SEA, Ltd. PROJECT NO. 153405	ISSUE DATE: September 21, 2010

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TEMPE TOWN LAKE DOWNSTREAM DAM FAILURE

Date of Loss: July 20, 2010

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I. PROJECT SUMMARY

PROJECT ASSIGNMENT

On July 29, 2010, Stantec Consulting Services, Inc. acting on behalf of the City of Tempe, Arizona and Bridgestone Industrial Products America, Inc. requested SEA, Ltd. to investigate the July 20, 2010 failure, of the Tempe Town Lake Downstream Dam, in Tempe, Arizona. This investigation was assigned to the direction of Dr. Robert Carbonara, Senior Analyst, as SEA Project No. 153405.

SCOPE OF PROJECT

Specifically, SEA was requested to render, if possible, a professional opinion regarding the cause of the dam failure.

CONCLUSIONS

- **The Tempe Town Lake Downstream Dam failure was the result of intra-carcass pressurization (ICP).**
- **The cause of the ICP was a combination of age of the dam and the environmental conditions in which it existed.**

II. PROCEDURES

- On July 29, 2010, Dr. Carbonara visited and photographed the site of the dam failure in Tempe, Arizona.
- Sections of Dam Span No. 2 and Dam Span No. 3, were received at SEA on August 16, 2010.
- Samples from Dam Span No. 1, were received at SEA on August 24, 2010.
- Samples from Dam Span No. 2, were examined and photographed.
- The Tempe Town Dam pressure log, was reviewed.
- The "Technical Proposal on Bridgestone Rubber Dam for City of Tempe, Arizona - Rio Salado Town Lake Project," dated October 28, 1996, was reviewed.
- Drawings of the location of the samples cut from Dam Span No. 2, were reviewed.
- As-Built drawings of the dam, were reviewed.
- News media accounts of the July 20, 2010 failure, were reviewed.
- Photographs of the Tempe Town Dam prior to and following the failure, were reviewed.
- A drawing of the cross section of the dam body typical construction, supplied by Bridgestone, was reviewed.

III. DISCUSSION

THE INCIDENT

On July 20, 2010, around 9:45 p.m. PST (21:45) Span No. 2 of the Tempe Town Lake Downstream Dam failed, releasing water from the Tempe Town Lake into the Salt River bed. Following this incident, the other three spans of the dam were deflated.

THE TEMPE TOWN DAM

The Tempe Town Lake Downstream Dan was constructed in 1998/1999, commissioned in June 1999 and Tempe Town Lake was open to the public on November 7, 1999. The dam consists of three ~22' high concrete piers located intermittently across the Salt River with an inflatable rubber bladder between each of the piers and between the end piers and the shore. The length of the bladder between the shore and the first pier on each side is ~180'. The length of the inner two bladders is ~201'. The diameter of each bladder is 16' when inflated. The bladders are designated as Number 1, 2, 3, and 4 with No. 1 on the south shore and No. 4 on the north shore. The failure occurred in Bladder No. 2, the inner bladder nearer the south shore. **Figure 1** shows the dam following the failure, arrow indicates failed dam span.

