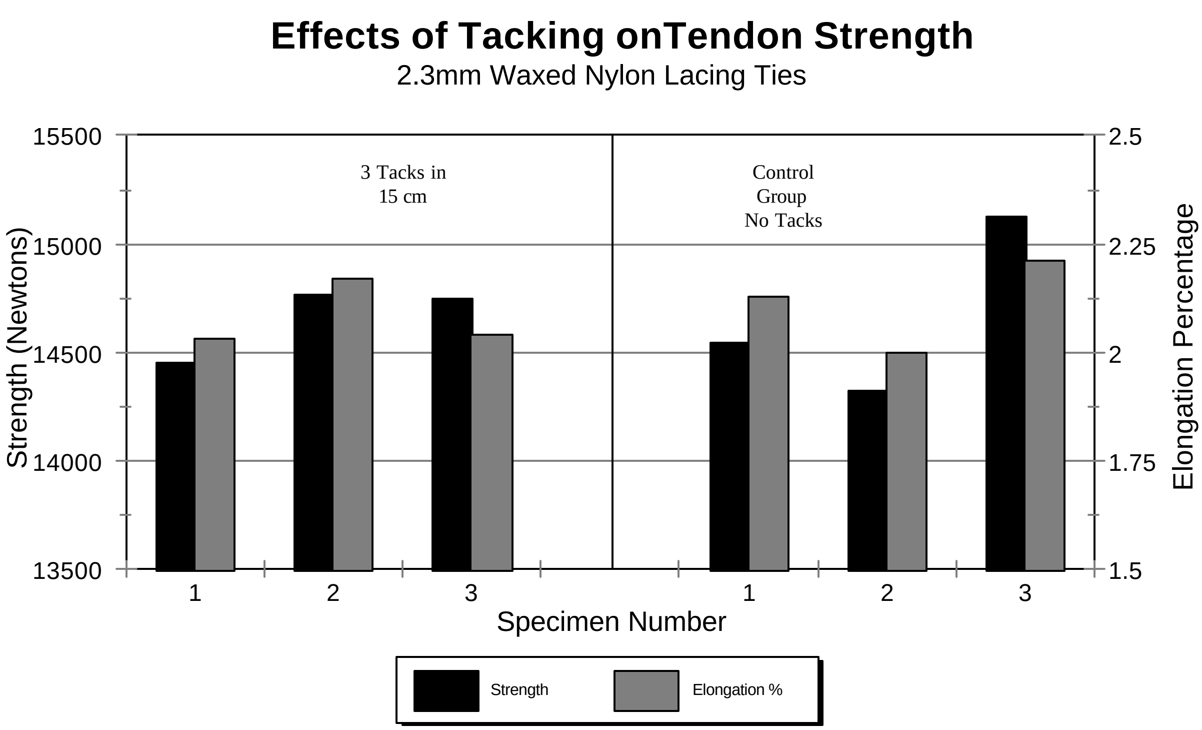

Figure 3 - Effects of tacking on tendon strength

EFFECTS OF AGING AND SENSITIVITY TO LIGHT OF ZYLON

The strength degradation of Zylon is influenced by the age of the braided rope. Evaluation of tendons of the same age and from the same reels by the rope manufacturer and Raven yielded strength test values that varied less than 10%. The 10% variance is acceptable because this is within the strength range, 15% min to max, which is commonly experienced in the same reel and reel to reel data. The elimination of the test procedures as a contributing factor to the decay of strength properties, also, indicated that the rope decay could be associated with aging.

A reel of braided rope was set aside for the evaluation of the effects of aging. It was stored in heavy black polyethylene film and only removed to extract test specimens. The rope lost approximately 10% of its strength in six months and approximately 15% in 14 months. The same reel indicated strength stability for the next 18 months.

