FRACTAL REACTOR: AN ALTERNATIVE NUCLEAR FUSION SYSTEM BASED ON NATURE'S GEOMETRY

Todd Lael Siler

Psi-Phi Communications, LLC
4950 S. Yosemite Street, F2-325
Greenwood Village, Colorado 80111 USA

Abstract

The author presents an update on the development of the Fractal Reactor concept. This nature-inspired theoretical device uniquely combines magnetic and quasi-inertial containment mechanisms to generate and tap the energies of high temperature plasmas. The Fractal Reactor concept considers building a fusion power reactor based on the *real* geometry of nature, rather than the *virtual* geometry that Euclid postulated around 330 BC. Nearly every architect of plasma fusion devices has been influenced by this extraodinary mathematician's three-dimensional geometry with its idealized points, lines, planes, and spheres. This classical geometry continues to be used to represent the natural world and to describe geometrical objects—including the closed containment systems with their closed surfaces that are designed to make the magnetic fields and coils as smooth as possible. These design schemes do not accurately portray the complexities of nature's structures and processes.

The physical analogy Siler uses to make his point is best demonstrated by trying to force a "square peg" (Euclidean geometry) into the roughly "round hole" (fractal geometry) of nature. *Instead of flowing with nature's way, we're working against it.*

The author argues that *all* of the present magnetic and inertial confinement systems—including the Stellarator, the Self-Organized Field [magnetic confinement] systems, such as the Spherical Torus and Spheromak, ITER, the Magnetic Mirror Machine, Reversed Field Pinch fusion device, and various Laser Fusion devices—are based a classical [Euclidean] geometry that neither directly nor adequately represent the geometry of nature. In recent years, nature's geometry has been more accurately described by statistically self-similar fractals. He further emphasizes that there is a fundamental difference in the vessel chamber designs of these plasma fusion devices, which may make a world of difference in terms of their performance and effectiveness. Consequently, the nuclear fusion community will most likely encounter more of the same problems they have faced over the past 50 years, because of this potentially basic design flaw that affects how we model and mimic the dynamics of a star.

In the interest of advancing the integrated art-science-technology of engineering controlled nuclear fusion technology, the author respectfully requests the plasma fusion community to investigate the alternative plasma fusion energy system proposed here. Given that this community of scientists, engineers and entrepreneurs intends to build fully viable, commercially feasible, nuclear fusion energy systems that are competitive with other electricity producing technological innovations, it may be prudent to take this naturalistic perspective in designing devices that more closely approximate the forms and functions of nature.

Siler, T.L. (2007). "Fractal Reactor: An Alternative Nuclear Fusion System Based on Nature's Geometry," in 13th International Conference on Emerging Nuclear Energy Systems, [pp.239-246] edited by Prof. Dr.-Ing. Sumer Sahin, June 03-08, Istanbul, Turkey; ICENES 2007 Conference was hosted by Gazi University, Ankara and Bahcesehir University, Istanbul.

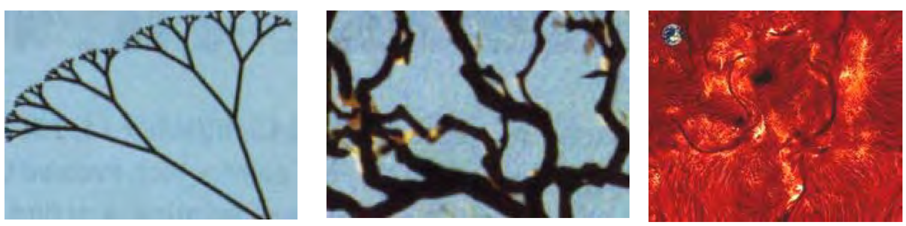
I. EXPLORING THE POSSIBILITIES OF THIS NATURE-INSPIRED INNOVATION

Every plasma fusion physicist dreams of gleaning the Holy Grail of endless energy: the creation of a safe, environmentally-friendly, fusion energy system that can effortlessly and inexpensively power our world for the next 1,000 years or more—thus satisfying the requirements of our all-purpose energy-related needs while avoiding producing climatic changes, which we see from burning fossil fuels that emit CO_2. Fusion technologists have already begun calculating the wealth of details, which must be accounted for in their business proformas that track how well this fusion power system will be managed and marketed. To out perform its competitors, it must produce power for approximately 0.3 cents/KWh.

What remains an enigma is how this system will actually accomplish this feat: sustaining and harvesting dense, 300 - 500 MK (million degrees Kelvin) plasmas for energy purposes. This concept paper addresses that enigma.

The Fractal Reactor concept considers the possibility that a controlled, thermonuclear fusion energy system might be more effective if it more closely embodies the physics of a star, which, I hypothesize, is nature's *star* "fractal reactor." [1] Implying, stellar bodies are composed of fractal forms and dimensions that are statistically self-similar,[2] as shown in Figures 1 & 2.

This concept contrasts the current containment mechanisms of both magnetic and inertial containment systems for confining and heating plasmas. All of these systems are based on Euclidean geometry and use geometrical designs that, ultimately, are inconsistent with the Non-Euclidean geometry and irregular, fractal forms of nature. [3]



Exact Self-Similarity (Fractal dimensions) | **Statistical Self-Similarity** (Fractal dimensions) | **Surface of the Sun** (Fractal dimensions)

Figure 1. Comparison of different kinds of natural fractal images. Photos from Richard P. Taylor article, "Order in Pollock's Chaos," in ***Scientific American***, December 2002; p.118.); "A Brief History of Chaos." DOT photo of the Sun's active region AR10786; the field measures 182 x 133 arcsec. (The inserted photo of Earth shows the scale).

"Fractals have come to be referred to as the geometry of nature. They are shapes or behaviors…that have similar properties at all levels of magnification," writes Priya Hemenway in *Divine Proportion Phi: In Art, Nature, and Science* (2005) "The term fractal is used to describe a particular group of irregular shapes that do not conform to Euclidean geometry…Just as the sphere is a concept that includes raindrops, basketballs, and Earth, so fractals are a concept that unites clouds, coastlines, lightning bolts, and trees."[4]

Coupled with the reality of fractals is this peculiar balance between these two binary concepts: order and chaos. In the context of nuclear fusion systems, these two concepts are represented by closed and open containment systems, as well as astochastic [deterministic] processes and stochastic [non-deterministic] processes respectively; in terms of the latter, these processes refer to the fact that "the next state of the environment is partially but not fully determined by the previous state of the environment." [5]

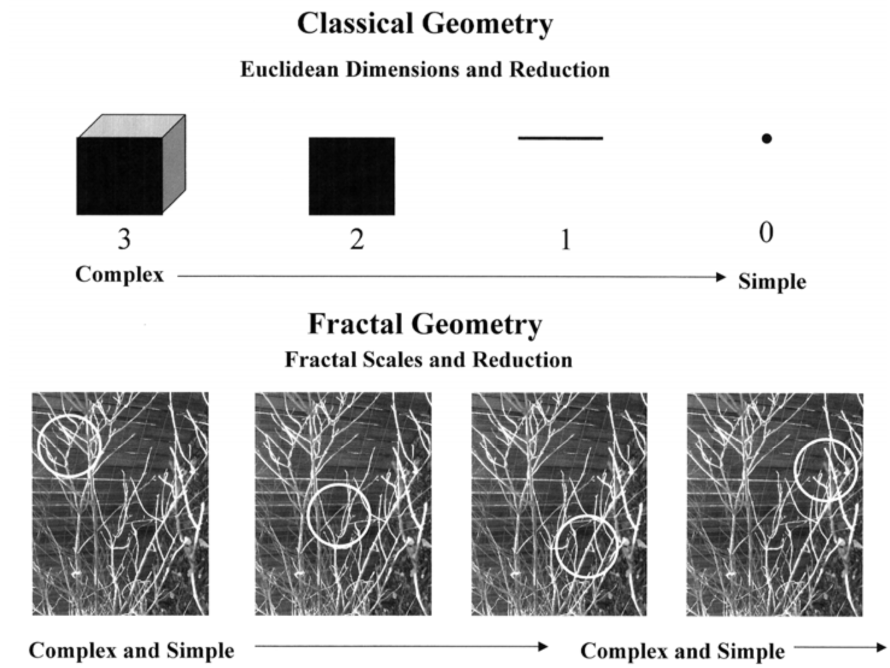


Figure 2. Chart comparing fractal and classical geometries. (Inspired by and based on Rhonda Roland Shearer's article "From Flatland To Fractaland: New Geometries In Relationship To Artistic And Scientific Revolutions," in *Fractal Geometry and Analysis, The Mandelbrot Festschrift*, C.J.G. Evertsz, H. O. Peitgen and R. F. Voss, eds., [World Scientific Publishers, July 1996]; 617-625; also "Real Or Ideal? DNA Iconography In A New Fractal Era," *Art Journal* 55, no. 1, College Art Association [Spring 1996]: 67)

The defining difference between the Fractal Reactor concept and other nuclear fusion concepts can be best understood by contrasting these two precepts: the reality-based precept of the Fractal Reactor, which states that *form determines function*, and the ideality-based precept, popularized by the 20th century architect Louis Sullivan, which states that "form follows function."

In the context of designing plasma fusion reactors, Sullivan's statement would imply that the form of the containment mechanisms follows the function or process of the hot plasmas these mechanisms generate, contain, and attempt to control. From this perspective, the function determines the form; meaning, plasma physicists work from the inside out: from the plasmas to the magnetic confinement mechanisms that generate the fields that shape and contain the plasmas. In effect, they envision the kinds of plasma conditions they want to create, and then they try to create what they envision.

To this end, as one plasma physicist, Dr. Fred Alan Wolf, has noted, "We know how to solve the usual Euclidian geometric (or Vlasov-Maxwell) equations of plasma physics and magnetohydrodynamics, and so we tend to design machines that these equations can describe. Hence we can solve the theoretical problem, because our minds have been formed to follow the functions of classical science and math. Unfortunately, nature doesn't work that way. It seems we have turned the problem upside down—*it should be form determining function as indicated in the Fractal Reactor concept*. In other words we can see what Nature designs so why not follow her?" [6]

The Fractal Reactor concept challenges the conventional thinking about "form follows function," providing abundant evidence to the contrary. It shows how form *determines* function, which we see in innumerable patterns of nature.

