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MINIMIZING THERMAL EFFECTS IN
FLUIDIZED-BED DEPOSITION OF DENSE,
ISOTROPIC PYROLYTIC CARBON

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OF DENSE, ISOTROPIC PYROLYTIC CARBON

R. L. Beatty,¹ J. L. Scott, and D. V. Kiplinger²

ABSTRACT

High-density isotropic pyrolytic carbon coatings on ceramic fuel microspheres can be deposited from propane at much lower temperatures and at higher rates than from methane, but the high heat capacity and heat of formation of propane would complicate heat supply to a large-scale coater. We compared deposition from propane and propene (which has smaller heat requirements) at 1150 to 1300°C with fluxes varied by dilution with helium. Either gas undiluted gave coatings denser than 2.0 g/cm³ at 1250°C at 10 μm/min. Propyne and propadiene gave similar coatings more rapidly, and with no heat requirement, but the range of conditions was limited by the instability of these gases, and the coatings were less dense than those derived from propane or propene under similar conditions.

INTRODUCTION

Pyrolytic carbon coatings serve as containment vessels for uranium-thorium oxide or carbide microspheres that are used to fuel high-temperature gas-cooled reactors.³ Usually the coating comprises at least two layers: a low-density inner buffer layer, which shields the outer layer from recoiling fission fragments and provides void volume for fuel swelling,⁴ and a high-density outer layer, which acts as a pressure vessel.⁵ The outer layer should be isotropic and have a relatively high

¹Present address: 317 Northeast 47th Street, Seattle, Wash. 98105.

²Present address: Adler Company, Rockwood, Tenn. 37854.

³W. V. Goeddel, "Coated-Particle Fuels in High-Temperature Reactors: A Summary of Current Applications," Nucl. Appl. 3, 599-614 (1967).

⁴H. Beutler, R. L. Beatty, and J. H. Coobs, "Low-Density Pyrolytic-Carbon Coatings for Nuclear Fuel Particles," Electrochem. Technol. 5, 189-194 (1967).

⁵J. W. Prados and J. L. Scott, "Mathematical Model for Predicting Coated-Particle Behavior," Nucl. Appl. 2, 402-414 (1966).

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density, near 2.0 g/cm^3 , for maximum resistance to fast-neutron-induced dilation.⁶ A typical fuel particle with a two-layer coating is shown in Fig. 1.

Fig. 1. Particles of UO_2 With Typical Two-Layer Pyrolytic Carbon Coating. Etchant: HNO_3 and H_2O_2 . 200X.

Processes for depositing dense, isotropic pyrolytic carbon are thus essential. These were first developed^{7,8} using methane at temperatures near 2000°C . Disadvantages of the methane process were slow deposition, maximum 1 to 2 $\mu\text{m/min}$, and the high temperature; both contribute to a

⁶J. C. Bokros and A. S. Schwartz, "A Model to Describe Neutron-Induced Dimensional Changes in Pyrolytic Carbon," Carbon 5, 481-492 (1967).

⁷R. L. Beatty, F. L. Carlsen, Jr., and J. L. Cook, "Pyrolytic-Carbon Coatings on Ceramic Fuel Particles," Nucl. Appl. 1, 560-566 (1965).

⁸J. C. Bokros, "The Structure of Pyrolytic Carbon Deposited in a Fluidized Bed," Carbon 3, 17-29 (1965).

relatively high process cost. Subsequently we found⁹ that dense, isotropic coatings could be deposited from propane near 1250°C at 10 $\mu\text{m}/\text{min}$. Bard et al.¹⁰ in a further study of propane along with other hydrocarbons produced dense deposits in the same temperature range but did not attempt to produce isotropic coatings or to attain high deposition rates.

The coatings deposited at high rates from propane⁹ possessed the required high density and isotropy. However, the process was difficult to control because of the additive heat requirements of the heat capacity of propane and its endothermic decomposition. As shown in Table 1, a 5.3-kw input to the fluidized bed is required to compensate for a propane flow of 1 mole/min. Temperature control is difficult to achieve even in a 1-in. coater, which consumes 0.1 to 0.2 mole/min of propane, and would be much more difficult for a directly scaled up production coater consuming propane, for example, at 50 times that rate.

