CASE HISTORY—PEER-REVIEWED

Failure Analysis of an Ambulance Cathode Ray Tube Monitor Bracket

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Abstract An aluminum alloy ambulance monitor bracket that fractured in-service was analyzed to determine the mode, mechanisms, and causes of its failure. After visual inspection, cause-and-effect analysis was conducted to identify all the possible factors that may have contributed to failure. The bracket arm was investigated using macro- and micro-fractography, chemical analysis, optical microscopy, and hardness testing to assess the failure characteristics and material properties. Finally, simulations were conducted with SolidWorks® to evaluate the component loading and stress distributions that led to fracture. The failure of the bracket was attributed to long-term, low stress amplitude, unidirectional dynamic bending high-cycle fatigue of the bracket arm, applied by the monitor weight in conjunction with vehicular vibrations while driving. Failure was most likely caused by: (1) the unsatisfactory surface condition of the arm produced by thermal cutting, including large inclusions, jagged edges, and a heat-affected zone; (2) the poorly designed component geometry, which promoted a stress concentration at the point of failure; and (3) the inadequate material strength, given the component geometry and applied cyclic stress requirements. Several options for improved component reliability were recommended.

Keywords Aluminum alloy · Thermal cutting · Fractography · Hardness · Stress analysis and modeling · Fatigue

Introduction

The interior design of an ambulance is optimized for ergonomic and efficient emergency treatment of injured or ill individuals, as well as their transportation to and from treatment centers. To that end, computer monitors are commonly found in ambulances to display job and patient information to the paramedics. Several years ago, an ambulance model was equipped with a custom aluminum bracket to mount a cathode ray tube (CRT) monitor within the vehicle, as shown in Fig. 1. This component included a $340 \times 135 \times 6$ mm horizontal plate, which was bent vertical at the sides to secure the monitor and was screwed onto a bracket system with two 6-mm-thick support arms. This assembly was bolted to the ambulance through the hole in a $55 \times 50 \times 19$ mm bolting plate, at the far left of Fig. 1a. As shown in Fig. 2, the bracket arms featured drag lines on the contour edges that were consistent with a laser or similar thermal cutting procedure [1]. All parts except the monitor plate were covered with a black protective coating.

Unfortunately, several of these brackets were found to fail while in-service, which posed significant safety hazards to the vehicle occupants. The failure occurred at the inside bend of one of the two arms connecting the monitor plate to the bolting plate, denoted as Arm “1” in Fig. 1. Whereas that arm was completely split through, the adjacent Arm “2” featured only a small crack at its inside bend, as shown in Fig. 1b. Also, the bolting plate of the failed component

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Fig. 1 Photographs of the failed CRT monitor bracket, previously sectioned above the fracture in Arm 1 for analysis: (a) top view, (b) fracture area, and (c) bottom view

Fig. 2 Comparison of the edge surface roughness in (a) the bracket arm and (b) a laser cut component [1]

was found to be plastically deformed rotationally about Arm 2, as shown in Fig. 1c. At the time of analysis, only the one fracture surface present at Arm 1 in Fig. 1 was available, as the opposite fracture surface had already been cut out of the component.

The objective of this study was to determine the most probable mode, mechanism, and cause of failure in the ambulance CRT monitor bracket. The current investigation included macro- and microscopic examinations, energy-dispersive x-ray spectroscopy (EDX), hardness testing, and component stress analysis simulations. The results of this work will enable the production of improved brackets with enhanced product reliability.

Root-Cause Failure Analysis

Prior to nondestructive and destructive testing of the failed component, cause-and-effect analysis was conducted to assess all possible factors that may have contributed to the failure of the CRT monitor bracket (Fig. 3). These factors can be separated into either materials, manufacture, methods, operator, measurement, or environment categories. First, the component may have failed due to improper bracket design, including geometric and materials selection considerations. As shown in Fig. 1, the monitor plate was situated asymmetrically about the bracket arms, such that uneven bending moments are expected between

the two arms. As well, the component geometry promotes stress concentrations at the inside bends of the two bracket arms, which may have insufficient cross-sectional areas and/or radii of curvature to support the loading. Regarding the materials, the wrought aluminum alloy selected may not have had sufficient mechanical properties given the bracket geometry and loading requirements. This includes considerations of the alloy heat treatment condition and its metallurgical impurity content.

