

Live in a Healthy Space Contest

**Synthetic Biology Approaches to Next-
Generation Space Nutrition**

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Executive Summary

To celebrate the 50th anniversary of the Stanford Torus, we, students of Stanford Online High School, are proud to present “NOVA Stanford Torus”. A proposal that inherits O’Neill’s dream and redesigns it with modern technology. To secure food for 10,000 people for a long-term interplanetary travel, we propose our Synthetic Biology Food System, a novel approach to produce healthy and diverse meals for everyone on our spaceship. We focus on having a well-balanced daily nutrient diet using a cell-free and cell-based synthetic biology system, a technology that uses DNA and microorganisms to create new ways of making food. We will make proteins using cell-free protein synthesis, a method that uses cellular components without living cells. This method requires minimal equipment, is independent of seasonal conditions, and offers high protein purity, simplicity, and cost-effectiveness, making it ideal for use in space. Engineer yeasts or bacteria can act as a factory, and we can make carbohydrates and fats. By using the most advanced technologies, we developed a novel platform to design combinations of nutrients to make unique meals. Various nutrients will be produced in bioreactors, and we will combine these base materials to design our own unique tastes. For this reason, NOVA has developed the Space Cooker, a device that allows users to design personalized meals that are both nutritious and enjoyable. This is a revolutionary transformation for long-term space travel.

- Settlement Type: area within settlement
- Settlement Location: in space
- Agriculture Area Size: 250 hectares (using synthetic biology technology)
- Number of people to be supported: 10,000
- Indicate a time frame: multi-generations
- Gemini was used to help create images.

1. Introduction

NASA and Stanford University proposed the Stanford Torus in 1975, a vision of human expansion into space. Fifty years have passed since Gerard K. O' Neill's vision for future space travel (O'Neil, 1989). Now in the 21st century, we have made remarkable progress in technology, robotics, and autonomous systems, far superior to anything from the 70's. We are now in a position where we are ready to reimagine O'Neill's dream with modern technology. As students of Stanford Online High School, we are proud to present "NOVA Stanford Torus". A proposal that inherits O'Neill's dream and redesigns it with modern technology, as this marks the 50th anniversary of the Stanford Torus. That is our proposal for the 2026 NSS Gerard K. O'Neill Space Settlement Contest. We believe that humanity is ready to transition from Earth dependence to solar system independence.

To secure food for 10,000 people for a long-term interplanetary travel, we propose here our Synthetic Biology System capable of producing healthy, diverse meals for everyone on our spaceship.

2. Method of Growing: Synthetic Biology Systems

A well-balanced diet is crucial for maintaining health, requiring daily intake of carbohydrates for energy, proteins for tissue repair and enzymes, healthy fats for nutrient absorption and brain function, and vitamins, minerals, water, and fiber for body support. A balanced nutritional diet leads to immune, mental, and physical health. Microgravity can affect the absorption of carbohydrates, proteins, fats, and vitamins, leading to deficiencies (Dakkumadugula, 2023). We focus on having a well-balanced daily nutrient diet using cell-free and cell-based synthetic biology systems, a field that uses DNA as a template and microorganisms to create new ways of making food.

2.1. Cell-free protein synthesis

Proteins are made from DNA through a process in which DNA is copied into RNA, and the RNA is then translated into protein. This process occurs inside all living cells. Cell-free protein synthesis (CFPS) is a method of producing proteins *in vitro* using cellular components instead of living cells (Hunt, 2025). In this method, the cellular components necessary to make proteins from DNA are extracted and purified from bacteria or yeast. Once the cellular components are prepared, they are mixed with DNA to produce the desired protein. Because this process needs minimal equipment, it has strong potential for use in space. Also, this approach has multiple advantages, including its independence from seasonal and geographic factors, high protein purity, controllability, simplicity, and cost-effectiveness. Recently, cell-free protein synthesis has emerged as a new market, with projections indicating growth from USD 315.03 million in 2024 to USD 716.26 million by 2034 (Patil, 2025). It is ideal for the drug and food industry due to faster and efficient protein production compared to traditional methods. We aim to produce proteins of both plant and animal origin, such as soy, milk, meat, and grain, using cell-free protein synthesis. The system will consist of mixing the cell-free protein synthesis components, such as ribosomes, tRNA, amino acids, polymerase, energy as ATP, and magnesium, with the DNA template of the desired protein (Figure 1A). With this technology, we can make thousands of proteins using just the DNA template for each protein and the cell-free components. Companies like Tierra Biosciences and Sutro Biopharma scale up cell-free protein systems in bioreactors to produce proteins for their products (Tierra, 2020; Sutro, 2025). Protein powder for food production can be used as a dietary supplement or incorporated into foods such as pasta, bread, salads, or soups, offering a flexible and high-protein diet. Also, the protein powder can be added to a 3D food printer to create a variety of high-protein foods, allowing for both nutritional value and enjoyable meal options in space.