The purpose of the present study was twofold, first to extend the range of conditions studied earlier⁹ for rapidly depositing dense, isotropic coatings at relatively low temperatures from propane, and second to study alternative carbon sources that might reproduce the desirable coatings without the energy absorption problem. Extension of the propane work will be discussed later. We sought to improve the thermal balance of the coating process by first considering effects imposed on a fluidized bed by given hydrocarbons. As shown in Table 1, this is approximated by the total of two parts, heat capacity integrated from the gas entrance temperature to the coating temperature and heat of formation at the coating temperature. Thus, elimination of thermal effects by the fluidizing gas requires a hydrocarbon that liberates enough heat on decomposition to nullify its own integrated heat capacity, or some mixture with carrier gas that achieves the same overall heat balance. Butane is listed in Table 1 to show why we did not consider higher

⁹R. L. Beatty, Pyrolytic Carbon Deposited from Propane in a Fluidized Bed, ORNL-TM-1649 (January 1967).

¹⁰K. J. Bard et al., "Pyrolytic Carbons Deposited in Fluidized Beds at 1200 to 1400°C from Various Hydrocarbons," Carbon 6, 603-616 (1968).

Table 1. Thermal Properties of Coating-Gas Components

Gas	$\int_{298}^{1500} C_p d\tau$ (kcal/mole)	ΔH_f at 1500°K (kcal/mole)	Net Heat Generated at 1500°K (kcal/mole) (kw at 1 mole/min)	
Helium	6	0	-6	-0.4
Methane	19	-22	-41	-2.9
Acetylene	19	53	34	+2.4
Propane	45	-31	-76	-5.3
Propene (propylene)	38	0	-38	-2.6
Propadiene (allene)	31	42	11	+0.8
Propyne (methyl- acetylene)	31	41	10	+0.7
Butane	59	-37	-96	-6.7

alkanes. Methane, which has been used in many coating studies, has a pronounced heat requirement and has been experimentally tractable primarily because it is normally used in low concentrations and at high temperatures where coating properties are not extremely sensitive to deposition temperature. Since the exothermic decomposition of acetylene greatly overrides its integrated heat capacity, blending acetylene with propane was our first consideration for nullifying the propane heat requirement. An appropriate blend of these two gases did succeed in making the fluidized bed essentially athermal, but coating results were unsatisfactory. The two hydrocarbons apparently did not decompose at the same rate, and the coatings were very inhomogeneous.

In this study we used only the C_3 hydrocarbons listed in Table 1, with propane as the reference. As shown, propene (propylene) should absorb only half as much energy as does propane, and propadiene and propyne should yield a small energy excess. Considerations in hydrocarbon selection were that propene is probably one of the first propane pyrolysis

products and that pyrolysis of propene yields some propadiene¹¹ and propyne.¹² Also, Pratt et al.¹³ have produced satisfactory coatings from propene.

EXPERIMENTAL

Equipment

We deposited carbon coatings in a 1-in., conical-bottom fluidizing chamber shown in cross section in Fig. 2. The included angle of the cone was 36°. The coating chamber, disentrainment section, and 4-in.-long gas inlet tube were made of graphite. The gas inlet tube above the water-cooled injector slightly preheated the fluidizing gases and reduced bottom heat loss so that the coating chamber was nearly isothermal axially.

We measured temperatures in the fluid bed with a mullite-sheathed, Pt vs Pt-10% Rh thermocouple and on the wall of the coating chamber with a disappearing-filament optical pyrometer. Temperature control for all coating runs was based on the thermocouple signal, which was fed to a strip chart recorder. The optical pyrometer readings were taken to determine radial thermal gradients of different coating runs; these values were then used to compare thermal effects of the different hydrocarbons studied. We coated particles at 1150, 1200, 1250, and 1300°C.

