Design and Prototyping of Life Support and Agriculture for Extended Space Habitation and Travel

Martin Dudziak, PhD
TetraDyn Ltd.
151 Alger Lane, Broadway, Virginia 22815
martinjd@tetradyn.com

Abstract
An experimental design is presented for a modular, reconfigurable multi-function platform that can be constructed in near-orbit or deep-space, for use in life support and emergency repair/reconstruction tasks within extended long-distance and long-duration space missions. This design is based upon a series of predecessor designs and deployments originating in applications ranging from emergency services to environmental monitoring and testing labs. The novelty in this "PodAtrium" architecture is the emphasis upon multi-functionality for structural components as well as internal apparatus including furnishings that are composed of basic elements that can be disassembled and reassembled as necessary and as demanded by the needs of a crew operating in isolation from any support craft or stationary habitation such as an exoplanetary base. Attention in the present phase of research and development has been upon the use of structural elements within a PodAtrium complex that can serve alternatively for a hydroponics-based greenhouse, a fuel-cell based power plant, and an asteroid mining operation, each of which could conceivably fulfill important roles at different times in the lifespan operations for a long-distance interstellar space vehicle with human crew onboard.

Keywords
agriculture, energy, habitation, life-support, sustainability, reusability

1. Introduction

The challenges of extreme long-distance and long-duration space travel and habitation require consideration of potentially radically different architectures and systems. A total "clean slate" in thinking about systems design including structural engineering is required. This "clean slate" is for more than what is generally the most common topic of discussion in "starship" design circles – propulsion and fuel. "Life support" – including mechanisms for dealing with consequences of structural and systematic breakdowns, or unforeseen changes in requirements for shelter, workspace, residence, food, water, non-propulsion fuels, and other commodities – requires a fresh start in how any type of large-scale, very-long-duration mission can be undertaken.

Almost all suggested "starship" (i.e., interstellar mission) designs to date have tended to be based upon the notion of a singular "spaceship" that has everything onboard and is itself a fixed physical architecture. Such a design leaves many gaps and room for disaster "down the road" when it comes to the critical maintenance of production and variance in production for food, water, air, power and shelter itself for space inhabitants. Operations must provide for not only fault tolerance but truly fail-safe performance, and part of how any species in any circumstances is able to approach such a goal-state is through adaptability and at many different scales of action. In biology we find this simply everywhere. From the molecular level to the performance of many creatures (not only humans, not only primates and not only mammals!) for interchangeable use and re-use of objects to fit the current and critical need of the moment, be it a need driven by necessity for survival or desire for pleasure.

An intensely modular and multi-functional architecture is required for spaceships that will carry life forms (and for that matter, even a population of robots) to distant interstellar and multi-generational destinations. There is a need for an "organic" (organism-like) model of system integration and symbiosis that extends beyond the most common and popular historical models, experiments, and thought-experiments for interplanetary and interstellar travel. The spaceship itself must possess and manifest some of the same characteristics of biological engineering that are found in what we typically regard as “living creatures” and which are the mainstay of survivability and adaptation to new surroundings, environments, situations.

In other words, it would be excellent if certain components of a spaceship or space base could, when needs arise and change, be transformed and re-used in order to replace some physical assemblies (e.g., residence, agricultural use, fabrication workspace), or to increase some functional outputs (e.g., electrical energy, propulsion fuel, food or water production). It would be excellent if different parts of a ship or base could be very repaidly converted, with minimal disassembly and minimal risk-intense labor, into other components as the situation arises. Foreseeable needs change. Supplies and availabilities change. Special circumstances arise. Reconfigurability and reusability are solutions for both minimizing the need for “extra (redundant) baggage” and the risks from losing critical resources due to no possibility of resupply or repair. All the better if the “building block’ materials can be manufactured or even, literally, grown during the mission. We are not talking about spaceships having a timber forest, but with materials like PLA (polylactic acid) and explorations in synthetic biology there are interesting possibilities indeed.

2. StarGate Alpha Project

"StarGate Alpha" is a current new-generation experimental platform that has been designed and is presently in the early stages of construction by Team TetraDyn and a growing collaborative consortium. The work is entering into the physical stage and two teams at two sites will be active in this next phase – One is at a facility in western Virginia (USA) and the second is planned for a site in Northern Ireland (UK). “StarGate Alpha” (“SGA”) is a "PodAtrium." This is an architecture employing multiple modular units (“nPods”). The main body of this paper discussed these structural design elements and methods of assembly, because this is the first stage of work in building any platform, earth-based for simulation and testing (as with the SGA; construction goal: 2014) and later in near-earth orbit (goal: 2018-2020).

An nPod is a “<u>P</u>urposive <u>O</u>perational <u>D</u>esign Structure” that can be constructed from a variety of materials and in a variety of geometries, and which can be assembled and disassembled easily into larger structures (“PodAtriums”). Moreover, all of the nPods are designed and constructed in such a manner that they may be disassembled into basic structural and functional elements that can be employed as basic construction “blocks”. In essence, this is a kind of LEGO or Knex or Erector Set approach to building almost everything that goes into a large-scale complete spaceship system, and indeed, the aforementioned “toys” have directly been an inspiration in the design of nPods and PodAtriums, coupled with the real-life experience of building precursors using many different materials and structures, ranging from tents to shipping containers to trailers. Figures provided below in this paper illustrate a few of the precursor projects leading up to “PodWorld” and also the elementary designs for PodAtrium structures that are intended for the “StarGate Alpha” experimentation laboratory soon to be built in both USA and UK.

This particular platform, “StarGate Alpha” (SGA) incorporates reconfigurable and redirected-function modules for agriculture (including selective livestock cultivation), hybrid energy generation and management with an emphasis upon independence from other vessel or station power systems, and structural and habitation features for short-term life support during periods of necessary reconstruction, sequestration or quarantine due to CBRNE emergencies. Often the thought about “chem-bio-radiation-nuclear-explosive” is relegated to thoughts about earth-based disasters, terrorists, accidents. There are many natural and accidental circumstances where a toxic chemical or biological release, for instance, could demand rapid reconstructive engineering onboard an interstellar craft. The system must be prepared for dealing with such situations. That such a comprehensive roster of functions has been targeted for one experimental platform is deliberately based upon the simple fact that any and all of these factors and possible conditions need to be addressed and accommodated in any realistic starship lifecycle and its design.

An important feature of the SGA design is the emphasis upon multi-functional utility for such a platform to serve in many space-based physical environments as well as on terrestrial-like planets. The experiment has been proceeding through design and simulation and is entering into phase-1 of a physical prototype environment. The goal of the project now is to demonstrate the effectiveness and the critical importance of an agri-energy-life-support "PodAtrium" that will function equally well in space and on a planet such as Earth. In phase-1 of SGA, emphasis is upon multi-modal agriculture using hydroponic, bromeliad and aquatics, combined and supported with a hybrid "permaculture" approach to energy, water, and air maintenance. The physical structures being designed and constructed will employ composite materials such that the actual prototype system could be feasibly demonstrated on a space mission in earth-orbit or deep-space. Phase-1 involves building the self-sufficient, stand-alone PodAtrium and then performing agricultural and energy/fuel production tasks on site with zero or minimal interaction with the outside environment. Phase-2 extends this into a stable high-orbit platform ("HALO" – High Altitude Lift and Launch Operations) or ideally into near-earth orbit.

Figures 1, 2 and 3 below provide three schematic illustrations of how nPods can be routinely assembled and reassembled into different configurations based upon whatever are the overall system requirements. As will be shown further, the dimensionality of an nPod, by definition, is not restricted to a particular geometry (such as a rectangular prism, as shown here). These illustrations (alpha, beta and gamma layouts, as examples taken among many) are shown in the *"total abstract"* - there can be any number of basic functions which need to be thus aligned – food production, water production, various types of fuel production (e.g., artificial photosynthesis), residence, medical care, "fab-lab" for mechanical workshop tasks, and even laboratories for the study of extraterrestrial objects of interest.