2.2. High-Purity Protein Produced in a Few Hours

The cell-free protein synthesis approach has become very attractive compared to conventional methods because it produces high-purity proteins and allows easy purification after expression. Since it does not involve living cells, it does not require cell lysis, resulting in high-purity proteins in a few hours compared to the cell-based protein synthesis that requires days for the cells to grow and many purification steps to obtain the purified protein (Shimizu, 2001) (Figure 1B).

The high purity of cell-free synthesized proteins offers a remarkable advantage over cell-based protein production. The protein product contains fewer impurities, so a smaller mass is required to give the same amount of functional protein. The high purity enables the production of high-protein foods and drinks that taste better, as less material is needed to achieve the desired protein content. This advantage is important not only for space missions, but also in our daily lives. Many adults consume high-protein supplements that often have poor flavor due to the large quantity of protein powder required. Producing proteins through cell-free synthesis could improve the taste and acceptability of high-protein foods and drinks, enhancing nutritional intake and quality of life in space and on Earth.

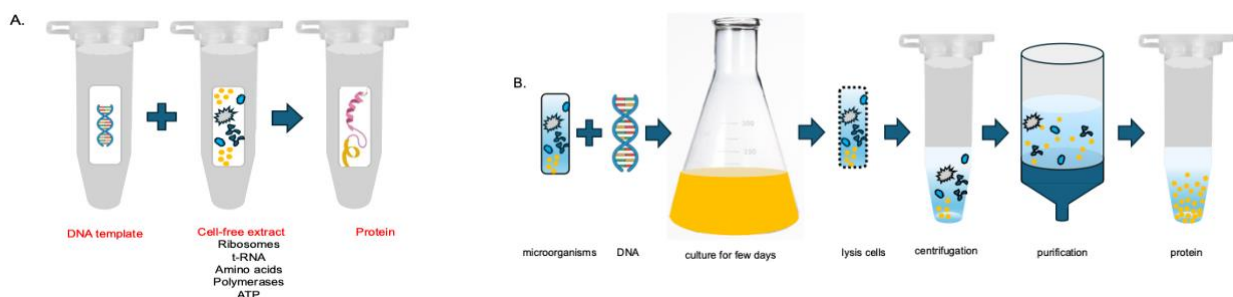


Figure 1: Cell-free and cell-based protein synthesis. A. Cell-free protein synthesis: One tube contains the cell-free protein synthesis components, and the other contains the DNA template of the desired protein. When the tubes are combined, the desired protein is synthesized. B. Cell-

based protein synthesis: DNA is added to a microorganism and cultured for a few days in the incubator. Cells are lysed, and purification steps are necessary to obtain the protein.

2.3. Cell-free protein does not depend on microorganisms

Another major advantage of cell-free protein synthesis is that it does not depend on microorganisms, and only the target protein is produced. In contrast, when using microorganisms, there is a risk of producing other proteins because the host cells have their own transcriptional and translational machinery to make proteins (Figure 1).

2.4. Shelf-stable pellets

One of the main challenges of using cell-free protein synthesis in space is maintaining the stability of the cell-free protein synthesis components. To evaluate this, we used commercially available pellets from the BioBits Central Dogma Lab Kit (KT-1102-01) (BioBits®), which contain the necessary cell-free components. These components are lyophilized, so we tested whether the lyophilized pellets remain stable at -20°C for long periods. We compared 11-month-old pellets with newly purchased pellets to assess their stability. Each pellet was mixed with the DNA template and checked for transcription, the process of synthesizing RNA from DNA, and translation, the process of synthesizing proteins from RNA. The DNA sequence contained an adapter sequence for green RNA fluorescence and a red fluorescent protein (Figure 2). So, RNA will fluoresce in green, and protein will fluoresce in red. Both the 11-month-old and newly purchased BioBits pellets showed green fluorescence at 15 minutes after adding DNA (tube 2), indicating active RNA synthesis, compared with the water negative control (tube 1). Red fluorescence corresponding to protein expression appeared 20 hours later on both the 11-month-old and newly purchased BioBits pellets (Figure 2, Table 1, Appendix 1). These results demonstrate that BioBits pellets remain functional after 11 months of storage at -20°C . We are keeping cell pellets at -20°C and will test whether the pellets maintain stability for longer storage periods. The lyophilized cell-free synthesis tubes are lightweight, which is a major advantage for

