BACKGROUND AND REFERENCES CONCERNING AMALGAMATED RESEARCH INC.'S INVENTION AND IMPLEMENTATION OF THE CONCEPT'S AND USE OF ENGINEERED FRACTALS FOR CONTROLLING FLUIDS

1. U.S. Patent No. 5,354,460 1994, M. Kearney, K. Petersen, T. Vervloet, M. Mumm.

This patent introduced a fractal distribution and/or collection system. As opposed to using nozzles, orifice pipe, etc. for fluid distribution, the fractal distributor was designed to exhibit extreme symmetry from large to small scale. Any individual fluid path from the center to an exit point can be used to generate all other paths, to a close approximation, using symmetry operations. We refer to this property as "universal path symmetry". The resulting path symmetry provides equivalent hydraulics (equivalent flow rate, equivalent time of passage, equivalent pressure drop, etc.) to each exit or collection point. In addition to the symmetry between paths and the scaling symmetry within paths, the structures are often used as mirror image distributor and collector pairs - providing additional flow symmetry and plug flow characteristics. As additional fractal iterations are added to the distributor, fluid flow approaches closer and closer to a perfect surface distribution or collection.

From an engineering point of view, another unusual characteristic is that the devices exhibit an invariance to scaling. Larger or smaller devices can be designed by adding or subtracting bifurcations while the symmetry of the device is maintained. This overcomes scale-up problems often encountered in taking a process from pilot to full scale operation. We have constructed functional surface distributors ranging in diameter from a few cm to 6.7 meter.

Applications have been diverse including chromatography, ion exchange, distillation, clarification, etc.

This patent also illustrates the use of self-affine fractals wherein the fractal is "stretched" in one direction relative to a different direction. In the figure above, it can be seen that the fractal configuration is distorted in this manner as the fractal approaches the center of the structure. We discovered with this 1994 device that self-affine fractals can be a very useful design technique, in this case, to properly fit the geometry of a given vessel.

Amalgamated Research Inc. has installed over 45,000 square feet of this type of fluid transporting fractal which is a combination of self-similar fractal, self-affine fractal and larger scale symmetric branched structure.

2. Kearney M. and Kochergin V., "A Liquid Distributor for Industrial Chromatography Columns: An Approach Based on Fractal Geometry", AIChE Fifth World Congress of Chemical Engineering, July 14-18, 1996, San Diego, California.

This paper lists a number of the benefits of fluid transporting fractals when used for chromatography:

"A. All distribution points are hydraulically equivalent to one another. For example, comparing the path to a distribution point near the center well with a distribution point near the outer edge verifies the equal path length and hydraulic characteristics. This feature translates to minimization of pressure drop as a design consideration. All points receive equal fluid even as flow rate varies widely.

B. High distribution point density, which can be varied as desired, together with equivalence of flow to each orifice allows for minimization of individual point momentum. Turbulent mixing at the distributor exit is therefore minimal.

C. There is no time lag to separate distribution points because the path to each is equivalent. With respect to this factor, the concentration of separated components will not be forced to vary across the diameter of the column.

D. Because the point density can be increased indefinitely (within practical manufacturing constraints), channeling due to the distributor can be completely eliminated.

E. The distributor is configured to fit circular cross sections. With respect to layout, compromises in distributor efficiency are not necessary."

Also in this paper, the close relationship of natural fluid transporting fractals and engineered fractal distributors was recognized:

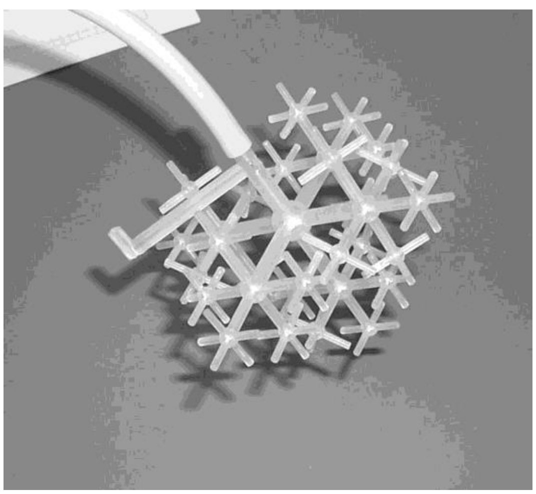
"Nature has evolved numerous instances of distribution related fractal structures. Examples are the arteries and veins in mammalian vascular systems and the bronchi of lungs. For these examples the geometry is self-similar for 15-20 bifurcations. One clear reason for such structures is the space filling capability they provide. They also exhibit a practical scale-down of distribution from a macroscopic structure, such as a heart, to microscopic structure, such as a capillary. These and other fractal characteristics can be of value to engineered distributor design."