Since the early 1980s, nature's patterns have been described as statistically "self-similar fractals," a term introduced to the world by the mathematician Benoit Mandelbrot, who discovered and introduced us to his simple Mandelbrot Sets. "Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line," writes Mandelbrot in his groundbreaking book, *The Fractal Geometry of Nature* (1983).[7] Case in point: this Maple Tree seed, which was one of many creativity catalysts and sources of inspiration for the Fractal Reactor concept.

The precept ventured here considers how the form of the fractal magnetic containment mechanisms determines the function of the plasmas in this alternative fusion device.

More to the point: the Fractal Reactor examines the influences and dynamic relationships between the fractal-shaped magnets and the self-organizing behaviors and functions of the hot plasmas these magnets generate, shape and attempt to contain. The concept considers the types of magnetic field patterns we would like to generate, using the unique configuration of magnets described in this paper. [8]

Granted: in the theoretical Fractal Reactor device, stochastic processes naturally happen. And, yes, there maybe less control of the plasmas than plasma physicists would prefer. However, if we ingeniously applied our imaginations and engineering acumen in new ways, it may be possible to balance the stochastic processes of plasmas so that they can be managed in a more predictable, steady state—even as their behaviors still resemble stellar plasmas, which are always far from equilibrium.

Most controlled nuclear fusion schemes seek more control by designing closed magnetic containment systems that have closed surfaces. Their strategy is to make the magnetic fields and coils, or containment mechanisms, as smooth as possible, in order to mitigate the leaking of plasmas and magnetic fields. Presumably, the more closed the system is, the less the magnetic fields will leak. But no magnetic containment system is completely closed with closed surfaces, so leakage always happens. In fact, as astrophysicists have informed nuclear fusion systems designers, this constant leakage occurs even in the vacuum of deep space, where the forces of gravitational attraction are about as closed a system as nature has created in compressing and containing plasmas.

2. FOLLOWING NATURE'S WAY OF GENERATING AND SUSTAINING PLASMAS

The Fractal Reactor concept uniquely combines both magnetic and quasi-inertial confinement mechanisms (see Figures 3-5). The fractal magnets are designed to approximate the gravitational forces in a star that contribute to the compressional heating of plasmas in conjunction with the common dynamo phenomenon, which commonly occurs when the self-organizing, superheated plasmas generate their own intense magnetic fields, which, in turn, sustain their high-temperatures and density.

Basically, I'm attempting to reverse engineer and re-create the power of the Sun on a relativistic scale. But I'm taking a different, unbeaten path to realizing "the impossible" than my competitors, by considering the possibilities of applying fractal geometry to help improve the effectiveness of the containment systems and vessels of fusion machines.

This alternative path, or approach, to controlling the forces that govern plasmas explores exerting intense forces on the plasmas by the fractal, superconducting magnets that approximate the gravitational forces in a star and that initiate the essential dynamo phenomenon.[9]

Grasping the physics of this basic phenomenon, which has been observed in the Spheromak and Spherical Torus, may provide key insights into heating plasmas using a combination of confinement mechanisms.[10]

In examining the dynamo phenomenon, Dr. David Hill, one of the leaders of the Sustained Spheromak Physics Experiment (SSPX) at Lawrence Livermore commented: "…the main magnetic fields are generated by the plasma itself. It's a physical state the plasma wants to make naturally…The necessary strong magnetic fields are generated inside the plasma [by the magnetic dynamo]. In this regime, the plasma-fast-moving, superhot ions and electrons-produces its own confining magnetic fields. The magnetic fields pass through the flowing plasma and generate more plasma current, which in turn reinforces the magnetic fields…The dynamo drives the configuration [of fields and currents] towards a stable, minimum-energy state."[11]

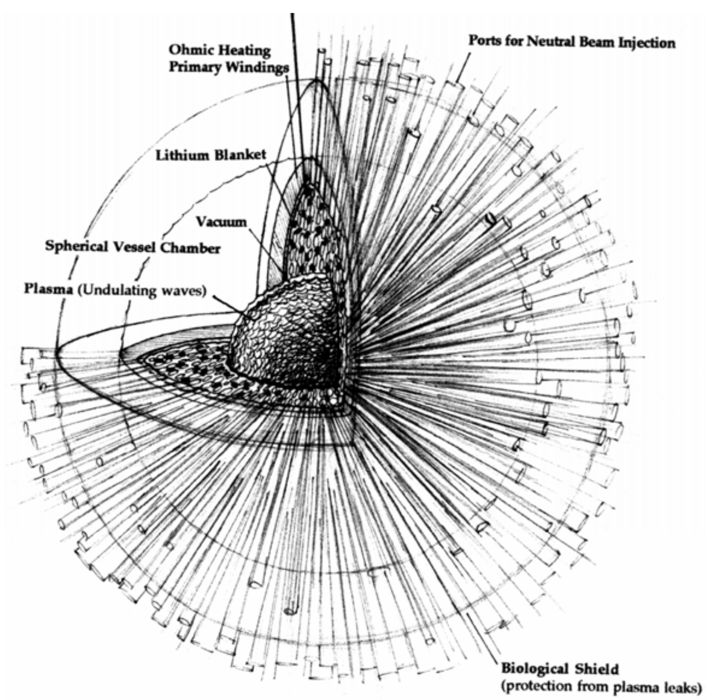


Figure 3. A cut-away view of the roughly spherical-shaped Fractal Reactor. Note that the spicule-like ports for the neutral beam injection may be significantly fewer in number and more loosely organized than shown here. Also, these elements might be incorporated in the Ohmic heating primary windings and electromagnets. This drawing shows the general shapes of the integrated, magnetic and quasi-inertial confinement systems for this alternative, controlled nuclear fusion device. (Drawing by Todd Siler.)

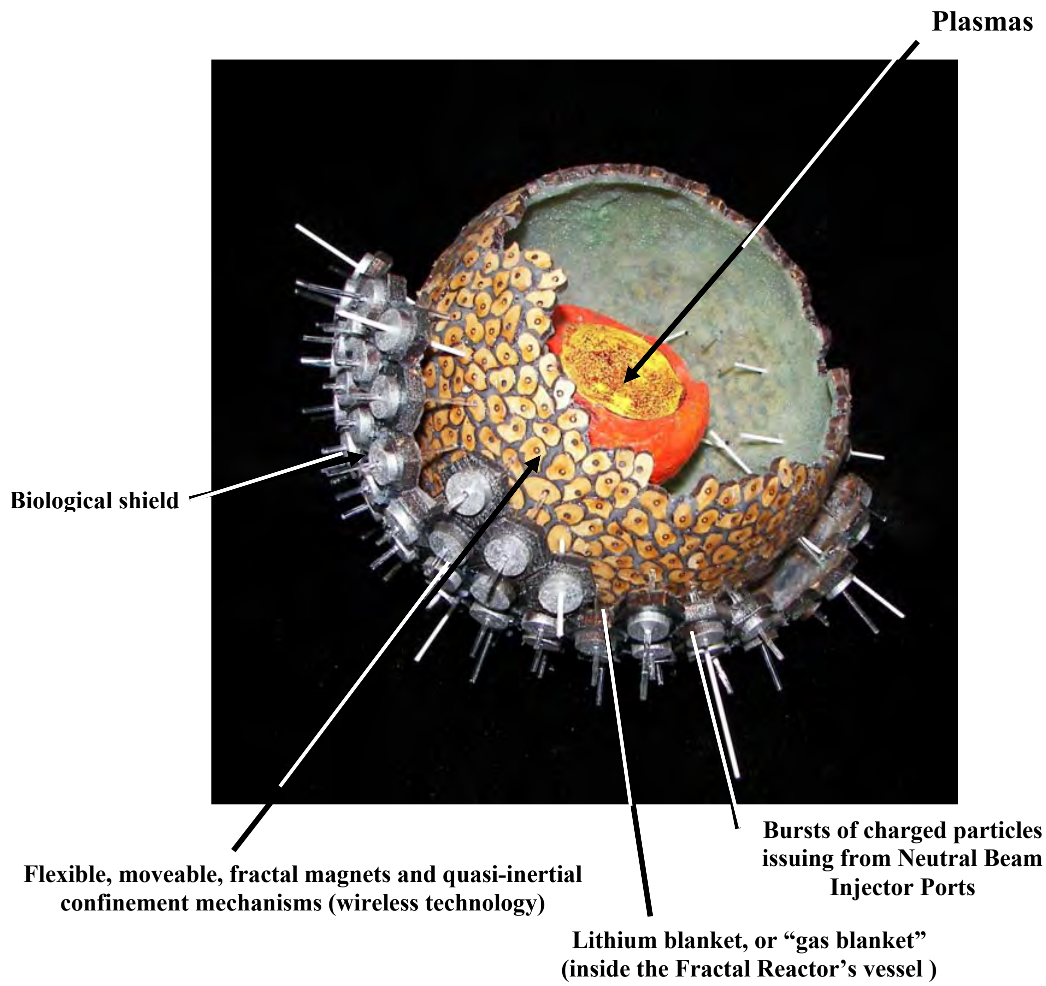
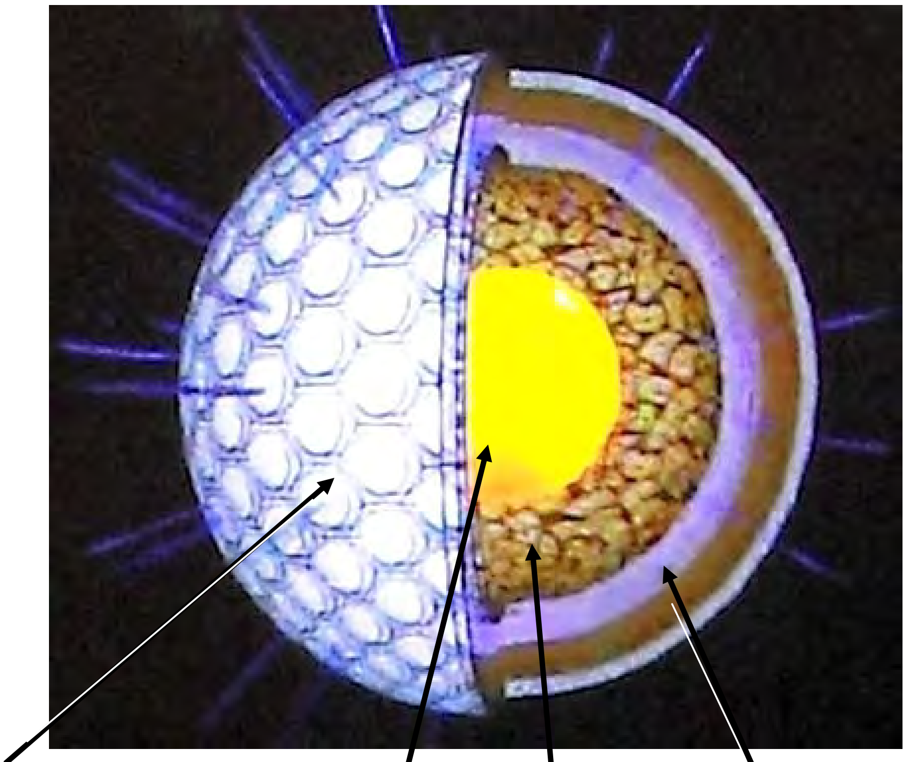
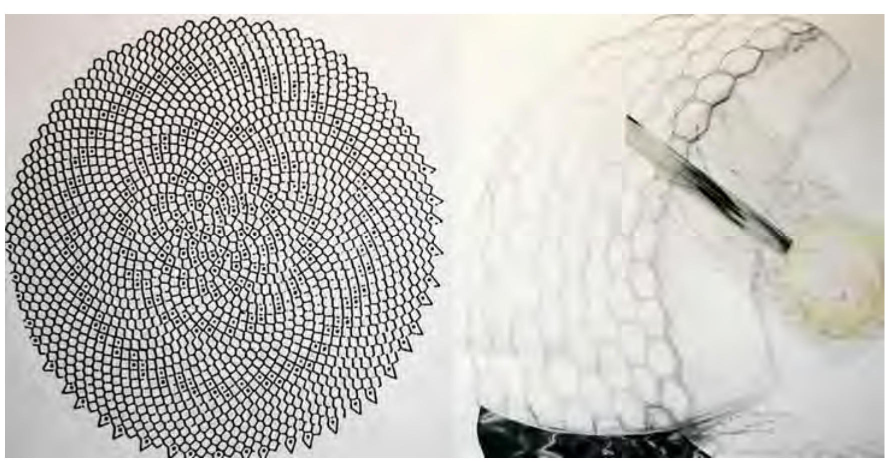


