The Development of Worm Drives

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Introduction

A worm drive is a geared power transmission device in which a worm meshes with a worm gear to transmit power between two non-intersecting shafts that are oriented at a right angle. The worm drive has been an active and challenging topic of technological study since Leonardo da Vinci (1452–1519). Significant breakthroughs achieved for high-speed applications in the last century can largely be attributed to the progress in tribology, which introduced dissimilar materials for the worm and worm gear, as well as closed housings to facilitate oil lubrication rather than grease lubrication in an open environment. The modern worm drive is a commonly used power transmission device to achieve high-speed reduction in a relatively small footprint, although with potentially limited load-carrying capacities and high wear rates. This paper provides a comprehensive compilation of state-of-the-art information on enveloping worm drives and future prospects.

In mechanical power drives of skewed axes, worm drives are commonly employed for speed reduction with high ratio (generally 20 to 300, higher ratio is also available) in a small footprint. Unlike other types of gear drives, characterized by rolling plus sliding between the meshing flanks, there is little rolling in the worm drive. The movement of a worm drive is purely caused by screw motion — sliding on the mated surfaces; therefore, the load capacity for worm drives is relatively limited and friction greatly affects the efficiency. The allowable transmitted power for worm drives is generally in several tens of kilowatts (less often for 100–1,000 kW) (Ref. 1). Worm drives present unique lubrication challenges, as the lubricant is continually scraped aside due to the abovementioned sliding motion. Consequently, the high temperature in many cases will be the limiting factor on the worm drive before the mechanical loading limitations are reached.

Worm drives have been widely used in various applications where 1) noise is a concern; 2) space is limited; 3) absorption of shock loading is required; and 4) no or minimum maintenance is required. In some literature the advantage of fast braking or emergency stopping was indicated; unfortunately, this concept of a self-locking worm drive has been disproved. In theory, worm drives in the static condition may have trouble driving the worms by the worm gears, depending on the lead angle of worm thread. If, however, the self-locking drive is subjected to shock or vibration, which is the typical case for many applications, the drive can no longer be self-locking and back-driving occurs (Ref. 2). Worm drives make up approximately 10 percent of all mechanical power transmissions (Fig. 1).

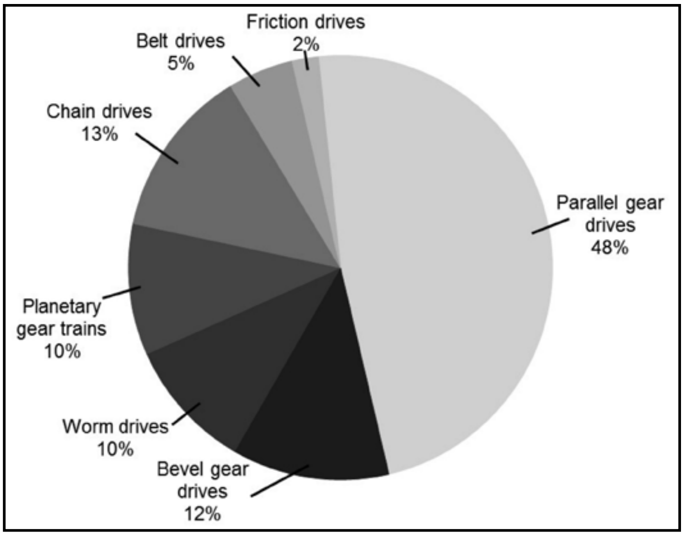

Figure 1 Global distribution of mechanical power drives in which worm drives make up approximately 10 percent of all drives (Ref. 1).

