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SAFETY BRIEF

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Auger Elevator - Failure Modes and Effects Case Study*

by Dennis B. Brickman** and Ralph L. Barnett†

Abstract

A fatal accident occurred when a right angle gear box on an auger elevator disintegrated freeing the outboard end of a rotating PTO shaft. The tractor, acting as a stationary power source, flailed the PTO shaft which then struck and killed a farmer. No similar occurrences have been reported for the nearly 2000 similar units which have been used for over a decade. This paper studies a number of fundamental failure modes in order to determine which failure modes created the accident. Systematic analysis showed that the accident was caused by unusual misuse of the product. Known safety control concepts do not preclude this unforeseeable event.

INTRODUCTION

A tragic accident occurred when the gear box on an auger elevator failed, releasing the appliance end of a PTO shaft while the tractor end was driven at the standard speed of 540 rpm. At the time of the accident, the tractor was oriented with its longitudinal axis perpendicular to the longitudinal axis of the auger elevator. The tractor was being used as a stationary power plant and transmitted a torque to the input side of a right angle gear box by means of a telescoping PTO shaft with universal joints on both ends as depicted in Figure 1.

Two thousand nominally identical auger elevators with an average age of ten years are currently in use. There is no record of a similar accident known to the gear box manufacturer, auger elevator manufacturer, or auger elevator distributor. The goal of this investigation was to probe the nature of the system to establish whether it was sufficiently forgiving

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with respect to its reasonably foreseeable[1] loading environments. The formal objectives of the program were to determine whether the original design was reasonably safe for the expected use and reasonably foreseeable misuses, to establish whether a retrofit program was required and, if so, to redesign the machine.

ACCIDENT INVESTIGATION

After the accident, various investigators made the following observations:

Gear Box Fractures

Fig. 2 is an exploded view of the gear box involved in the subject accident. Two of the six inboard bearing supports were being utilized in this application. After the accident, the input inboard bearing support was fractured as shown in Fig. 3; the output bevel gear and the output shaft appear on the right side of Fig. 3. The cast iron fracture surfaces were subjected to metallurgical examination and were found to be free of casting defects. The cast aluminum bearing cap on the input side appears in Fig. 4 where the individual fragments have been reassembled. It should be noted that one of the four retaining bolts is missing. An examination revealed that the bolt was broken off in the housing and was not present at the time of the gear box failure.

An extensive search of the accident site was conducted using seven metal detectors, but a group of input components was never recovered as indicated in Fig. 2. The entire output assembly, including the output bevel gear, remained *in-situ* in pristine condition. The remaining parts in Fig. 2 were all intact and operational.

Lubrication

After the accident, a significant quantity of oil remained in the gear box housing and a film of oil covered the surviving components. In addition, the victim's clothes and the soil beneath the gear box were covered with oil which clearly came from the failed gear box. Subsequent examination of exemplar gear boxes showed that no oil leakage occurred when a bolt was removed from the input bearing cap. All investigators concluded that the gear box failure could not be attributed to a lack of lubrication.

Output System

The gear box output shaft was coupled to the auger elevator output drive line shaft with a simple shear plate coupling containing a shear bolt. The original 6.35 x 50.8 mm (0.25 x 2 in.) grade 2 shear bolt was found in perfect condition after the accident. Furthermore, the output drive line shaft rotated freely together with the screw conveyor auger and drive chain as illustrated in Fig. 1. All investigators determined that excessive output torque was not a causative factor in the gear box failure.

PTO Shaft

The telescoping PTO shaft consisted of a solid rectangular member inserted in a tubular rectangular member. This assembly was in turn covered by a floating cylindrical PTO guard. The use of the rectangular cross-section guaranteed the proper alignment of the universal joints thus eliminating improper phasing as a causative factor. Furthermore, there was no indication that prior damage or corrosion impeded the proper telescoping action of the PTO shaft. All PTO shaft damage happened after the fracture of the gear box which eventually released the outboard end of the PTO shaft and threw it 50.9 m (167 ft) from the accident site.

EXPECTED LOADING ENVIRONMENT

In normal operation, a PTO shaft is a two-force member whose ends act as hinges and whose loading is only through the hinge points. All thrusts through such a member must lie along an axis through the hinge points, that is, through the member. The telescoping nature of the PTO shaft guarantees almost zero thrust, and consequently, the force delivered to the gear box input shaft will have zero components in the x, y, and z directions ($F_x = 0$, $F_y = 0$, $F_z = 0$) as illustrated in Fig. 5. Universal joints can only transmit torsion. Consequently, $M_y = 0$ and $M_z = 0$. Therefore, the only resultant load that can be transmitted to the gear box input shaft is the torsional load $M_x = T$, where T is the output torque of the tractor PTO neglecting inefficiencies.