Figure 4. 3D visualization of the Fractal Reactor concept. This cut-away view shows the interconnected, irregular-shaped fractal-like, super-conducting magnets that continually move and oscillate, creating roughly spherical wave-like [minima/maxima] magnetic fields. The plasma is wide ranging in terms of its density, temperature, time/duration and confinement. (Model fabricated by Roger Leitner, based on Siler's drawings.)

Note: the superconducting magnets move at different rates, generating variances in the movement of magnetic currents of plasma, and initiating the dynamo phenomenon. One alternative design for the fractal magnets is the Nobel-Prize winning "BuckyBall," or Icosahedral Fullerene C_{540} – only *fractalized*. The magnets could be carefully controlled, increasing and decreasing the pressures and temperatures of plasma within the core of the Fractal Reactor – thus controlling the degrees of compacting the hydrogen isotopes deuterium and tritium. Note that this device would not be limited to the D-T fuel reactions exclusively.



Figures 5a&b. Top: Image attempts to show the motions of the superconducting magnets in the Fractal Reactor and the roughly spherical fractal magnetic fields they generate. The 3D computer-visualization was created the Anark Corporation, a media production company. Bottom: This interpretive drawing shows the interactions of these magnets with the plasmas they generate. It also presents a possible Prototype of the Fractal Reactor magnetic confinement system. This image of a Sunflower structure could serve as the general design for the fractal superconducting magnets Note the self-similarity of the elements. (Drawing inspired by and based on Jay Kappraff, *Connections: The Geometric Bridge Between Art and Science*. McGraw-Hill, 1991.)



The Fractal Reactor concept uses the physics of the Sun as its principal model and prime source of design principles. It creatively explores ways we can learn about how our current magnetic confinement and inertial fusion devices are analogous to the systems operating within a star. In doing so, this creative inquiry challenges the fusion industry to consider more realistic and naturalistic ways of representing the designs and dynamics of controlled fusion energy systems.

Since the late 1990s, I've often wondered whether this fundamental issue concerning our classical geometrical designs for the containment vessels and confinement mechanisms may be hindering rather than helping our success in sustaining and harvesting hot plasmas for energy purposes. Perhaps, by experimenting with fractals in nuclear fusion technology, we may be better equipped to generate and manage high performance plasmas.

I conceived of the Fractal Reactor concept as a catalyst for discussing the possibility of redesigning the vessel geometry of a plasma fusion device, in an effort to make it more effective and efficient system.

While presenting this concept at the 2001 and 2003 Symposia on "Current Trends in International Plasma Fusion Research," in Washington, DC,[12] my PowerPoint presentation was accompanied by an interactive, 3D visualization that broadly shows how the principles of statistical self-similarity and scaling invariance, which are central to fractal geometry, may be applied to plasma physics. Note that this sophisticated computer-animation also helped differentiate the Fractal Reactor concept from all the other controlled thermonuclear fusion devices—from the Spheromak to the Z-Pinch machines,[13] as well as other Inertial Laser Fusion devices—that relate to the key aspects of this concept.

Although the temperatures of the plasmas generated in the Fractal Reactor may not reach the record-breaking temperatures of plasmas produced in Sandia Labs' "Z machine" that generated a three billion degrees Fahrenheit (or 2 billion Kelvins) plasma using hydrogen-boron (pB11) fusion—that's 100 times the temperatures at the core of the Sun!—they may, nevertheless, reach temperatures suitable for sustaining thermonuclear reactions on a regular cycle of burning plasmas.[14]

The visual suppositions and premises posed by the Fractal Reactor concept aim to spark innovative thinking on how we can consistently generate, control, and sustain thermonuclear reactions in such a way that they more accurately replicate nature's way—including the way it manages unstable, self-organizing plasmas with radical temperature gradients.

To this end, I aim to apply common sense, observational science, and "best practices" in reverse engineering [15] the dynamics of a star.

3. FROM SCULPTURAL SKETCHES TO MATHEMATICAL MODELS OF REALITY

To move beyond symbolic Artist Concepts, physical analogies and visual suppositions, I've begun the process of composing a computational model. When completed, this mathematical model will demonstrate how the irregular-shaped, fractal, superconducting magnets and quasi-inertial confinement mechanisms in his new system will work in real-life.

My plans for advancing the development of this work center on collaborating with plasma physicists and mathematical physicists who can create the necessary mathematical models that are both descriptive and predictive. Using various mathematical tools, including nonlinear partial differential equations, the models will demonstrate:

(1) The actual movement and behavior of the roughly spherical, fractal superconducting magnets and the complex magnetic fields they generate;
(2) The 3D plasma simulation codes for showing the nuclear physics of the self-organizing plasmas that are generated and confined in this new fusion system;
(3) The motion of the fractal magnets in the Fractal Reactor and their interactions with the high-temperature plasmas they generate; and
(4) The chain of mechanisms involved in transferring and transforming the neutrons captured in the lithium gas blanket into useful energy, which turns the turbines that ultimately result in gigawatts of electricity (10^9 GW)

I have received some excellent advise by a number of outstanding plasma physicists on how to proceed with developing the Fractal reactor concept. Professor J.C. Sprott, Department of Engineering Physics at University of Wisconsin—Madison suggested that the specialists who write 3D plasma simulation codes consider "creating some new math that marries hydrodynamic and Maxwell's equations with fractal boundary conditions." That made sense to me, as Maxwell's equations interrelate a wide range of phenomena: electric fields, magnetic fields, electric charges, and electric currents.

This suggestion was corroborated by Professor Jay Kappraff in the Mathematics Department at New Jersey Institute of Technology, who emailed me after reading the concept paper: "Your fractal reactor sounds very interesting. I recommend that you look at the work of N. Rivier on froths since they form natural fractal like patterns like the ones you illustrate. The idea of connecting plasmas to natural system has the right ring to it. However, it will be quite a task to wed the hydrodynamic and Maxwell's equations to your geometry. It seems as though some new kinds of mathematics may have to be used to accommodate fractal boundary conditions." [16]

Dr. Kappraff's thoughts on this strategy were resonant with another excellent plasma physicist, Dr. Manos Chaniotakis at MIT's Fusion Lab, who was very insightful, too. Dr. Chaniotakis suggested a couple of viable ways to advance my project with the creation of the three separate but interrelated computational models I've listed. He suggested the system of equations I would need to use to begin to compose a mathematical model (e.g., Maxwell-Boltzmann probability distribution equations used in statistical mechanics). He also explained that the MHD treatment of this configuration of magnets would be extremely complex to model. Additionally, Dr. Chaniotakis suggested the types of key questions I would need to address concerning the magnetic field gradients in the magnetic topology. But he first recommended that I experiment with various configurations of dipole magnets—increasing their random arrangement, and then observing what happens.

In the process of cobbling together the various mathematical tools and approaches that can be incorporated in the computational models, I first turned to this definition of the Maxwell–Boltzmann probability distribution published in the free dictionary, Wikipedia [17]:

> "The temperature of any (massive) physical system is the result of the random motions of the molecules and atoms which make up the system. These particles have a range of different velocities, and the velocity of any one particle is constantly changing due to collisions with other particles. Nevertheless, for a large number of particles, the fraction of particles within a particular velocity range is practically constant. The Maxwell distribution of velocities specifies what this fraction is for any velocity range as a function of the temperature of the system.
>
> The distribution can be thought of as the magnitude of a 3-dimensional vector if its components are distributed as a normal distribution with standard deviation *a*. If X_i are distributed as , then
>
> is distributed as a Maxwell–Boltzmann distribution with parameter *a*.
>
> The Maxwell–Boltzmann distribution with *a* = 1 is equivalent to the square root of chi distribution with three degrees of freedom. Additionally, if Z is distributed as a Maxwell–Boltzmann distribution with parameter a, then
>
> will be distributed as a chi distribution with three degrees of freedom.
>
> The root-mean-square of a Maxwell–Boltzmann distribution is . Since $\sqrt{2} < 2\sqrt{2/\pi} < \sqrt{3}$, it follows that the mode is less than the mean, which is always less than the root-mean-square.
>
> The Maxwell–Boltzmann distribution forms the basis of the kinetic theory of gases, which explains many fundamental gas properties, including pressure and diffusion. The Maxwell–Boltzmann distribution is usually thought of as the distribution of molecular speeds in a gas, but it can also refer to the distribution of velocities, momenta, and magnitude of the momenta of the molecules, each of which will have a different probability distribution function, all of which are related." [18]

One caveat about applying the Maxwell–Boltzmann distribution was noted in the Wikipedia definition: "There are many cases where the conditions [in a gas], such as elastic collisions *do not apply* [italics mine]. For example, the physics of the ionosphere and space plasmas where recombination and collisional excitation (i.e. radiative processes) are important: especially for electrons. If you applied the Maxwell distribution and its assumptions here, you would get the wrong numbers, and you miss the basic physics of the problem." [19]

Although the dynamics of the self-organizing plasmas we plan to generate and confine in the Fractal Reactor are, in principle, related to the dynamics of large-scale space plasmas, I don't believe we will be facing that same problem of recombination and collisional excitation—certainly nothing that's not manageble. But that remains to be determined. In composing the mathematical model to describe the nuclear physics of the Fractal Reactor, this potential problem will be considered along with a number of key assumptions we will have to take into account before applying the appropriate mathematical expressions.