Furthermore, the manufacturing process of the bracket, specifically the arms, was a possible contributor to the failure. Although no processing details were available from the manufacturer, by visual inspection, the bracket arms were likely extruded or cold rolled to a uniform thickness of 6 mm, contoured with laser cutting or similar thermal machining methods, and finally coated, possibly at elevated temperatures for better adhesion. Thermal cutting removes material via controlled metal melting or vaporization, and it tends to cause a jagged cutting surface that can act as stress concentration sites. This is especially true for the older techniques from when CRT monitors were more prevalent than liquid crystal display (LCD) monitors. As well, thermal cutting usually promotes a heat-affected zone (HAZ) with reduced mechanical properties near the surfaces of the contour [2], and coating at an elevated temperature may have thermally treated the alloy to further compromise mechanical properties. It is well known that fatigue life is very sensitive to the surface condition of the component [3]. Also, each of these manufacturing

processes may introduce impurity inclusions into the component, which could act as crack initiation sites.

Moreover, failure may have been promoted by the loading configuration on the bracket arm. The weight of the CRT monitor may have been excessive, especially if the bracket was used to support additional components or its own weight was not considered in the design. As well, it is possible that the ergonomics of the ambulance interior led to unexpected stresses on the component. For instance, individuals may have come into contact with the bracket, either intentionally or accidentally. The monitor may have also been installed unevenly on the monitor plate, which would promote a greater differential in the induced stress field within the bracket. Cyclic or dynamic stressing of the bracket possibly occurred, either thermally due to weather fluctuations or mechanically due to ambulance vibrations while in-service. The former factor is likely less significant, given the controlled temperature required within ambulances, even when not in use. However, failure due to vibration-induced fatigue has been reported in automotive environments [4–6]. Due to random vibration excitations from the road surface throughout their service life, components mounted on the vehicle body and frame can experience limited vibration durability, especially in cantilever configurations. The typical vibrations in large vehicles would be enhanced by harsh driving, which is often required when rapidly transporting patients in medical emergencies. Also, improper installation of the bracket could have contributed to increased vibration levels, for example, if the bracket was bolted too loosely to the

Fig. 3 Fishbone diagram of possible factors contributing to the CRT bracket failure

ambulance interior. Finally, inadequate maintenance procedures of the bracket may have prevented the identification of crack initiation before catastrophic failure.

Evidence Analysis

The previous section outlined many possible causes that could have contributed to failure. In this section, testing conducted to identify the likely predominating factors is detailed. This includes fractography, microscopy, x-ray microanalysis, and hardness testing.

Fractography

Figure 4a shows an optical stereomacrograph of the entire fracture surface in Arm 1, which was unscrewed from the bolting plate for analysis. Note that the orientation of the sample in this stereomacrograph relative to its orientation in Figs. 1b and 2a is indicated by the coordinate system in the images. The surface displayed a fracture pattern consistent with unidirectional bending fatigue with a low nominal stress [7]. Most of the fracture surface consisted of Stage II fatigue crack propagation, featuring a smooth texture with beach marks curving leftward from the top to the bottom of the image. The beach mark directions indicated that Stage I fatigue initiation occurred around the top left corner of the surface, corresponding to the edge of the bracket arm closest to the bolting plate and facing Arm 2 and propagated toward the right of the figure. The large extent of the Stage II beach mark zone indicated that the cracking occurred most likely due to long-term (high-cycle), dynamic, low-amplitude loading [8]. At higher magnifications, scanning electron microscopy (SEM) revealed the presence of microscopic fatigue striations perpendicular to the direction of fracture propagation (parallel to the beach mark directions) with little macroscopic plasticity (Fig. 5). This behavior is unlike the typical ductile nature of many aluminum alloys under static tensile loading and further supports that fatigue was the predominant bracket failure mode.

On the right side of the macroscopic fracture surface in Fig. 4a, corresponding to the edge of the bracket arm cross section closest to the monitor plate, a dull and fibrous Stage III static overload zone could be seen. The material appears to have been deformed out of the plane, suggesting the applied loading direction was toward the opposite fracture surface of the arm. Microscopically, there is evidence of the dimpled topography typical of ductile fracture in this zone (Fig. 6). However, much of the fracture surface in the Stage III region appears flattened, indicating post-failure damage due to abrasion of the two mating fracture surfaces. Such damage is consistent with unidirectional

bending, as this edge of the arm would likely experience compression following crack propagation.