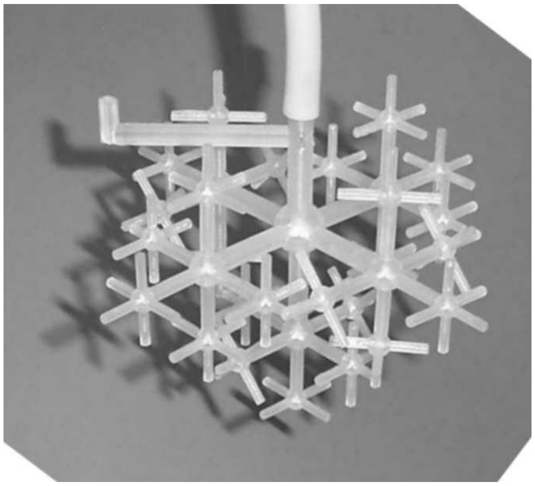
This paper presented measurements demonstrating successful scale-up from three inch diameter to 14 foot diameter chromatography columns using fractal distribution and that following these tests fractal distributors were successfully used in commercial chromatographic columns with diameters up to 22 feet diameter.

3. 1996 Fluid transporting fractals with dimension = 2.32.

In 1996, in collaboration with the Technology Center at 3D Systems Corporation, Amalgamated Research Inc. demonstrated the first construction of a fully functional engineered fluid transporting fractal for volume processing. Shown below are photos of the 1996 structure. This device has a non-integer fractal dimension of 2.32 and is used for controlled distribution and/or collection of fluids. The initiator geometry and the non-integer dimension were chosen to provide a device with a desired space filling density and a geometry which will fit into a processing vessel with a cone shaped bottom. This early device demonstrated ARi's concept of using engineered fluid transporting fractals with non-integer dimensions, in this case the fractal dimension >2 and < 3.

This structure is an embodiment of the general variations taught in ARi's U.S pat. No. 5,938,333.





4. Kearney, M., "Engineered Fractal Cascades for Fluid Control Applications", *Proc*., Fractals in Engineering, Institut National de Recherche en Informatique et Automatique (INRIA), Arcachon, France (June 1997).

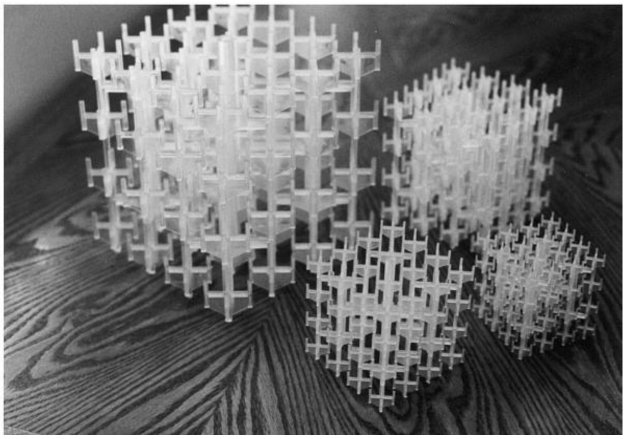
In this paper and the corresponding meeting (Fractals in Engineering 1997) Amalgamated Research Inc. presented to the engineering community, for the first time, the general invention and concepts for the use of engineered fluid transporting fractals:

A. The scaling and distribution provided by an engineered fractal can be used as a functional alternative to the detrimental uncontrolled and non-symmetrical characteristics of scaling and distribution via turbulence. For example, engineered fractals can be used in place of the often inefficient mechanical or uncontrolled mixing encountered in many engineering unit processes such as nozzle introduced distribution, impellor driven mixing or bubbled gas distribution into a liquid. An example was given for a gas-liquid aerator/reactor application (see slide below).

B. Fractals can be used to provide controlled formation of macroscopic fluid structure. For example, a fluid can be introduced into another fluid with a specific geometry. This is normally not possible to accomplish.