Theoretically, the torque T will be transmitted to the output shaft through the gear box. Since the shear bolt limits the magnitude of the output torque, the input shaft is exposed to a limited torque with all other force and moment components being zero. There is no structural loading that is simpler than the theoretical loading on the input shaft. In order to explain the observed gear box fractures, it is necessary to study misuse conditions which would produce a new loading environment.

MISUSE LOADING ENVIRONMENTS

Stowage Mode

If the PTO shaft is folded so that it is parallel to the axis of the screw conveyor, the resulting large rotation at the universal joint gives rise to an interference between the gear box input shaft and the flared-end bell of the PTO guard. This interference produces a moment M_y. Some manufacturers cut a crescent-shaped notch in the edge of the flared-end bell to eliminate this interference and its associated moment. Most farmers do not force the PTO shaft into a parallel stowage position and consequently produce low values of M_y.

Testing of an exemplar auger elevator revealed that the PTO shaft can be stowed parallel to the screw conveyor with a moment of M_y = 1,152 Nm (850 ft-lbf). No damage occurred to the flared-end bell in terms of permanent deformation and no distress occurred to any gear box components during this extreme stowage scenario.

Critical PTO Shaft Speed

Approximate calculations of the critical

[1] To be foreseeable, an event must be statistically significant.

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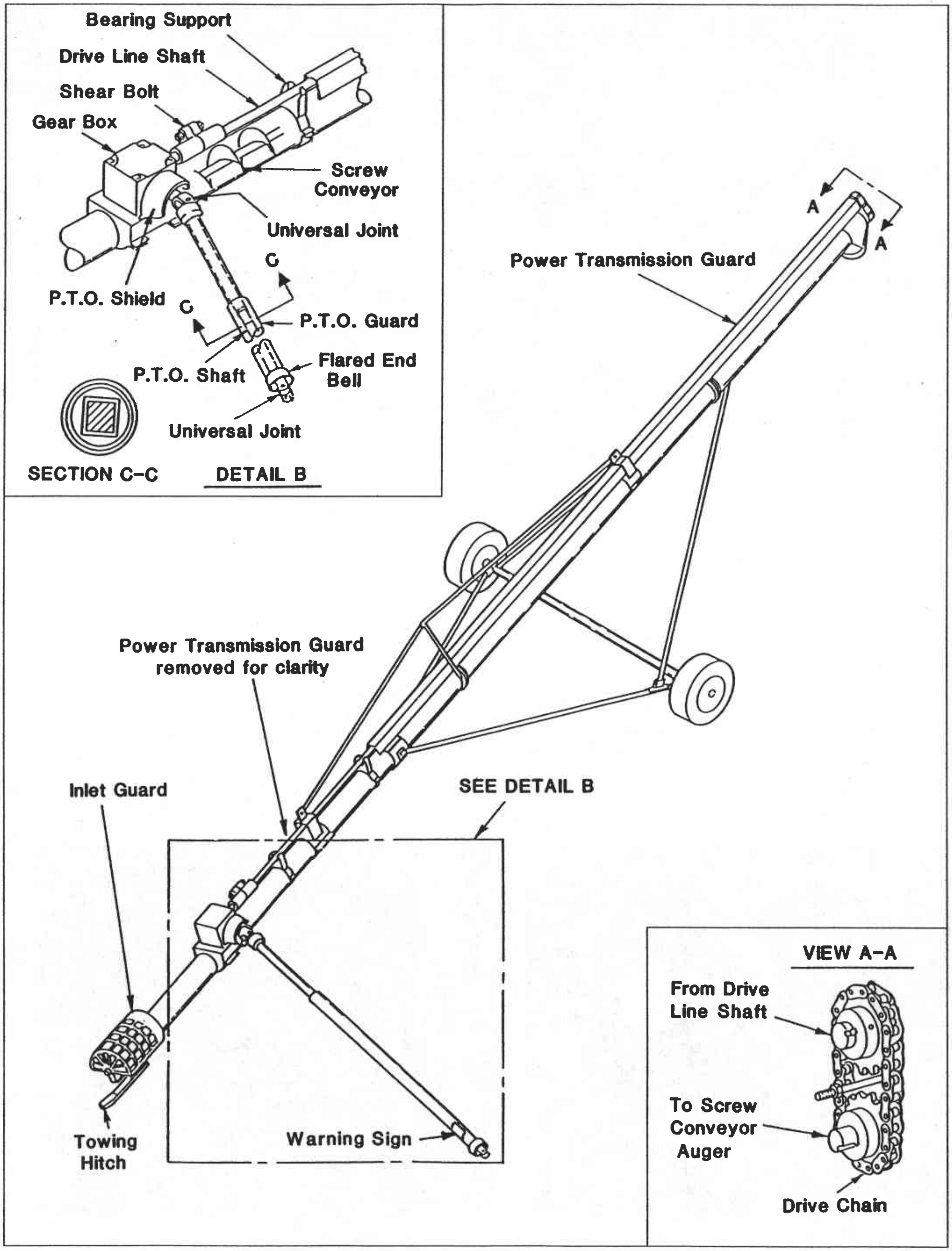

