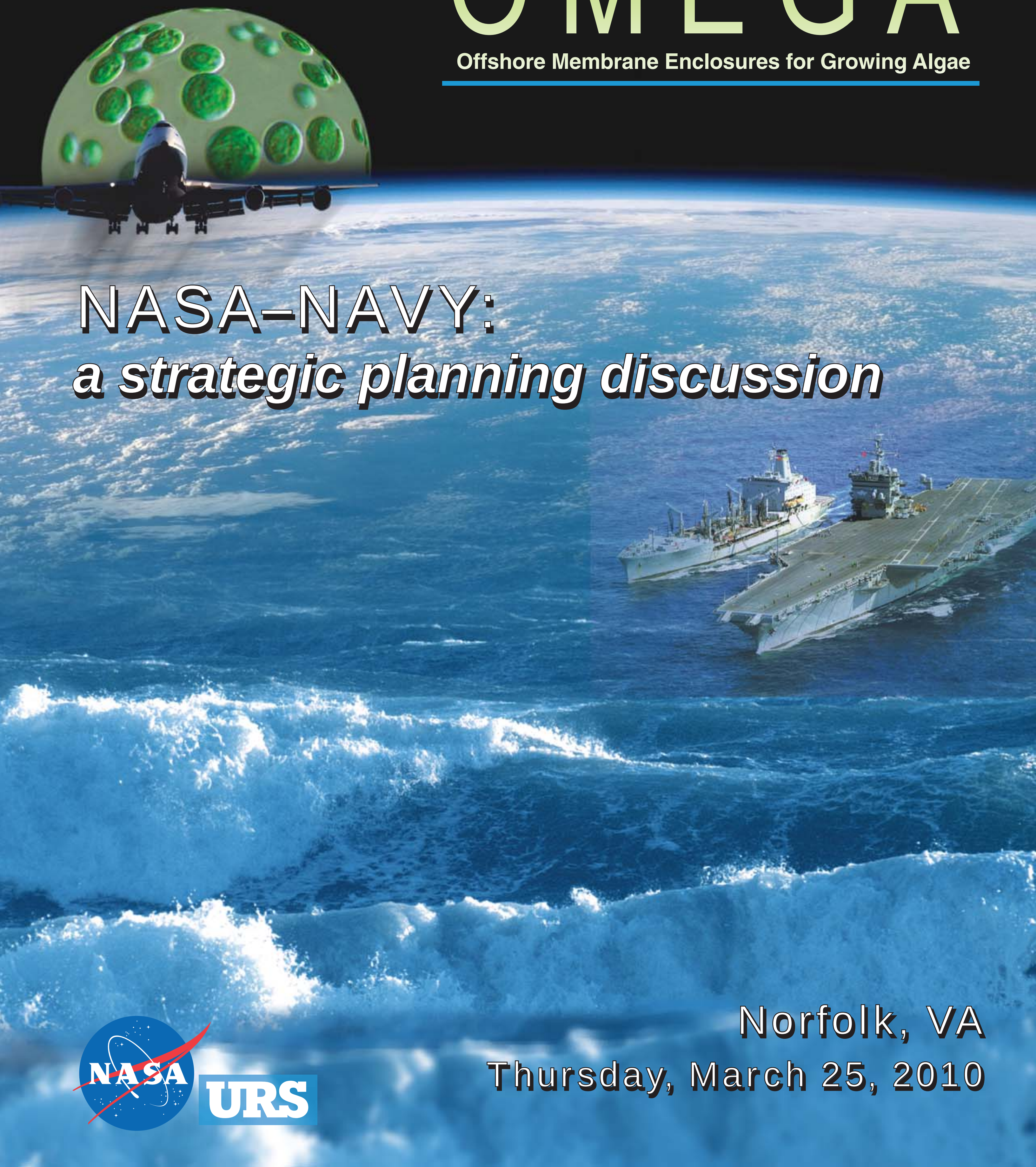
OMEGA

Offshore Membrane Enclosures for Growing Algae



NASA–NAVY:

