1992

An Innovative Approach for the Screening and Development of CFC Alternatives

L. R. Grzyll
Mainstream Engineering Corporation

C. F. Parrish
Mainstream Engineering Corporation

AN INNOVATIVE APPROACH FOR THE SCREENING AND DEVELOPMENT OF CFC ALTERNATIVES

By

Lawrence R. Grzyll and Clyde F. Parrish
Mainstream Engineering Corporation
Rockledge, Florida 32955

ABSTRACT

We are successfully using computational chemistry techniques to identify a series of compounds for use as CFC replacements. Our approach allows us to screen compounds, based on their molecular structure, where no thermodynamic, physical, or toxicological data exists. This approach has been used successfully to identify a series of compounds for use as nontoxic two-phase heat transport fluids for manned spacecraft thermal control systems. We are also using this approach for the development of Halon and CFC-113 solvent replacements. This approach is also useful for the development of CFC alternatives for refrigeration applications.

INTRODUCTION

Chlorofluorocarbon (CFC) compounds, and to a lesser degree hydrochlorofluorocarbon (HCFC) compounds, cause destruction of the ozone layer in the atmosphere. The ozone layer consists of low concentrations of ozone in the stratosphere between 7 and 28 miles in altitude[1]. Ozone is formed by the interaction of ultraviolet (UV) radiation from the sun with molecular oxygen. Harmful UV radiation is absorbed both in this process and by ozone itself. Eventually, ozone decomposes back to molecular oxygen due to its low molecular stability, producing a steady-state concentration. The presence of chlorine in the atmosphere, however, catalyzes destruction of the ozone layer and shifts the steady-state ozone concentration in the stratosphere to dangerously low levels. CFC and HCFC compounds are one source of this atmospheric chlorine. Many of the CFC and HCFC compounds have long atmospheric lifetimes, eventually making it to the stratosphere and destroying ozone.

A second atmospheric problem, the greenhouse effect, is also associated with the presence of CFC and HCFC compounds in the atmosphere. Many gases, including the CFCs, can trap infrared radiation in the atmosphere and contribute to global warming. This absorption is due to the carbon-chlorine and carbon-fluorine bonds in the molecule[1] and takes place as long as the molecule is intact in the atmosphere.

The two problems described above show the potential threat that CFCs and HCFCs pose to the atmosphere. This danger exists both in the presence of chlorine in these compounds and in the atmospheric lifetime of these compounds. The solution is to find alternative compounds that have either no chlorine or short atmospheric lifetimes. Many of the most-used CFC and HCFC compounds are currently banned or are in the process of being banned due to the Montreal Protocol and DOD Directive 6050.9[2]. Because of this, the need exists to find alternatives to replace these CFC and HCFC compounds for refrigeration applications.

THE REQUIREMENTS OF A REFRIGERANT FOR VAPOR-COMPRESSION SYSTEMS

The working fluid in a vapor compression system must satisfy a number of requirements[1], which are listed in Table 1.

TABLE 1 - REQUIREMENTS OF A REFRIGERANT

Chemical:
Stable and Inert in System
Health, Safety, and Environmental:
Nontoxic Nonflammable Does Not Degrade Atmosphere
Thermodynamic and Transport Properties:
Appropriate Vapor Pressure For the Application Appropriate Critical Properties For the Application High Heat of Vaporization Appropriate Vapor Heat Capacity Low Viscosity High Thermal Conductivity
Miscellaneous:
Satisfactory Oil Solubility High Dielectric Strength of Vapor Low Freezing Point Compatibility With Materials Easy Leak Detection Low Cost

The first requirement is chemical stability within the system. However, the ideal refrigerant should also decompose in the conditions of the atmosphere which are not present in the vapor-compression system. The next most important properties are related to health and safety. The refrigerant must be nonflammable and have low or no toxicity in order to conform to industrial codes. Also, the refrigerant should not contribute to ozone depletion, smog formation, or global warming.