Published Toyobo data indicates that exposure to sunlight also degrades the Zylon strength and requires light shielding to retain the strength. Light exposure test specimens were prepared and subjected to fluorescent light to determine the effect of the plant lighting on tensile properties. Three specimens were tested each month for 12 months for the effects of light on the rope's strength. The strength for these specimen was reduced approximately 55% in 12 months (4.6% average/month). Examination of the equivalent twelve month strength loss for the shielded lot indicated that approximately 12.5% of its strength was lost for other causes not definitely identified. The retained strength percentage over time is represented in Figure 4 for shielded and unshielded tendons.

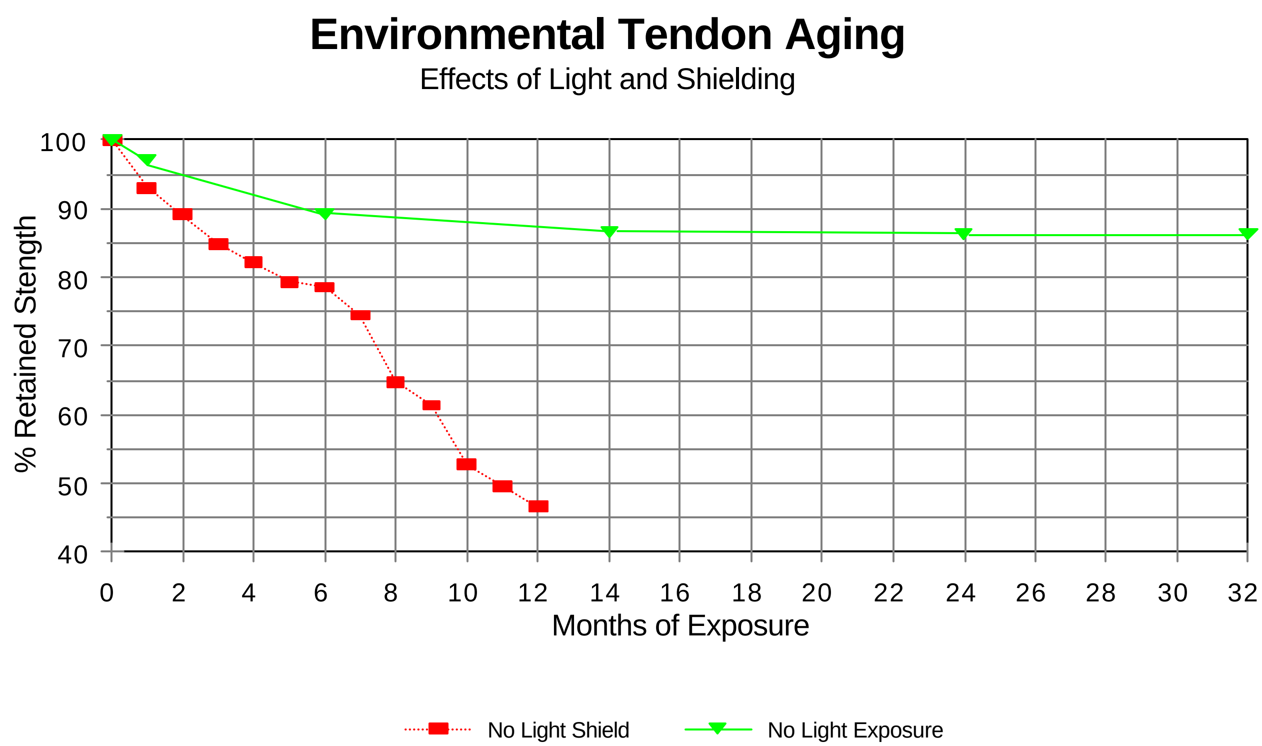

Figure 4 - Effects of tendon aging

During the manufacture of the 520500 cubic meter Phase IV balloons, the maximum light exposure that the shielded tendon could have received was estimated at 500 hours at 50 fc (foot candles) of fluorescent lighting. The unshielded portion of the tendon would have received an estimated maximum of 58 hours of periodic light exposure. Previous evaluations have indicated that the white pigment (Titanium Dioxide) polyethylene tendon shielding used in the balloon assembly was approximately 99% effective in blocking the light.