a strategic planning discussion

Norfolk, VA

Thursday, March 25, 2010

Forward

This briefing packet provides a short introduction to OMEGA and a truncated version of our project approach, with an example of the kind of work break down structure (WBS) used to guide our Phase I activities. It is meant to give you an impression of how we are approaching the challenge of creating the world's first marine photobioreactor (PBR) that will scale to address the strategic energy problems confronting the United States and the world. Some of our conceptual PBR designs and plans for logistics are included to communicate the path we have taken. We have also included an aerial photograph of the experimental tanks we are using at the Cal Fish and Game, followed by concluding remarks.

The overarching purpose of the strategic planning discussion in Norfolk is to establish the relationship between the NASA OMEGA Team and the Navy, to unite the strengths of both agencies, and to map a mutual way forward along the project's established critical path.

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Project Scope Overview

The primary goals of this project plan are to demonstrate the feasibility of the OMEGA system for: 1) production of biofuels and fertilizer, 2) processing of wastewater, and 3) sequestration of CO_2. To reach these goals, a diverse OMEGA implementation team will address technical, environmental, and economic challenges.

Technical approach

An experimental test-bed system will be developed in which prototype OMEGA configurations can be evaluated for material and functional integrity as well as filling and harvesting logistics. Various OMEGA designs will be tested for algae growth in wastewater, fouling on internal and external surfaces, and structural integrity against leakage, breakage, and component failures. The necessary facilities to design, build, and test OMEGA systems will be constructed at the California Fish and Game (CFG) facility in Santa Cruz, CA.

Environmental approach

In the CFG outdoor tanks and field sites, the impact of OMEGA on the environment will be evaluated both by long-term exposures and by simulating OMEGA failures that release treated wastewater and freshwater algal biomass. In addition to experimentation, OMEGA will be presented to environmentalists and to state and local government agencies to determine what social, policy, and permitting issues will need to be addressed to deploy OMEGA on various scales in different offshore locations. This process will involve presentations and discussions as well as applications for actual permits.

Economic approach

The life-cycle costs and effects of OMEGA will be analyzed and compared to other technologies to show that the system is robust and economically viable. Life cycle analysis will be used to complete a lifecycle impact assessment for OMEGA system parameters (e.g., energy, CO_2, solid waste and materials) from cradle to grave. The pros and cons of OMEGA relative to other alternative energies will be quantified and evaluated alongside capital and operating cost for design and deployment, products (e.g., aviation fuel and fertilizer) and services (wastewater treatment and CO_2 sequestration). The ideal footprint for the OMEGA system, which includes not having to compete for agricultural land or freshwater resources, uses untapped wave energy for mixing, and utilizes waste products, will be essential in showing economic viability and positive environmental impacts.

MILESTONE – OMEGA Preliminary Engineering Analysis

During this task a set of design criteria and guidelines will be established. Based on these criteria a preliminary engineering analysis of the bio-reactors will be performed, followed by a scale model used to complement the findings obtained analytically. The preliminary engineering analysis will focus on the enclosure for the OMEGA bio-reactors. Analysis of mooring structures, anchors and connection to outfall pipe is not covered in this task. This task will be carried out in a series of subtasks as follows:

Preliminary engineering analysis of major structural elements of the closed photo-bio-reactors

URS will perform a preliminary engineering analysis of major structural elements following the criteria set forth in the previous sub-task. Engineering analysis performed during this sub-task will be limited to: (1) bio-reactor's enclosure, (2) plastic welds, (3) cable and hoses, and (4) enclosure/hoses connections.

Preliminary engineering analysis will be performed for the <u>three</u> enclosure configurations defined in the previous sub-task. This analysis will be limited to the structural integrity of the bio-reactor's enclosure. Analysis of the following items is <u>not</u> included in this sub-task: (1) hydraulic modeling of the bio-reactor filling, harvesting, and dewatering, (2) anchors, (3) wincher, (4) outfall pipe and manifold, (5) bio-reactor/outfall connection, and (6) mooring structure.