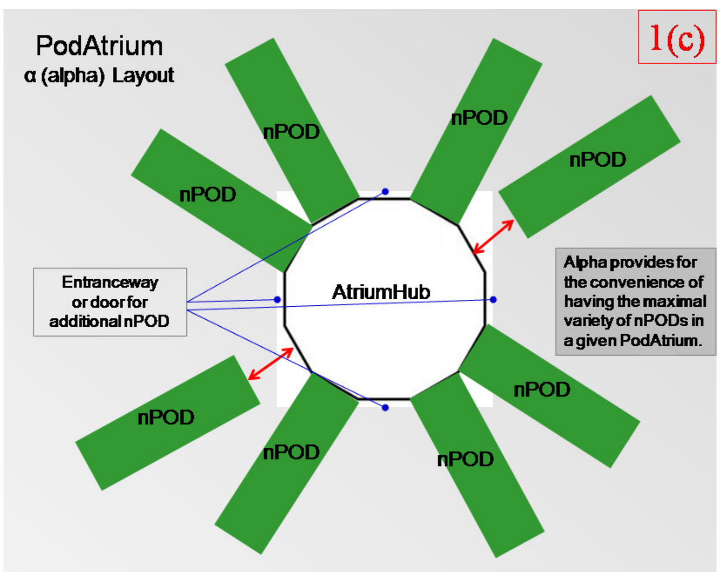

Figure 1: Alpha configuration of PodAtrium layout (abstraction)

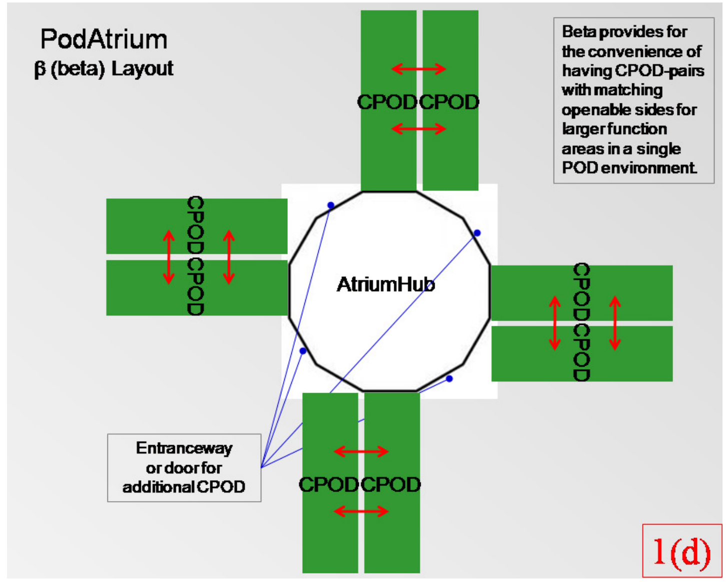

Figure 2: Beta configuration of PodAtrium layout (abstraction)

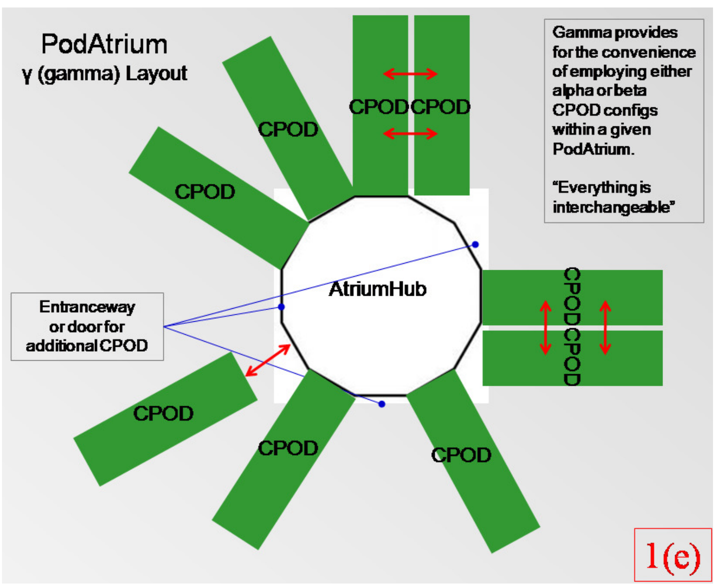

Figure 3: Gamma configuration of PodAtrium layout (abstraction)

3. Precursors and Early Prototypes of nPods ("Inspirational" Phase)

Precursors of nPods include singular and compound structures that were designed and erected for many applications. All precursor work involved "fixed" designs and architectures – thus, none of the "total reconfigurability" of nPods and PodAtriums. These included the use of shipping containers for educational purposes in remote villages of Costa Rica, Central America and the Caribbean [1], emergency and general-use provisions for electrical power generation and battery recharging [2], modular and mobile laboratories for environmental monitoring of air, water and soil samples [3], and rapidly deployable air-inflated structures for provisioning of blast-resistant and toxin-barrier workspaces within hazardous industrial complexes (petrochem field) [4]. Figures 4, 5, 6 and 7 provide collage views of several such prior projects. The nPod design is a consequence of the author and colleagues working for an extended period of more than two decades in such types of application and system design, fabrication, and use.

Figure 4: Intel-sponsored computing-lab pod structures deployed in Central America 2000-2002

Figure 5: Private-funded community power recharging station deployed in India 2005

As radically different as such early pod-like structures may seem from what are now the subject of the SGA Project, these have performed multiple important learning tasks, in addition to the foremost and most valuable task of serving the needs of people in varying circumstances of need and in most cases poverty. Consciously, however, the work with these structures was driven toward the goal of refining how to construct easily, manage easily, transport easily, and transform easily, structures that could provide the maximum of services (e.g., water purification, computing, analytical chemistry, biomedical testing) in the most compact physical spaces and with a realistic opportunity to transform these units from one function (e.g., emergency use or environmental testing) into another, and "at a moment's notice." Setting up and operating these "service pods" in very remote, often harsh and challenging environments, and without many of the conveniences of the modern industrialized world, provided a unique learning-testing experience that is almost the closest one can come – within affordability for contemporary space-focused R&D projects - to modeling what operations could be like in an exoplanetary environment.

Figure 6: Air-inflated structures used in studies and experiments on rapid mobility and blast-resistance