Figure 1. Auger Elevator

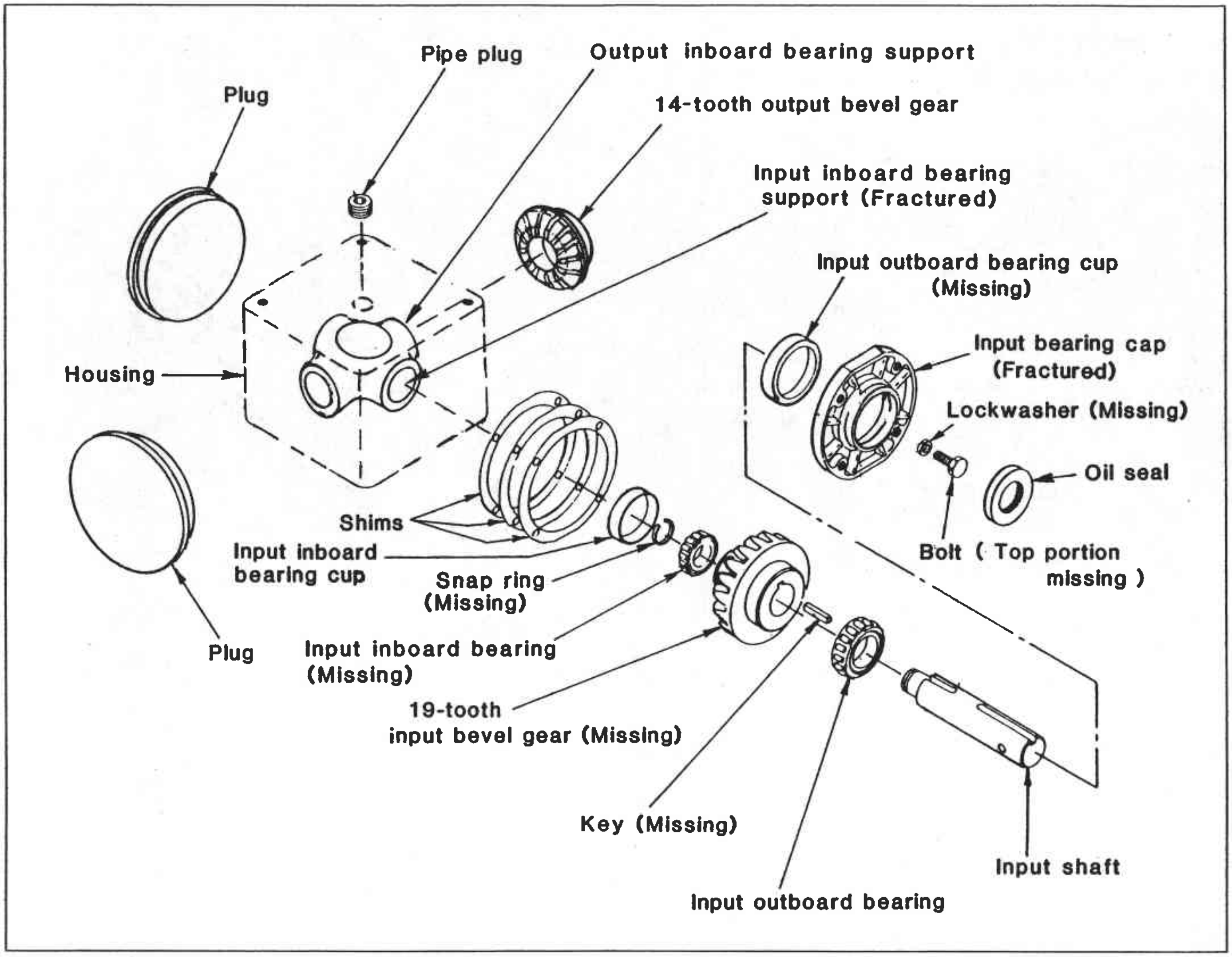

Figure 2. Gear box exploded view

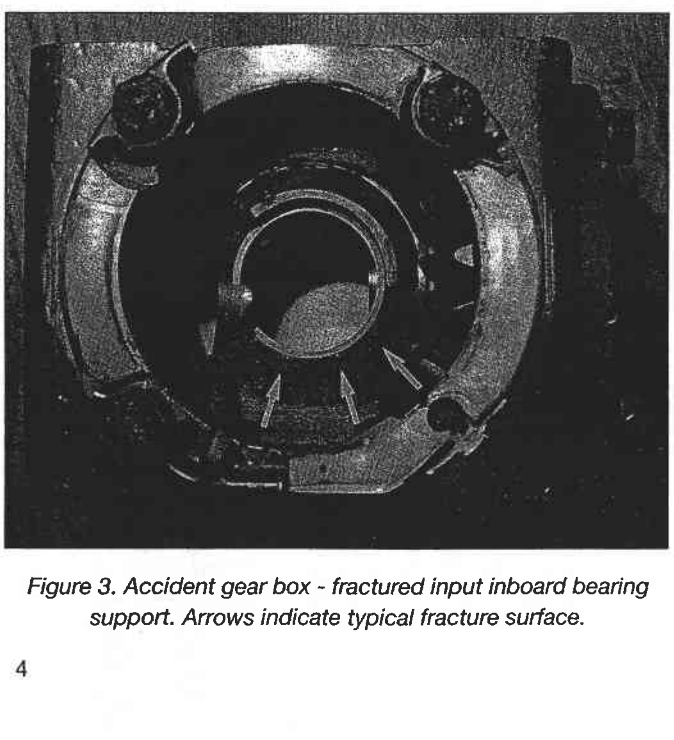

Figure 3. Accident gear box - fractured input inboard bearing