Preliminary engineering analysis of major structural elements of the bio-reactor enclosure will be performed in two stages: (1) analytical procedures, and (2) computer modeling.

In the first stage, reasonable assumptions will be used to simplify the problem, such that analytical methods can be used (e.g. using basic formulations that can be solved by hand, spreadsheet or MathCAD routines). These simplified analytical procedures will be used as a first approach to guide the second stage towards the analysis of those items that result more critical from a design standpoint. In the second stage, advanced computer modeling (e.g. Finite Element Models) will be used to model particular conditions that are likely to control the design of the bio-reactor's enclosure.

Two deliverables will be prepared within this subtask: (1) Draft preliminary engineering analysis – technical memorandum and (2) Preliminary engineering analysis – technical memorandum. Following submittal of the draft technical memorandum, a review meeting will be held to discuss comments to the document. The preliminary engineering analysis will be issued once comments received during the review meeting are incorporated into the draft preliminary engineering analysis. Two copies of each deliverable will be provided.

Test Procedure and Data evaluation of scale model

NASA will build and operate a scale model of the bioreactor. URS will prepare a test procedure for the scale models based on the findings of the preliminary engineering analysis. The test procedure will define the scenarios to be tested, as well as those variables to be measured.

Test results for each of the scenarios tested will be provided to URS for their analysis. Data will be analyzed to establish the validity of the results and evaluate how the results of the model compare to those obtained analytically.

Four deliverables will be prepared within this subtask: (1) Draft scale model procedure – technical memorandum, (2) Scale model procedure – technical memorandum, (3) Draft scale model data evaluation – technical memorandum, and (4) Scale model data evaluation – technical memorandum. Following submittal of draft technical memorandums, a review meeting will be held to discuss comments to the document. The final versions will be issued subsequently. Two copies of each deliverable will be provided.

The preparation and execution of the actual scale model is not included within URS' scope of work. Execution of activities within this sub-task is dependent on collection of data from the scale model. Schedule changes might arise as a result of delays on the construction and operation of the scale model.

Environmental and Permitting Reconnaissance

NASA will identify three potential sites for an Algae OMEGA pilot plant installation. URS will conduct q permitting reconnaissance of these three sites to determine what permits might be required for such an installation at each of the sites as well as the cost and time required to secure all of the required permits. The first step in this process will be to research each to determine whether there are any obvious fatal flaws that would preclude issuance of appropriate permits. Upon completion of the fatal flaw evaluation, URS will identify the lead agency for each site. The lead agency has the responsibility for undertaking the NEPA/CEQA review. We will consult with the probable lead agency and determine what permits will be required at the candidate sites. Once the lead agency has been identified and a list of permits drawn up, URS will develop an estimated cost to complete the NEPA/CEQA review process and acquire the required permits.

Life Cycle Analysis (LCA)

URS will undertake a scalable lifecycle analysis for OMEGA and two baseline alternatives. The lifecycle analysis will compare the full range of environmental and social effects assignable to the multiple products produced by OMEGA and compare these to alternative technologies or production systems (e.g., ethanol). In involves an assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence.

The first phase of the LCA involves formulating the goal and scope of the study. The goal and scope should address the overall approach used to establish which unit processes are included in the LCA (e.g., energy, CO_2, and solid waste). The lifecycle inventory is the next phase. It involves data collection and modeling of the product system, as well as description and verification of data. This encompasses all data related to environmental (e.g., CO_2) and technical (e.g., intermediate chemicals) quantities for all relevant unit processes within the study boundaries. The final important phases are the lifecycle impact assessment and interpretation of the LCA results, some of which may be valued in the benefit cost analysis below.