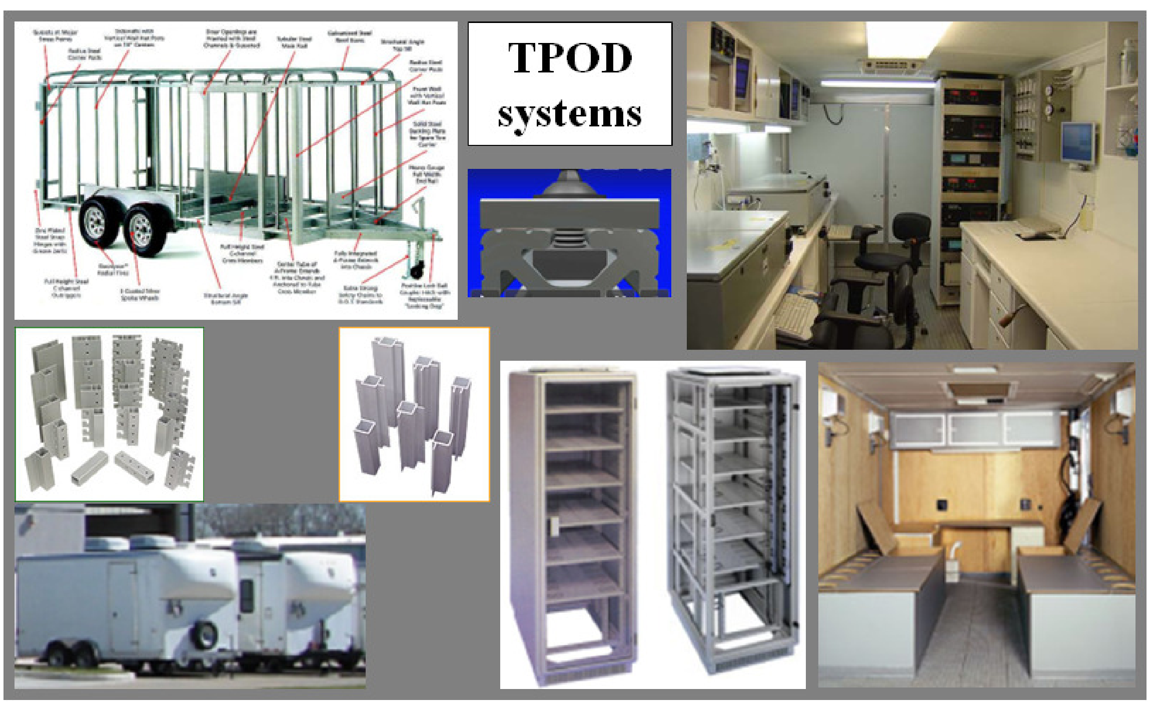

Figure 7: Ecoasis TPODs – Trailer-based emergency/environment units and modular assembly elements

4. nPods and PodAtriums – the Engineering Archetypes

All of the various precursors employed different structures and composition materials. All were proto-experiments leading to the nPod – "n" for n-sided, n-shaped, and "n" being the composition material for its structural elements. Make something that can be made from almost any material and shape at hand, and reshaped according to the needed function, and one has versatility, adapatability, and survivability. without these three attributes, there can be no realiable, sustainable mission to the stars, by robots, humans, or both.

The basic nPod, and any PodAtrium built from nPods, derives from the principle that any one major and common structural element should be usable in as many different configurations and for as many different purposes as possible, and that construction, disassembly and reassembly should be as simple, easy, straightforward as possible – an operation that can be done in minimum time, with minimum number of persons (or robots), with minimum consumption of energy, and at minimum risk to the local operation or to other structures and inhabitants nearby. Thus, in simple words, build and play and mix-and-match and do it all at the least expense, with no accidents to nearby Anything. Remembering, all the time, that this applies for any place and situation on Earth, but also, for any use in Space. Deep Space. Interstellar Space. Space without Home Depot, Exxon or Bob's Small Engine Repair.

The physical nPod evolved out of mathematics and computational algorithms designed for control and optimization in assembly and configuration of nPod-based structures. First came the model and the software, the **nPOD Design and Layout Schema (nDLS).** The purpose of the nDLS is to simplify planning, assembling, and deployment of any nPod systems. nPODs are described by logical schemas that identify specific coordinate locations for all elements and all equipment that is positioned on nPOD component faces including interior walls, floors and ceilings. By referencing a specific nDLS identification code, one knows where any specific piece of equipment or structural part is or belongs.

The full abstract nDLS for a given nPOD object is:

> [nPOD identifier].[nPOD component identifier].[nPOD sequence location].[nPOD component type].
> [Face identifier].[Entity-coordinate-location set]. [Position-orientation set].
> [Specification-attribute set].[Constraint-discriminator set]

From the nDLS is derived the **nDocSim**. The nDOCSIM is a web-based, mobile-accessible database and expert system for use in specifying, designing, ordering and organizing parts for, shipping and transporting, and operating an nPOD. This system is used by the TetraDyn team responsible for the given nPOD project before, during, and after fabrication. This system is also used, in a limited fashion, by any customer/client purchaser or lease-holder of an nPOD. nDOCSIM makes extensive use of the nDLS and there is strict code enforcement for nDLS program correctness. This strict control applies to all aspects of nPOD design, specification, fabrication, operation, and includes all aspects of reconfiguration including disassembly, transport, replacement of components, elements and onboard equipment, and reassembly.

The implementation of the nPod specification and assembly control software is in PHP and Java and constitutes the **nPOD Programming Language (nPL)**. The nPL is a formal programming language for the design, assembly and operation of nPod systems. It is a functional language and is currently script-based. In nPL one can express different functions and procedures to be executed by either humans or robots, either computationally or physically, pertaining to nPods and the various devices and equipment that are incorporated with(in) nPods. nPL is designed to allow for easy and efficient expression of algorithms and methods of work, and many of these are not intended for automated processing on a computer but for sequential/parallel physical activity. nPL enables clear and concise expression and the power of rule-checking.

4.1 nDLS, nPL, nDOCSIM – the Computational Foundations of nPods

The heart of nPL is the nDLS and the heart of the nDOCSIM is nPL. Essentially, nPL offers a set of scripts for manipulating different expressions within the nDLS and enabling the nDOCSIM to operate.

The following excerpt from the nDLS as expressed in EBNF (Extended Backus-Naur Form) illustrates some of the high-level features (syntax) of the language created for specification and control of nPod and PodAtrium design that can in principle be handed over to a crew of humans – or robots. Certainly it is the approach to be taken by a crew of humans who are managing a crew of robots – on Earth or in Space.

```
<nPOD_id> ::= <unique_name>      /* original def <nPOD_id> ::= 'nPOD_' <unique-
_name>   */
<unique_name> ::= <ent_id>     /* de facto, at least three characters, using "a-z", "A-Z",
"0-9" */
<nPOD_component_id> ::= <core_component> | <aux_component>
<core_component> ::= 0       /* a unique central core element such as an OctaPod for an
octagonal PodAtrium */
<aux_component> ::= 1 | 2 | … | 255
          /* a unique component or component-location; these begin in an arbitrary
"North" direction and are numbered consecutively in a clockwise direction; 255 is
arbitrary cut-off */
<nPOD-seq-loc> ::= 1 | 2 | … | n          /* in theory, there is no limit but 3 or 4 would be
typical max */
<nPOD_component_type> ::=
          'nGon' '(' <nGon_subtype> ')' |
          'xPod' '(' <xPod_subtype> ')' |
<nGon_subtype> ::=                        ||| etc. |||
```

From this logic, there arises the basic nPod frame element (Figure 8) and variants that follow (Figures 9 – 10) for all the types of frame element uses that can be needed in any type of PodAtrium. All are derivatives of the basic alpha frame element. The variations are either in orientation or in the addition of struts and cables for providing special strength for a floor base or ceiling panel, or for the incorporation of a passageway (e.g., doorway) or the fitting of some type of equipment.

Given that there is essentially only one fundamental frame element (*Alpha* type, - see fig. 8) this means that a wide variety of nPods can be built, or taken apart and reused elsewhere, as the need arises. All other elements including Beta, Gamma, Delta and composite types (also see figs. 8-10), are constructed and can be configured in real time in a space-based operational setting, from Alpha elements. With the nDLS and nDOCSIM software, it is possible to maintain complete accounting of all nPod elements, within even a city-sized installation such as a base vessel, and also to perform straightforward optimization calculations in order to plan the most economical and "organic" deployment of any nPod types in order to meet current or expected situations, both emergency and non-emergency in nature.

As is briefly discussed in Section 6 below, the nPod elements are designed to be constructed themselves from virtually any material. Steel, aluminum, polylactic acid (PLA), compositions which are themselves power-generation units (hydrogen production and hydrogen fuel-cell units, or RTG (radioisotope thermoelectric generators), or even, hypothetically, synthetic biological components – living vines and limbs, perhaps, of a synthetic species yet to be designed. The same versatility applies to the surface materials that will cover the exteriors and interiors of the nPods. All emphasis here is upon the structures, the skeletons, providing shape and strength, but of course the nPods are enclosed, covered, sealed. But with what depends, again, upon the need and function of the unit in space. Is it a greenhouse, or a human habitation, or a "fab-lab" or a warehouse or a power generation unit or simply "in reserve" for the future?