The graphite resistance furnace shown in Fig. 2 heated the coating chamber as well as the gas preheating tube. High power input and low mass of heated components made the furnace response very rapid. Manual power control was thus advantageous since thermal effects of coating

¹¹A. Amano and M. Uchiyama, "Mechanism of the Pyrolysis of Propylene: The Formation of Allene," J. Phys. Chem. **68**, 1133-1137 (1964).

¹²Y. Sakakibara, "The Synthesis of Methylacetylene by the Pyrolysis of Propylene. I. The Effect of Pyrolysis Conditions on Product Yields; II. The Mechanism of the Pyrolysis," Bull. Chem. Soc. Japan **37**, 1262-1268, 1268-1276 (1964).

¹³R. B. Pratt, J. D. Sease, W. H. Pechin, and A. L. Lotts, "Pyrolytic Carbon Coating in an Engineering-Scale System," Nucl. Appl. **6**, 241-255 (1969).

Fig. 2. Low-Temperature Particle Coating Furnace.

runs could be anticipated by the operator. Temperature control was thus much better than would have been possible with a fully automatic system, which would adjust power on call from a signal showing temperature change.

Materials

The fluidized-bed substrate particles were sol-gel thoria microspheres¹⁴ of -50 +60 mesh or nominally 275 μm in diameter. We fixed the batch size for all experiments at 28 g. Since approximately 60- μm -thick coatings were deposited in each run, the combined mean surface area of the microspheres, thermocouple, and coating chamber was fixed at 1000 cm^2 .

We fixed the total fluidizing gas flow rate at 4 liters/min and used hydrocarbon concentrations of 100, 50, and 25%. With the 1000 cm^2 surface area and 4 liters/min total flow, these concentrations correspond to hydrocarbon fluxes¹⁵ of 4, 2, and 1 $\text{cm}^3 \text{ min}^{-1} \text{ cm}^{-2}$, respectively. We studied the four C_3 hydrocarbons listed in Table 2 and two diluents, helium and hydrogen.

¹⁴P. A. Haas and S. D. Clinton, "Preparation of Thoria and Mixed-Oxide Microspheres," Ind. Eng. Chem. Prod. Res. Develop. 5, 236-244 (1966)

¹⁵Hydrocarbon fluxes are measured in cubic centimeters per minute per square centimeter of deposition surface.

Table 2. Hydrocarbons Studied

Systematic Name	Common Name	Grade	Minimum Purity (%)
Propane	Propane	cp	99
Propene	Propylene	cp	99
Propadiene	Allene		99
Propyne	Methylacetylene		96

Characterization

The particle coatings were characterized by density and preferred orientation. We crushed the coatings from several particles and measured the density of the fragments with a density gradient column.¹⁶ We determined preferred orientations qualitatively by examining polarized-light photomicrographs of polished sections.¹⁷⁻¹⁹

We also characterized the coating process by determining the deposition rate and efficiency of each run. Deposition rate, the mean linear rate at which the coating deposits, was determined from the run time and coating thickness as measured from microradiographs.²⁰ Deposition efficiency (%) is 100 times the weight of carbon deposited divided by the calculated weight of carbon supplied. The deposited carbon weight included deposits on the coating chamber and thermocouple as well as the particle coatings.

RESULTS AND DISCUSSION

Propane and Propene Comparison

In our study, propane was the reference hydrocarbon and propene was the substitute of greatest interest. We therefore used these two gases at the four temperatures and three fluxes considered. Densities, deposition rates, and efficiencies are shown as contour plots in Fig. 3. Helium was the diluent for these experiments. Coating densities above 2.0 g/cm^3 were obtained at all fluxes and all temperatures below 1300°C .

¹⁶D. C. Canada and W. R. Laing, "Use of a Density Gradient Column to Measure the Density of Microspheres," Anal. Chem. 39, 691-692 (1967).

¹⁷R. L. Beatty, F. L. Carlsen, Jr., and J. L. Cook, "Pyrolytic-Carbon Coatings on Ceramic Fuel Particles," Nucl. Appl. 1, 560-566 (1965).

¹⁸R. L. Beatty, Pyrolytic Carbon Deposited from Propane in a Fluidized Bed, ORNL-TM-1649 (January 1967).