Worm Drives: State of the Art

The geometry of an enveloping worm drive is mainly based on the concept of involute profile. The 1937 British standard BS 721 rendered the involute profile as the standard thread form. The German standard DIN 3975 (Ref. 3) has classified the most common thread profiles of worm into five different forms, i.e. — ZA (straight-sided axial profile with a turning tool); ZN (straight-sided normal profile with a turning tool); ZK (grinding wheel or milling cutter); ZI (involute helicoid); and ZC (concave with grinding wheel). Technical report ISO/TR 10828 (Ref. 4) also has similar designations (A, C, I, K and N) for the worm geometry. The American standard — AGMA 6022-C93 — (Ref. 5) has no equivalent to the ZC form. The first four forms — ZA, ZN, ZK and ZI — vary in their radii of curvature. The differences in curvature are very slight for the smaller-size and higher-ratio worms, but are significant in the larger-size and lower-ratio worms. The actual profile used and the amount of curvatures obtained for the worm is not as significant as the accuracy with which the worm gear tooth profile matches the particular worm profile selected. Material pairs for worm drives can be metallic, metallic-plastic, and plastic depending on the operating requirements and conditions. In metallic pairs the selection of materials for the worm and worm gear is more limited than it is for other types of gears. The threads of the worm are subjected to fluctuating stresses and the number of stress cycles is fairly high. Therefore the surface endurance strength is an important criterion in the selection of worm material. The core of the worm should be kept ductile and tough to ensure maximum energy

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absorption. The magnitude of contact stresses on the worm gear teeth is the same as that on the worm threads. However, the number of stress cycles is reduced by a factor equal to the speed reduction. Dissimilar or heterogeneous materials, especially steels-to-bronzes, are recommended for worms and worm gears for tribological advantages (Refs. 6–7). Steel-to-bronze results in much lower friction forces that do not exist in other metal combinations. It also results in sacrificial wear of the bronze and little to no wear of the steel, yielding improved contact over time.

The steels used for worms are: normalized carbon steels (40C8 and 55C8); case-hardened carbon steels (10C4 and 14C6); case-hardened alloy steels (16Ni80Cr60 and 20Ni2Mo25); and nickel-chromium steels (13Ni3Cr80 and 15Ni4Cr1). The case-hardened steels are typically with a surface hardness of 60 HRC and a case depth of 0.75 to 4.5 mm. The commonly used worm gear bronzes are tin bronzes, manganese bronzes, aluminum bronzes, and silicon bronzes.

Tin bronze gears are typically casted by centrifugal, continuous, investment, or sand cast methods (Refs. 8–9). Figure 2 shows the microstructure of the cast tin bronzes consisting of cored dendrites; they have a composition gradient of increasing tin as they grow. The last liquid to solidify is enriched with tin upon cooling, and forms alpha and delta phases. The alpha and delta phases fill in the areas between the dendrite arms. Cast or wrought manganese bronzes are the toughest materials in the bronze family, with good wear resistance, but do not possess the same degree of corrosion resistance, wearability, or bearing quality as the tin bronzes or aluminum bronzes. Aluminum bronzes are similar to the manganese bronzes in toughness, but are lighter in weight. They are available in both cast and wrought forms and can be heat treated to attain higher mechanical properties. Their bearing quality is better than manganese bronzes but inferior to tin bronzes (Ref. 9).

For lightly loaded applications, the British standard B721 (Ref. 10) and AGMA American standard 6022-C93 (Ref. 5) allow several alternative worm gear materials, such as gray cast iron, ductile iron, or soft steel. The development of plastics for lightly loaded worm drives, e.g.—food processing machinery—began in the early 1970s (Ref. 11) and currently there is no standard dedicated to the specification of plastics for worm drives.

The manufacturing methods of steel worms are dictated by the tread profile selected. Worms now can be turned on a lathe by a knife tool with straight edge aligned with the base tangent in a plane tangential to the base cylinder. This is similar to cutting screw threads. Worms can be ground by a thread grinding machine, using a grinding wheel dressed with a double-conical form. Worms can be also milled in a thread miller or similar machine, using a double-conical milling cutter with an included angle equal to two times the pressure angle of the worm. After manufacturing, worms require a number of finishing operations, including heat treatment and final dimensional and surface finishing. Bronze worm gears are most commonly produced by hobbing. Two hobbing methods—radial in-feed and tangential feed—are available, depending upon the lead angle and required accuracy of tooth profiles. Either method can be used to produce throated worm gears. Fly cutting is another method used for the quick manufacture of limited quantities of worm gears, such as the breakdown situation (Ref. 12). Plastic worm drives can be manufactured with the same machining process, as are metallic drives, by hobbing or milling. The very low cutting forces permit high infeed rates. Large quantity and small size of worms and worm gears can also be produced by injection molding.