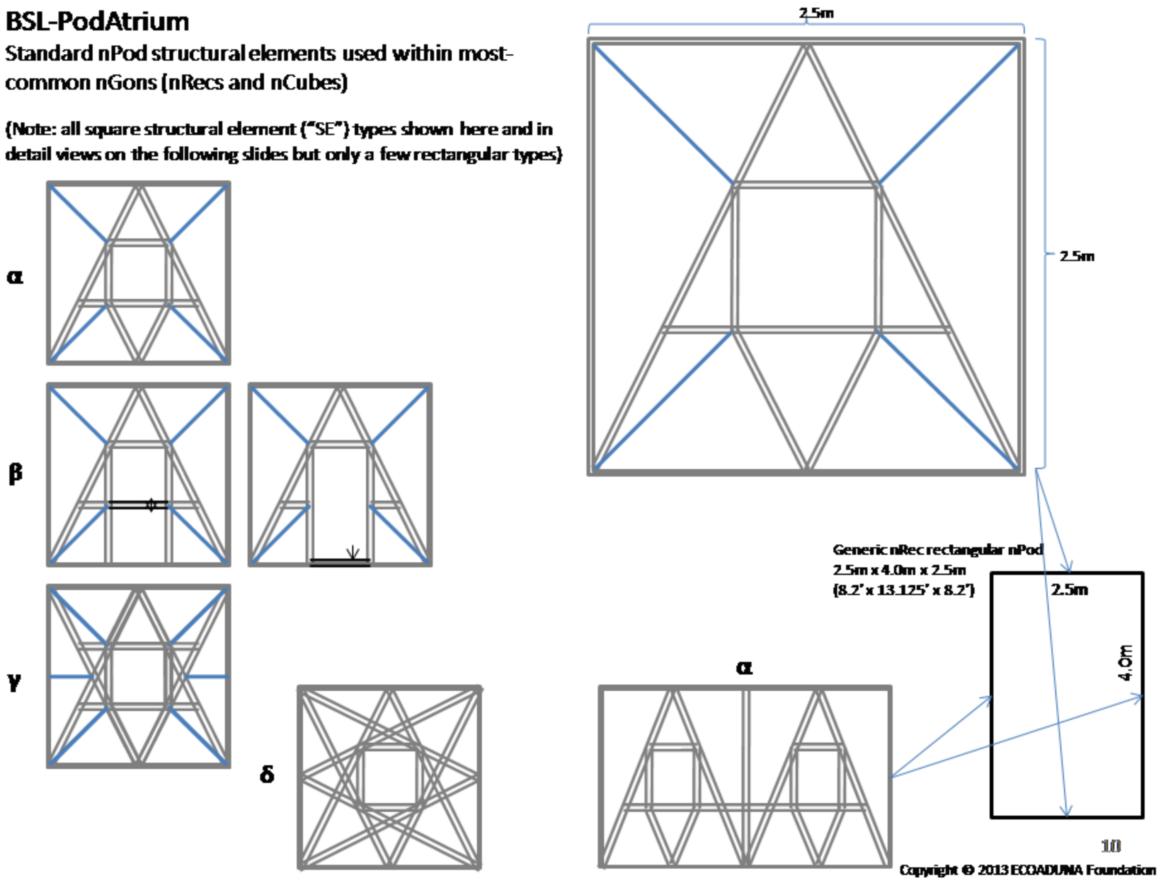

Figure 8 – Fundamental nPod Frame Element Panel – Alpha Config

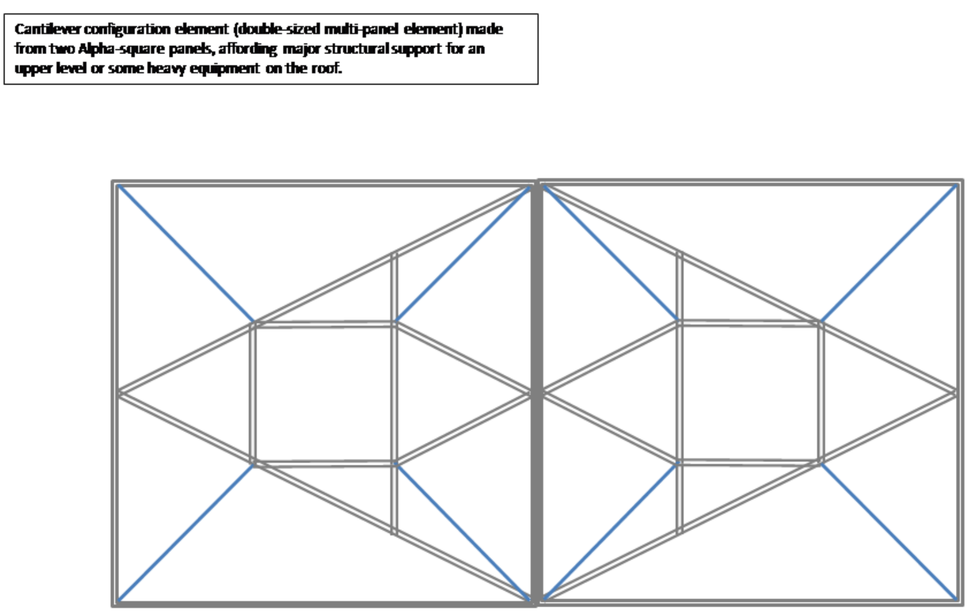

Figure 9 – Two Alpha elements make a cantilever structure for multi-level nPod complexes

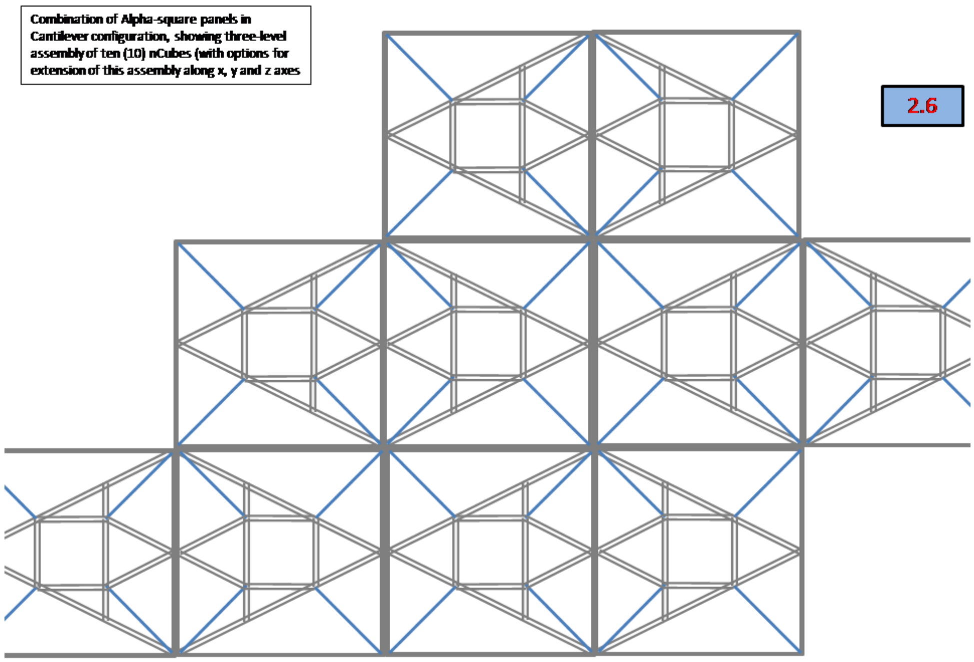

Figure 10 – Combining Alpha and Cantilever elements for large multi-level PodAtriums