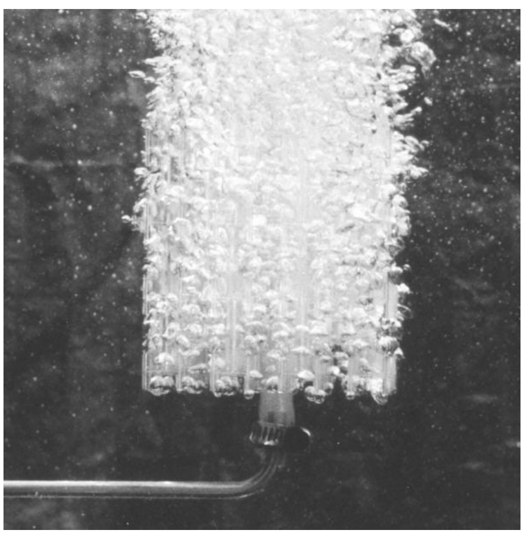
C. Fluid flow through an engineered fractal can provide dynamic alteration of a fluid structure's measure of dimension. This means that engineered fractals can be used to allow fluid to make rapid transitions to desired geometries represented by the fractal dimension.

Below are some of the slides shown at Fractals in Engineering 1997:



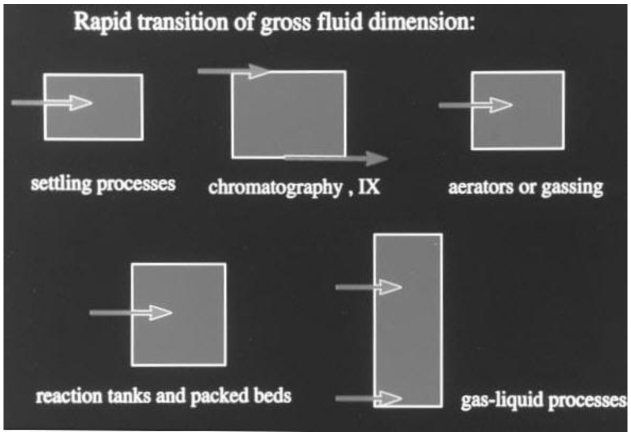
Fractals in Engineering 1997

The slide above illustrates several manufactured fractals for volume processing. These examples demonstrate variable space filling density and variable channel sizing. These fractals are embodiments of the variations taught in ARi's U.S. Pat. No. 5,938,333. Also compare these examples with the volume processing fractal with dimension = 2.32 shown in the photos under topic 3.



Fractals in Engineering 1997

The slide above illustrates a multi-phase gas to liquid distribution by a volume processing fractal (aerator/reactor operation). The total number of paths and exits in this device is 512. Note the homogeneity of the gas distribution and the controlled macro-structure of the fluid introduction. This is an illustration of a fractal controlling the geometry of fluid scaling and distribution - a result essentially impossible with free turbulence. Also note that small scale turbulence is allowed *after* the controlled introduction by the fractal to take advantage of its useful characteristics (e.g., enhanced heat and mass transfer).



Fractals in Engineering 1997

The slide above illustrates a few applications for fluid transporting fractals. These include control of single or multi-phase flows in settling (clarification), chromatography, ion exchange, aeration, reaction, and other gas-liquid processes such as distillation.

Also presented at this meeting was our observation that engineered fluid transporting fractals can exhibit a functional invariance to scaling. By adding or subtracting bifurcations from such a device a process can be scaled-up without loss of operating characteristics. This overcomes a key problem encountered with the scale-up of many fluid processes.