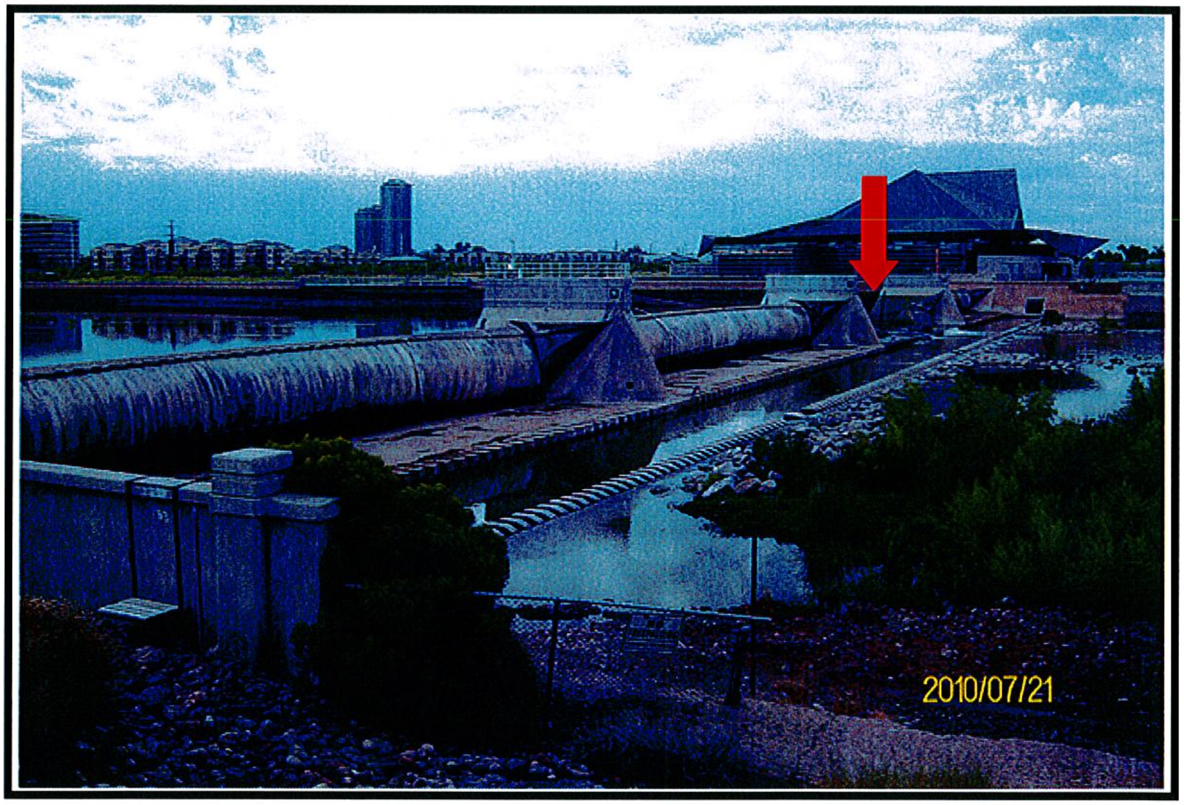

FIGURE 1: The dam following the July 20, 2010 failure, looking southeast from downstream. Arrow indicates failed dam span.

The bladders are made from eight layers of rubber that are bonded together into roughly rectangular sheets ~220' by ~25' by ~1" thick. Each bladder is made from two of these sheets. The sheets are joined along one of their long edges. This is an edge joint, not a lap joint, which forms a lip lengthwise along the dam and is configured into fins to direct the flow of water over the dam. The other long edges are brought together and mechanically fastened to one another and to the foundation that spans the river, by steel plates and bolts anchored into the foundation. **Figure 2** shows the shape of the dam in cross section.