5. nPod Types – Getting Down to Applications

The initial objective in the nPod and PodAtrium project, and specifically for StarGate Alpha ("SGA"), has been to design an architecture, and with it the physical components, for building many different components of a spaceship or space station. The focus was and remains upon food, water, power, and other production tasks, as well as for residence and other types of shelter and accommodation for humans and any other living creatures onboard such a vessel or station. The following are four examples of different nPods that can be constructed using the exact same types of indeed the same numbers of nPod elements. Overall, taken together, these constitute the four principle functions that are deemed to be not only critical but the most likely to face needs for increase or decrease in number and changes in location within something like an interstellar spaceship. These are:

- DAQ – Data Acquisition and Collection nPod
- BSL – Biological and Chemistry Laboratory/Workspace nPod
- C4 – Command Control Communications and Computing nPod
- EMP – Electro-Mechanical-Power (Energy) Pod

Are these the only uses for nPods? Hardly. However, these are four major functions needed for any interstellar mission vessel or base, even if entirely roboticized. Furthermore, these are four that can easily be coverted, with a minimum of work, expense of energy, and risk, into one another, and these are among the four functions that will be most likely to change in needs and numbers during a mission's duration. We have targeted these four functions also because they are all part of the "natural" outlay of nPods for the SGA in its phase-1 implementation on Earth and in phase-2, as intended, in near-earth orbit. figures 11 – 14 illustrate the high-level layouts of each of these four types. The materials used for the structures are the Alpha type nPod frame elements, and for phase-1, made from standard 1" steel tubing. The materials for the interior hardware and furnishings are the same "80x20" brand of erector-set type components used in earlier trailer-based and container-based pods as shown in Figures 4-7 above.

