Introduction: The development of compact processing hardware for the production of propellant fuels and oxygen from available resources on Mars or elsewhere presents a number of technical challenges including process miniaturization and thermal energy integration. Our approach to this problem consists of developing integrated reactors, heat exchangers, and separations units using microfabrication techniques that have the potential of realizing very compact systems with high throughputs and high thermal efficiencies.

Background: At the Department of Energy’s Pacific Northwest National Laboratory, researchers have used precision engineering techniques, originally developed for the electronics industry, to fabricate and test a variety of microcomponents that perform many of the standard unit operations used in thermal and chemical process systems. This effort is now in its sixth year, and has reached the point where the development of integrated systems is underway for a number of applications.

Advanced microcomponents currently in development include microchannel heat exchangers, gas absorbers, liquid-liquid extractors, reactors, and microactuators for pumps, valves and compressors. Systems performing chemical processing, power generation and refrigeration are also in development.

Heat and Mass Transport Advantages in Engineered Microstructures: Heat and mass transfer is particularly rapid in systems utilizing engineered microchannels, and extraordinary performance has been demonstrated in microchannel heat exchangers, absorbers and reactors. For example, microchannel heat exchangers have been demonstrated with very high convective heat transfer coefficients (10,000 – 15,000 watts/m²-K for single phase liquids, 30,000-35,000 watts/m²-K for evaporating fluids).

A example of a microchannel heat exchanger is shown at lower left. Typical dimensions of microchannels are 100-300 microns wide and one to several millimeters deep, supporting heat fluxes exceeding 100 to 150 watts/cm². By themselves, microchannel heat exchangers are interesting articles that demonstrate how rapidly diffusion takes place across a thin fluid film; in combination with other microcomponents, new approaches to chemical processing problems are made possible.

Microchannel chemical reactors: We have shown that heterogeneous reactions with relatively fast intrinsic kinetics can be miniaturized with significant performance improvements in the reactor hardware. For example, we have conducted investigations involving the catalytic, partial oxidation of hydrocarbons in microchannel reactors (one element of this reactor is pictured at lower right) that demonstrate high conversions and selectivity for reaction products. Experiments with other reactors have demonstrated similar results.

Preliminary investigations have suggested that reactions of interest to NASA are good candidates for miniaturization using microfabrication techniques. For example, the Sabatier process, which produces methane and water from carbon dioxide and hydrogen, is an exothermic reaction with equi-
ISPP PROPELLANT PRODUCTION BASED ON MICRO CHEMICAL SYSTEMS.
R.S. WEGENG, W.E. TEGROTENHUIS AND A.L.Y. TONKOVICH

Equilibrium limitations on the maximum conversion; at higher temperatures, lower conversions are obtained. For this reason, effective heat removal is needed in order to keep reaction temperatures down. It is therefore an excellent candidate for development using an integrated microchannel reactor/heat exchanger approach.

**Microchannel separations units:** We are also investigating the development of novel separations systems based on microchannel architectures. For example, preliminary experimentation suggests that both solvent extraction and gas absorption are processes that can be enhanced through miniaturization. The former process being dominated by mass transport, and the latter being dominated by a combination of both heat and mass transport, microchannel test articles have preliminarily demonstrated the potential for high performance. Accordingly, our efforts are focused on the development of microchannel contactors that can reduce transport times (and therefore residence time requirements) by constraining transport distances to no more than a few hundred microns.

Other separations processes that are strong candidates for miniaturization include gas adsorption and distillation. Over the next year, we intend to examine a number of ISPP separations needs, including separation of carbon monoxide and carbon dioxide, plus separation of water vapor from methane and from oxygen, to define the potential operational characteristics and advantages/disadvantages of employing a microtechnology approach to these needs.

**The development and scaleup of integrated micro chemical systems:** As with the case of electronics, the scaleup of micro chemical systems is often made possible through the use of multiple components operating in parallel. This also provides potential advantages in terms of system reliability, redundancy, flexibility and operation.

A number of integrated, fullscale micro chemical systems are in development at PNNL. These include a microtechnology-based heat pump and integrated fuel conversion components. The heat pump employs microchannel condensers and evaporators, plus a heat-actuated, thermochemical compressor, which in turn includes microchannel gas absorbers, desorbers, and heat exchangers. All of the components of the heat pump system have been demonstrated, and system level testing should be underway by November.

The fuel conversion components together will make up an onboard, automotive processing system for the production of hydrogen from liquid hydrocarbons. The hydrogen would then be used by onboard fuel cells for power generation. Reactors and heat exchangers in the system perform fuel vaporization, partial oxidation, water-gas-shift, and preferential oxidation reactions, and waste energy recovery operations. One component of the system, pictured at lower right, consists of four reactor and heat exchanger cells which operate in parallel, is only 1” by 3” by 4” in volume, and provides waste heat recovery and fuel vaporization functions for half of the fuel stream for the automobile.

Besides providing compact hardware solutions for individual ISPP components, the use of microsystem technologies may also provide an opportunity to improve overall system performance. For example, the inclusion of microchannel heat exchangers within individual components, including adsorbers, reactors and separations units, provides an opportunity for improved thermal integration. It is also possible that energy requirements for operating ISPP technologies could be reduced through the inclusion of microtechnology-based heat pumps, properly designed to operate between, say, an adsorption unit and a cryogenic separations unit. We intend to attempt to identify and preliminarily characterize opportunities for such system advantages over the next year.