Benefit Cost Analysis

URS will use benefit cost analysis (BCA) to compare the lifecycle benefits and costs of OMEGA for four (4) different scenarios. This task will combine information generated in other tasks to determine the economic attractiveness of the OMEGA system relative to the baseline alternatives identified in the LCA. For this task, URS will use discounted cash flow analysis to develop a tool to compare both the financial and net social benefits of OMEGA. The financial analysis will model project cashflows including revenues (including carbon credits), operating and capital and expenses, taxes and costs of finance. All assumptions used in developing the financial model will be tested using sensitivity analysis. This analysis will answer the question "*how profitable and what is the return on investment for the OMEGA system*". Alternatively, the net social benefit cost analysis will identify and quantify wherever possible, the public and private economic, environmental and social (i.e., green job creation) benefits and costs associated with the OMEGA system. This analysis will answer the question "*when all economic, environmental and social tradeoffs are considered, is investment in OMEGA economically justified*?" Once again sensitivity analysis will be used to test key assumptions.

The analyses will identify the mix of public and private beneficiaries and the magnitude of these benefits. Such information is critical for developing financing/funding and cost sharing arrangements. URS will write a technical memorandum documenting this task and the assumptions used.

Develop Business Case

URS will work with NASA Ames to prepare a business case that "tells the story" for the development of the OMEGA system from the initial industry and political drivers, to the alternatives analyzed, and recommendations for further development and implementation. The OMEGA business case is a concise document that will advocate a particular course of action to decision makers, drawing together all the analyses and arguments available in support of the advocated decision. It will summarize all of the information obtained from the engineering, environmental and economic approaches, and additional information including recommended procurement, financing, implementation and timing.

Energy Return on Investment Study

URS will estimate the energy return on investment for the OMEGA system by combining information on energy use from the LCA (Task 3.8), and annualized lifecycle costs identified in the Benefit Cost Analysis (Task 3.9). The return on investment provided by OMEGA will be benchmarked with the unit cost of energy production for other alternative energy technologies.

Dilution Modeling

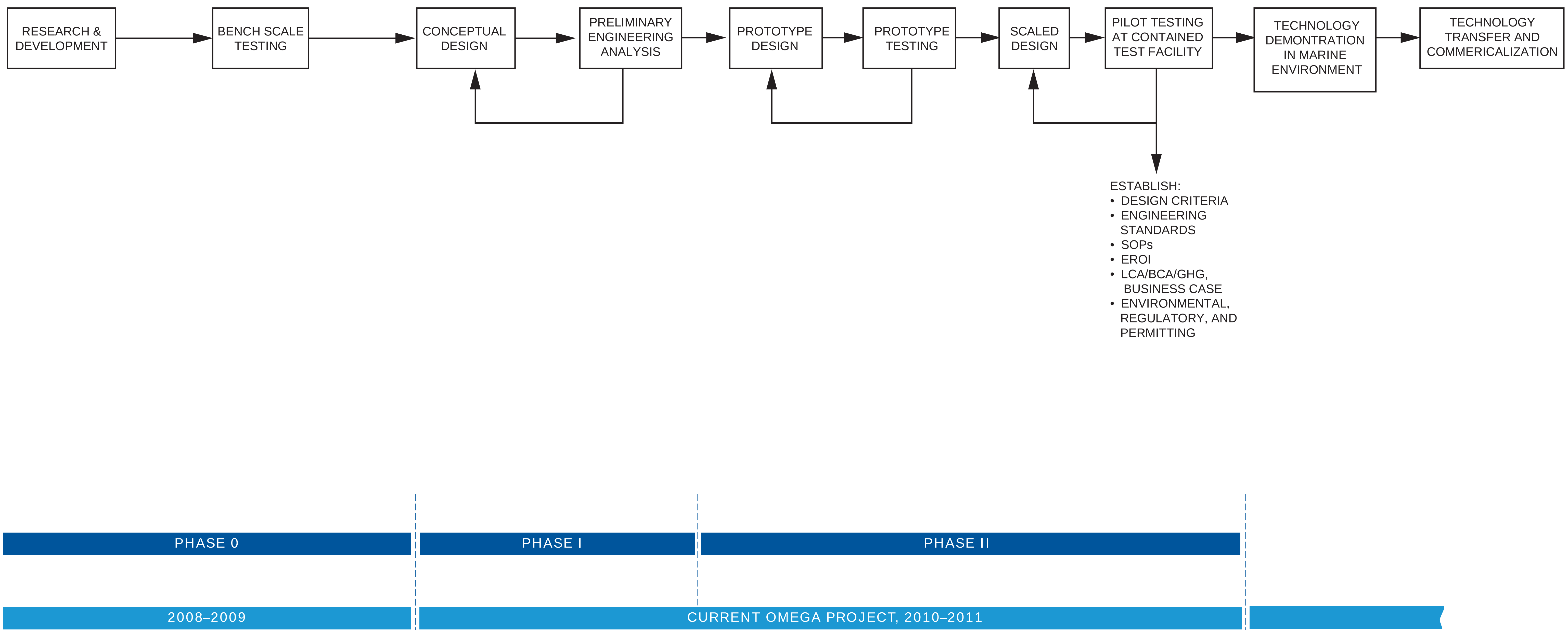
Under normal operating conditions the OMEGA enclosures will exchange oxygen and carbon dioxide between the algae enclosure and the ambient water through gas permeable membranes. There will be no discharge from the enclosure into the ambient waters. However, if there were a failure of the membranes or damage to the enclosure there could be a discharge of the enclosure contents into the ambient waters.