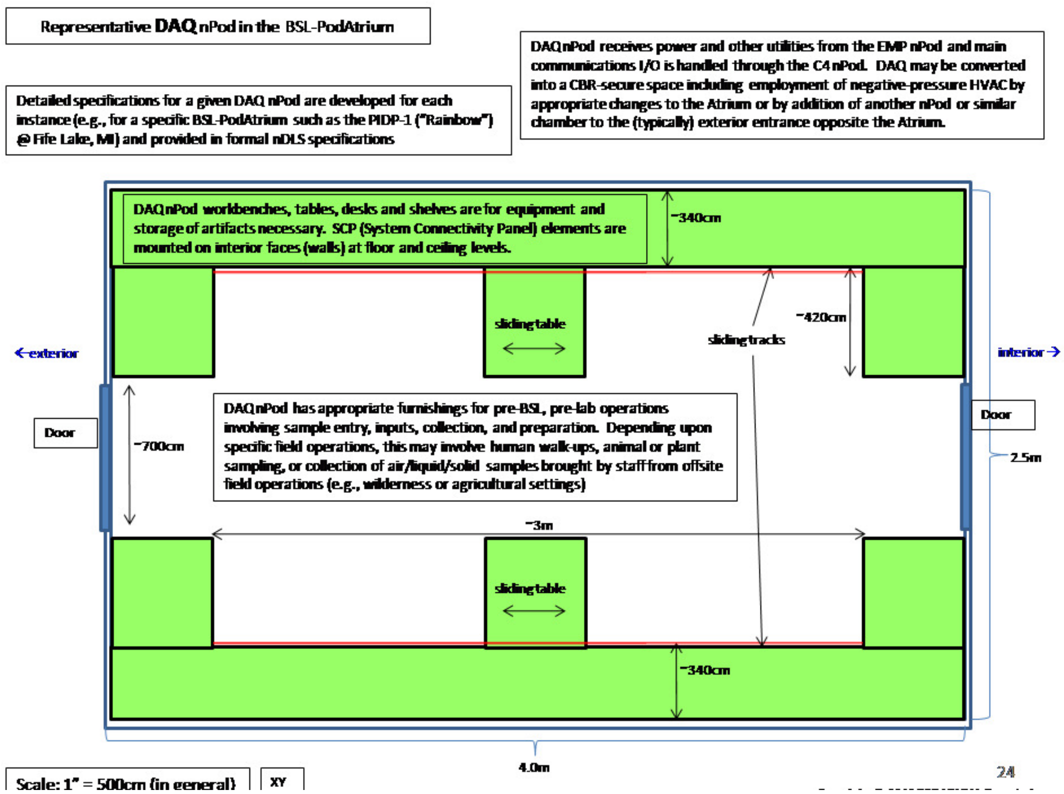

Figure 11 – DAQ – Data Acquisition and Collection nPod

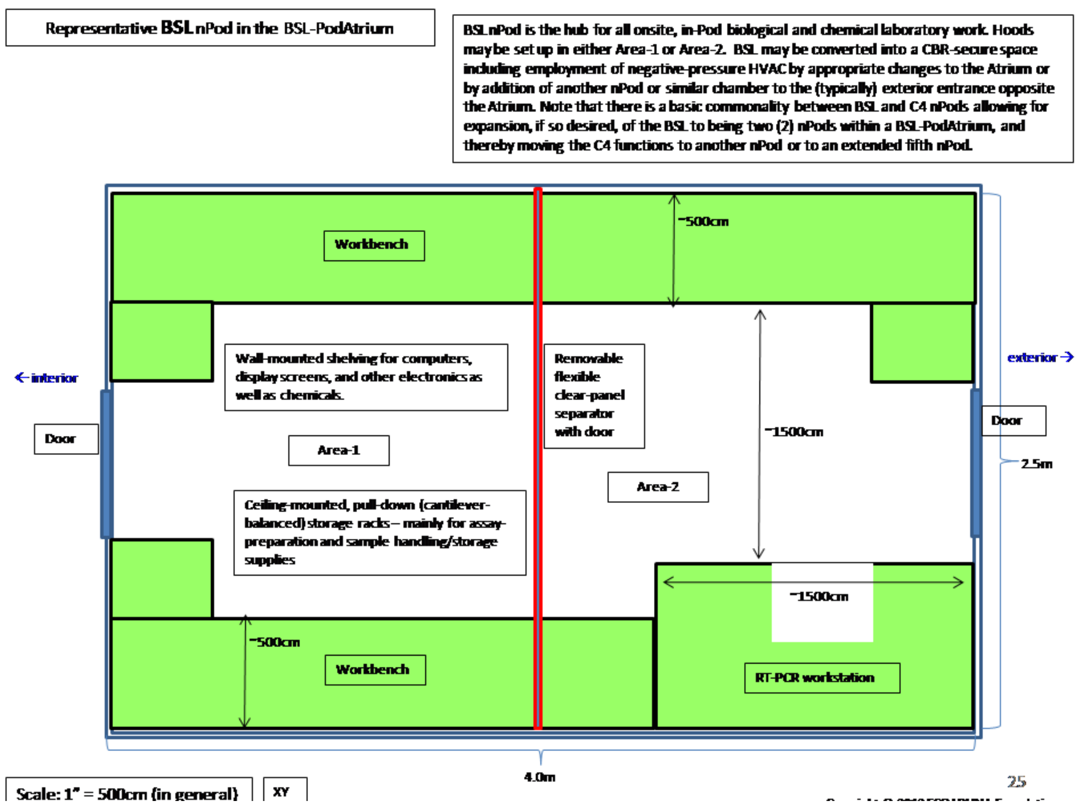

Figure 12 – BSL – Biological and Chemistry Laboratory/Workspace nPod

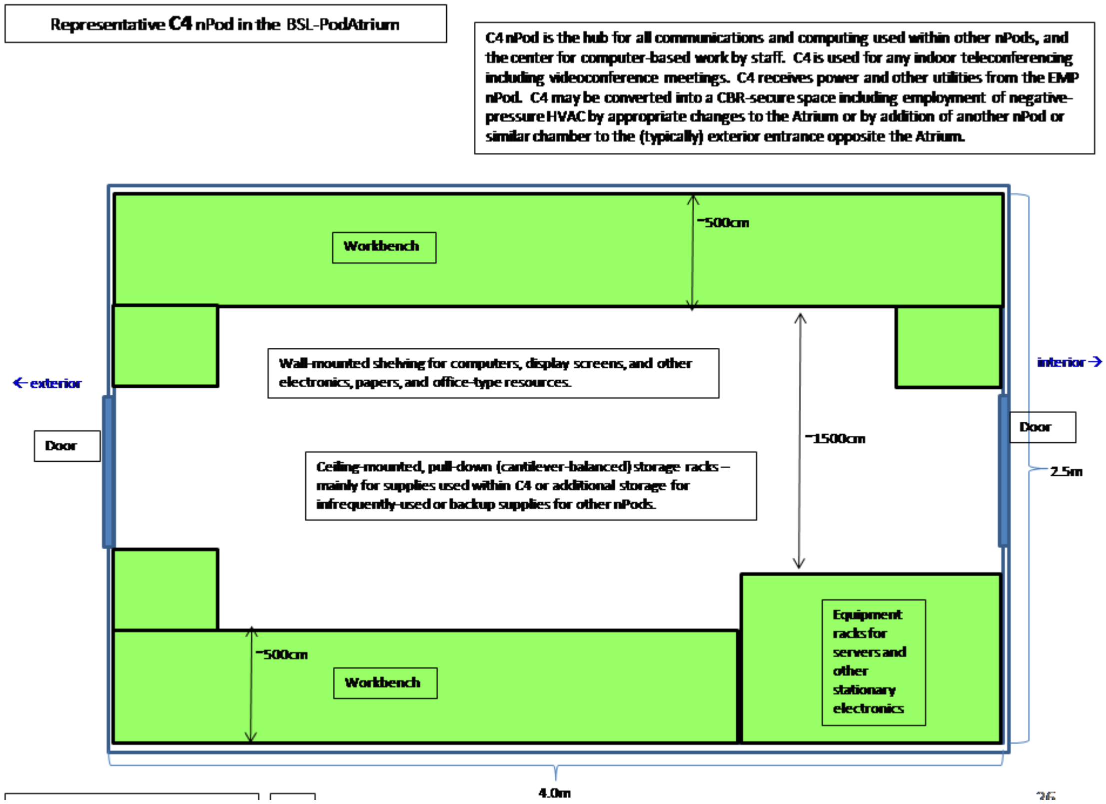

Figure 13 - C4 – Command Control Communications and Computing nPod

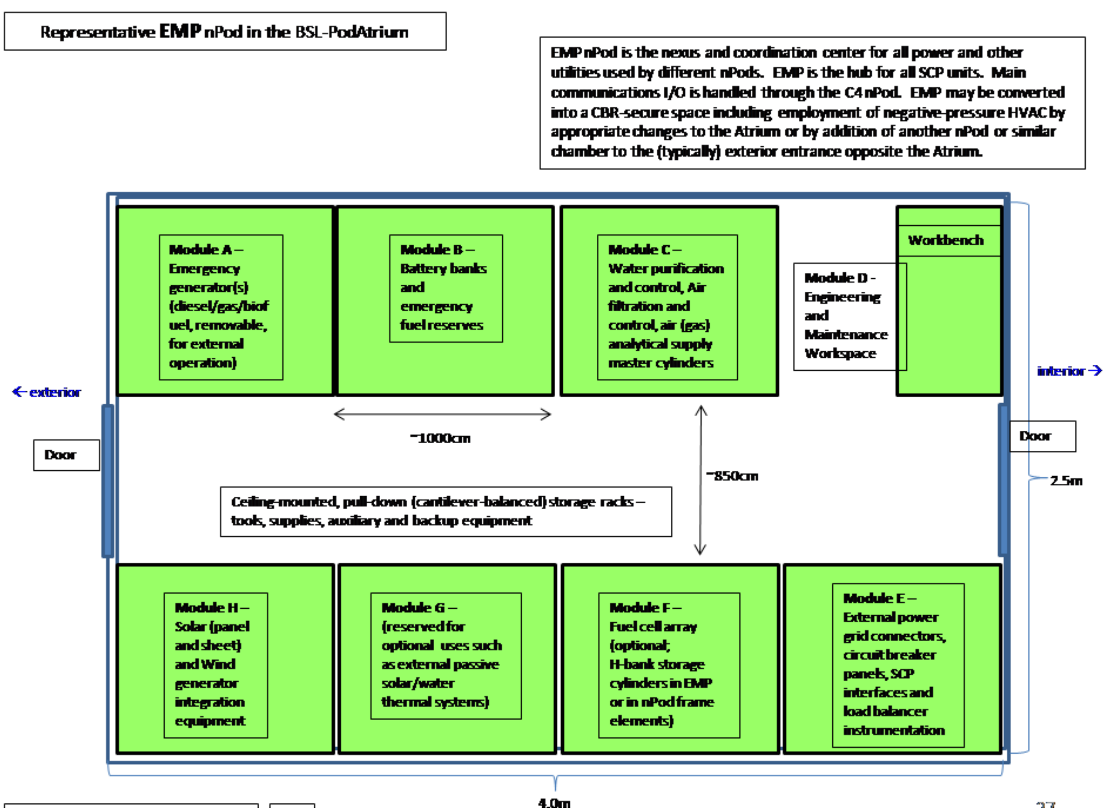

Figure 14 - EMP – Electro-Mechanical-Power (Energy) Pod

6. nPod Frame Element Composition

From what materials and elementary building-block units can nPods be constructed? The illustrations above indicate the use of tubes, rods, shafts, linked together to form principally square frame elements that in turn are linked together to form completed nPods. Here again is where versatility and interchangeability of parts is the rule, the norm, and not the exception.

Thinking radically outside the box is a critical need for designing an interstellar mission of exploration and any spaceship to operate within such a mission. We are accustomed to building craft for our seas and skies out of wood, steel, aluminum, and lately carbon composites. From what should nPods in Space be constructed, for both their critical structural frame elements - the "Alpha", "Beta", "Gamma" and "Delta" elements – and the exterior/interior shell coverings, the panels, and those structural furnishings inside? Metal is one general material, and for phase-1 the SGA will be built in part from simple steel tubing. No welding required! This is important – simplicity, safety, ease, and above all, simplicity. the same applies to carbon composites and PLA-type plastics – also planned for phase-1 here on Earth, in quiet, peaceful rural Virginia. But may be we consider other materials? There are two types of special interest: (1) systems that generate power, actual equipment, that need not be using up space inside an nPod or any other structure, but which can actually compose the structure itself, and (2) futuristic, conceivable albeit not yet here, synthetic organics, synthetic biological materials, which could emulate and even surpass the capabilities of wood and other fibre-based construction materials. Remember that the МИР (MIR) space station which operated so successfully and so long in Earth orbit actually had significant elements of its construction made from – balsa wood.

Figure 15 illustrates the concept behind the employment of power generation systems within the actual structures of nPods and thus PodAtriums and thus entire sections, even the majority sections, of large spaceships and space bases. This is taken from earlier work by the author and tetraDyn Ltd. in the hybrid automotive and electric vehicle arena (Project "THERA"). Figure 16 illustrates the basic composition of a standard RTG (radioisotope thermoelectric generator), another power generation device that could be conveniently employed within the actual structural elements of space-based nPods. In both cases of hydrogen fuel cell systems and RTGs, one gains the triple benefit of (1) structural strength and integrity, (2) power generation, and (3) mass-material defense and protection against radiation and penetration by both small and larger external objects.