As discussed previously, Stage I fatigue initiation was identified as occurring on the left edge of the fracture surface in Fig. 4a based on the orientation of the beach marks. Stereomicroscopy revealed several possible origins for the failure. A large, ~ 1 -mm-long secondary crack could be seen at the mid-plane of the cross-section thickness, extending into the width of the fracture surface from the edge. A similar, but smaller, ~ 0.5 -mm-long secondary crack could be seen toward the top left corner of the fracture surface, as shown in Fig. 4b. Also in that figure, a notch could be seen at the top left corner of the fracture surface. Beach marks extending from the top of the fracture surface down to the large, mid-plane crack are elucidated in Fig. 7. This indicated that primary fatigue initiation may have occurred at the small crack and/or the notch at the top left corner. Yet, several smaller cracks were seen along the left edge of Fig. 4b between the ~ 1 -mm and ~ 0.5 -mm cracks. These appear as fatigue ratchet marks, which would suggest that the failure had multiple origins.

The likely failure initiation sites are displayed at higher magnification in Fig. 8. The internal surfaces of the cracks were very smooth, implying that they were not formed by plastic deformation during failure. Rather, their flatness appears more likely to be the result of controlled melting and solidification, either about inclusions (for the two cracks) or at the top of a thermally cut drag line (for the top corner notch). To support this, energy-dispersive x-ray (EDX) microanalysis was used in conjunction with backscattered electron (BSE) imaging in the SEM to evaluate the chemical composition of the alloy in the crack regions (Fig. 9). The tips of the two cracks were found to contain regions high in oxygen content, especially for the larger crack, shown in Fig. 9b. For example, the EDX Spectrum 1 in Fig. 9b shows that 20.0 wt.% oxygen was detected on the larger crack surface, whereas the Spectrum 2 in Fig. 9c shows that only 3.8 wt.% oxygen was detected in a nearby region of the alloy. The former is likely residue of inclusions that were present in the cracks prior to failure, explaining the smooth surfaces of the cracks and their orientation perpendicular to the fracture propagation direction. Since both are on the edges of the fracture surface, the inclusions were probably introduced during the thermal cutting operation. Both inclusions appear to have adhered to the opposite fracture surface during failure, or were dislodged from the material. The latter may have occurred during the cyclic loading, directly following failure, or during removal, transportation or storage of the failed component. Unfortunately, the opposite surface was not available for analysis to determine whether the inclusions were still present.

Fig. 4 Stereomicrographs of (a) the entire fracture surface and (b) the top left corner, in which suspected crack initiation sites and the propagation direction are indicated by white and black arrows, respectively

Fig. 5 Scanning electron micrographs of the brittle Stage II fatigue region at (a) 400x magnification and (b) 852x magnification

Fig. 6 Scanning electron micrographs of the ductile Stage III fatigue region at (a) 20x magnification and (b) 200x magnification

A rough estimate of the compositions of the alloy and coating materials used was also determined with EDX. As shown in Fig. 9c, the aluminum alloy was found to have

very low concentrations of Mg, Si, Fe, and Cr. This is consistent with 6000 series wrought aluminum alloys. Given its widespread use, this alloy most likely

corresponds to 6061 alloy, which has the nominal composition presented Table 1. The EDX results also enabled some analysis of the component coating. As demonstrated in Fig. 9d, the component coating was found to be organic and contain Ca, yet the exact product was not determined. Furthermore, the dark spots found scattered about the fracture surface in Fig. 9a were C-based. This was probably contamination that arose during component handling and storage post-failure.