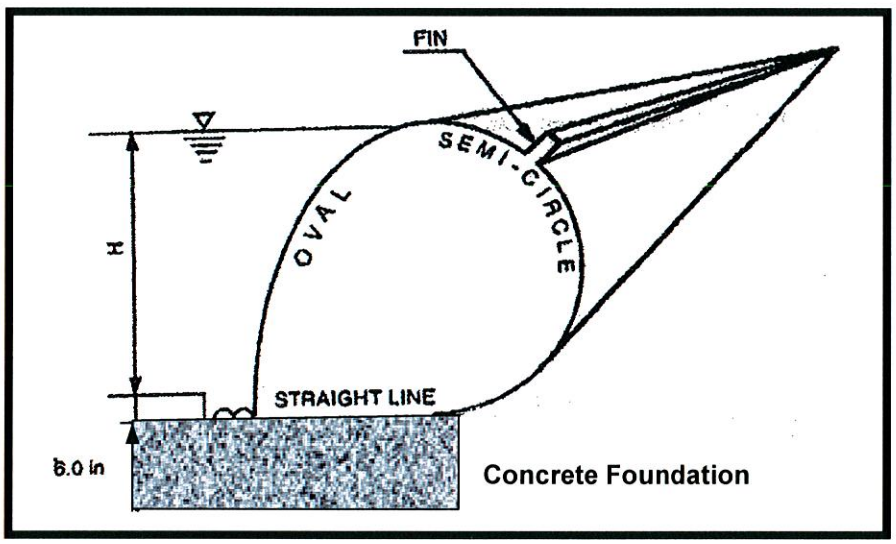

FIGURE 2: Schematic of constructed dam.

The outer layer of both the top and bottom sheets of the bladders are made from a compound of natural rubber (NR), styrene butadiene rubber (SBR), and ethylene propylene diene monomer (EPDM) rubber. A portion of the bottom section of the outer layer is filled with ceramic chips. The inner layer of both the top and bottom sheets are made from a compound of NR and SBR. The six intermediate layers are made from nylon fibers coated with NR /SBR. These six nylon fiber layers act as reinforcements for the rubber dam. **Figure 3** is a schematic of the typical bladder construction. **Figure 4** is a photograph of the cross section of the Bladder No. 2.

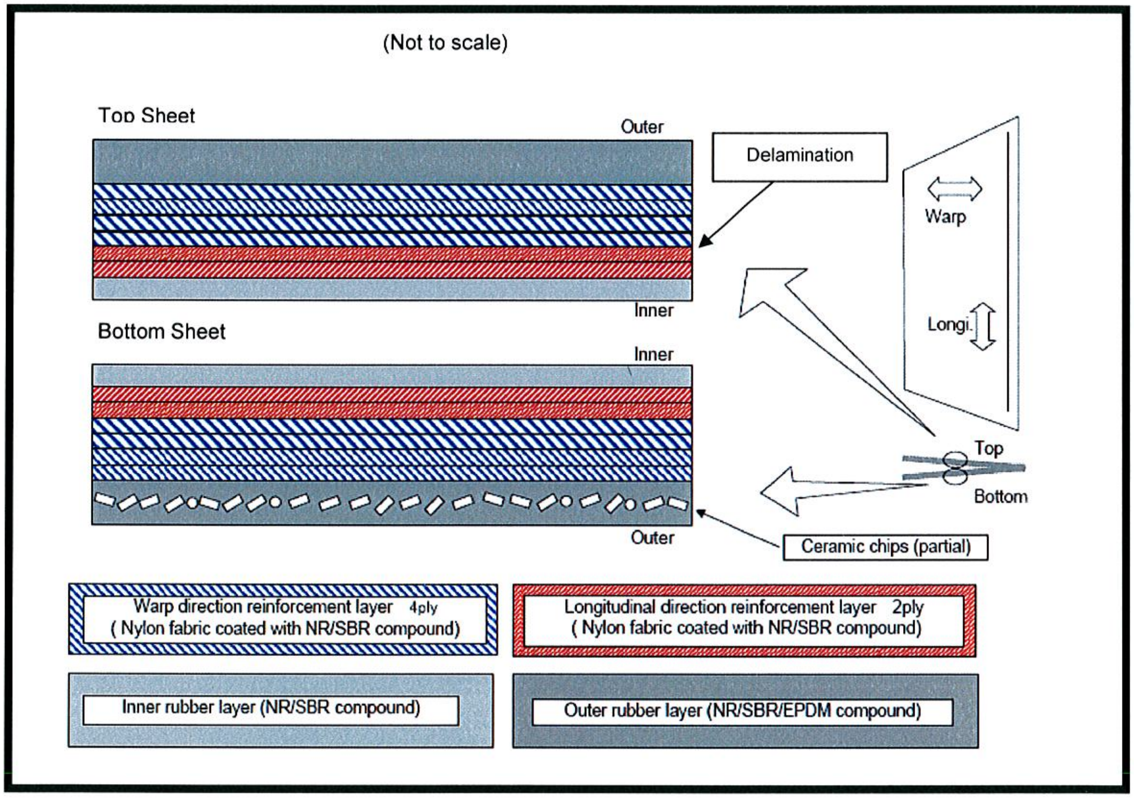

FIGURE 3: Cross-section of bladder rubber.