The tooth contact analysis reveals that the contact area between the worm threads and worm gear teeth tends to be a long, thin ellipse that is distorted into a banana shape by the nature of surfaces (Refs. 13–14). The surface entraining direction in the contact ellipse is effectively along the major axis of the contact ellipse. This entraining action causes unfavorable tribological behavior and leads to thinner oil film thickness. Previous works addressing the worm contact analysis are also available (Refs. 15–17).

The efficiency of a worm drive can be between 50 and 96 percent, depending on lubricant; speed; surface roughness; load; material pair; worm profile; worm gear size; worm thread number; and temperature (Refs. 18–21). With unfavorable entraining action and mostly sliding contact, most worm drives have far more friction in the gear mesh than those of parallel and bevel drives, which results in a significantly lower efficiency. A simple analysis reveals that supplying all the worm drives in the United States with a lubricant that allows a relative increase of 5 percent in the mechanical efficiency, compared to a conventional mineral oil, would result in savings of US$ 0.6 billion per annum (Ref. 22). The efficiency calculations for worm drives are standardized in AGMA 6034-B92 (Ref. 23); BS 721 (Ref. 10); DIN 3996 (Ref. 7); and ISO/TR 14521 (Ref. 24).

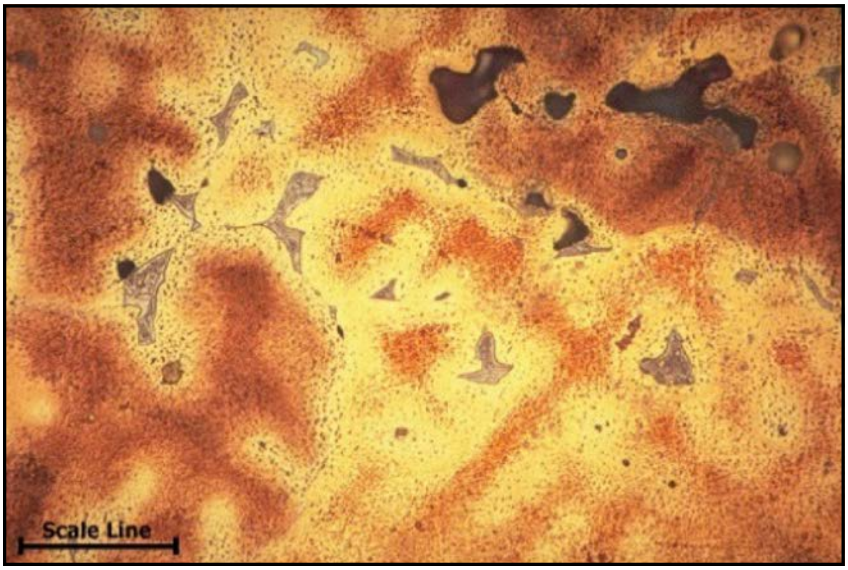

Figure 2 Microstructure of tin bronze as cast (scale line length ~50 microns) (Ref. 8).