¹⁹R. J. Gray and J. V. Cathcart, "Polarized Light Microscopy of Pyrolytic Carbon Deposits," J. Nucl. Mater. 19, 81-89 (1966).

²⁰R. W. McClung, E. S. Bomar, and F. J. Gray, "Evaluating Coated Particles of Nuclear Fuel," Metal Progr. 86, 90-93 (1964).

Fig. 3. Effects of Temperature and Hydrocarbon Flux on Density and Deposition Rate and Efficiency of Carbon Coatings Deposited on 275- μ m Thoria Kernels in a 1-in. Fluidized Bed. Helium was the diluent.

Maximum density for propene deposits was 2.07 g/cm^3 obtained at 1200°C at $1 \text{ cm}^3 \text{ min}^{-1} \text{ cm}^{-2}$ propene flux and at 1150°C at 1 and $2 \text{ cm}^3 \text{ min}^{-1} \text{ cm}^{-2}$. Maximum for the propane deposits was 2.12 g/cm^3 at 1200°C , $2 \text{ cm}^3 \text{ min}^{-1} \text{ cm}^{-2}$. The deposition rate plots for the two gases are very similar, as are the deposition efficiency curves. As in earlier fluidized-bed carbon studies,^{17,18,20} deposition efficiency increases rapidly with temperature, and deposition rate, therefore, increases with temperature as well as with increasing hydrocarbon flux.

The propane results agree well with earlier work,¹⁶ except that higher densities were obtained in the present study. Since density is a strong function of temperature, this may be due to different temperature-control methods used in the two studies. As discussed in the Experimental section, temperature control in the present work was based on readings

from a bed central thermocouple, while control in the earlier work was based on corrected optical readings on the outside of the coating tube.

The similarities of the coating densities and the deposition rates and efficiencies obtained with propane and propene show that for a given temperature and carbon flux or concentration, the deposition reactions are only slightly affected by the extra hydrogen associated with the propane. Thus, if sufficient energy is supplied to the system to effect the first dehydrogenation step in the propane decomposition without lowering the bed temperature, then subsequent dehydrogenation and polymerization reactions of propane and propene probably follow similar paths.

As expected, both propane and propene cooled the fluidized bed during coating, and compensating power increases were required to maintain the run temperature. Also as expected from the thermodynamic data in Table 1, propane cooled the bed twice as much as did propene - that is, the differences between the thermocouple and optical pyrometer readings were twice as great for propane as for propene. With propane, the optical readings were about 12°C per liter per minute higher than the thermocouple readings, and with propene, the difference was about 6°C per liter per minute. We could not equate the power absorption values of Table 1 with furnace power increases because raising furnace power increased losses to the wall, and the furnace was not set up as a calorimeter. Neither could we accurately calculate radial thermal gradients from the values in Table 1 because of uncertainties in fluidized-bed geometry. We therefore emphasize that the above thermal gradients are strictly a comparison between propane and propene and the numbers apply only to the system shown in Fig. 2.

Microstructural composites of the propane-derived coatings are shown in Figs. 4 and 5 and of the propene-derived coatings in Figs. 6 and 7. The bright-field photomicrographs in Figs. 4 and 6 suggest some differences in porosity of the coatings, but this was not verified by the density measurements. We attribute the porous appearance, therefore, to pullout of amorphous carbon during metallographic preparation. The polarized-light photomicrographs in Figs. 5 and 7 show that most of the coatings are isotropic; there is no indication of a Maltese cross.¹⁹

PHOTO 94520

Fig. 4. Effect of Deposition Temperature and Propane Flux on Microstructure of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, bright field.

PHOTO 94519

Fig. 5. Effect of Deposition Temperature and Propane Flux on Microstructure of Carbon Coatings Deposited on 275- μ m Thoria Kernels in a 1-in. Fluidized Bed. As-polished, polarized light.

PHOTO 94518

Fig. 6. Effect of Deposition Temperature and Propene Flux on Microstructure of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, bright field.