5. U.S. Patent No. 5,938,333 1999, filed 1996. M. Kearney.

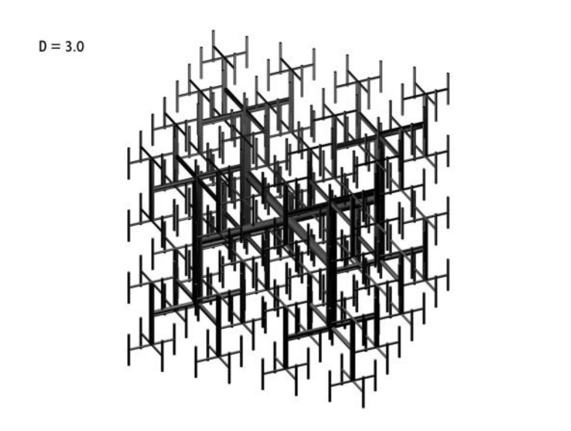
This broad patent covers volume processing fractals. As examples, refer to the fractals shown in the slides from Fractals in Engineering 1997 and the photos of the dimension = 2.32 fractal under topic 3. This patent covers devices with the general benefits described in the 1997 Fractals in Engineering paper (see patent claims for precise statement of patent coverage). A few application examples for these structures include control of single or multi-phase flows in chromatography, ion exchange, adsorption, absorption, distillation, aeration, scrubbing, extraction, mixing and reactor processes. Other diverse applications taught by this patent include avoidance or suppression of turbulence caused by fluid jets, pluming or wake sources.

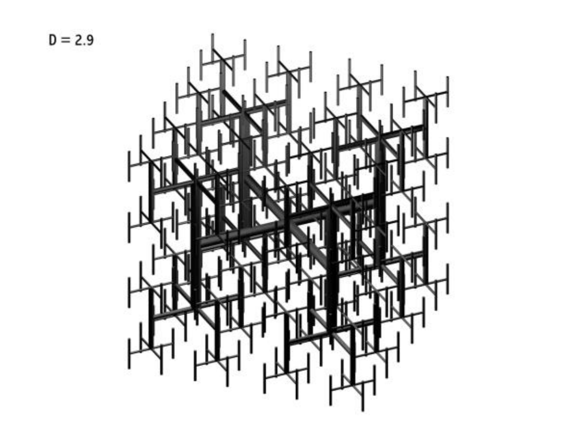
Flexibility of fractal design:

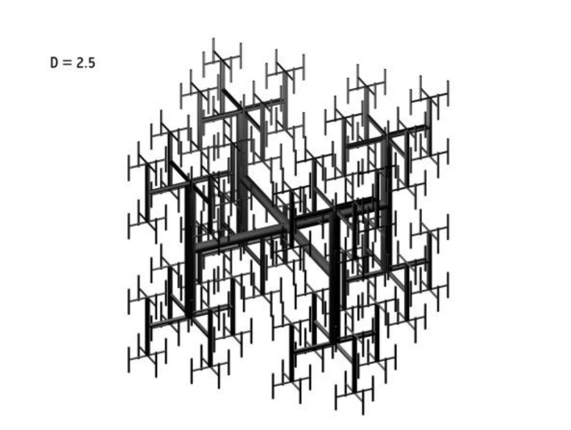
Engineered fractals allow for precise control of the geometry of fluid scaling. This patent describes several ways that fluid transporting fractals can be varied to provide desired scaling and distribution geometry. These methods include:

A. Variation of scale-down factors to modify space filling characteristics.

The fractal dimension is a measure of the space filling characteristics of a fractal. As the calculated dimension is reduced, space is less filled by the object, as can be seen by comparing the following fractals with D = 3.0, D = 2.9, and D = 2.5 and the same initiator (Note that the difference between D = 3.0 and D = 2.9 is practically indiscernible). The fractal dimension of an engineered structure is a key design criteria. Because fractals have a dimension associated with them, certain aspects of design are straightforward. Using the fractal dimension, fractals can be designed in a logical manner to approximate surfaces, volumes and non-integer patterns.







B. Variation of the fractal cut-off.

Smaller and smaller iterations of structure are added to an initiator to produce a fractal. The space filling characteristics can be altered by adjusting the number of iterations. The smallest scale used in a device is referred to as the fractal cut-off. In some cases, the cut-off may be constrained by manufacturing limits and cost restrictions rather than design intentions.

C. Variation of the structure with respect to symmetry.

Fractals can be engineered with variations of the object's scaling symmetry. For example, the scaling factor can be different in different directions. This can result in self-affine "stretched" fractals. The scaling factor can also change with change in iteration number. Another related technique is to vary the symmetry characteristics of the initiator. Note that the initiator is the original large scale structure geometry duplicated in the smaller descendent generations.

D. Variation of the structure with respect to the number of branches per node.

The figures above (D = 3.0, D = 2.9, D = 2.5) illustrate fractals with 8 branches per node. Altering the branch count is a useful design parameter. The fluid transporting fractal illustrated under topic 3, with dimension = 2.32, has 5 branches per node.