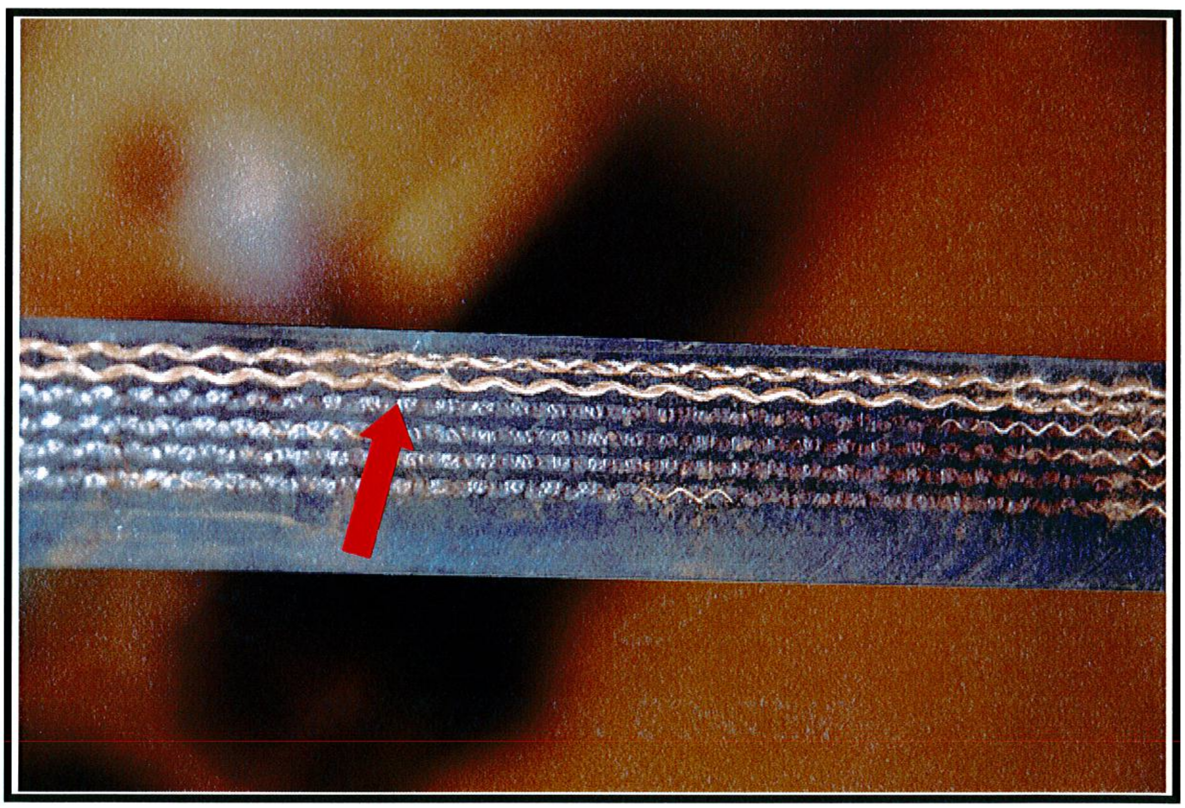

FIGURE 4: Cross-section of Bladder No. 2. Arrow indicates location of the delamination.

THE CAUSE OF THE FAILURE

Portions of the failed Dam Span Bladder No. 2 were examined and photographed. **Figure 5** shows the location of the samples that were cut from the Bladder No. 2 and sent to SEA.