PHOTO 94517

Fig. 7. Effect of Deposition Temperature and Propene Flux on Microstructure of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, polarized light.

With each gas the most anisotropic coating was produced at the lowest temperature and lowest flux. Increases in either temperature or flux resulted in more nearly isotropic coatings.

Comparison of Four Hydrocarbons and Two Diluents

We extended the comparison of hydrocarbons by coating with propadiene and propyne at a flux of $1 \text{ cm}^3 \text{ min}^{-1} \text{ cm}^{-2}$ (25% concentration in helium) and at 1 and $2 \text{ cm}^3 \text{ min}^{-1} \text{ cm}^{-2}$ (25 and 50% concentrations in hydrogen). Undiluted or diluted with 50% He, both propadiene and propyne decomposed so rapidly by gas phase nucleation that the coating chamber was blocked with soot before a run could be completed. Hydrogen dilution retarded the decomposition rates enough that 50% concentrations of propadiene and propyne could be used. Addition of 75% H_2 , of course, further reduced the reaction rates of propadiene and propyne while virtually eliminating carbon deposition from propane and propene.

Coating densities are plotted as functions of deposition temperature for the different hydrocarbons in Fig. 8. The propane and propene

Fig. 8. Effects of Temperature, Diluent Type, and Hydrocarbon Flux and Species on Density of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed.

data from Fig. 3 are repeated for comparison. In all cases, densities of propadiene- and propyne-derived coatings are lower than densities of coatings deposited under comparable conditions from propane or propene. Substitution of hydrogen for helium dilution increased coating density in all cases.

Since the basic difference between the hydrocarbons used in this study was the extent of their hydrogen saturation, one might expect that mixing hydrogen with the unsaturated hydrocarbons to obtain a fluidizing gas composition equivalent to propane would cause their reaction paths to simulate that of propane. In fact the density plots of Fig. 8 and the deposition rate and efficiency plots of Figs. 9 and 10 show that addition of hydrogen to propadiene and propyne does produce results very close to those obtained with propane and propene. The simulation of the propane results by propene without hydrogen addition may be related to the easily abstractable hydrogen atom of propene.²¹⁻²³

Deposition rate curves plotted in Fig. 9 and deposition efficiency curves in Fig. 10 show consistently higher values for propadiene and propyne than for propane and propene used under comparable conditions. Substitution of hydrogen for helium reduced both deposition rate and efficiency.

Coating microstructures are shown in Figs. 11 through 18. A few of the bright-field photomicrographs show apparent porosity, but again we could not correlate this with density and we attribute it to pullout of amorphous carbon. No coating that shows any trace of anisotropy under polarized light exhibits any apparent porosity under bright-field illumination. As evidenced by the polarized-light photomicrographs, anisotropy increases with decreasing temperature, decreasing hydrocarbon flux

²¹A. Amano and M. Uchiyama, "Mechanism of the Pyrolysis of Propylene: The Formation of Allene," J. Phys. Chem. 68, 1133-1137 (1964).

²²Y. Sakakibara, "The Synthesis of Methylacetylene by the Pyrolysis of Propylene. I. The Effect of Pyrolysis Conditions on Product Yields; II. The Mechanism of the Pyrolysis," Bull. Chem. Soc. Japan 37, 1262-1268, 1268-1276 (1964).

²³M. Szwarc, "The Kinetics of the Thermal Decomposition of Propylene," J. Chem. Phys. 17, 284-291 (1949).

Fig. 9. Effects of Temperature, Diluent Type, and Hydrocarbon Flux and Species on Deposition Rate of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed.

Fig. 10. Effects of Temperature, Diluent Type, and Hydrocarbon Flux and Species on Deposition Efficiency of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed.

PHOTO 94516

Fig. 11. Effect at 1150°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275-μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, bright field.

Fig. 12. Effect at 1150°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275- μ m Thoria Kernels in a 1-in. Fluidized Bed. As-polished, polarized light.

Fig. 13. Effect at 1200°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275- μ m Thoria Kernels in a 1-in. Fluidized Bed. As-polished, bright field.