A second cautionary note about applying the Maxwell Boltzmann Distribution earmarked in Wikipedia considered the cases where, and I quote, "the quantum thermal wavelength of the gas is not small compared to the distance between particles, there, the theory would fail to account for significant quantum effects." [20]

Again, I am not sure we need to be concerned about these specific effects. However, this issue regarding the 'quantum thermal wavelength of the gas' will be duly noted and evaluated before we embark on applying the Maxwell–Boltzmann distribution equations.

One additional note about these probably distribution equations, which is germane to the selection of the mathematical machinery we will be using to run the engine, so to speak, of our computational model: "Originally suggested by Maxwell who assumed all three directions would behave in the same fashion, a later derivation by Boltzmann dropped this assumption using kinetic theory," we learn from the Wikipedia lexicon. "The Maxwell–Boltzmann distribution can now most readily be derived from the Boltzmann distribution for energies:

where N_i is the number of molecules at equilibrium temperature T, in a state i which has energy E_i and degeneracy g_i, N is the total number of molecules in the system and k is the Boltzmann constant. Because velocity and speed are related to energy, Equation 1 can be used to derive relationships between temperature and the speeds of molecules in a gas. The denominator in this equation is known as the canonical partition function." [21]

4. FROM MATHEMATICAL MODELS TO REALISTIC IMPLEMENTATION

The theoretical physicist Fred Alan Wolf, Ph.D., author of the American Book Award for Science *Taking The Quantum Leap* (Harper Perennial, 1982), has written: "What science does best is create art, and what art does best is envision new science." [22]

That statement is deeply relevant to the creative act of composing mathematical models, as well. Moreover, it resonates with the best practices of the distinguished physiologist, science history, and polymath Dr. Robert S. Root-Bernstein, co-author of *Sparks of Genius* (Houghton Mifflin, 2000), who describes how "art is science, and science, art—artscience." [23]

In many respects, the purpose of my presentation at ICENES is to use *artscience* (art that fully integrates scientific inquiry) to respectfully question the path plasma fusion community has taken over the past fifty years. I think it's imperative at this time to revisit this fundamental question: Can we do a better job of more reverse engineering the physics of stars, whereby we can figure out a more effective way of balancing the natural chaos of self-organizing plasmas and their Stochastic processes with more some measured means of controlling and managing the hot plasmas?

In other words, what is nature doing that we need to be more cognizant of and clever at replicating and applying our knowledge of engineering plasmas?

And even more to the point: What is the *ideal* design for the Fractal Reactor? How will this device manage the plasma instabilities in the same way that a star does?

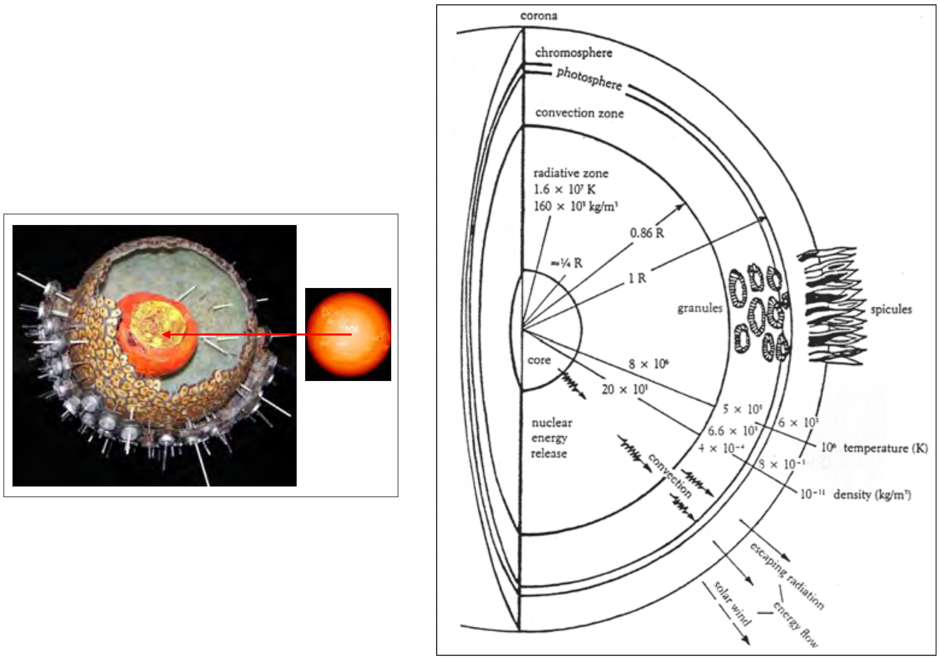
Insightfully answering these three fundamental questions will take a most adventurous collaboration of mathematical physicists and fusion specialists. I'm hoping that the concept intrigues a number of innovators attending the ICENES conference who may be interested in collaboratively composing some mathematical models that meet the challenges in realizing this technological innovation.

The first of many challenges is determining the physical size of the Fractal Reactor. Given that this device can be built on a wide range of scales because of the self-similar fractal dimensions—from a medicine ball structure (approximately 3ft. diameter) that uses wireless technology to a spherical, room-size vacuum environment (approximately 50ft. diameter) that resembles the architect Etienne Boullee's monumental building, "Cenotaph to Sir Isaac Newton" (1789)—I have taken into consideration the following four interrelated issues:

(a) the size of the plasma, which can have the diameter of a baseball;
(b) the size of the fractal magnets that are needed to generate an incredibly hot, dense baseball-size plasmas, which would have (on a relativistic proportional scale) one solar mass unit of energy;
(c) the cycle of burning plasmas that's needed to sustain the controlled thermonuclear reactions in a commercially viable way; and
(d) The means of converting the neutrons captured in the lithium blanket into energy required for the turbines to produce the necessary gigawatts of electricity needed to power a city the size of New York City.

After discussing this issue of scale with one of my colleagues, Dr. Charles Benson, an architect who designs and builds complex commercial properties and who has extensive expertise in systems designs, we concluded that several separate mathematical models may need to be composed to describe three different scenarios for the sizes and conditions of the burning plasmas: from the very smallest to the largest.

Perhaps, the ideal size of the plasmas will be determined when we reduce the Sun (see Fig. 6.) on a relativistic scale to the size of a baseball or basketball.



Figures 6. This visual supposition relates the known dynamics of a star to the unknown dynamics of high-temperature plasmas we plan to generate in the Fractal Reactor. The superconducting magnets act like the gravitational forces in a star to compressionally heat and contain the plasmas. (Diagram of "Structure of the Sun" from Michael Zeilik and Elske van Panhuys Smith, *Introductory Astronomy and Astrophysics*, 1987.)

Originally, I considered using the mathematical simulations and modeling techniques from our analyses of stars to model the dynamics and characteristics of the plasmas generated in the Fractal Reactor. [24] For example, this polytropic model of the Sun (see Fig. 7) could be used to calculate the size and shape of the Fractal Reactor's plasmas on a relativistic scale.

3. Model of the Sun

Use an n = 3 polytropic model to represent the internal structure of the Sun. The two parameters to fix are $M = M_\odot$ and $R = R_\odot$.

(a) Plot the physical temperature (in K) vs. radial distance in units of $r/R_\odot$. Plot $\log T$ vs. $r/R_\odot$. Do the same for the physical density (g cm^{-3}). Again, plot $\log \rho$ vs. $r/R_\odot$. Instead of using the values for the central density, ρ_0, and central temperature, T_0, deduced for an $n = 3$ polytrope with $M = M_\odot$ and $R = R_\odot$, take the "known" values of $\rho_0 = 158$ g cm^{-3} and $T_0 = 15.7 \times 10^6$ K.

(b) Compute the nuclear luminosity of the sun using the above temperature and density profiles. Take the nuclear energy generation rate to be:

$$\epsilon(\rho, T) = 2.46 \times 10^6 \rho^2 X^2 T_6^{-2/3} exp(-33.81 T_6^{-1/3}) \quad \text{ergs cm}^{-3}\ \text{sec}^{-1}$$

where ρ is in g cm^{-3}, T_6 is the temperature in units of 10^6 K, and X is the hydrogen mass fraction (take $X = 0.6$). Note that the units of $\epsilon(\rho, T)$ are ergs cm^{-3} sec^{-1} and not ergs g^{-1} sec^{-1} as given in the lecture. Reduce the problem to a dimensioned constant times an integral involving only functions of ϕ and ξ. (There will also appear a "T_0" inside the integral for which you can plug in the value of 15.7×10^6 K, or $T_{06} = 15.7$.) Show the value of your constant and the form of the dimensionless integral. Evaluate the nuclear luminosity of the Sun in units of ergs sec^{-1}.

SOURCE: Massachusetts Institute of Technology, Physics Department, Earth, Atmospheric, and Planetary Sciences Department; Astronomy 8.282J-12.402J "Computational Problem Set 2 Polytropic Models for Stars"

Figures 7. This polytropic model of the Sun is used in astrophysics to render the dynamics and anatomy of a star.

Implicit in the premise explored here is that our human-made plasmas would share similar dynamics, behaviors and properties to these solar plasmas and their "internal solar machinery."