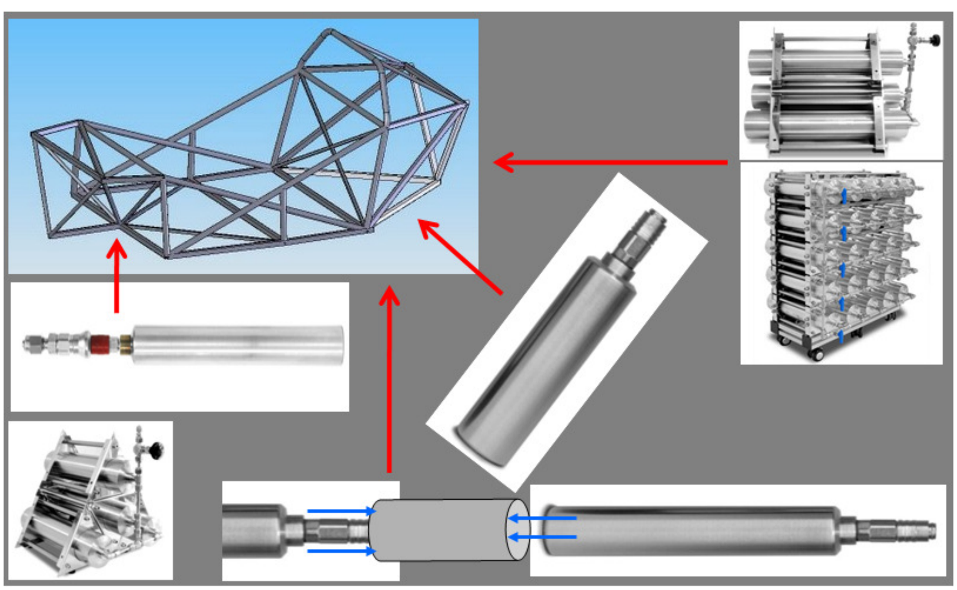

Figure 15 – Hydrogen Fuel Cell Storage and Generator Units - as nPod Structural Elements

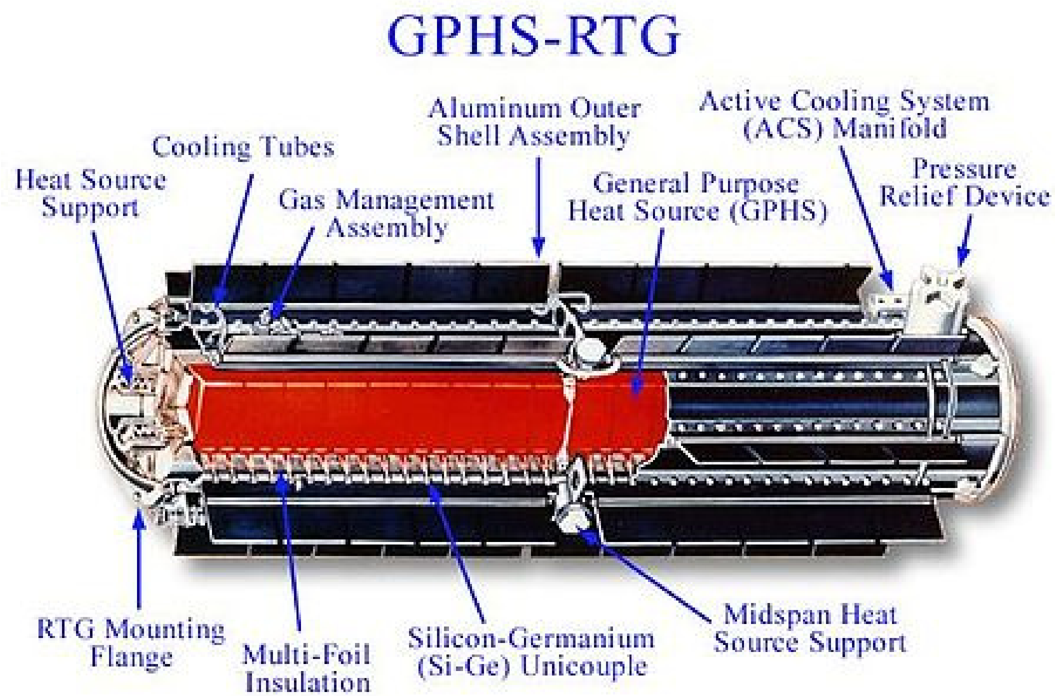

Figure 16 - RTG – Radioisotope Thermoelectric Generator – as an nPod Structural Element

7. Conclusion

The challenges of extreme long-distance and long-duration space travel and habitation require serious “thinking outside the box.” That phrase has been used so often that it often now seems trite. However, in the case of an interstellar spaceship, there are going to be many “boxes.” They may be in many different shapes and sizes. Rectangles, parallelograms, and prisms of any type are not necessarily what will need to be deployed! However, the fact remains, that the “boxes” need to be very adaptable and easily changed and moved around. Nobody knows what types of situations will arise in an interstellar mission other than that there will be many that are varied and unexpected. nPods and PodAtriums offer a path to some very rock-solid “in the box” architectures that can also allow, at any time during The Mission, for creatively getting “outside the box” with respect to physical structures and functions.

For instance, any of the nPod frame elements that have been designed thus far and are intended for use in StarGate Alpha are also capable of being used in the construction and deployment of what are seemingly very different, even radically different, geometries. Consider the ROC – the rhombicuboctahedron nPod. In Figure 17 are presented a few views of a very different type of nPod and PodAtrium. However, the same nDLS algorithms and software apply, and the same nPod frame elements.

The ROC has its own set of unique advantages for spaceship and space-based station construction. The ROC panels themselves can contain the structural skeleton elements, thus simplifying assembly and disassembly. Also, a ROC structure can be fabricated in a manner that results in a collapsible structure of panels that can be entirely connected to each other during transport, thus enabling simpler accordion-style motion assembly into a full volume, without risk of panel elements and other parts slipping and floating away in zero-g space and causing innumerable problems for the assembly crew. This method of compact transport also can aid in reducing weight and the volume required for such transport operations.