Fig. 14. Effect at 1200°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275- μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, polarized light.

PHOTO 94511

Fig. 15. Effect at 1250°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275- μ m Thoria Kernels in a 1-in. Fluidized Bed. As-polished, bright field.

Fig. 16. Effect at 1250°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275- μ m Thoria Kernels in a 1-in. Fluidized Bed. As-polished, polarized light.

PHOTO 94509

Fig. 17. Effect at 1300°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275-μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, bright field.

Fig. 18. Effect at 1300°C of Diluent Type and Hydrocarbon Flux and Species on Microstructure of Carbon Coatings Deposited on 275-μm Thoria Kernels in a 1-in. Fluidized Bed. As-polished, polarized light.

or concentration, substitution of hydrogen for helium, and use of propane or propene rather than propadiene or propyne. It seems likely that all of these factors that increase anisotropy do so because they decrease the tendency for homogeneous nucleation with concomitant deposition of gas-borne droplets. As discussed by Bokros²⁴ in relation to his study of carbon deposition from high methane concentrations, this would mean that more of the coating is formed by direct condensation of planar polymers having high molecular weight.

As expected from the data in Table 1, propadiene and propyne heated the fluidized bed slightly unless a large amount of diluent gas was added. Hydrogen, which is not listed in Table 1, absorbs nearly 0.6 kw at a 1 mole/min flow rate. Therefore, addition of 50% H₂ to either propadiene or propyne did not quite cancel the heat generation; a very small temperature rise occurred on initiation of coating with this mixture. This rise was easily compensated by reducing furnace power. When 75% of either hydrogen or helium was added to propadiene or propyne, a nearly athermal process resulted; furnace power adjustments required to maintain a constant coating temperature were minimal. Thus we can deposit dense, isotropic coatings by a virtually athermal process using a mixture of either propadiene or propyne and hydrogen.

SUMMARY AND CONCLUSIONS

We have extended work on low-temperature fluidized-bed pyrolytic carbon deposition from propane to include use of the undiluted gas. We deposited isotropic coatings having densities greater than 2.0 g/cm³ at 10 μ m/min at 1250°C using undiluted propane. This type coating has performed extremely well in irradiation tests, and costs of coating would be much lower than for methane-derived coatings produced at high temperature. The principal problem with the undiluted propane coating process is its enormous energy absorption and concomitant control difficulty in process scale-up.

²⁴J. C. Bokros, "Variation in the Crystallinity of Carbons Deposited in Fluidized Beds," Carbon 3, 201-211 (1965).

We found that propene can be substituted for the propane without detriment to any of the desirable coating properties. Since both propane and propene are relatively inexpensive and both are easily handled in bulk as liquified gases, there seems to be no disadvantage to using propene relative to propane. The advantage in using propene is that it absorbs only half as much energy in the coating process as does propane if fluidizing gas preheating is not significant. The advantage in using propene would be even greater if the gas stream were preheated, since the energy absorbed by propene results entirely from its heat capacity rather than from chemical reactions.

We found that the coating process can be made athermal without sacrificing coating properties and with only a slight reduction in coating rate, to 6 $\mu\text{m}/\text{min}$, by using a mixture of hydrogen with either propadiene or propyne. The optimum mixture for nullifying thermal effects is probably about two parts hydrogen to one part propadiene or propyne. The only disadvantage of this process is the relatively high cost of propadiene and propyne.

We have shown that thermal effects imposed on a fluidized-bed coating process by the fluidizing gas can be accurately predicted and compensated for on the basis of heat capacity integrated from the gas inlet temperature to the coating temperature plus the heat of formation of the species involved. This consideration obviously can be extended to include many other hydrocarbons and gas mixtures in addition to those used in this study.

In consideration of coating process costs as well as thermal effects that influence process controllability, we recommend the use of propene undiluted or slightly diluted with inert gas (not hydrogen) for production-scale deposition of dense, isotropic pyrolytic carbon coatings. As discussed above, the energy absorption could be minimized by preheating the propene within the restriction of avoiding premature decomposition.