temperatures for these engines will be 600°C to 1200°C, far exceeding the performance limits (about 250°C) of all currently marketed lubricants.

DOE has conducted research into a new method for attaining effective lubrication at elevated temperatures by depositing lubricating films from the gas phase. Completed studies show that bearing lubrication may be continued to temperatures well above the stability of the liquid lubricant by delivery to the high-temperature bearings in a vapor state. Experimental data indicate that a wide variety of conventional liquid lubricants can be used in a homogeneous gas phase, diluted with an inert carrier gas such as nitrogen or mixtures of nitrogen and oxygen, to produce a low-friction, polymer-like film on metal-bearing surfaces at high temperatures. Studies were successfully carried out at temperatures as low as 200°C and as high as 1600°C.

This technology should be useful in high-temperature lubrication of adiabatic or low-heat-rejection engines as well as in high-temperature, metal-forming operations. Further research on gas-phase lubricant delivery to ceramic surfaces will also affect development of ceramic parts for new, more efficient, advanced engine designs.

Base Oil Separation and Characterization

The Research Committee on Lubrication of the American Society of Mechanical Engineers estimates that friction and wear losses in mechanical systems account for up to 11% of total annual U.S. energy consumption. A wide variety of lubricants are currently required for reducing energy losses from friction and wear in many important energy conversion applications. To formulate better lubricants and establish lubricating base oil specifications and standards, an understanding of the influence of the molecular structure of the lubricant on its friction/wear characteristics needs to be developed.

An extensive series of experiments to determine the tribological properties of base stock oils was completed with DOE funding. Three lubricating base oils of various viscosity grades from Mideastern crude oils were separated into various molecular compound classes using high-performance liquid chromatography. The fractions were characterized using infrared spectroscopy, high-resolution mass spectroscopy, nuclear magnetic resonance spectroscopy, Fourier transform infrared spectroscopy, and elemental analysis. Each class of compounds was subjected to microsample, four-ball wear testing for friction/wear characterization and free radical titration testing for oxidation stability.

Results indicated that the organic acids subfraction of the polar fraction of the Mideastern 600 neutral base oil exhibited the lowest coefficient of friction. Having isolated and characterized the desirable components of base stock oils, researchers should now be able to further investigate and understand the relationship between the molecular structure and the lubricating qualities of base stock oils and, subsequently, to synthesize the "slipperiest" fraction en route to formulating superior energy-saving lubricants.

Intermediate- and High-Temperature Lubricants

New laboratory techniques and procedures are necessary to enable lubrication engineers to characterize and evaluate candidate lubricants with a range of important properties for elevated-temperature and energy-conserving applications. In response to this need, DOE developed a thermogravimetric analysis method for screening candidate high-temperature lubricants. The procedure uses a pair of experiments to obtain measures of volatility and oxidative stability, both of which are key parameters in the consideration of specifications for oxidation stability.

This analysis method was successfully used to evaluate two phosphate esters: trixylyl phosphate (TXP) and diphenyl t-butylphenyl phosphate (DPBP). Although both materials exhibited good oxidative stability, DPBP appeared to be somewhat more resistant to oxidation than TXP. At temperatures above 280°C, TXP showed an oxidation-induced, high-molecular-weight residue, and DPBP showed only normal (nonoxidative) evaporation.

As new candidate intermediate- and high-temperature lubricants are evaluated by this technique, in concert with other tribological tests, an extensive data base will be developed. This data base will be invaluable to lubrication engineers in improving the tribological performance of mechanical components and systems that operate at elevated temperatures.