support. Arrows indicate typical fracture surface.

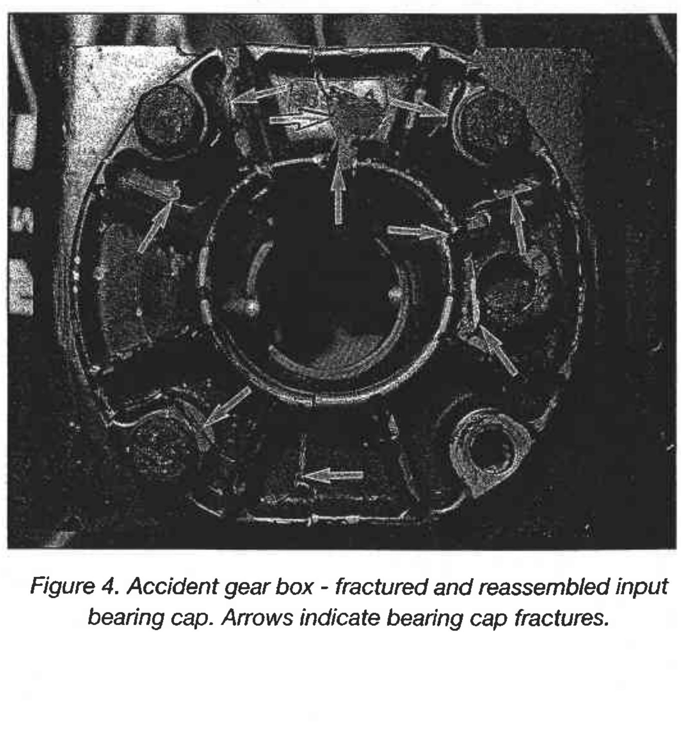

Figure 4. Accident gear box - fractured and reassembled input bearing cap. Arrows indicate bearing cap fractures.