Techniques A-D can, of course, be used in combination.

Combining the use of engineered fractals with process turbulence

While fractals can be thought of as highly controlled functional alternatives for the scaling and distribution feature of turbulence, they can also be used together with turbulence to take advantage of its beneficial characteristics - such as enhanced heat and mass transfer.

This patent teaches several methods for using fractals together with turbulence:

- Fractals can be used to provide an advantageous first stage of distribution prior to final turbulent mixing.

- Fractals can be placed in motion and thus cause turbulence while concurrently distributing fluid.

- Fractals can be used in a turbulent fluid flow passing through the fractal.

- Fractals can be designed to provide turbulent jetting.

- Fractals can be used as fluid collection devices from turbulent flows.

Note that the slide of aerator/reactor operation from Fractals in Engineering 1997 is an example of such a combination of fractal fluid control together with subsequent turbulence.

6. M. Kearney, "Control of Fluid Dynamics with Engineered Fractal Cascades - Adsorption Process Applications" Proceedings of the 1997 AIChE Annual Meeting November 16-21, 1997, Los Angeles, Ca.

(Later published: Kearney, M., "Control of Fluid Dynamics with Engineered Fractals – Adsorption Process Applications," Chem. Eng. Comm., **173**, pp. 43-52 (1999).)

This paper describes the advantages of using fluid transporting fractals for adsorption applications along with a general discussion of the advantages of fractals. General comments which apply to any process using engineered fluid transporting fractals include the recognition of ease of scale-up - a common problem in chemical engineering.

7. Kochergin, V., *et. al.,* "Performance Evaluation of a Liquid Distributor Based on Fractal Geometry," AIChE Annual Meeting, *Proceedings*, Part 1, pp. 69-74, (1997).

In this paper, liquid distributors based on ARi's fractal technology were tested for countercurrent gas-liquid operation on the J. Montz and TU Delft 1.4 m ID column hydraulics simulator (directed by Z. Olujic). Fractal distributors were constructed with two different space filling characteristics - a common fractal variable. In this case, the two fractals were designed for 50% and 60% open area.

It was demonstrated that these fractals could be operated at both high and low liquid loads and at relatively wide turndown ratios (greater than 10 to 1). Because of a relatively high open area, they are also suitable for high gas loads.

The two fractal distributors demonstrated high potential for providing an excellent quality liquid distribution at high and low liquid loads.

8. Amalgamated Research Inc. brochure 1997.

Text from this brochure:

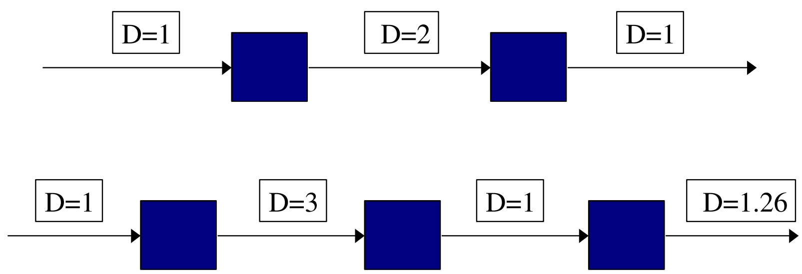
"ARi is the inventor of engineered fractal cascades (EFCs) for control of fluid dynamics. EFCs can be utilized for functional replacement of turbulence and controlled formation of fluid geometry. Examples include low turbulence mixers, turbulent to laminar conversion devices, and near ideal surface and volume fluid distributors. These fractals exhibit invariance to scaling and can be designed with dimensions ranging from a few centimeters to several meters.

Applications include control of single or multi-phase flows in preparatory or industrial chromatography, ion exchange, distillation, absorption, aeration, extraction and reactor processes."

9. Kearney, M., "Scaling with Engineered Fluid Transporting Fractals - The Functional Equivalence with Turbulence," Presentation at the AIChE Annual Meeting, November 15-20, 1998, Miami, Florida.

This presentation discussed ARi's general use of fractals for controlling fluids. Also discussed were the concepts of "process fractalization" and "fractal linking".

Below is an overhead from the 1998 AIChE presentation illustrating the concept of fractal linking. Fractals with a variety of dimensions, integer and non-integer are used, appropriate for each individual unit process in order to improve overall process efficiency.