Optical Microscopy

Optical microscopy was conducted on a cross section of Arm 1 taken from above the fractured area, parallel to the fracture surface but closer to the monitor plate. The sample was prepared through progressive grinding steps with SiC papers, followed by polishing with 5 μm alumina, 1 μm

diamond suspension, and finally 0.05 μm colloidal silica. As shown in Fig. 10, the alloy microstructure looked similar to conventional Al 6061, as expected from the EDX analysis. As indicated by the coordinate system in the image, the orientation of this micrograph is rotated 90° clockwise, relative to those in the previous section: The top edge in this figure corresponds to the edge of the arm contoured by thermal cutting (closer to the bolting plate), and the right edge in this figure was bounded by the extrusion or rolling operation used to create the bulk 6-mm-thick aluminum sheet. Whereas no difference could be observed in the microstructure between the bulk sample and the right edge, there is a clear HAZ at the top edge, where the secondary phases appeared larger with increased interparticle spacings. This HAZ is consistent with laser and plasma cutting operations and is known to compromise mechanical properties [2, 10].

Hardness Testing

Brinell and Rockwell hardness testing was conducted on the sample sectioned for microscopy, on the wider faces perpendicular to the thermal cutting edge. The sample was ground flat with a SiC paper to prevent any influence of the coating. Two readings of Brinell hardness (HB) were taken on the opposite sample face, resulting in values of 56 HB at the face center and 51 HB closer to the thermally cut edge. The lower hardness value closer to the cutting edge is consistent with the reduction in mechanical properties expected within the HAZ. Eleven readings of Rockwell hardness (E-scale) were taken distributed about the sample face, producing an average value of 56 ± 6 HRE. The variation of Rockwell hardness within the bracket arm was relatively large. Additionally, comparing the average hardness with the typical mechanical properties of Al 6061 (Table 2) indicated that the alloy used in the bracket was

Fig. 7 Low-magnification scanning electron micrograph displaying beach marks surrounding the fracture surface top corner

Fig. 8 Scanning electron micrographs of the likely fatigue initiation sites: (a) the ~ 0.5 -mm-long crack and notch at the top, and (b) the ~ 1 -mm-long crack at the mid-plane of the fracture surface thickness

Fig. 9 EDX analysis of the area surrounding the large, mid-plane crack: (a) the backscattered electron micrograph of the area, showing the analysis sites, (b) Spectrum 1 at the crack tip, (c) Spectrum 2 of the alloy, and (d) Spectrum 3 of the coating

Table 1 Nominal composition of Al 6061 alloy in wt.% [9]

Mg	Si	Fe	Cr	Cu	Mn	Zn	Ti	Others	Al
0.8–1.2	0.40–0.8	0.7 max	0.04–0.35	0.15–0.40	0.15 max	0.25 max	0.15 max	0.15 max	Bal.

probably in a process-annealed condition. Although 56 HB, as found in the bracket, is not quite as soft as the 30 HB reported for 6061 in the fully annealed condition, it is significantly less than the hardness values expected for either the T4 or T6 temper conditions, reported as 65 and 95 HB, respectively. Thermal cutting, as well as component coating if conducted at elevated temperatures, may cause some undesirable microstructural changes at the alloy surface. However, the measured hardness indicated that the material was likely ineffectively heat-treated prior to use in the manufacturing of the bracket. Had the alloy been age hardened to either the T4 or T6 temper conditions, the component may have had significantly higher strength and fatigue resistance.

Stress Analysis

The CRT monitor bracket was modeled in SolidWorks® to simulate the stress conditions that brought about its failure. Due to the complexity of the working environment of the component, likely involving both shocks and stochastic loadings that vary with the road conditions and vehicle speed, it is difficult to obtain accurate knowledge of the exact stress levels experienced during its lifetime. Therefore, these simulations were performed with several simplifications with the primary goals of qualitatively determining (1) the regions of maximum stress as well as (2) the loading configuration that likely caused the bulk deformation observed in Fig. 1. Accordingly, the patterns of stress distributions and deformation are emphasized,

Fig. 10 Optical micrograph of bracket arm cross section, indicating a heat-affected zone at the cutting edge

Table 2 Typical mechanical properties of Al 6061 [9]

Temper	Hardness (HB)	Tensile strength (MPa)	Yield strength (MPa)	Fatigue strength (MPa) ^a
Annealed (O)	30	124	55	62
Naturally aged (T4)	65	241	145	97
Artificially aged (T6)	95	310	276	97

^aData correspond to 5×10^8 cycles of completely reversed stress in R. R. Moore-type tests

without claiming validity of the magnitudes of the simulated stresses.