The thermodynamic and transport properties determine the performance of the refrigerant in the system[2]. As the critical temperature increases, the capacity of the refrigerant decreases due to low vapor pressure and low vapor density of the refrigerant (for a given evaporator temperature). However, the coefficient of performance (COP) of the system decreases as the condenser temperature approaches the critical temperature of the refrigerant, due to excessive compressor superheat and reduced heat of vaporization. This points to a tradeoff that must be faced regarding the critical properties and the vapor pressure of the refrigerant. The specific heat of the vapor, c_p°, has a lesser effect on performance. High volumetric capacities are associated with low values of c_p°. However, there is an optimum value of c_p° to maximize COP. The value of c_p° affects the performance of the systems through its influence on the shape of the two-phase region of a temperature-entropy diagram. Low values of c_p° give traditional bell-shaped domes, while high values of c_p° cause this dome to be slanted to the right (see Figure 1). Low values of c_p° result in excessive compressor superheat, decreasing COP. With a high c_p° the compression process may end in the two-phase region. The ideal compressor exit condition would be as close to the saturated vapor line as possible without being in the two-phase region. This results in low compressor superheat. Low viscosities and high thermal conductivities are desired to minimize pressure drop and maximize heat transfer.

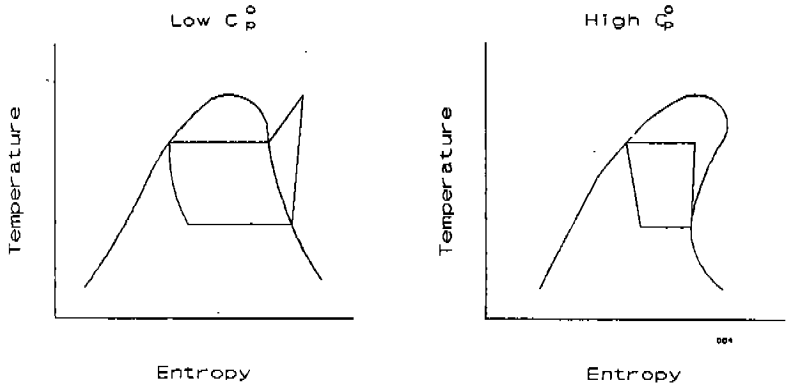

Figure 1 - Effect of Vapor Heat Capacity on Shape of Two-Phase Region on Temperature-Entropy Diagram

A number of miscellaneous properties are also desired[2]. High oil solubility and high vapor dielectric strength are desired for most compressors. The working fluid must have a freezing point below the lowest temperature in the system. Compatibility with materials, easy leak detection, and low cost are also desirable.

THE DIFFICULTY IN FINDING SUITABLE ALTERNATIVES

The above section defined the criteria a refrigerant must posses to be suitable. However, finding these properties for the large number of potential molecules that exist is difficult. There are 15 possible one-carbon CFCs, HCFCs, and hydrofluorocarbons (HFCs); 55 possible two-carbon CFCs, HCFCs, and HFCs; and many three-carbon CFCs, HCFCs, and HFCs that may have suitable properties. In addition to the halocarbons and hydrocarbons, many other families of compounds may be suitable. For example, the Navy and the National Institute of Standards and Technology are currently investigating several fluorinated ether-based compounds for use as refrigerants[3]. The problem is that a large percentage of these compounds have not been characterized, i.e., their properties are either unknown or untabulated. This fact limits serious consideration of CFC and HCFC alternatives to compounds that have had their properties characterized. Thus, many compounds are eliminated from serious consideration simply because their properties are unknown.

AN INNOVATIVE APPROACH TO FIND ALTERNATIVE COMPOUNDS

An innovative approach to identify and evaluate alternative refrigerants is to use the automated data analysis and pattern recognition techniques available in computational chemistry systems. Computational chemistry systems use pattern recognition and statistical techniques to correlate a molecule's structure with its physical, chemical, thermodynamic, and other properties. These computational chemistry systems have been used to develop new pharmaceuticals, and to predict toxicity and many other physical and chemical properties[4].

Structural-activity research developed rapidly after the early 1970s when computers became readily available. Three examples[4] of methodologies that have been used to handle the structure-activity problems are the Hansch linear free-energy method that uses physicochemical parameters, the Free-Wilson method, and quantum mechanical methods. Many of the studies have been directed to the pharmaceutical, pesticide, antitumor, and environmental areas. Most of these structure-activity relations (SAR) are very complex, particularly the quantum mechanical methods.

A program was developed which was designed for use in SAR and structure-property relation (SPR) studies. This program, developed by Dr. Peter Jurs at the Pennsylvania State University, is called ADAPT, which is the acronym for automatic data analysis and pattern recognition techniques. This concept was used in the 1960s to reduce data collected by mass spectrometers and later for data reduction for other analytical instruments. Pattern recognition methods uniquely fit these diverse data sets because no exact functional form is fitted to the data; rather, relationships that provide similarity are found, and used. Once these relationships are found, they can be used to find relationships with members not in the original data set.