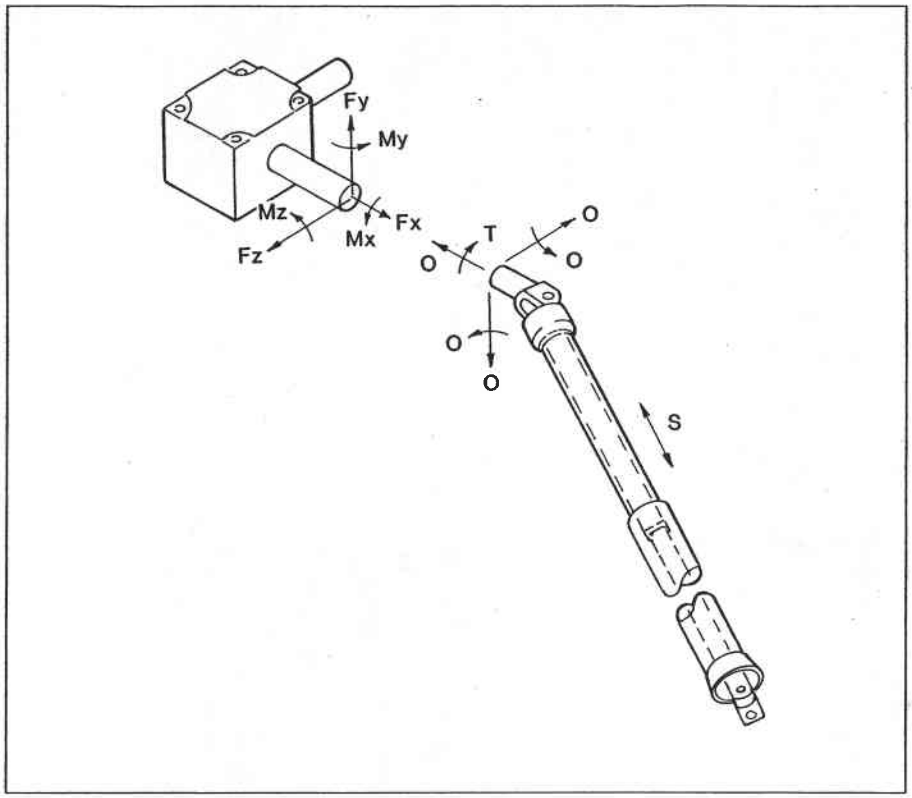

Figure 5. Most general expected loading - input shaft

speed of a rotating shaft indicate that the PTO shaft can be extended far enough to cause it to go into resonance at the standard tractor PTO speed of 540 rpm.[1] Almost all farmers know about this phenomenon and keep their PTO shafts as short as possible. Resonance introduces large transverse bending forces into the PTO shaft which changes its structural behavior from a two-force member to a simply supported beam. Here, large shearing forces, F_y and F_z, can be generated. To study this failure mode and effect, the PTO shaft on a duplicate auger elevator was extended far enough for the entire PTO shaft and auger elevator system to go into resonance.

The system was operated at resonance for one hour and almost everything on the auger elevator failed except the gear box. All the drive line support bearings were destroyed, the inlet guard and drive line power transmission guards fell off the auger elevator and the gear box and drive line shaft rotated out of position. Disassembly of the gear box revealed no distress of the input inboard bearing support or the input bearing cap.

Tramp Metal

Tramp metal can arise from the careless reassembly of the bearing cap or from the failure of internal gear box parts, such as snap rings, keys or input bevel gear teeth. If these metallic objects fall into the inrunning nip between the two bevel gears, a prying or wedging action takes place that will load up the entire running gear system. The following tests were conducted to study this phenomenon:

1. A hardened snap ring was inserted into the inrunning nip of a stationary exemplar gear box and the auger elevator was subsequently operated for 20 minutes. This test was repeated using 2, 3, 4, and 10 snap rings ranging in hardness from 46.1 R_c to 46.8 R_c.
2. A gear tooth with a hardness of 30.9 R_c to 32.8 R_c was removed from a duplicate input bevel gear and cemented into the bottom land of a functional input bevel gear of an exemplar gear box. This gear box was then operated for 20 minutes.
3. A hardened 6.35 mm (0.25 in.) solid cylindrical pin was injected upward into the inrunning nip of an operating gear box. This test was repeated 5 times using pins ranging from 1.27 cm (0.5 in.) to 4.45 cm (1.75 in.) in length and from 61.4 R_C to 62.4 R_C in hardness.
4. An exemplar gear box with a fractured input inboard bearing support, shown in Fig. 7, was mounted on an exemplar auger elevator and operated for 20 minutes. The hardness of the input inboard bearing support fragments ranged from 92.9 R_B to 94.2 R_B.

The results of the tramp metal testing program were as follows:

1. The tramp metal parts were all broken by the meshing gears. For example, Fig. 6 shows a hardened pin after being injected into the inrunning nip created by the bevel gears.
2. No distress of any kind was inflicted on the gear box components.
3. No telltale marks were observed on either the input or output bevel gears. Recall that the output bevel gear on the accident gear box showed no nicks or imperfections.

Collapsing the PTO Shaft

If the PTO is telescoped in far enough, it will "bottom out" and give rise to an axial compression force S. This force S produces a general loading on the gear box input shaft of F_x, F_y, and F_z, where F_x will always be axial compression and the shear forces F_y and F_z will be in either direction. The associated moments are the same as the expected loading case, that is, $M_x = T$, $M_y = 0$, and $M_z = 0$.

To study the effect of pure axial compression on the input shaft ($F_x < 0$, $F_y = F_z = 0$), an exemplar gear box was compression loaded in a universal testing machine to failure. The cast iron input inboard bearing support fractured under an ultimate compressive load of 66,367 N (14,920 lbf). The appearance of the input inboard bearing support fracture was similar to the accident gear box as shown in Fig. 7; however, in contrast to the accident gear box, no failure occurred in the cast aluminum input bearing cap. Indeed, no loading is transferred to the input bearing cap since the input shaft slides freely through the oil seal.