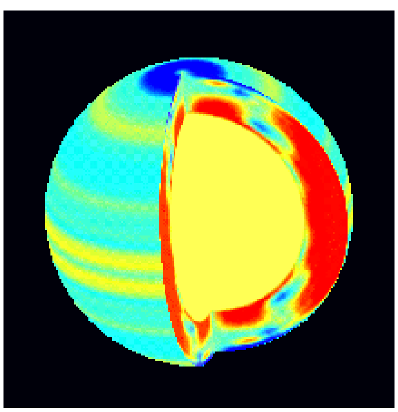
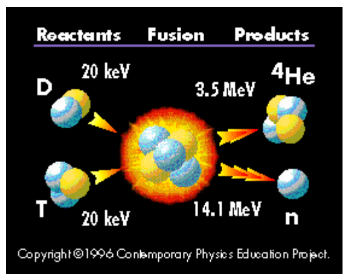


Figure 8. Three-dimensional view shows the different speeds of the layers of plasmas inside the Sun in relation to its surface. Note how the Jets of plasmas change colors in the polar areas, signifying the presence of strong shearing layers (tachocline, towards 0.7 Rs) and their continuous rotation and re-structuring along the latitude axis. These measurements were made using the heliosismology techniques and Soho instruments. (© 2006 CNES or other source).

In addition to using the tools of astrophysics, we plan to use the tools of Magnetic Fusion Energy (MFE) scientists to create this computational model and simulate the behavior of the plasmas in this alternative fusion device. As Dr. Keith Thomassen, Deputy Associate Director for MFE at Lawrence Livermore Labs, relates: "Simulations of individual phenomena—physics 'packages'—now exist as essential tools for analyzing fusion experiments…Phenomena such as the equilibrium of the plasma, turbulent transport, stability, and heating, are examples of such processes and are interdependent. Thus, codes that simultaneously describe all these phenomena have these packages "hard wired" together, and the codes are extremely complex. A contributor to this complexity is the disparate time and spatial scales of these phenomena.” [25]

In any event, we aim to use the MFE tools to create the 3D plasma simulation codes and to render other key physics processes involved in the Fractal Reactor’s *control* and *sustain* these intense D-T reactions as shown in Figure 8.

D + T => He-4 + n



For first generation fusion reactors

The "D-T" reaction has the highest reaction rate at the plasma temperatures which are currently achievable; it also has a very high energy release. These properties make it the easiest reaction to use in a man-made fusion reactor. As the figure shows, the products of this reaction include an alpha particle (Helium-4 nucleus) with 3.5 MeV energy, and a neutron with 14.1 MeV energy. The neutron escapes from the plasma (it has no charge and is not confined) and can be trapped in a surrounding "blanket" structure, where the n + Li-6 => He-4 + T reaction can be used to "convert" the neutrons back into tritium fuel. -- *Hannah Cohen.*

Notes:

•1 eV = 1.6022E-19 joules;

•Average particle thermal kinetic energy is 1 eV per 11,600 K. **SOURCE: http://FusEdWeb.llnl.gov/CPEP/**

Figure 8. The Fractal Reactor will make use of the D-T fuel, while exploring other combinations of reactants. (Diagram courtesy of Contemporary Physics Education Project ©1996)

4.1 MAKING THE FRACTAL REACTOR A VIABLE COMMERCIAL ENTERPRISE

When you consider the growing complexities of our energy needs worldwide, every effort must be made to make controlled nuclear fusion technology work in practical ways —however, *exotic* it may seem, or far-reaching.

To give you a general sense of the amount of energy human beings consume, Peter Huber and Mark P. Mills, coauthors of *The Bottomless Well: The Twilight of Fuel, The*

Virtue of Waste, And Why We Will Never Run Out of Energy (Basic Books, 2005) provide us with some pretty daunting figures:

> "Think of our solitary New Yorker on the Upper West Side as a 1,400-watt bulb that never sleeps—that's the national per-capita average demand for electric power from homes, factories, businesses, the lot. Our average citizen burns about twice as bright at 4:00 p.m. in August, and a lot dimmer at 4:00 a.m. in December; grown-ups burn more than kids, the rich more than the poor; but it all averages out: 14 floor lamps per person, lit round the clock. Convert this same number back into a utility's supply-side jargon, and a million people need roughly 1.4 "gigs" of power—1.4 gigawatts (GW). Running at peak power, Entergy's two nuclear units at Indian Point generate just under 2 GW. So just four Indian Points could take care of New York City's 7-GW round-the-clock average. Six could handle its peak load of about 11.5 GW. And if we had all-electric engines, machines, and heaters out at the receiving end, another ten or so could power all the cars, ovens, furnaces—everything else in the city that oil or gas currently fuels.
>
> The U.S. today consumes about 100 quads—100 quadrillion BTUs * —of raw thermal energy per year. We do three basic things with it: generate electricity (about 40 percent of the raw energy consumed), move vehicles (30 percent), and produce heat (30 percent). Oil is the fuel of transportation, of course. We principally use natural gas to supply raw heat, though it's now making steady inroads into electric power generation. Fueling electric power plants are mainly (in descending order) coal, uranium, natural gas, and rainfall, by way of hydroelectricity.
>
> Thus, "1 million people need roughly 1.4 "gigs" of power—1.4 gigawatts (GW)."[26]

Consider how these numbers have steadily risen since this 1995 Energy Information Administration Annual Energy Review reported:

> "The average single-family household consumed 98 million Btu of energy in a recent year…To put those quantities in perspective, 1 million Btu equals about 8 gallons of motor gasoline. One billion Btu equals all the electricity that 30 average Americans use in 1 year. One trillion Btu is equal to 474 100-ton railroad cars of coal intended for electric utilities. And 1 quadrillion Btu is equal to 470 thousand barrels of oil every day for 1 year.
>
> In 1993, the Nation used 84 quadrillion Btu of energy: 34 quadrillion Btu of petroleum, 21 quadrillion Btu of natural gas, 19 quadrillion Btu of coal, and 10 quadrillion Btu of other energy sources. British thermal units are useful for more than just calculating volumes of consumption. Price equivalents are usually expressed in cents per million Btu, and the homeowner often thinks of Btu in terms of dollars and cents. In 1993, a ton of coal used to generate electricity cost more than twice as much as a barrel of oil. The barrel of oil, however, contained about 6.2 million Btu, while the ton of coal contained 21 million Btu, over three times as much energy."[27]

5. RESEARCH OPPORTUNITIES FOR ADVANCING THE FRACTAL REACTOR

In order to build the Fractal Reactor, the following fields of knowledge should be integrated in the collaborative work by a diverse team of researchers specializing in: fractal geometry, mathematical physics, plasma fusion reactor technology, magnetic field theory, fluid dynamics, thermodynamics, magnetohydrodynamics, super-computing science and technology (for managing the data on parallel processors or Cray III computers), mechanical engineering, unified field theory, and the visual arts.

The integration of this disciplinary knowledge is essential for creating computational models and simulations to represent the general dynamics of the Fractal Reactor as they may occur in an Engineering Test Reactor and a Pilot Plant.

Core Design Team

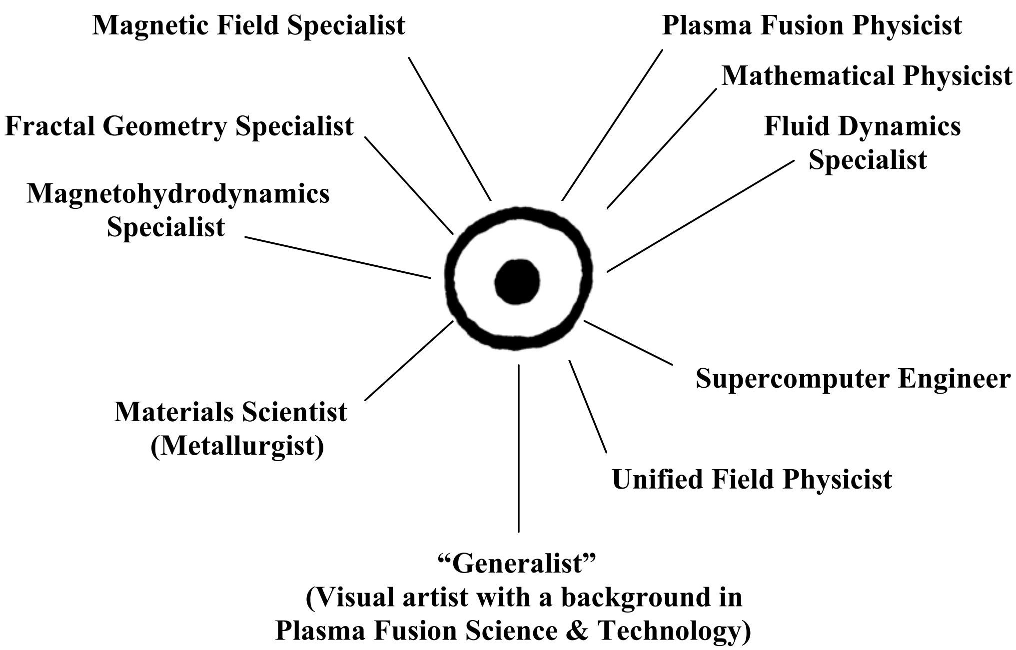


Figure 10. To date, my main collaborators have included these “Generalists”: architect Charles Benson, Chief Operating Officer of Advanced Technological Resources (ATR), Inc., sculptor Roger Leitner, and software engineer Jason Giles of the Anark Corporation (www.anark.com), who was kind enough to compose the interactive, 3D visualization of the Fractal Reactor concept based on my drawings and models.

The next steps to our R&D entail putting the intuitions that power the Fractal Reactor concept to the test by describing the physics of this device in terms of computational models that can be further explored by the plasma fusion community.

The computational models we aim to collaboratively create with the help of some adventurous mathematicians and plasma physicists will accomplish the following three objectives as demonstrated by some visually compelling, 3D computer-simulations:

(1) the models will show and describe mathematically the actual movement of the roughly spherical, fractal-shaped, superconducting magnets [shown in all three examples of the photos];
(2) the complex movements between the magnets and the hot dense plasmas that these magnets generate by compressing and containing the deuterium-tritium fuel. The Fractal Reactor concept generally describes the interrelationship between the magnetic fields produced by the moving magnets and those created by nature's *dynamo effect* in the plasmas themselves; and
(3) the possibility of controlling and sustaining thermonuclear reactions by applying fractal geometry to plasma fusion technology.