Computer-assisted structure-property studies with ADAPT are based on the following principles:

1. Compounds can be represented by molecular descriptors, which is an ADAPT term for the computational-chemistry-based calculations that numerically encode structural features of the molecule or physical measurements related to structural features of the molecule.

2. Statistical or pattern recognition methods can be used to discover a relationship between molecular structure as represented by the descriptors and physical properties.

3. This SPR can be used to predict the properties of uncharacterized compounds.

These concepts have been applied to find the solution of many complex SARs and SPRs. For example, ADAPT was used to develop a relationship to classify the toxicity of 143 acrylates. Five stable clusters of acrylates were found by using objective clustering methods that were based on calculated chemical and physical properties[5]. A set of six descriptors that coded shapes of molecules were found to correlate with biological activity[5]. Carbon-13 NMR spectral simulation has been accomplished for a limited number of terpenes, carbohydrates, cyclohexanones, and decalones with good agreement[7-9]. This program has also been used to predict the toxicity of organophosphorous compounds[10] and the normal boiling points of alcohols[11].

The approach used by ADAPT to develop SPR studies begins with the assumption that there is a relationship between chemical structure and the property of interest. ADAPT itself is a system of executable programs that provide the chemical researcher with a complete system for performing SPR studies. The steps involved in the SPR study, regardless of the property of interest, are as follows:

1. Develop a main study set by selecting molecular structures and their properties of interest.

2. Draw the molecular structures (with molecular drawing software) and enter the structures and their properties to ADAPT.

3. Model the structures into 3-dimensional conformations using internal ADAPT programs.

4. Generate a set of basic, whole-molecule descriptors for all structures in the study set. These descriptors fall into four classes: geometric, electronic, topological, and physicochemical. Table 2 presents examples of ADAPT descriptors.

5. Reduce the number of descriptors by eliminating redundant descriptors using internal ADAPT feature selection programs. These programs identify redundant descriptors by performing pairwise and multiple regression analysis.

6. Develop coefficients for the SPR using multiple regression programs and other regression techniques.

7. Validate the SPR for internal consistency using internal ADAPT statistical routines.

8. Use the SPR to predict the properties of untested compounds.

TABLE 2 - EXAMPLE ADAPT DESCRIPTORS

Descriptor Class	Descriptor Types
Topological (Molecular Connectivity)	Number and Type of Atoms Number and Type of Bonds Number of Rings Number of Ring Atoms Number of Lone Electron Pairs Molecular Size Degree of Branching Molecular Shape
Geometric (Molecular Geometry)	Moment of Inertia Surface Area Molecular Volume Radius of Gyration
Electronic (Electronic Structure)	Dipole Moment Electron Density Electronegativity Molecular Charge Atomic Charge Intermolecular Charge
Physicochemical (Physical/Chemical Properties)	Molecular Polarizability Molar Refraction

USE OF ADAPT IN SCREENING AND DEVELOPMENT OF CFC ALTERNATIVES

We have successfully used ADAPT to identify a series of compounds for use as nontoxic heat transport fluids for habitat two-phase thermal control systems[12-13]. Future lunar and Martian transport vehicles will place increasingly stringent requirements on the heat acquisition and thermal management systems. To meet the low-mass, high-power requirements, two-phase fluid systems have been identified as the most suitable thermal management system. The key to developing such a system is the selection of an appropriate working fluid. NASA has developed a two-phase working fluid design criteria for the thermal control subsystem environment, which is given in Table 3. Past studies have attempted to identify suitable compounds by surveying over 1000 characterized fluids contained in commercial databases[14-15]. No fluids contained in these databases were suitable due to toxicity, flammability, or catalytic oxidation stability concerns.

TABLE 3 - NASA TWO-PHASE WORKING FLUID DESIGN CRITERIA		
Parameter	**Environment 1**	**Environment 2**
Freezing Point	< 0°F	< - 103°F
32° F Vapor Pressure	> 1 atm	> 1 atm
158°F Vapor Pressure	< 10 atm	< 10 atm
95°F Saturated Vapor Density	> 0.04 lb/ft^3	> 0.04 lb/ft^3
95°F Heat of Vaporization	> 100 Btu/lb	> 100 Btu/lb
Other Fluid Characteristics		
Nontoxic Nonreactive Nonflammable Noncorrosive Stable To Catalytic Oxidation		

Our approach to this problem was to screen uncharacterized compounds using the computational chemistry approach. We first identified groups of compounds that had suitable toxicity, flammability, and catalytic oxidation stability characteristics. We then used computational chemistry techniques to develop SPRs correlating molecular structure with the various physical and thermodynamic properties from a set of characterized compounds. These SPRs were examined for internal consistency and statistical significance using routines contained in the software system. These SPRs were then used to predict the properties of uncharacterized compounds that had suitable toxicity, flammability, and thermal stability.