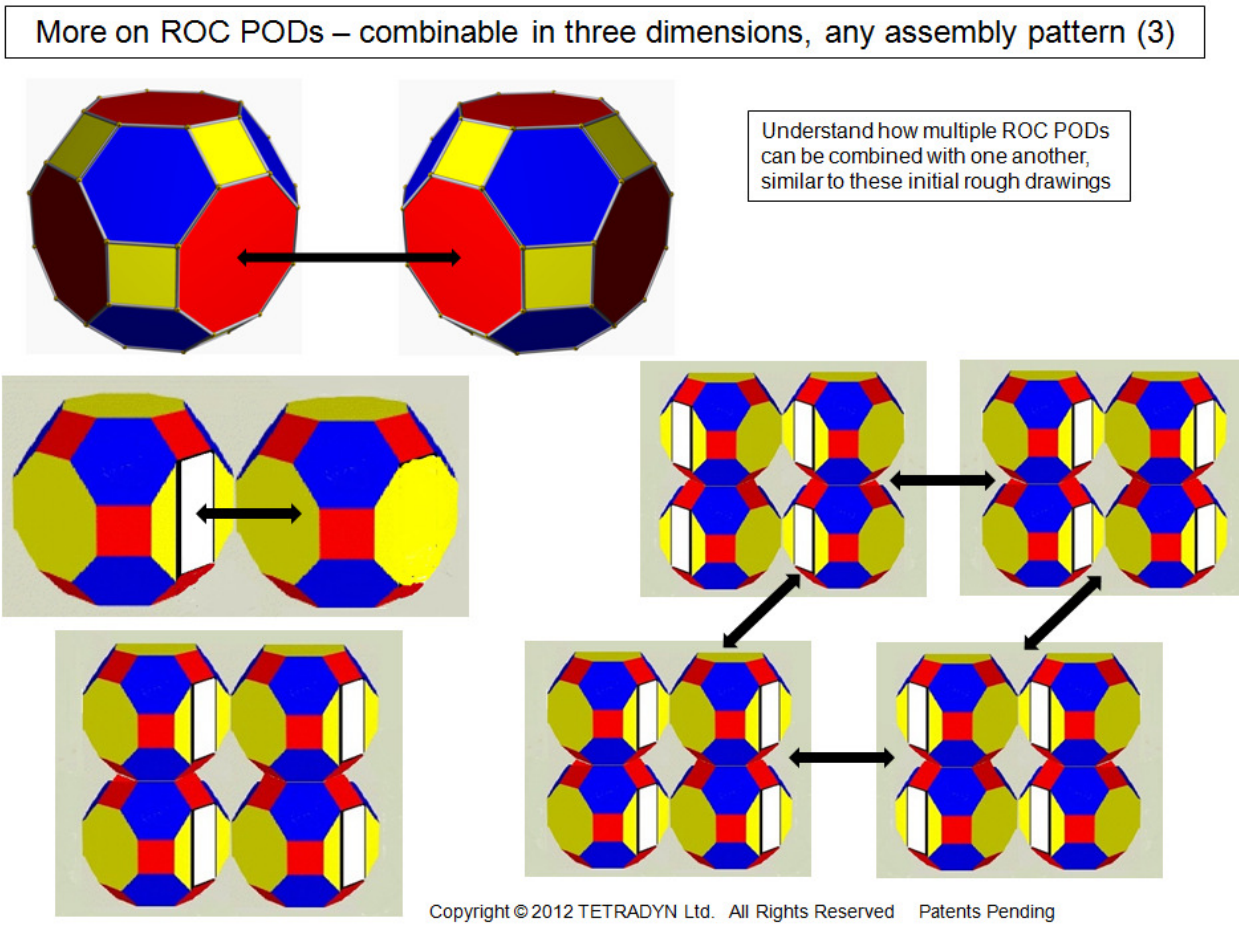

Figure 17 – ROC (rhombicuboctahedron) type of nPod and multi-nPod assemblies

Finally, one simple illustration (figure 18 below) portrays the current status of the SGA experimental platform design and an illustration of the next phase of work. Based upon projected, expected and anticipated resources and support, a physical PodAtrium for experimentation with several of the agricultural and energy tasks described and mentioned briefly here will be constructed and staffed by a crew of technical and volunteer staff. This installation will allow for physical demonstration of the modularity in design and reassembly, and for several longer-term experiments particularly in novel hydroponics agriculture along with simulations of water and fuel production.

Notice that in this Earth-based phase-1 installation, there are facilities for not only agricultural and laboratory work but for education, seminars, workshops, and public communications. It is essential to convey a new level of both understanding and also enthusiasm for the space sciences, and for manned space exploration and inhabitation, into the general public. The relevance of something as bold, great, and long-term as interstellar space exploration is something that is not well understood or accepted by the mainstream population of Earth. We can change this. We must change it. And we shall change it, by demonstrating, right on planet earth, right in the "fields of wheat" so to speak, even literally, by building the starGate Alpha and presenting it to The World, both onsite and online: "Here, people, you can not only see the science and technology being done, but you can even participate directly in the process. Experience it, and understand how important this mission is for us all, for all our Futures."

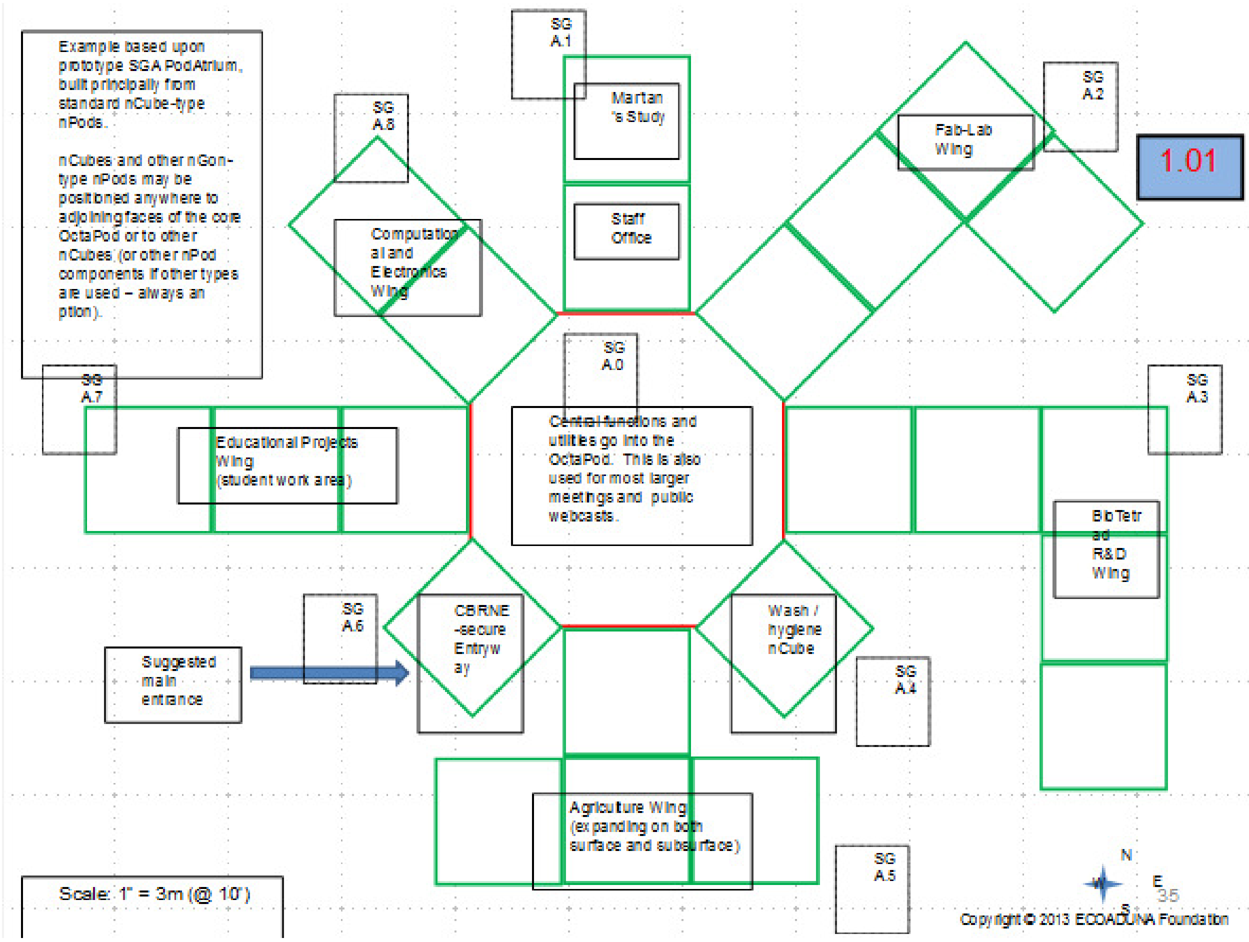

Figure 19: Phase-1 PodAtrium, StarGate Alpha, (planned for construction, 2014, in Virginia)

End Notes

[1] Projects included self-sustained, solar-powered internet stations set up in remote villages in Central America and the Caribbean, involving Intel Corporation (author was employed as sicneitst and manager), MIT, Lincos Project, and with financial and in-kind support from Apple, Microsoft, Cisco and Sun.

[2] Author was involved as co-designer for several “EcOasis Pod” systems that were single-instance projects built for specific sites in Louisiana, Mexico, India and Afghanistan during 2005 through 2010.

[3] Trailer-based environmental monitoring labs designed and built by author and subcontractors for petrochem facilities in the Houston and Galveston areas.

[4] Study performed under support from US Army, US Air Force, Dept. of Homeland Security and Canadian government for development and proofing of blast-resistant structures based upon air-inflated building components, for use in both industrial and counter-IED applications.