All components of the bracket were modeled as a single part with the software's built-in mechanical properties for Al 6061 alloy. The bracket was positioned with the bolting plate and monitor plate oriented parallel with the ground, as found when in-service (Fig. 11). The model did not account for microstructural variation or inclusions, the rough surface finish associated with thermal cutting, or the component coating. As a boundary condition, the hole in the mounting plate was selected as a perfectly rigid fixture during loading. As well, the model was simplified to consider failure due to only a single sudden loading, rather than random cyclic loading. The loading was selected as the weight of an average CRT monitor, 14.1 kg [11], applied as a surface pressure downward on the monitor plate, normal to it. Two loading conditions were simulated for the bracket, given the same applied force value: one where the load was evenly distributed on the entire monitor plate, and a second where the load was only distributed over the left half of the monitor plate, on the Arm 2 side. These two conditions are defined graphically in Fig. 11a and c, respectively. SolidWorks® SimulationXpress was then used to analyze the static nodal von Mises stress distribution in the component.

As shown in Fig. 11, the critical areas of highest stress were found to be at the inside bend of the two bracket arms, exactly where Arm 1 fractured. Moreover, for either arm, the stress was found to be highest at the corner closest to the opposite arm, corresponding to the top left corner of the fracture surface in Fig. 4. This would explain why failure initiated near the smaller crack there, rather than at the larger crack in the middle of the arm thickness. For the even loading condition modeled in Fig. 11a and b, the monitor

weight was well-distributed between both arms. Within each arm, the highest static stress was simulated as approximately 72 MPa. In contrast, for the uneven loading condition modeled in Fig. 11c and d, Arm 2 was found to have a larger maximum static stress of approximately 86 MPa, whereas the maximum static stress in Arm 1 was found to be approximately 65 MPa. It should be noted that all three of these maximum stress levels are above the typical yield strengths of 6061-O, yet below the typical yield strengths of either 6061-T4 or 6061-T6 (Table 2). However, as described above, the magnitudes of the stresses are not expected to accurately portray the complex vibrations experienced by the bracket while in-service. The true stochastic stress amplitudes were likely significantly lower than the simulated static stresses, leading to the fatigue fracture patterns described in the “Fractography” section. Rather, the physical locations of the critical stresses determined by the simulations are of interest to this analysis.

It is possible that a CRT monitor lighter than average may have been used in the ambulance, which would have resulted in lower stresses. On the other hand, the jagged surface finish of the arms due to thermal cutting would act as stress risers in the arms, thereby reducing their fatigue resistance. Although these factors are expected to influence both arms similarly, Arm 1 failed prior to Arm 2, despite the higher simulated stress in the latter. This can be attributed to the large inclusions and the corner notch found in the Arm 1 fracture surface. Given that they are stress concentration sites, this indicated that the inclusions likely played an active role in promoting the initial failure of Arm 1, even in the uneven loading condition.

The component was modeled again with the same geometry and loading conditions, yet with the addition of a

Fig. 11 Loading conditions and simulated critical stress regions for (a, b) even loading and (c, d) uneven loading

0.5-mm-thick crack through the Arm 1 cross section. This enabled qualitative analysis of the bracket deformation after failure. As shown in Fig. 12, the bulk rotational deformation of the bolting plate relative to the mounting plate of the actual component seen in Fig. 1c is consistent with the uneven loading condition. The plastic deformation post-failure likely brought the two opposing fracture surfaces into contact subsequently in the stress cycle, creating the flattened microscopic Stage III fatigue overload zone observed in Fig. 6. Furthermore, after the failure of Arm 1, Arm 2 becomes responsible for supporting a much larger proportion of the loading, with maximum static stresses estimated at approximately 130 or 240 MPa for the even and uneven loading conditions, respectively. These values are between the typical tensile strengths of 6061-O and 6061-T4. Given that only a small crack on the edge of the inside bend of Arm 2 is observed in Fig. 1b, compared to the through-section fracture of Arm 1, the fracture of the former occurred over a significantly shorter time. Therefore, the crack at the edge of Arm 2 and the bulk deformation of the bracket are most likely both secondary damage that occurred suddenly after the total failure of Arm 1.