The purpose of this task is to provide an estimate of the mixing of the enclosure contents with the ambient waters and the corresponding dilution. This task consists of the following five subtasks.

Mixing of a discharge into an ambient water body is usually divided into two different regimes, the near-field and the far-field. In the near-field the mixing is due to the characteristics of the discharge. For example the discharge flow rate, effluent density relative to ambient conditions, size of the discharge and effluent velocity. In the far-field the dilution is due to the characteristics of the ambient environment, e.g., temperature and salinity, and current speed and direction. In developing discharge permits, such as NPDES permits, the regulatory agencies are most often concerned about near-field dilution. For spills and unintended discharges agencies maybe also concerned about the far-field dilution since that may be necessary to accurately estimate the size of the impact.

Risk Management

The proposed pilot project has a number of risk factors in the financial, technical and environmental fields. They will be managed by utilizing a project specific risk register which quantifies the cost and scheduling issues associated to each potential hitch. The risk register will be developed and updated regularly throughout design and construction.



REFERENCES	
TITLE	
OMEGA PROJECT CRITICAL PATH	

REVISIONS			
NO.	BY.	DATE	DESCRIPTION
△	VSA	3/23/10	
△			
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NASA OMEGA PROJECT
NASA AMES RESEARCH CENTER
MOUNTAIN VIEW, CA

DRAWN BY: VSA
DESIGNED BY: MM
CHECKED BY:
APPROVED BY:

NASA OMEGA PROJECT

OMEGA PROJECT CRITICAL PATH

JOB NO. 26817633
DATE 03/23/10
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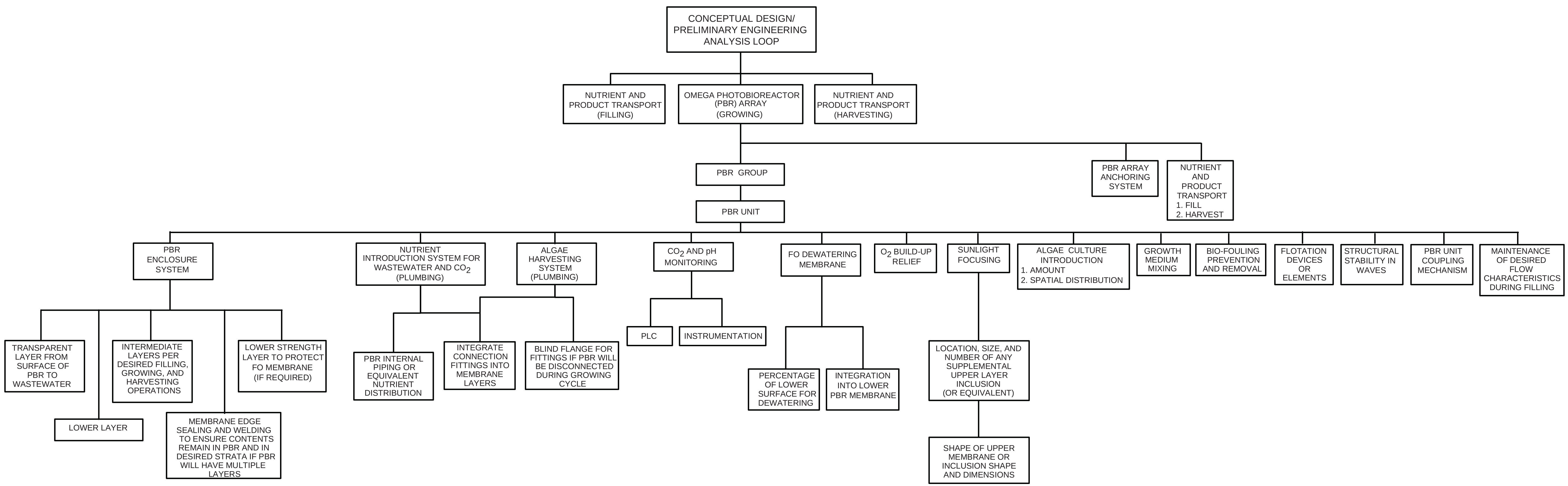

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TITLE	NO.	BY.	DATE	DESCRIPTION
PHASE I: CONCEPTUAL DESIGN/PRELIMINARY ENGINEERING ANALYSIS LOOP	1	VSA	3/23/10	

NASA OMEGA PROJECT
NASA AMES RESEARCH CENTER
MOUNTAIN VIEW, CA

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DESIGNED BY: MM
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APPROVED BY:

NASA OMEGA PROJECT

PHASE I: CONCEPTUAL DESIGN/PRELIMINARY ENGINEERING ANALYSIS LOOP

JOB NO. 26817633
DATE 03/23/10
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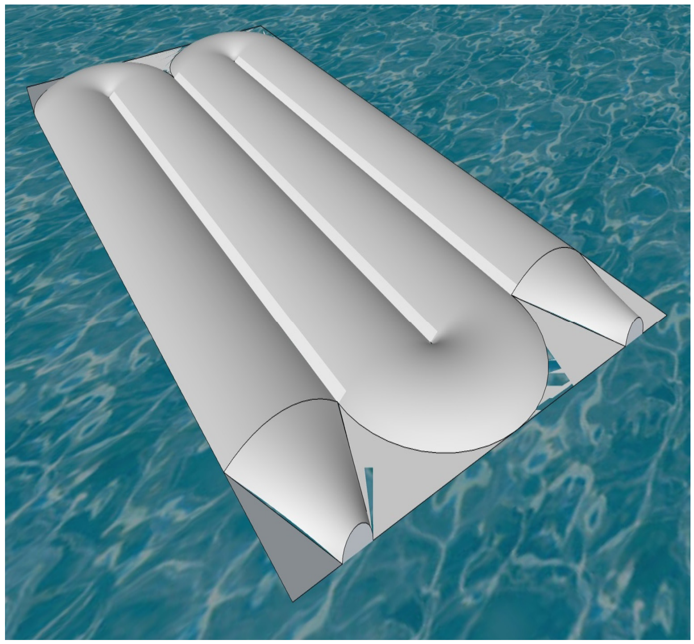
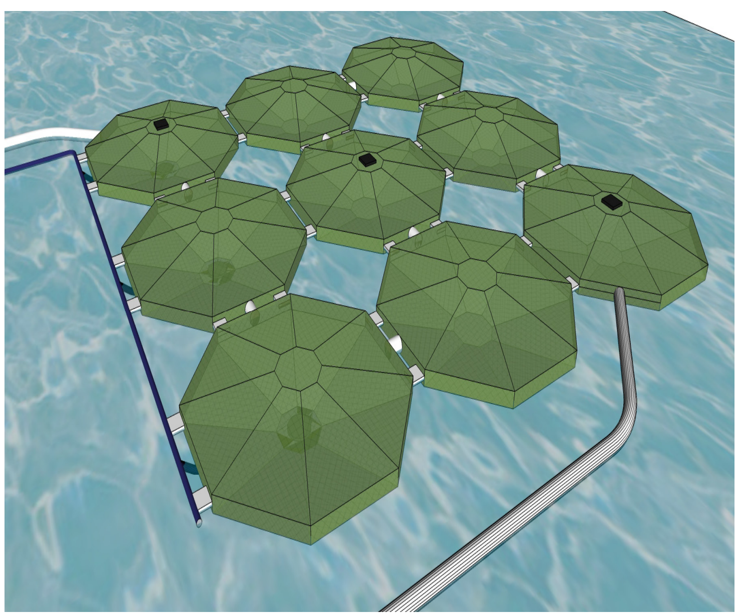
Photobioreactor designs known as batch and continuous flow are under engineering review for materials, hydraulics, and function. The continuous flow systems are currently favored, focusing on designs configured as plug-flow (a) and completely mixed systems (b). In the coming weeks, prototypes of both of these systems will be constructed, using high-density polyethylene (HDPE) for tank testing to monitor strength, durability, mixing, and functionality.