The overall approach was based on selecting compounds that met the most critical requirements first and then apply less critical criteria. Therefore, we started with toxicity and catalytic oxidation stability, the most critical needs, and then screened the other properties of Table 3. Although other classes of compounds may meet the design requirements, we selected perfluorocarbons as the class of compounds to investigate. Perfluorocarbons have physical properties similar to their corresponding hydrocarbon but they are nonflammable and less-reactive. Many of the perfluorocarbons are nontoxic, for example, octafluorocyclobutane has very low toxicity and is considered a safe propellant for food products[16-17]. Perfluorocarbons are also reported to be very stable in the presence of catalytic oxidizers at temperatures as high as 850°C[18-19].

To affectively apply ADAPT to develop regression equations that can predict the properties of untested compounds from their molecular structure, it is necessary to start with a consistent database of property information. Several commercial databases were considered, resulting in selection of the DIPPR[19] database as a source of property data on C_4, C_5, C_6, and C_7 perfluorocarbons. We then expanded this database search using *Chemical Abstracts* to develop a final list of properties on these perfluorocarbons.

We next used ADAPT to develop five SPRs for the C_4 and C_5 characterized perfluorocarbons: freezing point, 32°F vapor pressure, 158°F vapor pressure, 95°F saturated vapor density, and 95°F heat of vaporization. The SPRs developed were compared to the experimental values yielding excellent results. Figures 2-6 show plots of predicted versus actual values for these SPRs. The correlations developed were multi-variable linear equations, as seen in Table 4. These SPRs had correlation coefficients with the measured properties ranging from 0.91 to 0.99. All of these SPRs were validated for internal consistency using ADAPT statistical routines.