6. SUMMARY

At this point, only the computational models will help advance the Fractal Reactor concept. Ultimately, we need to simulate the operation of this alternative plasma fusion device in real-life, demonstrating how the physics of this device can initiate and sustain the thermonuclear reactions that occur in stars.

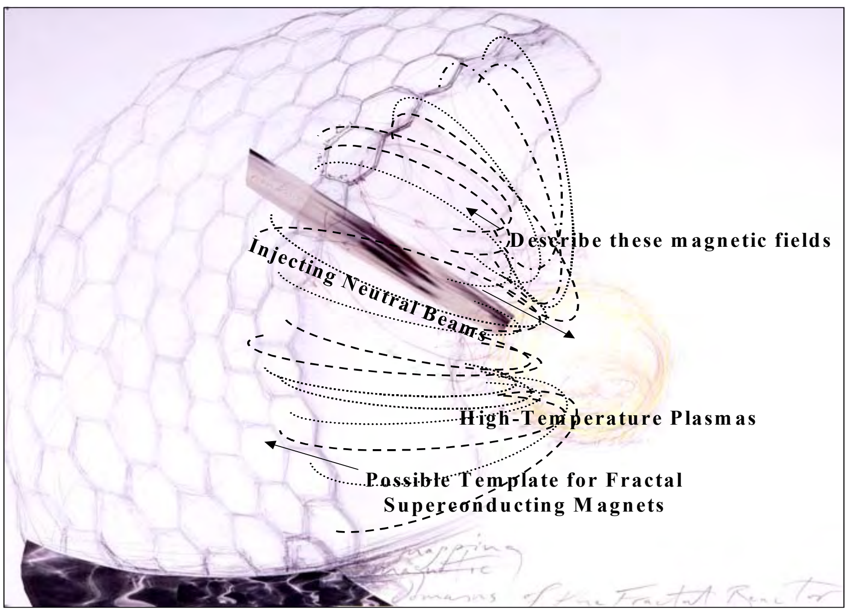


Figure 11. This Artist's Conception interprets the movement of the superconducting magnets in the Fractal Reactor and their interactions with the plasmas they generate. ©Todd Siler

One overarching final note: Charles Benson recently pointed out to me a Renaissance masterpiece by Raffaello Sanzio "School of Athens" (1509-1510) in the Stanza della Segnatura, Vatican. He felt this particular artwork highlights the differences between the fractal concept of nature and classical geometry. Raphael's prophetic painting contrasts two complementary philosophical perspectives, which he represents divisively as Aristotle and Plato. Plato is depicted as pointing upwards to the cosmic divine—conveying his ideals and passion: to understand the heavens. Aristotle is shown to be reaching outward to grasp the natural world and the elements of earth—conveying his passion to realistically see and glean nature for what it is. I tend to look at the world from an Aristotelian viewpoint, observing the nonlinear shapes and irregular forms of the natural environment, while studying those shapes and forms that influence every aspect of the environment.

Benson ventured farther down the path of this analogy, by relating two complementary geometries: the catenary, [28] which is nature's creation (in the same way fractals are), whereas the parabola is human-made. On the back of an envelop he sketched this simple design (Figure 12) that shows the relationship between these two geometries, to which he added this poignant statement-picture: "Life exists between the metaphorical parameters of the catenary and the parabola."

Perhaps, the present-future life of nuclear fusion technology exists there, too.

My takeaway from this sweeping insight with regard to the Fractal Reactor is that somewhere between these two structures lies the magnetic field lines in the Fractal Reactor, which like the cables in a catenary, are "acted upon by a uniform gravitational force (its own weight)." When we begin to model the physics of those dynamic cable-like field lines, they may resemble this curious relationship between this catenary (gravity curve) and parabolic (logarithmic curve) structure, which Benson musefully call's "Nature's smile."

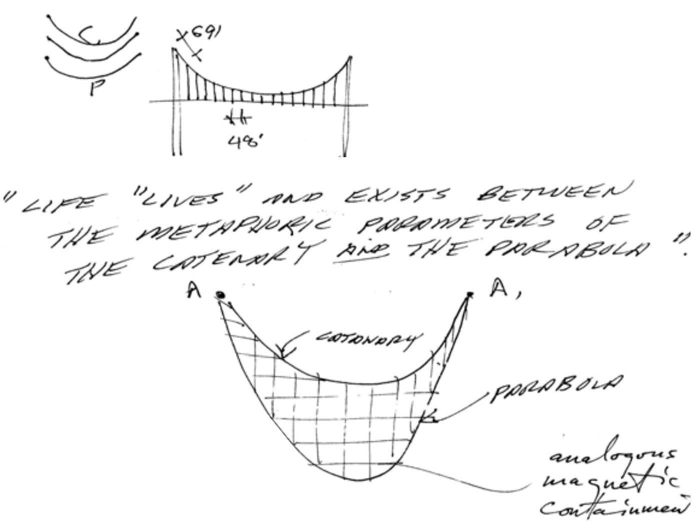
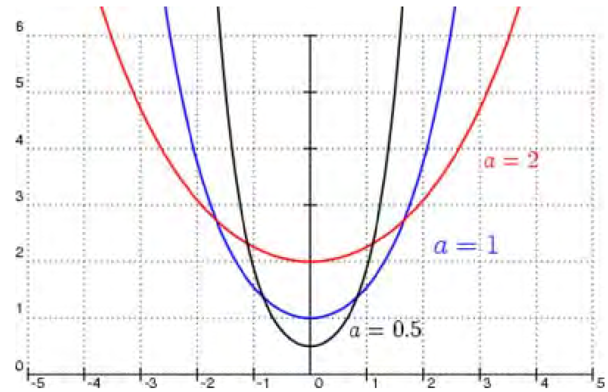


Figure 12. "In mathematics, the *catenary* is the shape of a hanging flexible chain or cable when supported at its ends and acted upon by a uniform gravitational force (its own weight). The chain is steepest near the points of suspension because this part of the chain has the most weight pulling down on it. Toward the bottom, the slope of the chain decreases because the chain is supporting less weight." (SOURCE: http://en.wikipedia.org/wiki/Catenary)



Catenaries for different values of the parameter.

$$y = a \cdot \cosh\left(\frac{x}{a}\right) = \frac{a}{2} \cdot \left(e^{x/a} + e^{-x/a}\right)$$

in which:

$$a = \left(\frac{T_o}{P}\right).$$

where T_o is the horizontal component of the tension (a constant) and P is the weight per length unit."

(SOURCE: Wikipedia http://en.wikipedia.org/wiki/Catenary)

Figure 13. Think beyond our metaphors and models of physical reality: these ever-changing catenaries could represent the changing shapes of the magnetic field lines in the Fractal Reactor.

As we begin to picture how these different catenaries can represent the changing parameters and shapes of the magnetic field lines that stream from the movable fractal magnets in the Fractal Reactor (depicted in Fig. 11), we also need to visualize how these magnets would work synergistically in generating these fields.[29]

One of the more technically difficult tasks ahead of us concerns the fabrication and manufacturing of the fractal magnets. We're wondering if an existing technology in a totally different industry could be re-purposed and retrofit to serve the functions of the Fractal Reactor device. Perhaps, it's possible to use micro-electromechanical systems (MEMS) in the design of very small fractal-shaped magnets for a compact system. Additionally, electrical engineers could create a remote control device that would enable the *wireless* superconducting magnets to be operated in the manner suggested in this concept paper.

We are currently exploring this possibility.

REFERENCES AND NOTES

1. This premise was first presented in T. Siler, “Fractal Reactor: A New Geometry for Plasma Fusion,” in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment* (National Research Council of Canada, Ottawa/NRC Research Press, 2002).

   A. Bunde and S. Havlin, (eds.), *Fractals and Disordered Systems.* 2nd rev. (Springer, 1996); K. Falconer, *Fractal Geometry.* (Wiley, 1990), and *Fractals: Non-Integral Dimensions and Applications*. (Wiley, 1991); *IFIP Conference on Fractals in the Fundamental and Applied Sciences* (North-Holland /Elsevier Science Publishers, Co., 1991); L. Nottale, *Fractal Space-Time and Microphysics: Towards a Theory of Scale Relativity*. (World Scientific, 1993); R.P. Taylor, “Order in Pollock’s Chaos,” in *Scientific American*, December 2002; p. 118.
2. J. Briggs, *Fractals: The Patterns of Chaos.* (Simon & Schuster, 1992).

   Review Euclid’s classic book *Elements,* which was written at the time of Ptolemy; note that in *Phaenomena,* Euclid relates his spherical geometry to render celestial objects studied in astronomy.

   In T. Phillips, “The Transparent Sun” (Science@NASA), we learn that a group of applied mathematicians at the St. Andrews Solar Magnetohydrodynamics (MHD) Theory Group, Scotland, is studying the nonlinear interaction between the Sun's magnetic field and its plasma interior or atmosphere. Note: their mathematical modeling techniques are informed by observational data from satellites, such as SoHO, Yohkoh and TRACE.
3. B. Mandelbrot, *The Fractal Geometry of Nature*. (W.H. Freeman, 1982).

   Read J. Kappraff, *Connections, The Geometric Bridge between Art and Science.* (McGraw-Hill, 1991); I. Toth, "Non-Euclidean Geometry before Euclid," in *Scientific American* (November 1969), pp. 87-98.