(a) Plug-flow system



(b) Completely mixed system

OMEGA
Site Aerial Photograph

REFERENCES	NO.	BY.	DATE	REVISIONS
TITLE				DESCRIPTION
Phase I Prototype Test Location	△	VSA	3/23/10	

NASA OMEGA PROJECT
NASA AMES RESEARCH CENTER
MOUNTAIN VIEW, CA

DRAWN BY: VSA
DESIGNED BY: KEE
CHECKED BY:
APPROVED BY:

NASA OMEGA PROJECT
PHASE I:
PROTOTYPE TEST LOCATION

JOB NO. 26817633
DATE 03/22/10
SCALE 1" = 30'
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NASA and the U.S. Navy collaboration on OMEGA for the fuel of the future

The National *Aeronautics* and Space Administration and the U.S. Navy share a practical and profound interest in "green" fuels based on their commitments to air transportation and national security on the one hand and global warming and the need to find alternatives to fossil fuels on the other. It is now widely acknowledged that the best source of alternative fuels or biofuels is algae or more specifically microalgae. Algae, like other plants, use CO_2 and sunlight to grow and therefore in the process of growing remove this green-house gas from the atmosphere. The productivity of algae greatly exceeds all other biofuel crops by a wide margin. It is estimated, for example, that algae could provide the entire annual supply of aviation fuels for the U.S. (~21 billion gallons) in a cultivation area half the size of Connecticut, which is <2% of the U.S. agricultural land currently under cultivation. Furthermore, it has been suggested that large quantities of algae can be produced without competing with agriculture for land, water, or fertilizer. Algae do not require agricultural land because they are traditionally cultivated in open ponds or closed photobioreactors, which can be located away from agricultural land—in deserts, for example. Algae require water and fertilizer, but they can grow on the water and residual nutrients in treated domestic wastewater—water not currently used for agriculture. If all this is true, why aren't algae a major contributor to biofuel production?

The major reasons algae are not currently contributing to biofuels have to do with logistics and economics. The logistics problems stem from the scale of algae farms required for producing the quantities of biofuel needed to meet the economics. Such farms will use millions of acres of non-agricultural land and require huge quantities of wastewater. The logistics problems are apparent, if we equate non-agricultural land with deserts and consider that big cities are the best sources of wastewater. Most big cities are not near deserts, which means wastewater will need to be transported great distances—transporting water is not only difficult, it is prohibitively expensive.[1] On the other hand, perhaps we do not need to equate non-agricultural land with deserts.