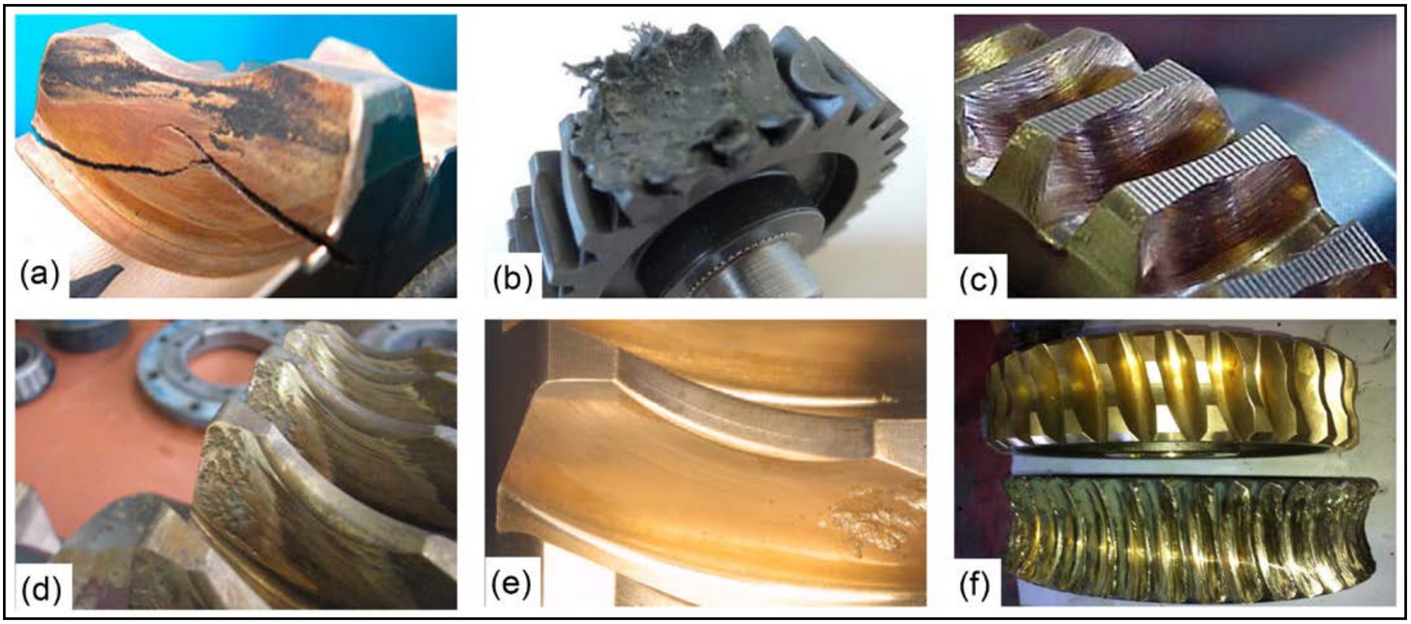

Figure 3 Wormgear failures: a) tooth breakage (Ref. 25); b) deformation and melting of plastic gear (Ref. 26); c) scuffing (Ref. 27); d) corrosion pitting (Ref. 28); e) pitting (Ref. 29), and f) wear — before (top gear) and after (bottom gear) usage.

In general, an increase in the noise level and vibration can be expected when worm drives fail. Different failures often leave characteristic clues on the worms and/or worm gears. Worm gear failures (Fig. 3) may be classified into two modes: 1) structural failure mode that includes tooth breakage due to impact or bending fatigue, tooth deformation and melting for plastic worm gear, and 2) surface failure mode that includes scuffing, case cranking, pitting and wear.

Future Outlook

It has been more than 80 years since the first standard for worm gearing was published, and worm drive development has progressed to maturity. Although the focus of gear research efforts has been dynamically changed, worm drives have constantly remained an active field. A brief review of the state of the art, such as the one presented here, may be helpful for better foreseeing future prospects. The following is the outlook for worm drives from the authors' point of view.

Plastic worm drives. There is increasing demand from automotive, home/medical appliances, and food processing industries for worm drives that pair metallic and plastic, or plastic only materials. This demand is driven by the lower cost, lighter weight and lower noise that can be achieved with plastics. Table 1 shows a list of metallic-plastic or plastic-plastic material pairs that have been developed specifically for worm drives. Plastics of interest include general-purpose plastics, general-purpose engineering plastics, quasi-super engineering plastics, super-engineering plastics, as well as glass fiber- and carbon fiber- reinforced plastic matrix composites. The latest development in worm material is the synthesis of carbon nano-tubes/polyacetal. The ongoing research direction of utilizing new developed plastics for worm drives focuses on wear resistance and surface temperature, since there is little rolling in the worm meshing. The plastic gear surface typically wears slowly, with a low specific wear rate if the gear is loaded below a critical value; however, the plastic gear wear rate will be increased dramatically when the load reaches a critical value for a specific geometry. The possible reason of the sudden increase in wear rate is due to the gear operating temperature reaching the material melting point under the critical load condition (Ref. 30).

A future challenge for the development of new plastics for worm drives is the cost of raw material and manufacturing processes. As an example (Ref. 36) for home appliance

Table 1 Metallic-plastic or plastic pair solutions

Metallic or Plastic	Plastic	Remarks/References
JIS S45C steel, $H_B = 210$	Carbon fiber/Polyaminobismaleimide (PABM) resin matrix	Carbon fiber/Polyaminobismaleimide (PABM) show excellent wear re-sistance but the cost is expensive
	Glass fiber/Polyaminobismaleimide (PABM) resin matrix	
	MC polyamide (nylon)	
	PE polyamide (nylon)	
JIS S45C steel,	Mica filled polyamide (nylon)	The material is inexpensive with insufficient wear resistance
Steel	Polyetheretherketone (PEEK)	Good load-carrying capacity
	Polyamide PA 4.6	Inferior load-carrying capacity [33]
Steel	Reinforced glass fiber/Polyamide resin matrix	50 wt% glass fiber is relatively superior than 25% wt% glass fiber [34]
Synthesis of carbon nano- tubes (CNT)/ Polyacetal (poolyoxymethylene POM) matrix	Synthesis of carbon nanotubes (CNT)/Polyacetal (polyoxymethylene POM) matrix	[35]