In September 2001, Toyobo issued additional technical information on the effects of visible fluorescent light and humidity upon the strength of the Zylon fibers. The Toyobo strength decay from visible light corresponds very closely to the Raven findings in 2000. The manufacturer's information on humidity degradation of the fiber strength seams to indicate that high humidity is a major contributor to the "natural" Zylon strength decay. The Toyobo published humidity strength retention chart relates very favorably in graphic form to the strength retention plotted data in Figure 4.

Other factors that affect the Zylon rope strength are the supplied strand tenacity (gpd) and the braider's efficiency. The manufacturers stated strength yield efficiency is approximately 80% of the supplied strand theoretical strength. This efficiency has been demonstrated in the lots that have been evaluated by the braiders QC and confirmed by Raven QC when known variables that affect the strength are applied. The Zylon manufacturer reports tenacity values in the range of 39.6 to 42 gpd. The use of the lower tenacity fibers reflects directly into the resulting Zylon rope as predictable lower strength properties. The resulting strength from the lower tenacity yarns further corroborates the 80% strength yield estimates from the braider.

The results of the various investigations into the performance and material properties of Zylon rope allows Raven to predict the future performance of a rope with known properties. When the rope is subjected to established protective storage, processing and finished product techniques, the tensile performance up to 24 months is predictable.

ZYLON ROPE MATERIAL ISSUES

Braid configuration

The greatest impact upon the Zylon tendon mechanical properties occur from exposure to UV radiation, plant environments and individual strand length variations. The impact of individual strand variation upon the mechanical properties can only be controlled at the point of rope braiding. From past test experience, the rope using the sixteen strand configuration has demonstrated more consistent mechanical properties than the twelve-strand configuration. An imperfection in one strand of the sixteen strand construction impacts the mechanical strength by $1/16^{th}$ as compared to an imperfection in one strand of the twelve strand tendon which impacts the mechanical strength by $1/12^{th}$.

Analysis of the data indicates that the twelve and sixteen strand, 48000 denier braided Zylon tendons are interchangeable physically, mechanically and environmentally. The twelve and sixteen strand configuration process equally well in the manufacturing, assembly and handling operations at Raven.

Test and application of the twelve and sixteen strand Zylon rope at Raven indicated that they were equal in all performance areas except one. The strand length variation had a greater effect upon the twelve strand rope. When a length or physical variation occurs in one or more of the braiding strands in the rope, the effect upon the mechanical properties is significantly greater in the twelve-strand configuration. Individual strand length evaluations of several lots of rope indicates that the sixteen-strand configuration has significantly greater uniformity of strand lengths properties; thus, resulting in more uniform tensile properties. Due to the reduced impact of strand length variation upon the sixteen-strand tendon and its more uniform construction, sixteen-strand Zylon tendon was used in 520500 cubic meter Phase IV balloons.

Sensitivity to Braiding Variables and Test Sample Preparation

The Zylon braided rope's strength and performance is very sensitive to strand length variation and uniformity. The test sample acquisition and processing should minimize the physical disturbance of the braid and any disturbance created should be returned to original state. This can be accomplished by dressing (conditioning) the disturbance created during specimen preparation back into the Brummel bury and loop. This conditioning removes any strand length disturbance created during the preparation of the Brummel splice. Conditioning the tendon is accomplished by mechanically massaging the Brummel splice after it is secured at the end of the tendon. Previous test data has indicated that the Brummel termination has an ultimate tensile strength of greater than 2224 Newtons. This dressing operation and alignment procedure assures that the true tensile properties of the rope are determined. An evaluation of the effect of conditioned vs. unconditioned test specimen indicated that increased tensile strengths up to 2224 Newtons were experienced as seen in Figure 5. This indicates the rope's true tensile properties.