Using the test setup illustrated in Fig. 8, exemplar gear boxes were subjected to a shear force ($F_x = 0$, $F_y = 0$, $F_z > 0$) in the +z direction parallel to the output shaft. An

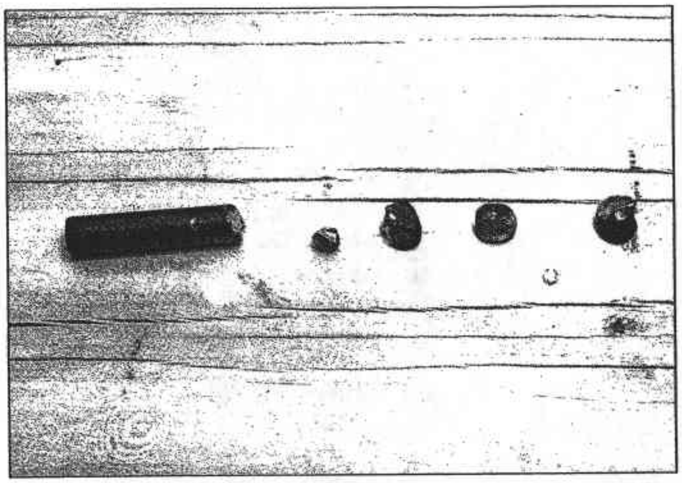

Figure 6. Hardened pin fractured by meshing gears

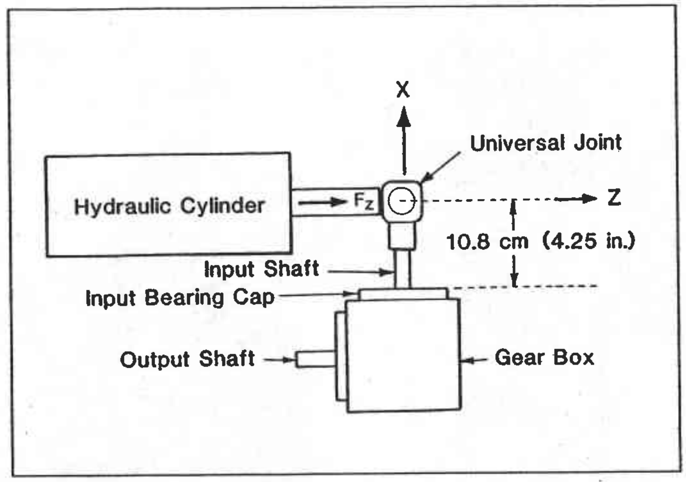

Figure 8. Test setup - shear loading

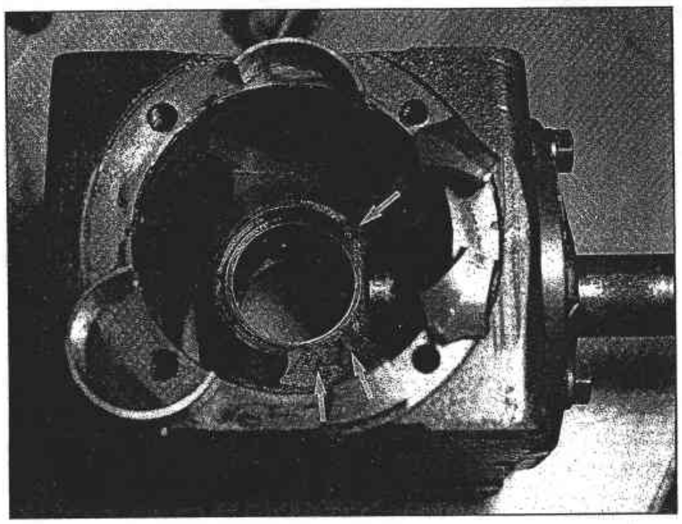

Figure 7. Exemplar gear box - fractured input inboard bearing support after compression loading. Arrows indicate typical fracture surface.