   Also read J. Gleick, *Chaos; Making a New Science.* (Penguin Books, 1987); M.R. Schroeder, *Fractals, Chaos, Power Laws: Minutes From An Infinite Paradise.* (W.H. Freeman, 1991).
4. P. Hemenway, *Divine Proportion, Phi: In Art, Nature, and Science* (Sterling Publishing, 2005); p.125.
5. To learn more about the random function of a stochastic process: http://www.dadamo.com/wiki/wiki.pl/Stochastic
6. Fred Alan Wolf, Ph.D. offered this comment after reviewing T. Siler, “Fractal Reactor: A New Geometry for Plasma Fusion,” in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment* (NRC Research Press, 2002).
7. On the website www.fractalwisdom.com/FractalWisdom/fractal.html, the anonymous authors relate how Benoit Mandelbrot, a Yale professor of mathematics, made his breakthrough while he was working at the IBM research laboratories. They write: “His pioneering research can be summarized by a simple mathematical formula: z -> z^2 + c. It is significant to understand that this formula could not have been discovered without computers. The Mandelbrot Set is a dynamic calculation based on the iteration of complex numbers with zero as the starting point. The order behind the chaotic production of numbers created by the formula z -> z^2 + c can only be seen by the computer calculation and graphic portrayal of these numbers. Otherwise the

formula appears to generate a totally random and meaningless set of numbers. It is only when millions of calculations are mechanically performed and plotted on a two-dimensional plane (the computer screen) that the hidden geometric order of the Mandelbrot Set is revealed…Mandelbrot conceived and developed this new fractal geometry of nature based on the fourth dimension and Complex numbers which is capable of describing mathematically the most amorphous and chaotic forms of the real world."

8. T. Siler, "Fractal Reactor: A New Geometry for Plasma Fusion," (pp. 105-120) in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment* (NRC Research Press, 2002).
9. Forest et al., Madison Dynamo Experiment (MDX), University of Wisconsin-Madison, 1999; J. Sherwood, "Magnetic Dynamo Appears to Shape Planetary Nebulae," *UniSci. Daily University Science News* (Jan. 25, 2001).
10. K.I. Thomassen et al, "The Spheromak Path to Fusion Power," in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment* (NRC Research Press, 2002).

    Read M. Peng, "Cost-Effective Spherical Torus Steps Toward Fusion Power," in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment* (NRC Research Press, 2002); Washington, D.C., March 8-12, 1999; pp. 24-26.

    Also, read T.A. Heppenheimer, *The Man-Made Sun: The Quest for Fusion Power*. (Little Brown and Company, 1982)
11. *A. Heller,* "Experiment Mimics Nature's Way With Plasmas"; D. Hill et. al work on Lawrence Livermore's Sustained Spheromak Physics Experiment (SSPX), in collaboration with the Sandia and Los Alamos National Laboratories. (Source: www.llnl.gov/str/Hill.html)

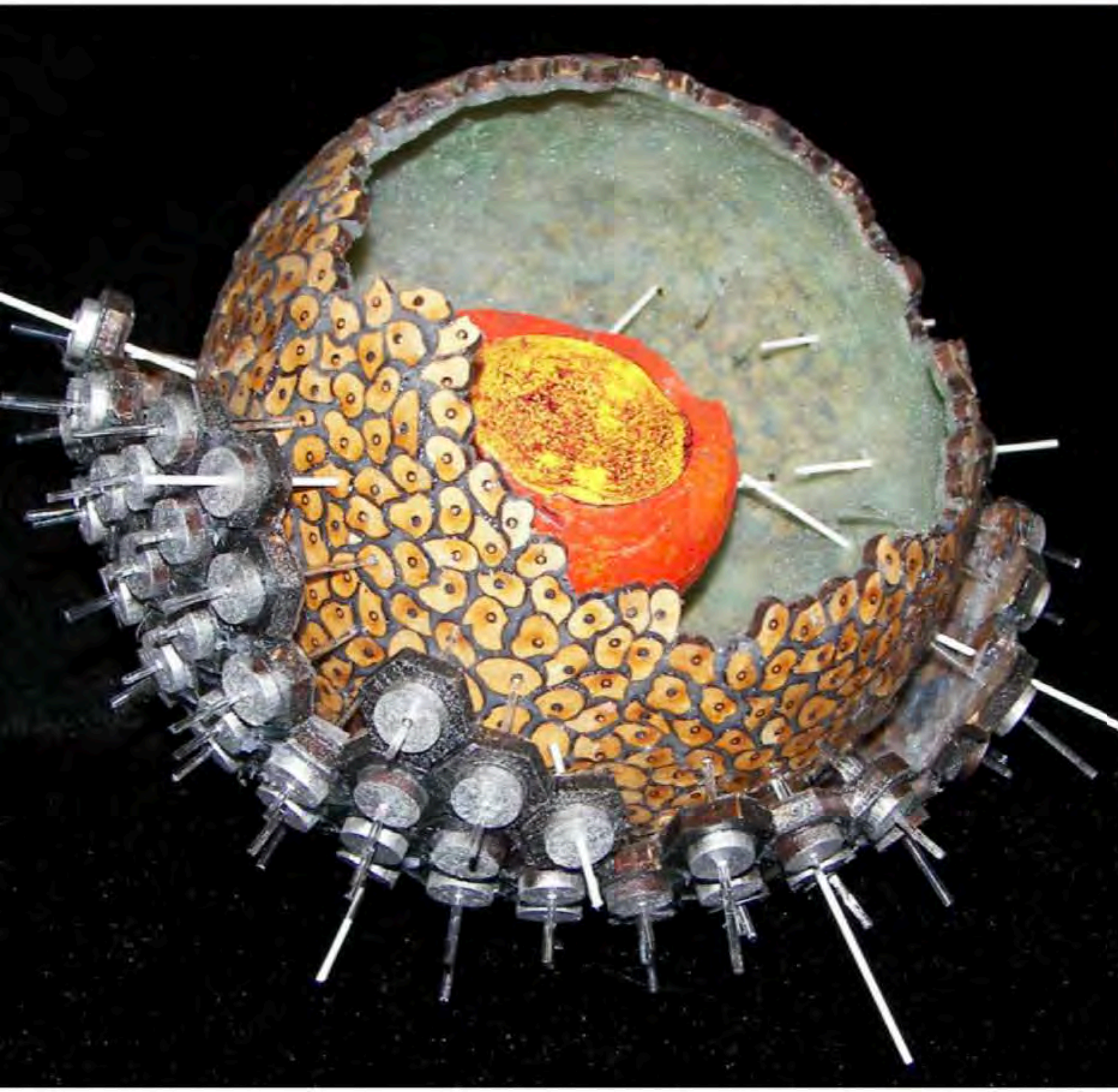
    Also read J. Herrera, "The Self-Organization Concept in Magnetic Confinement Fusion," in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment* (NRC Research Press, 2002.
12. These symposia on "Current Trends in International Plasma Fusion Research were organized under the auspices of the Global Foundation, Inc. and in cooperation with the International Atomic Energy Agency (IAEA), Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Naval Research Laboratory, and Sandia National Laboratory.
13. "Field-Reversed Pinch," in *Proceedings for the 3rd Symposium on Current Trends in International Fusion Research: Review and Assessment*, Washington, D.C., 8-12, March 1999.
14. http://www.scienceblog.com/cms/z_machine_exceeds_two_billion_degrees_kelvin_10171.html; also, visit: http://library.lanl.gov/cgi-bin/getfile?00285870.pdf

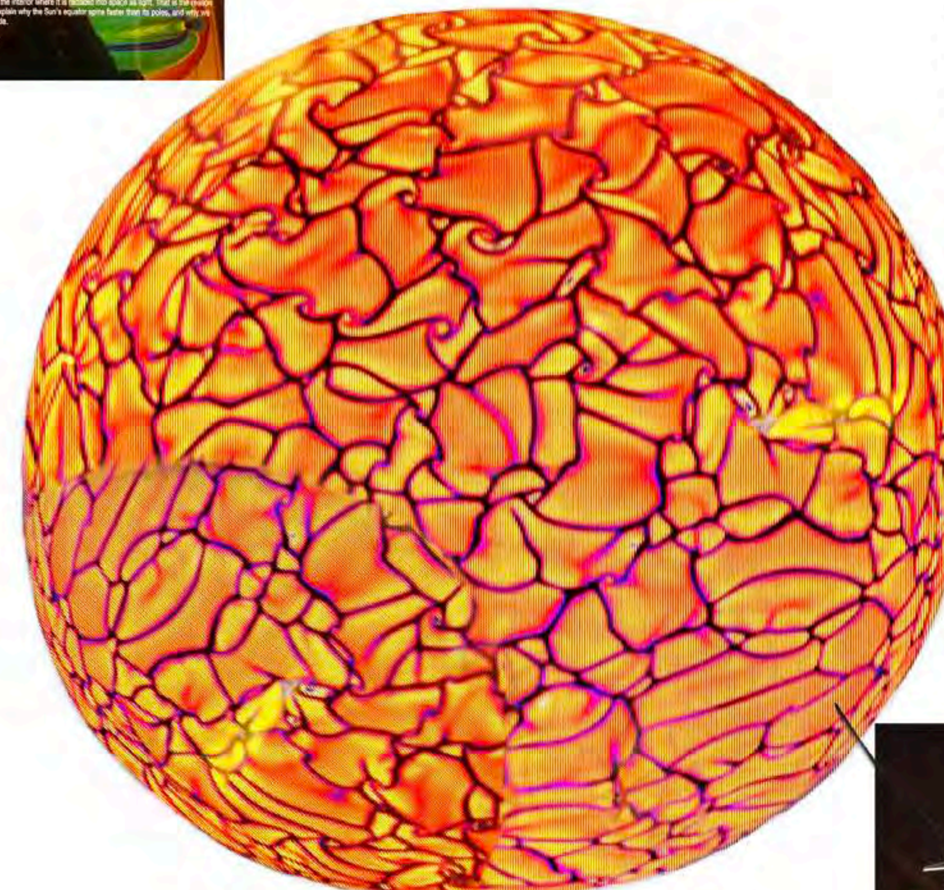
    Compare aneutronic fusion (http://en.wikipedia.org/wiki/Aneutronic_fusion).
15. The Society of Manufacturing Engineers defines Reverse Engineering as, "the process of taking a finished product and reconstructing design data in a format from which new parts or molds can be produced." (*Military Handbook MIL-HDBK-115*). In this instance, the *finished product* is the Sun; its *design data* has been gleaned by many decades of empirical studies and mathematical models informed by astrophysics.