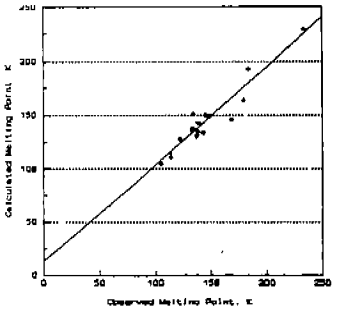

Figure 2 - Melting Point SPR

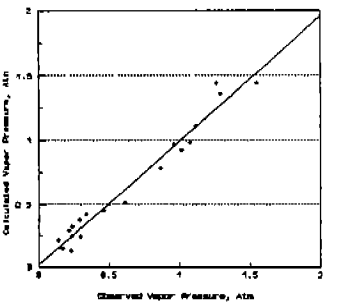

Figure 3 - 32°F Vapor Pres. SPR

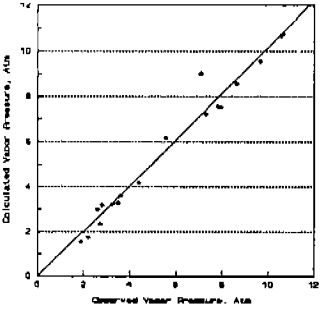

Figure 4 - 158°F Vapor Pres. SPR

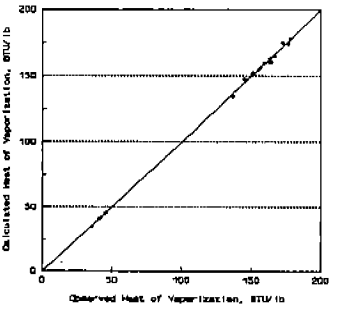

Figure 5 - 95°F Heat of Vaporization SPR

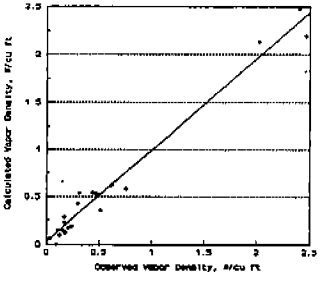

Figure 6 - 95°F Saturated Vapor Density SPR

TABLE 4 - FINAL SPR EQUATIONS

$$Tmelt = -0.4204*(MW) - 70.77*(PPSA3) - 138.2*(V3C) - 21.81*(KPAP2) + 154.7*(WPSA3) + 33.42*(NDB) + 93.60*(V5PC)$$

$$vp32 = -69430*(NC) + 122400*(V3C) + 231800*(RNCG) + 1009*(MOMI5) + 59640*(V4P) - 39190*(ALLP4)$$

$$vp158 = -664700*(NC) + 437700*(V3C) - 195600*(ALLP4) + 1577000*(V5P) + 290500*(WPSA3) + 171400*(V2)$$

$$hv95 = 7784000*(NC) - 7176000*(V3C) - 1392000*(PPSA3) + 20110000*(RPCG) + 1270000*(MOMI4) - 2764*(MOMI2) + 9110000*(V5P)$$

$$vd95 = -20.37*(NC) - 254.3*(RNCG) + 3.175*(RNCS) + 0.258*(PPSA2) - 2.935*(KAPA2) + 6.526*(WPSA3)$$

Note: The equations given above are with the ADAPT labels[20] used to represent the descriptors

A list of uncharacterized compounds that consisted of all possible structures of C_4 and C_5 perfluorocarbons (except those used to develop the SPRs) was assembled. The SPRs developed above were then used to predict the properties of these uncharacterized perfluorocarbons.

The results of this effort showed that three characterized perfluorocarbons; perfluorobutane, perfluorocyclobutane, and perfluoro-iso-butane; had properties close to meeting the NASA requirements. The only property that was out of the desired range was heat of vaporization, which was lower than desired. Applying the SPRs to uncharacterized compounds resulted in the identification of three additional compounds; perfluoromethylcyclopropane, perfluorocyclopentane, and perfluorocyclopropane; that had properties in the general range of the NASA requirements.

CURRENT EFFORTS USING ADAPT TO FIND CFC REPLACEMENTS

We are currently using ADAPT to screen and develop CFC alternatives on other efforts. One project is involved with development of alternatives to Halons 1211 and 1301 for fire extinguishing applications. Another project is involve with development of solvent replacements for CFC-113. These projects are described below.

Development Of Environmentally Acceptable Halon Alternatives

We are currently using the computational chemistry approach to screen and develop environmentally acceptable compounds to replace Halons 1211 and 1301 as fire extinguishing agents. We are currently developing SPRs for several independent evaluations of fire extinguishing agents. We are also developing a list of potentially effective compounds, with untested properties, for screening. The SPRs developed for each of the independent studies will then be applied to predict the fire suppression properties of the uncharacterized compounds. SPRs are also being developed for the prediction of ozone depletion potential (ODP) and global warming potential (GWP) for these uncharacterized compounds. The result of these predictions will be the selection of compounds for experimental evaluations that show the most promise for use as fire extinguishing agents.

The Development Of Solvents To Replace CFC-113

We are currently using the computational chemistry screening process to identify and develop suitable solvents for use in cleaning plumbing lines and other machined components. A quantitative method for comparing the effectiveness of various solvents is the use of solubility parameters. The controlling terms for the solubility parameter are the energy of vaporization per unit volume and the molar volume of each component[20]. The solubility parameter can be modified to include contributions from dispersive, polar, and hydrogen-bonding interactions. The solubility parameter is a useful tool to estimate the solubility of a solute in a solvent and is also useful in comparing the solvent characteristics of two different solvents. The approach used on this effort to screen and develop suitable solvent alternatives to CFC-113 is to develop a database of energy of vaporization and molar volume for various characterized solvents. This information, which is used to calculate the solubility parameter, is published for many solvents and could be used to develop SPRs correlating molecular structure to these properties for the characterized solvents. A list of uncharacterized solvent compounds would then be developed, and these SPRs would be used to predict the solubility parameters of untested compounds. These predicted values would then be verified in the laboratory, resulting in the development of suitable solvents.

CONCLUSION

The use of techniques found in computational chemistry provide a novel approach toward the screening and development of CFC alternatives. This approach allows compounds to be screened based on their molecular structure using SPRs. These SPRs can then predict the properties of compounds that have no characterized thermodynamic, physical, or toxicological properties, allowing the researcher to consider an extremely large number of compounds. Thus, the time and cost of preliminary screening of refrigerant alternatives can be minimized. Only those compounds that show high potential will proceed to the laboratory evaluation process. This approach has been used successfully to identify a series of compounds for use as nontoxic two-phase heat transport fluids for manned spacecraft thermal control systems. We are also using this approach for the development of Halon replacements and CFC-113 solvent replacements.