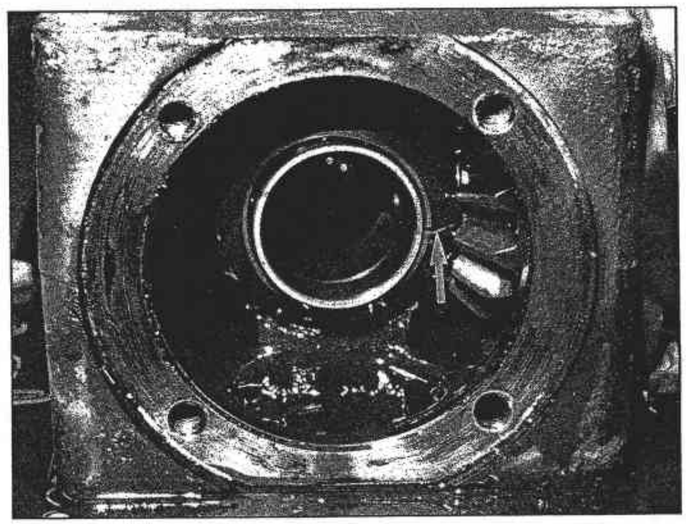

Figure 9. Exemplar gear box - arrow indicates fractured input inboard bearing support after shear loading

ultimate shear load of 22,704 N (5,104 lbf) was obtained with an exemplar gear box with 3 bolts in the input bearing cap. A second gear box achieved 25,324 N (5,693 lbf) with 4 bolts in the input bearing cap. In both cases, the input bearing cap fractured in a pattern similar to the accident input bearing cap and a single crack appeared in the input inboard bearing support near the output gear as shown in Fig. 9 and Fig. 10.

The complete failure mode observed in the accident gear box can be produced by a compression force transmitted through a collapsed or "bottomed out" PTO shaft which is not parallel in any direction to the gear box input shaft. The required fracture forces are too large to be applied statically by a tractor, and therefore, the fracture mode must be produced using impact. Such impact loads might arise if the position of the auger elevator is manipulated using the PTO shaft instead of the towing hitch.

FAILURE PREVENTION

Various investigators of the subject accident have proposed design alternatives to prevent gear box failure on the auger elevator.

Crescent Cutout in Flared End Bell

This particular proposal would eliminate bending forces associated with the misuse of strapping the PTO shaft tightly against the screw conveyor. The proposal, however, will have no effect on the present design since the associated stresses are less than 42% of those required to cause gear box distress. Furthermore, it should be noted that a farmer must apply 756 N (170 lbf) to a "bottomed out" PTO shaft at a distance of 1.52 m (5 ft) from the gear box input shaft to achieve a parallel stowage position.

Mechanical Upstream Fusing

Some PTO shafts are manufactured with a shear bolt located near the tractor end which limits the torque that can be transmitted to the input side of the gear box. These designs capture and retain both ends of the sheared connection after the shear bolt has severed and freewheeling proceeds. This proposal will not prevent gear box fractures caused by compression impact on a "bottomed out" PTO shaft. Excessive torque due to auger resistance or internal resistance from tramp metal did not occur in the system examined.

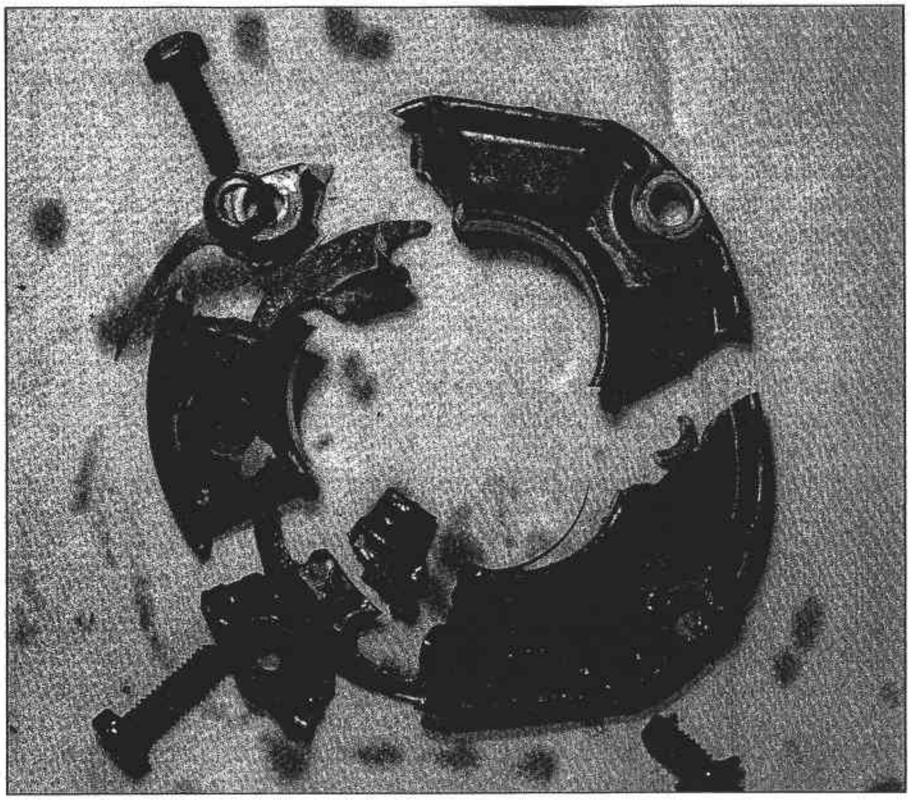

Figure 10. Exemplar gear box - fractured input bearing cap after shear loading

CAUTION

WHILE PTO IS ROTATING OBSERVE THE FOLLOWING:

KEEP IN A CLOSED POSITION AS MUCH AS POSSIBLE

KEEP U-JOINT ANGLES SMALL AND EQUAL

DO NOT EXCEED 15° MISALIGNMENT ON EACH U-JOINT

DO NOT REMOVE SHIELDS

Figure 11. Warning sign on PTO shaft

PTO Instruction

A proposal was made for a warning/instruction plate on the PTO shaft which admonishes against extreme joint angles and excessive PTO shaft extensions.[2] In this particular case, a warning sign of this type, shown in Fig. 11, was utilized and limited the joint angles to 15°. The operating conditions at the time of the accident were characterized by a modest PTO shaft extension and by small joint angles.

DISCUSSION OF THE RESULTS

Some failure modes leave fingerprints which enable practitioners to characterize the failure mode immediately. For example, the helical fracture surface in a brittle shaft indicates excessive torsion to mechanical engineers when it occurs in cast iron shafts and to physicians when it occurs in bones. In the subject case, however, such recognizable clues were not available and a systematic diagnosis was required. To simplify the problem, commonly recognized failure causation systems were studied. For example, the lack of lubrication is known to create excessive heat which can degrade the strength of materials and which can cause binding and welding of movable components. Excessive resistance of the output shaft caused by failure of downstream components or excessive resistance of the transported materials can subject the right angle gear box to torques not contemplated in the design. Improper phasing or extreme offset angles in universal joints introduce bending moments which are outside of the loading envelopes anticipated by the designers of right angle gear boxes. Early investigations eliminated these common failure modes as causative agents of the subject accident.

The investigators continued to eliminate potential failure modes by studying loading environments that arise from misuse. The stowage mode is a method of manually applying a moment to the input shaft by forcing the PTO into a parallel configuration with the auger tube. This mode produced no failure. Because it is possible for the PTO shaft to achieve a critical shaft speed, it was important to study this resonance condition as a potential failure mode. The elimination of this possible explanation of the accident was another step in the continuing simplification of the problem. The probability of tramp metal being introduced into a gear box is not very high, but the effects of internal binding of the bevel gears will subject the input side of the gear box to the full torque output of the tractor PTO system. This torque could easily destroy the input side of the gear box. The introduction of tramp metal under extreme circumstances indicated the forgiving nature of the gear box system and eliminated this potential mode of failure. Because the output bevel gear showed no indentations or external signs of distress, some investigators concluded that tramp metal could not have been introduced into the gear set. Our testing proved that even the introduction of large hardened metallic bodies may not damage the gear teeth.

Our studies eliminated the three potential bending moments (M_x, M_y, M_z) as causative agents of the subject failure. Furthermore, shear forces that arise from critical shaft vibration were also eliminated. Because the PTO shaft is telescoping, axial tension will not occur, eliminating this as a source of shear and tension on the input shaft. The remaining possibility is compression of the PTO shaft which can occur if the shaft is "bottomed out." Only under this circumstance could we produce axial compression and shear on the input shaft. The axial compression alone produced the fracture surfaces observed in the input inboard bearing support without damaging the associated input bearing cap. On the other hand, pure shear forces replicated the fracture mode of the input bearing cap with minor distress being introduced into the input inboard bearing support. A compression loading of a skewed PTO shaft will consequently produce the complete failure mode observed. Quantitative results show that a tractor is not heavy enough to induce statically the required compressive loading to fail the gear box and consequently impact loading is the only feasible method of achieving the observed failure mode.

The manipulation of the auger elevator by means of the PTO shaft as opposed to the towing hitch can produce the source system associated with the observed failure. External impact of the input shaft may also give rise to the requisite loading.

Mechanical fusing such as shear connectors on the gear box output shaft or on the tractor side of the PTO shaft are available to limit torsional failures of the gear box. The telescoping PTO shaft eliminates the transmission of tension through the PTO shaft. At the present time, no system exists for eliminating or limiting compressive loads transferred through a collapsed PTO shaft. The development of such devices must not only limit the axial compression, but must also prevent flailing of the PTO shaft. The likelihood of compression failure of the auger elevator gear box is so remote that it would not appear that the development of compression control devices such as compression fusing should be undertaken.

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