space missions since sending heavy loads into space is very expensive. Research is trying to further improve the stability of cell-free synthesis components to make stable long-term storage pellets at room temperature for space missions. This advancement would make it possible to produce fast and high-purity proteins. Also, producing these pellets in space requires only a small area to make the cell-free fluorescent components, which is much smaller than the large fields needed to grow the same amount of protein through agriculture. So, we can produce the cell-free components in a bioreactor in space to synthesize many different proteins. This technology is already in use, and the market has grown significantly in the past few years (Patil, 2025). Because of its advantages, such as simplicity, speed, and the ability to produce only the desired protein, it is an excellent option for use in space. This technology is a revolutionary sustainable protein production for both space missions and future food production on Earth.

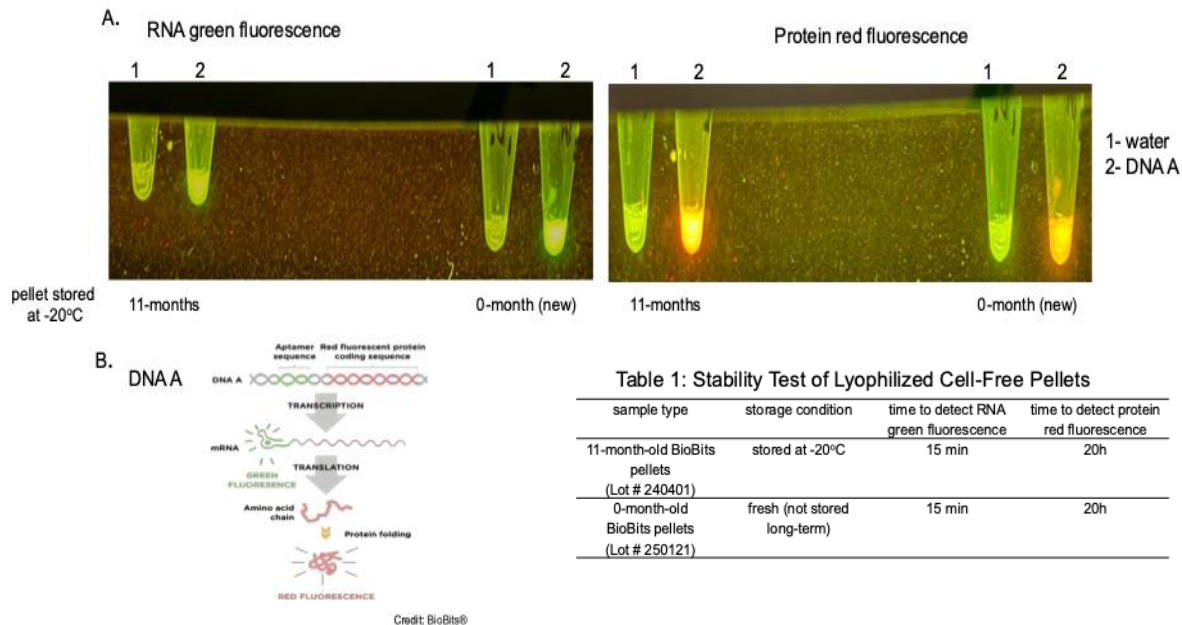


Figure 2: Stability of BioBits pellets at -20°C . (A) BioBits Central Dogma pellets were used to assess green RNA (left) and red protein (right) synthesis. Water (tube 1) and DNA A (tube 2) were added to the pellets, and the tubes were observed in the P51 viewer after 15 minutes for RNA green fluorescence and 20 hours for protein red fluorescence. (B) DNA A is designed to fluoresce green for RNA and red for protein.