This computational chemistry approach is the ideal methodology for the screening and development of alternative refrigerants. Alternatives to specific refrigerants (i.e. R-11 or R-12) could be developed by using SPRs to predict specific properties of untested compounds. No current work is underway to utilize this approach, but funding is being sought to utilize this computational chemistry approach toward development of alternative refrigerants.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration, Johnson Space Center, under contract NAS9-18471.

REFERENCES

1. Department of Defense Directive 6050.9, February 13, 1989.

2. McLinden, M. O. and Didion, D. A., "Quest For Alternatives," *ASHRAE Journal*, 32-42, December 1987.

3. Derra, S., "CFCs - No Easy Solutions," *R&D*, 56-66, May 1990.

4. Stuper, A. J., Brügger, W. E., and Jurs, P. C., Computer Assisted Studies of Chemical Structure and Biological Function, Wiley-Interscience, New York, 1979.

5. Lawson, R. W., and Jurs P., "Cluster Analysis of Acrylates to Guide Sampling for Toxicity Testing," *J. Chem. Info. Com. Sci.*, 30, 137-144, 1990.

6. Rohrbaugh, R., and Jurs, P., "Descriptions of Molecular Shapes Applied in Studies of Structure/Activity and Structure/Property Relationships," *Anal. Chem. Acta*, 199, 99-109, 1987.

7. Jurs, P., Sutton, P., and Ranc, M., "Carbon-13 NMR Spectral Simulation," *Anal. Chem.*, 61, 1115A, 1989.

8. Sutton, G., and Jurs, P., "Simulation of Carbon-13 Nuclear Magnetic Resonance Spectra of Alkyl-Substituted Cyclohexanones and Decalones," *Anal. Chem.*, 61, 863-871, 1989.

9. McIntyre, M., and Small, G., "Carbon-13 Nuclear Magnetic Resonance Spectrum Simulation Methodology for the Structure Elucidation of Carbohydrates," *Anal Chem.*, 59, 1805-1811, 1987.

10. Rohrbaugh, R., and Jurs, P., "A Structure-Activity Relationship Study of Organophosphorus Compounds," *Chem. Res. Toxicol.*, 1, 123-127, 1988.

11. Smeeks, F. C., and Jurs, P. C., "Prediction of Boiling Points of Alcohols From Molecular Structure," *Analytica Chimica Acta*, 233, 111-9, 1990.

12. Parrish, C. F. and Grzyll, L. R., "Development of Nontoxic Heat Transport Fluids For Habitat Two-Phase Thermal Control Systems," NASA Phase I Final Report, July 31, 1991.

13. Parrish, C. F. and Grzyll, L. R., "Development of Nontoxic Heat Transport Fluids For Habitat Two-Phase Thermal Control Systems," to be presented at the 1992 Intersociety Conference on Environmental Systems, Seattle, July 1992.

14. Giarratano, P. J. and Welch, J. F., "Nontoxic Heat Transport Fluids for Spacecraft Two-Phase Heat Transport Systems," NISTIR 89-3932, January 1990.

15. McLinden, M. O., "Working Fluid Selection for Space-Based Two-Phase Heat Transport Systems," NBSIR 88-3812, May 1988.

16. Hahn, B. and Riepe, G., "Fluorocarbon Gas Bubble Chamber," *Rev. Sci. Inst.*, 29, 184, 1958.

17. Clayton, J. W., DeLaplane, M. A., and Hood, D. B., "Toxicity Studies With Octafluorocyclobutane," *Ind. Hygiene J.*, 21, 382-8, 1960.

18. Rodgers, G. C. and Cady, G. H., "Pyrolysis of Perfluoro-n-pentane," *J. Chem. Soc.*, 3523, 1951.

19. Grosse, A. V. and Cady, G. H., "Properties of Fluorocarbons," *Ind. Eng. Chem.*, 39(3), 367-74, 1947.

20. "ADAPT Reference Manual, Revision 4.0" Molecular Design Ltd., 1990.

21. Parrish, C. F., "Industrial Solvents," Kirk-Othmer Encyclopedia of Chemical Technology, Vol. 21, 3rd Ed., John Wiley & Sons, Inc., New York, 1983.