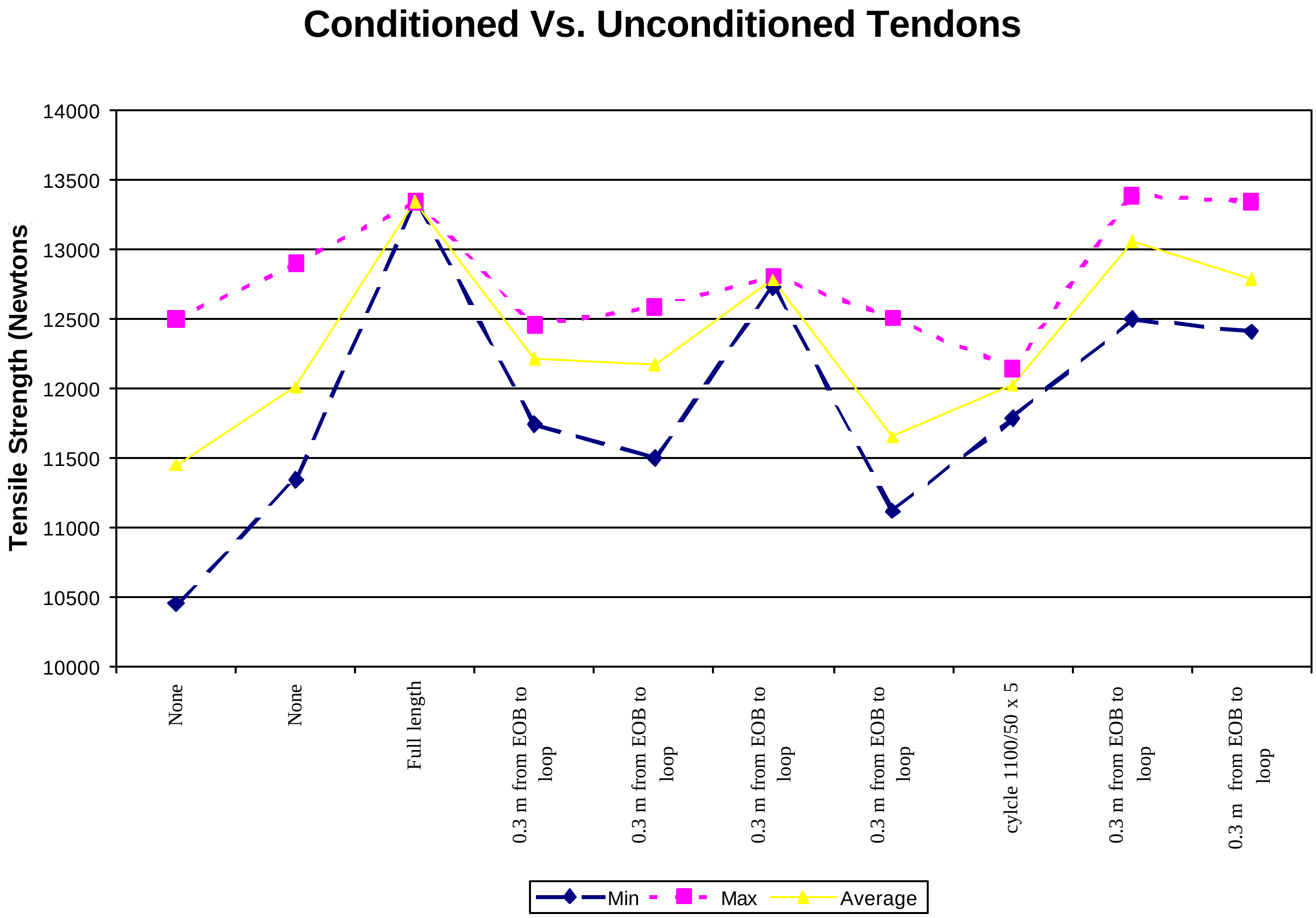

Figure 5 - Conditioning the tendon at the end of the Brummel Splice (EOB)

CONCLUSIONS

As the ULDB balloon moves from experimental to operational status, it may be a time to reevaluate the use of Zylon as the choice of tendon material for this particular balloon design. The material selection process must work hand in hand with the balloon designers to see that a new material will meet their requirements. It will be a delicate balance of tensile properties, manufacturing issues and the ability to resist UV and visible light damage for the flight durations required.

ACKNOWLEDGEMENT

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