Most major cities in the U.S. are located on the coasts and these cities are indeed producing copious amounts of wastewater (>11 billion gallons per day). Currently, most of this wastewater is dumped into the oceans through offshore outfalls and both the water and associated nutrient are not only lost at sea, in some cases the nutrients in the wastewater cause harmful algae blooms in coastal zones—wastewater, algae blooms, and there's no agriculture going on offshore…

NASA scientists and engineers are proposing OMEGA (Offshore Membrane Enclosures for Growing Algae) to meet the needs of large-scale algae cultivation for biofuels in a way that does not compete with agriculture for land, water, or fertilizer, and will not only help sequester CO_2 from the atmosphere, but will directly improve environmental conditions in marine ecosystems by preventing harmful algae blooms. The OMEGA concept involves floating photobioreactors made of flexible plastic modules filled with treated domestic wastewater from existing offshore outfalls. Located offshore, OMEGA obviously does not compete for cultivatable land and using wastewater, it does not compete for water or fertilizer, but OMEGA has many other advantages over land-based algae cultivation systems. For example, land-based systems require energy for temperature control and mixing the algae culture, but OMEGA uses the heat capacity and thermal inertia of the surrounding seawater for temperature control and it uses wave power to induce mixing. In addition, OMEGA takes advantage of the salt gradient between wastewater and seawater to protect the environment from the cultivated algae and for a process called forward osmosis, which stimulates algae growth, saves energy during harvesting, and cleans the water released into the marine environment. The salt gradient protects the environment from the cultivated algae,

[1] Arguably, if wastewater is transported to deserts, it should be used for growing food rather than algae to meet the world's food needs rather than our need for biofuels.

because OMEGA will cultivate freshwater algae in wastewater and if these algae escape into the surrounding seawater they will die. In other words, the algae in OMEGA cannot become invasive species in the marine ecosystem.

Forward osmosis uses the osmotic pressure between the low salt concentration of wastewater and the high salt concentration of seawater to move water across a membrane that excludes solutes and particles. The OMEGA system uses forward osmosis to slowly move water out of the OMEGA system, concentrating the nutrients and the algae in the process. The concentrated nutrients stimulate algae growth and the concentrated algae save energy needed for harvesting. In addition, both the forward osmosis and the algae inside OMEGA remove nutrients and other components of the wastewater, which cleans the water that is released into the surrounding environment. This process can help prevent harmful algae blooms and improve conditions in coastal ecosystems.

OMEGA has the potential to grow the vast quantities of algae that will be needed for the production of significant amounts of biofuels needed by our society. It can do this without competing with agriculture and while having a positive impact on the environment by providing advanced wastewater treatment and CO_2 sequestration. What then is needed to implement OMEGA on a scale and in time to make a difference in the world?

OMEGA faces the intrinsic challenges of all algae cultivation systems and some of its own. These challenges include biological, engineering, economic, and environmental challenges. Biological challenges include algal growth rates, invasive (weed) species, pest control, and the effects of pathogens. Engineering challenges include the and above all economics. OMEGA also has its own unique challenges associated with its offshore deployment. These include materials and designs that can withstand the rigors of the marine environment, logistics for filling and harvesting OMEGA modules under varying conditions, and finding locations for large OMEGA farms required for biofuels that will not impact the aesthetics of our coastal areas, fishing, and ship traffic of all kinds.

While these challenges are formidable and the rates of social and environmental change suggest we do not have a lot of time to meet them—perhaps less than ten years. On the other hand, the potential impact of OMEGA on the strategic energy future of the United States and on marine ecosystems, directly by wastewater treatment and indirectly through its effects on climate change, are all strong incentives to push forward with OMEGA at all costs. The success of OMEGA will depend on unprecedented innovation and highly integrated systems engineering combined with a profound understanding of the marine environment. With this in mind, what two organizations are better suited to take on the challenges of OMEGA and to put the US in a leadership role in biofuels, than NASA and the US Navy?