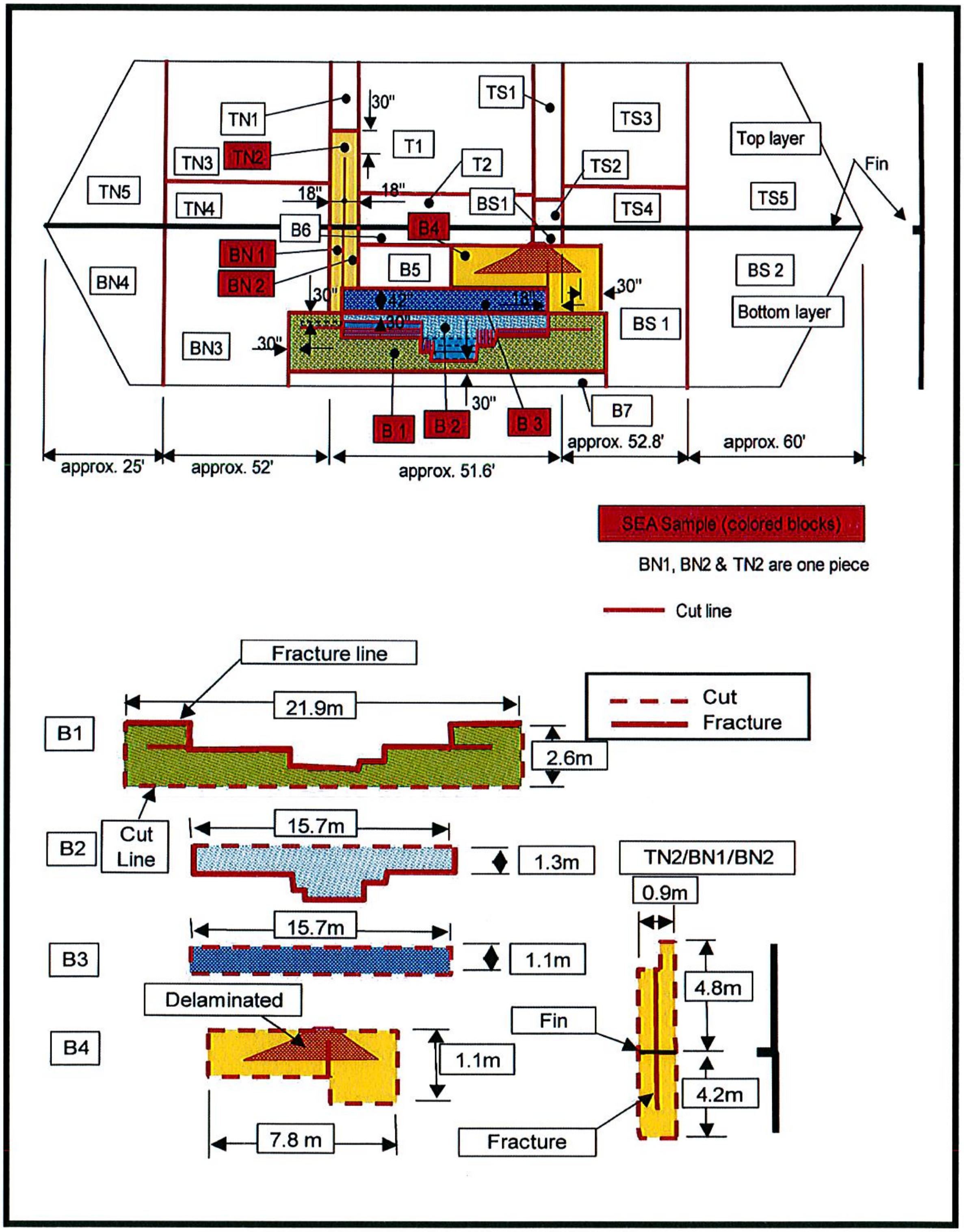

FIGURE 5: Location of bladder sections examined at SEA.