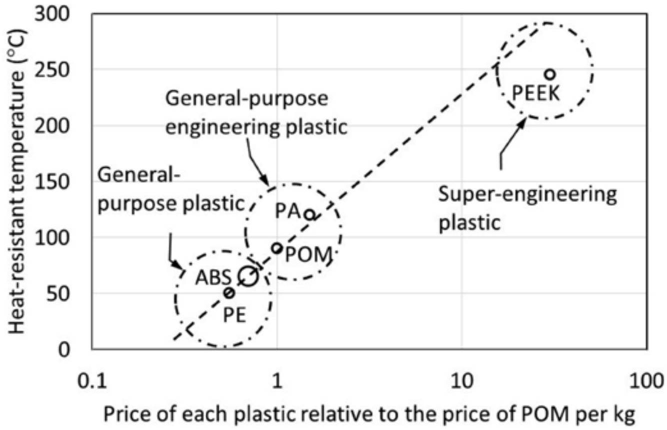

Figure 4 Heat-resistant temperature as a function of relative price to the price of POM per kg for plastics used for worm drives (Ref. 37).

industries, the molded fiberglass-reinforced POM gear cost is about a fifth of what the original machined metallic gear cost. Figure 4 shows an interesting indication that adopted from the study in (Ref. 37), addressing the heat-resistant temperature as a function of price of each plastic relative to the price of POM per kg. Even the price of super-engineering plastics can be more than one order higher than that of POM, so the future challenge in developing new plastics for worm applications will require low wear rate and high heat-resistance temperature while maintaining the cost similar to those of engineering plastic.

Integrated contact analysis for load capacity estimation. In steel-bronze worm drives, the maximum load capacity is determined mainly by tooth breakage and pitting. Detailed geometry data of the worm drive is needed to perform the analysis. Many mathematical contact models have been developed to date to predict the tooth contact. However, the excessive wear of the softer worm gear and change in the tooth contact during the run-in period remains a modeling challenge. In addition, the abrasive wear on bronze worm gears may compete with the pitting during the normal operation. The material removed by the abrasive wear may in fact reduce the affected pitting area (Ref. 38).

An integrated contact analysis would be more accurate to estimate the load capacity. The integrated contact analysis should include the information of geometry (radii of curvature), kinematics (surface sliding velocity) and elasticity (gear tooth stiffness), coupling with material wear mechanism and material Woehler diagram to predict the stress distribution on the worm gear flank. This calculation has to be done iteratively. At any instance, the contact stress distribution can be established. Based on the contact stress distribution, the material removal and material life of flank surface can be predicted. A new surface on the worm gear flank is formed for the next instance of the calculation.

Enhancement of efficiency calculation. There are several standards available to calculate worm drive efficiency; however, many restrictions exist when applying these standards to the calculation of worm drive efficiency. For example, AGMA 6034-B92 and DIN 3996 do not consider the effect of lubricant type and surface roughness on efficiency. Lubricants influence the efficiency of worm drive mainly through reducing power losses, which include churning losses and friction losses in hydrodynamic, elasto-hydrodynamic and boundary lubrication regimes. In conventional gear trains, synthetic oils can reduce power losses up to 8 percent for high-reduction worm drives (Ref. 39). In addition, the efficiency calculation in DIN 3996 is based on the empirical method from the worm drive with 20.5 of gear ratio. Applicability of worm drives with gear ratios other than 20.5 may be invalid (Ref. 40). Figure 5 shows the discrepancy among these standards — especially between AGMA and DIN/ISO standards. The efficiency of a worm gear pair calculated from the AGMA standard gradually increases with the rotational speed, while the efficiency from DIN/ISO standards seem to be insensitive to the rotational speed. To improve the efficiency calculation, local tooth friction and oil churning have to be obtained through the corresponding tribological behavior (lubricant, speed, surface roughness, load, temperature, and materials), gear size, worm profile, as well as thread number.