16. In 1974, Dr. Kappraff did his doctoral work at New York University's Courant Institute in magnetohydrodynamics applied to controlled fusion. He was very active with the fusion group led by Dr. Harold Grad, and performed the first bifurcation of a plasma equilibrium applied to the Stellarator.
17. This definition of the Maxwell–Boltzmann probability distribution is provided by Wikipedia. (http://en.wikipedia.org/wiki/Maxwell-Boltzmann_distribution).
18. Ibid.
19. Ibid.
20. Ibid.
21. Ibid.
22. F. A. Wolf's testimonial for T. Siler *Breaking the Mind Barrier* (Simon & Schuster, 1990).
23. From Dr. Root-Bernstein's insightful essay, titled "Exploring the Possibilities of 'Art as Science'," in Todd Siler, *Metaphorming Worlds* (Taipei, Taiwan: Taipei Fine Arts Museum, 1995).
24. T. Siler, "Fractal Reactor: An Initial Computational Model for an Alternative Plasma Fusion System," in *Proceedings for the 5th Symposium on Current Trends in International Fusion Research: Review and Assessment* (NRC Research Press, 2007).
25. K.I. Thomassen, E.B. Hooper, and D.D. Ryutov, "The Spheromak Path to Fusion Power," http://www-mfe.llnl.gov/, April 1998; T.A. Heppenheimer, *The Man-Made Sun: The Quest for Fusion Power*. (Little Brown and Company, 1982).
26. Peter Huber and Mark P. Mills, *The Bottomless Well: The Twilight of Fuel, The Virtue of Waste, And Why We Will Never Run Out of Energy* (Basic Books, 2005).
27. (http://physics.syr.edu/courses/modules/ENERGY/ENERGY_POLICY/units.html); http://www.jet.efda.org/pages/content/fusion6.html

    For more information, check the Monthly Energy Review, Annual Energy Review, State Energy Data Report, Household Energy Consumption and Expenditures, and Cost and Quality of Fuels for Electric Utility Plants; SOURCE: http://www.eia.doe.gov/oiaf/aeo/pdf/aeotab_2.pdf#search=%22100%20quadrillion%20BTUs%22)
28. "The word *catenary* is derived from the Latin word *catena*, which means 'chain.' The curve is also called the alysoid, funicular, and chainette. Galileo claimed that the curve of a chain hanging under gravity would be a parabola, but this was disproved by Jungius in a work published in 1669. The intrinsic equation of the shape of the catenary is given by the hyperbolic cosine function or its exponential equivalent." (SOURCE: Wikipedia http://en.wikipedia.org/wiki/Catenary)
29. The visionary architect, engineer, and inventor R. Buckminster Fuller, author of *Synergetics*, described synergetics as "either the output of a system not foreseen by the simple sum of the output of each system's part."

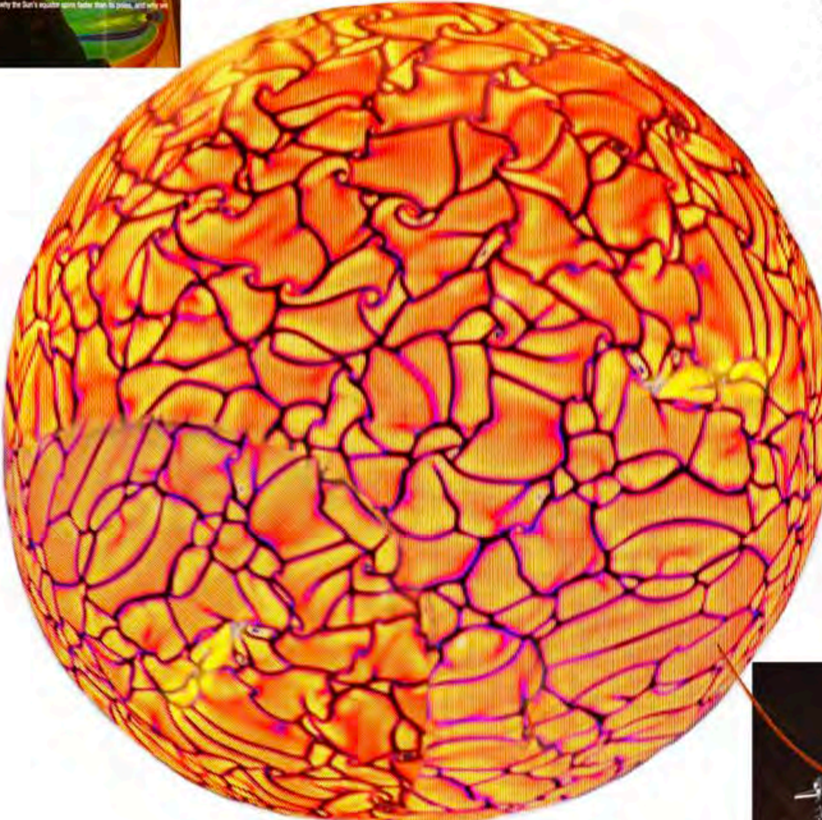
    For an in-depth understanding and application of this important concept, read this pioneer's work H. Haken: "Synergetics, an *Introduction: Nonequilibrium Phase Transitions and Self-Organization in Physics, Chemistry, and Biology*, 3rd rev. enl. ed. (Springer-Verlag, 1983) and H. Haken, *Advanced Synergetics: Instability Hierarchies of Self-Organizing Systems and Devices*. (Springer-Verlag, 1993).



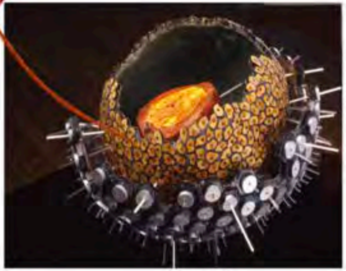


Metaphoring it!
What "If Nature was showing us "the blueprint" for designing the fractal-shaped magnets needed to compress and contain hot, dense plasmas for generating and sustaining nuclear fusion, but we overlooked the clues to "the patterns" in our Solar Convection Models?
You're looking at the template for the electromagnets(?) or superconducting magnets(?) of the "Fractal Reactor"!
There they are! Designed by Nature, the "Mother of All Invention."
Now, let's do what "Humanature" does best:
INNOVATE!

 A nuclear fusion energy system based on Nature's fractal geometry. Mixed media



Metaphoring it!
What If Nature was showing us "the blueprint" for designing the fractal-shaped magnets needed to compress and contain hot, dense plasmas for generating and sustaining nuclear fusion, but we overlooked the clues to "the patterns" in our Solar Convection Models?
You're looking at "the template" for the electromagnets(?) or superconducting magnets(?) of the "Fractal Reactor"!
There they are! Designed by Nature, the "Mother of All Invention."
Now, let's do what "Humanature" does best:
INNOVATE!

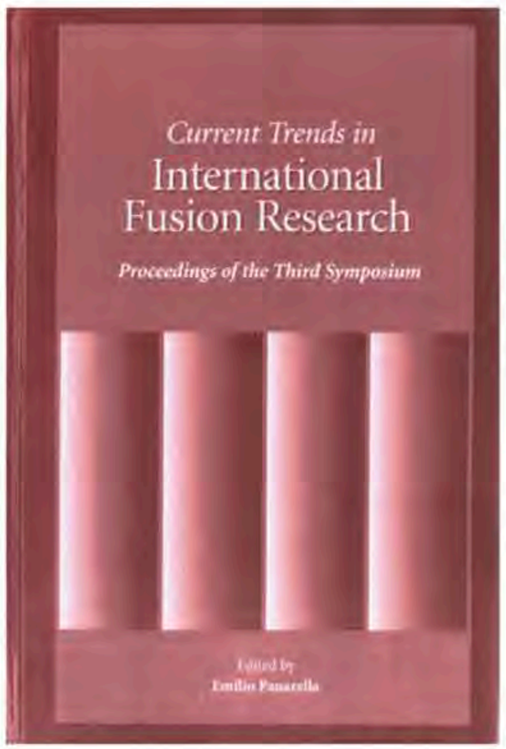


 Metaphorming the magnetic containment system of the Fractal Reactor (2015) Digital print. 18" x 24" ArtScience® Productions

©Todd Siler, ***Fractal Reactor*** (sculpture, 1996-2006) mixed media, 8” x 8” x 10” with custom-designed base composed of painted wood, 30” x 18” x 18”) with two drawings, “Visual Supposition and Premise I & II” (1996-2006) mixed media, 44” x 42” x 3” and 48” x 55”. ArtScience® Productions (Courtesy of Ronald Feldman Fine Arts, New York, NY)

©Todd Siler, ***Fractal Reactor: Re-Creating the Sun*** (1996-2006) Ronald Feldman Fine Arts, New York, NY (Sept. 9 – Oct. 7, 2006)

©Todd Siler, ***Fractal Reactor: Re-Creating the Sun*** (1996-2006) Ronald Feldman Fine Arts, New York, NY (Sept. 9 – Oct. 7, 2006)



"Fractal Reactor: A New Geometry for Plasma Fusion," Todd Lael Siler, in *Proceedings of the Third Symposium on Current Trends In International Fusion Research*, (pp. 105-120) edited by Emilio Panarella. (NRC Research Press, National Research Council of Canada, Ottawa, ON KIA OR6 Canada, 2003).

"Fractal Reactor: An Alternative Method and Apparatus for Plasma Fusion," Todd Lael Siler, in *Proceedings of the Fourth Symposium on Current Trends In International Fusion Research*, (pp. 411-426) edited by Emilio Panarella and Charles D. Orth. NRC Research Press, National Research Council of Canada, Ottawa, ON KIA OR6 Canada)

"Fractal Reactor: An Initial Computational Model for An Alternative Plasma Fusion System," Todd Lael Siler, in *Proceedings of the Fifth Symposium on Current Trends In International Fusion Research* [pp.289-312], edited by Emilio Panarella and Charles D. Orth. NRC Research Press, National Research Council of Canada, Ottawa, ON KIA OR6 Canada).

"Fractal Reactor: An Alternative Nuclear Fusion System Based on Nature's Geometry," Todd Lael Siler, in *13th International Conference on Emerging Nuclear Energy Systems*, [pp.239-246] edited by Prof. Dr.-Ing. Sumer Sahin, June 03-08, Istanbul, Turkey; ICENES 2007 Conference was hosted by Gazi University, Ankara and Bahcesehir University, Istanbul.

"Fractal Reactor: Re-Creating the Sun," Todd Siler, in *Leonardo Journal of Art, Sciences & Technology* Vol. 40, No. 3, pp. 270-278 (The MIT Press).

Realizing Human/Nature's Creative Potential™

Todd Siler, Ph.D.
ArtScience® Productions
P.O. Box 372117, Denver, Colorado 80237 USA
Mobile 720-988-8853 Email: toddsiler@alum.mit.edu
websites: www.ToddSilerArt.com and www.ArtNanoInnovations.com