Further idealized, static simulations were conducted to identify possible improvements to the component design, beyond evenly distributing the loading across both bracket arms. For example, by heat treating the aluminum alloy from the annealed condition to a T6 temper and maintaining the same simulation conditions, the maximum allowable CRT monitor weight to remain below the material yield strength can be increased from 12 to 54 kg. Equivalently, using an alternative alloy with a yield strength 160% greater than that of 6061-O would bring about a 350% increase in maximum allowable monitor weight. On the other hand, a 20% increase in the width of the bracket arms at the sites of maximum stress brought about a reduction in their simulated static stress levels to about 54 MPa, compared to 72 MPa for the even loading condition. This improvement would be sufficient to maintain the stress level below the Al 6061 yield strength, even in the annealed condition. Despite these values relying on a simplified model that does not account for surface effects, inclusions, non-rigid bolting, component resonance frequencies, or cyclic loading and fatigue, these simulations demonstrate the required strategies for failure prevention of the brackets.

Fig. 12 Simulated bulk deformation following arm fracture for (a) even loading and (b) uneven loading

Conclusions and Recommendations

Following extensive fractography, materials testing, and stress simulations, the most probable mode of failure of the ambulance CRT monitor bracket was determined to be high-cycle fatigue fracture. As substantiated by the fracture surface patterns, fatigue most likely occurred due to long-term, low stress amplitude, unidirectional dynamic bending of the bracket arms by the weight of the monitor, as a result of the dynamic vibrations of the ambulance while in-service. Fatigue initiation occurred at the edge of the Arm 1, on the inside bend closest to the mounting plate, predominantly at the corner closest to Arm 2. Three primary contributory factors were identified as initiating failure: First, the designed component geometry and loading conditions promoted high stress concentrations at the point of failure. Second, thermal cutting likely reduced the fatigue crack initiation resistance of the arm by deteriorating its surface condition. The cutting operation produced stress-rising drag lines as well as a heat-affected zone with further reduced mechanical properties. Additionally, two large cracks that probably contained oxide inclusions were present at the failure initiation site. These were likely also introduced by the cutting operation, given their positions along the cutting edge. However, confirmation of the presence of these inclusions and their origin was not possible, given the unavailability of the opposite fracture surface. Third, the aluminum alloy used was of a relatively low strength, possibly corresponding to a process-annealed 6061 alloy. Based on the designed arm cross-sectional area, this material may have had insufficient mechanical properties to resist failure even without the stress concentrators, depending on the true working conditions and the actual

weight of the CRT monitor used in the ambulance. Furthermore, it was determined that Arm 2 cracking and bracket rotational plastic deformation likely occurred following Arm 1 failure. The geometry of the bracket promoted uneven loading of the two bracket arms. Simulations indicated that the monitor may have been loaded unevenly by the user, with more weight situated toward the Arm 2 side of the monitor plate, resulting in post-failure fracture surface damage.

Several improvements are recommended for enhanced bracket reliability. The true dynamic loading conditions experienced by components in emergency vehicles are complex and very challenging to accurately simulate. Variations in the road inclination and surface conditions as well as the vehicle speeds and direction all contribute to the stochastic cyclic loadings experienced. As a result, component stress analysis may be limited to yielding qualitative data, given the necessity of certain simplifications and approximations. This may introduce difficulty into the design phase and impede effective failure prevention prior to manufacture. Hence, there is a need for further investigation into obtaining an accurate description of the vibration-induced cyclic loading of such components. In any case, the surface condition of the arms could be improved to reduce the stress concentrations and the influence of the heat-affected zone produced by thermal cutting. This can be accomplished by using processes like milling or water-jet machining to contour the arms. Otherwise, if thermal cutting must be used, a secondary finishing operation can be applied to improve the surface integrity and remove surface inclusions. As well, a higher-strength material can be used for the bracket arms to resist failure, either by selecting a different alloy or by heat treating the

alloy employed to a T4 or T6 temper. Finally, the component geometry can be redesigned to better distribute the stress field within the bracket. For example, more arms can be added, or the cross-sectional area of the arms in the critical regions of maximum stress can be increased. Given that the arms were most likely machined out of 6-mm-thick sheet metal, this can be conveniently achieved by increasing the width of the arms, or otherwise adding a second layer of material to the thickness. Although all of these improvements are suggested, implementing any one may significantly increase the bracket's resistance to failure.

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Conflict of interest None.

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