10. Kearney, M., "Applications of Engineered Fractals in the Sugar Industry", *Proc.*, 30th Biennial Meeting of the ASSBT, Orlando, Florida (February, 1999).

This paper describes benefits of fractals to the sugar industry and also discussed ARi's concepts of "process fractalization" and "fractal linking":

"Process Fractalization and Fractal Linking

We have found the term "fractalization" to be a convenient way of describing the progressive addition of fractals to improve performance of a fluid process. Fractalization is a logical program to consider because fluids are so often handled in an unorganized, inefficient manner. Amalgamated Sugar's Nampa, Idaho plant is presently using fluid transporting fractals in 17 ft. diameter chromatography columns, a 40 foot diameter sugar silo (a gas application), and a thin juice softener. Although the goals in each application are somewhat different, they are all dependent upon controlling the geometry of the fluid scaling process.

A related useful concept is that of linking together fractals of different dimension. That is, a series of fractals can be used throughout a process to provide rapid fluid transitions, back and forth between surfaces, volumes or patterns of non-integer dimension."

11. Kearney, M., "Engineered Fractals Enhance Process Applications", *Chem. Eng. Prog*., 96, No. 12, pp. 61-68 (2000).

This paper is a general review of ARi's development of fractal technology for control of fluids. In addition, a list of questions are presented which can be used to help determine if fluid transporting fractals are appropriate for a process:

- What unit processes in an operation require fluid scaling?

- Is fluid scaling a necessity but presently under poor control?

- Can benefits be gained if the distribution of a fluid property is narrowed?

- Is energy being wasted by using turbulence for scaling?

- Can some or most of the induced turbulence in a process be replaced with an engineered fractal?

- Does process scale-up result in inefficiencies which can be countered with the scale-down characteristic of an engineered fractal.

- Does a process require the rapid formation of a particular fluid geometry?

- Is very rapid but precise scaling required?

- Will introduction of symmetries to the scaling process be beneficial?

- Can scaling homogeneity be beneficial?

- Can a process benefit from scaling to a particular fractal dimension?

- Can a process benefit from scaling control which changes as a function of time?

- Is there a benefit to localized mixing of one fluid within another?

- Can a fractal retro-fit to a process be useful or should a process be entirely reconfigured with a fractal as a key design element?

- Can a process be enhanced from a combination of a fractal with turbulent scaling?

From the conclusion:

"Scaling and distribution are very general fluid handling requirements and apply to processes which require mixing and/or geometry transitions. Fractals are by definition deeply scaled and therefore address certain problems of scaling in a direct and logical manner. In some cases, an engineered fractal can be an effective functional substitute for turbulence. In general, engineered fractals can provide precise control of scaling and distribution and therefore can enhance the efficiency of fluid processes. "

12. M. Kearney, " Process Intensification Using Engineered Fluid Transporting Fractals", Process Intensification Topical Conference Proceedings of the AIChE Spring National Meeting, March 30 - April 3, 2003, New Orleans, LA.

This paper discusses process intensification with fractal technology. An example is given of a full scale ARi fractal ion exchange system operating at 700 gpm. The table below compares conventional ion exchange versus fractal ion exchange for a particular weak cation exchange application.
From the abstract:

"We have determined that engineered fluid transporting fractals can be used to accomplish many of the goals of process intensification. The fractals are used to control the scaling and distribution of fluids. Fractals allow fluid properties, such as eddy size or concentration distributions, to be adjusted in a highly controlled manner. This control is obtained by introducing symmetries into the fractal structures. In some cases benefits can include order of magnitude reductions in process size, energy use and device design pressure."

	Conventional IX	Fractal IX
Resin bed depth (inches)	40	6
Exhaustion flow rate (Bed volumes/hour)	50	500
Maximum resin bed pressure drop (psi)	50-70	1 or less
Relative process size	10	1

13. Other.

In addition to the documents above, Amalgamated Research Inc. holds several additional fractal related patents issued and pending including "multiple fractal" technology and fractal oriented vessel design. Development proceeds both in-house and in collaboration with industrial and academic partners.

14. Note on personnel

Employees involved in the development and industrial implementation of ARi's fractal technology include Mike Kearney, Vadim Kochergin, Ken Petersen, Mike Mumm, Larry Velasquez, Bill Jacob, John Cox, Tim Pryor, Tom Vervloet and Dennis Costesso.