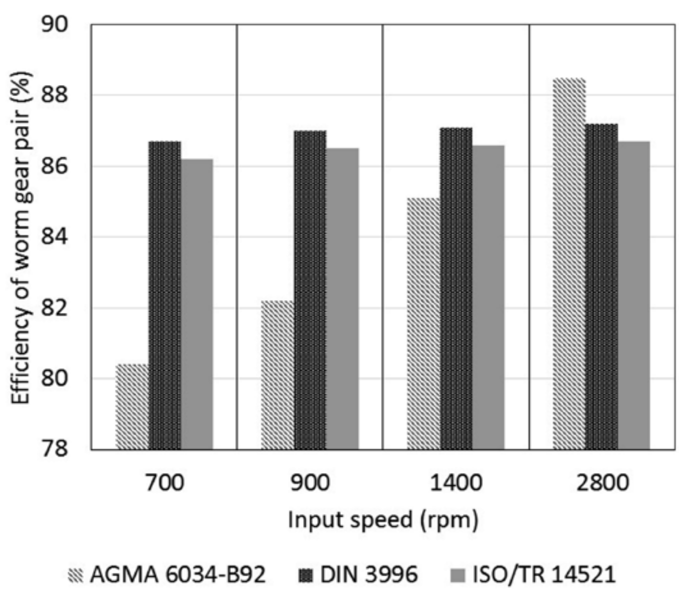

Figure 5 Efficiency of worm gear pair (gear ratio = 28, center distance = 150 mm) as a function of input speed based on the analytical calculation from AGMA, DIN and ISO standards.

Condition monitoring of worm drives. Condition monitoring is the process of monitoring a parameter of condition in machinery (vibration, temperature, particulates, etc.) in order to identify a significant change which indicates an ongoing fault in the machine. Condition monitoring has gained more attention as a result of maintenance operation of asset management. At one time, maintenance practices for gear drives were mostly reactive maintenance, i.e. — operate the geared drives until failure occurs. As the gear drives grew in capacity, preventive maintenance (PM) was then adopted to have periodic inspections of gear drive conditions. Such inspections are generally expensive and often require undesired scheduled downtime for the operation safety. As the condition monitoring techniques were developed during the 1970s and early 1980s to detect impending problems with obvious economic advantages in the aerospace and offshore oil structures (Ref. 41), predictive maintenance (PdM) and condition-based maintenance (CBM) techniques have become increasingly adopted for many gear drives — especially with drives of large sizes or drives deployed in a remote area. The condition monitoring techniques that have been attempted for the gear drives are vibration analysis, oil debris analysis, acoustic emission, temperature, and power analysis (motor current/voltage/torque).Several condition monitoring techniques for parallel gear drives have been well established; however, the application of condition monitoring on the worm drives is currently limited. Research studies of condition monitoring and diagnosis on worm drives have been conducted since 21st century (Refs. 27; 42–44) to benefit worm drives in a remote area. The condition monitoring and diagnostic techniques may for worm drives differ from those for parallel drives. Taking the vibration analysis for example, compared to other gears types where defects manifest as periodic impacts in the form of side-bands around the gear mesh frequencies, such distinctive defect symptoms are not obvious for worm drives due to their continuous sliding interactions. Many challenges remain unclear such as, in the vibration analysis, which mathematical process has the most sensitive feature, at what frequency range is this mathematical process effective to the worm kinematics, and how these mathematical processes perform product-by-product in different application fields (Ref. 43); but progress has been made toward an integrated approach to condition monitoring and diagnosis using oil debris analysis, vibration analysis, and/or other techniques in parallel.

Conclusions

Worm drives have greatly advanced since the progress made in geometrical modeling, tribology and manufacturing processes. Further innovations in worm design, manufacturing, and operation could help develop a vast set of new opportunities for worm drives. The focus should be placed on designing gears that have higher load capacity and efficiency, less heat and noise, low cost and improved lifecycle. This paper presents a comprehensive compilation of state-of-the-art information on worm drives, highlights future outlook, and addresses important and challenging areas of research and development that should be explored for the industry to better cope with the innovations that are likely to occur in the worm drives. **PTE**

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