Analysis of the failed portions of the Dam's Span Bladder No. 2 showed a delamination or separation of the layers of the rubber sheets. The area showing delamination has been worn smooth from the separated layers rubbing against each other, see **Figure 6**. The separation occurred between the 2-ply and 4-ply layers as seen in Figure 3. This separation is characteristic of Intra Carcass Pressurization (ICP). ICP is normally the result of an interior breach in the layers of rubber that make-up the carcass. In this case, the bladder carcass breach occurred near where the bladder made contact with the concrete apron. This is the location where the bladder curvature deviates from its "cylindrical" profile and flattens out on the foundation. This change in curvature is where the bladder flexes, much like the sidewall on an automotive tire. This flexure causes a constant back and forth motion resulting from the movement of the bladder caused by the force of the water against the dam. The back and forth movement within the bladder carcass can cause small internal tears which then become the accumulation location for any air that penetrates the carcass. The penetration of the carcass is a diffusion process that is governed by an Arrenhius-type equation shown below and in **Figure 7**:

$$D = D_o \exp -E/kT$$

Where: D = the diffusion rate in the carcass at temperature T
D_o = the frequency factor (a constant)
E = the activation energy for diffusion
k = the Boltzman constant
T = the carcass temperature in ^oK

FIGURE 6: Delaminated area of bladder (arrow).

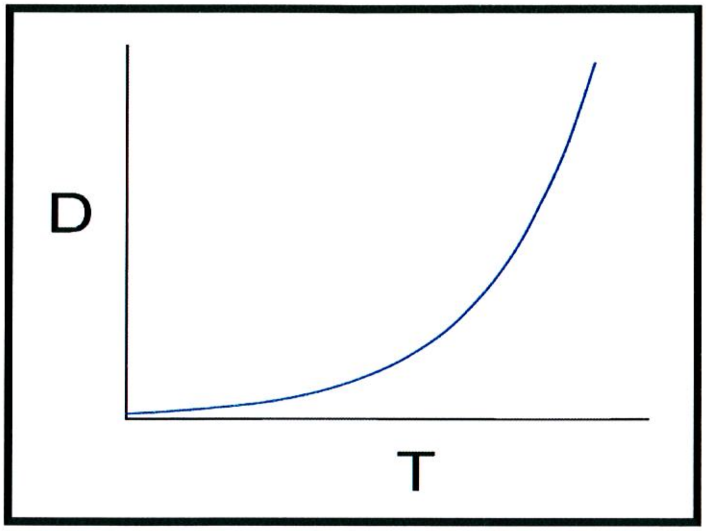

FIGURE 7: Arrenhius type curve showing exponential relationship between diffusivity (D) and temperature (T).

The total amount of air that accumulates depends linearly on the time over which the diffusion takes place.

The penetration of air into the bladder rubber depends on both the carcass temperature and time. As the diffusion equation shows, the carcass temperature is the dominant factor since it has an exponential dependence, where, as noted above, time has a linear dependence.

As the air penetrates the bladder rubber and accumulates at the internal tears, it builds up pressure, i.e., ICP. Over time, this accumulated pressure causes the separation or delamination of the layers of rubber that make-up the bladder wall.

The delaminated area no longer has the strength and structure of the other areas of the bladder and acts as a preferential site for failure, analogous to a stress riser. Although the pressure inside the bladder was only ~6 psi, the hoop stress in the bladder was ~600 psi. Once the accumulated air caused a large enough area of delamination of the layers, i.e., the effective stress riser, the hoop stress became larger than remaining strength of the bladder.

The failure was the result of the age of the dam (time) and the environmental conditions (temperature) in which the dam existed. The age of the dam was over 11 years and the temperatures in the Tempe area are extremely high, often exceeding 100°F.

IV. SIGNATURES

SEA, Ltd. hereby certifies the expressed opinions and conclusions have been formulated within a reasonable degree of professional certainty. They are based upon all of the information known by SEA, Ltd. as of the time this report was issued, as well as knowledge, skill, experience, training, and/or education.

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