2.5. Protein-based treatment

To stay healthy, we must be prepared to both prevent and treat diseases. Protein-based treatment is a form of treatment that uses proteins to prevent or treat diseases. Cell-free protein synthesis is an ideal system for producing proteins without relying on living cells. This technology is already being researched in universities and biotech companies to develop solutions for major health challenges (Arnold, 2023). Hormones and antibodies are both proteins used for medical purposes. Hormones like insulin can treat diabetes, other hormones are used to treat various hormonal disorders. Antibodies can be used for cancer therapy or infectious diseases (nfid.org, 2023). Sutro Biopharma produces antibodies by adding a specific DNA sequence to a cell-free system, which then produces the antibody used to treat cancer patients (Sutro, 2025).

With cell-free protein technology, we can live safely and stay healthy in space, producing proteins for both nutrition and medical treatment.

3.0. Carbohydrates, fat, and micronutrients:

We will use cell-based synthetic biology, which involves engineering yeast or bacterial cells to produce carbohydrates, fats, and micronutrients. The global synthetic biology market (proteins, fats, carbohydrates) is growing fast. Valued at approximately \$24.58 billion in 2025, it is projected to reach around \$192.95 billion by 2034 (Gokhale, 2025).

With our understanding of gene sequencing and the ability to modify it using the CRISPR system, we can engineer microbial cells to produce specific carbohydrates, fats, and micronutrients. These microbial cells act as factories. Many microbes are oleaginous, which produce excess lipids. NoPalm Ingredients company produces palm oil without palm trees by fermenting yeast (NoPalm Ingredients). Synthetic biology can make yeast-based lipid production cheaper, faster, and more sustainable (Gokhale, 2025). We will engineer oleaginous yeasts to produce animal and vegetable fats to use as ingredients in our food.

Scientists were able to engineer bacteria to produce sugars for food ingredients (Silver, 2010). Companies like Jennewein and Glycom A/S produce human milk oligosaccharides, which contain sugars found in breast milk that help an infant's gut health and protect against pathogens. These products are cheap and are used as ingredients in infant products, milk, and supplements (Procopio,2023).

Many companies are already using synthetic-biology technologies to make foods and ingredients that are more affordable and sustainable. We will take advantage of this new approach, which is suitable for producing food in space.

4.0. Agriculture Area Size:

Considering conventional agriculture on Earth requires 0.5 hectares per person, 10,000 people would need 5,000 hectares (about 50 km²) of farmland. However, by adopting synthetic, cell-free, and cell-based food production, it can reduce the land requirement to landless agriculture (Godfray, 2024). In our proposal, we estimate a 95% reduction in land use by using a synthetic-biology technology, requiring only about 250 hectares (approximately 2.5 km²). This estimate is based on data from companies that are already using synthetic biology. Impossible Burger, a company that uses synthetic biology in its products, requires 96% less land and 89% fewer greenhouse gases compared to a traditional beef hamburger. Their products are available in more than 30,000 restaurants and 15,000 grocery stores around the world (Voigt, 2020). NoPalm Ingredients company has 90% less carbon emissions compared to traditional palm oil companies and reduced land-use by 99% (NoPalm Ingredients). This is a revolutionary transformation for long-term space travel.

5.0. Food Science:

It is known that, on average, women need about 1,600 to 2,400 calories each day, and men need 2,000 to 3,000 calories a day, based on age and activity level (Zelman, 2024).

Macronutrients are essential nutrients that the body needs in large amounts to supply energy and support growth, metabolism, and overall health. The three main macronutrients are carbohydrates, fats, and proteins. 50 to 55% of total daily calories should consist of carbohydrates, most coming from fruits, vegetables, beans and legumes, and grains. Adults need to eat about 60 grams of protein per day, or 10 to 15% of total calories. Fat should be limited to less than about 28% of daily total calories or fewer than 90 grams per day (Bhupathiraju, 2023).

Throughout history, humanity has developed unique food cultures, and taste is different according to their environment, and all regions' ingredients have a great influence on the cooking method. Now, humankind stands on the threshold of a new era, moving from a planetary civilization to a space one. With this transition, our food culture will also undergo a dramatic transformation.

In a zero-gravity environment, body fluids shift upward toward the head, causing facial swelling and changing the taste. Aroma, which plays a vital role in stimulating appetite, is not the same as on Earth. For the first time, we realize that "cooking" itself is a cultural technique based on physical laws of the Earth. So, cooking in space is not simply about Earth's cuisine, it means redefining flavor and a new way of cooking. In an environment where neither open flames nor oil can be freely used, how can we recreate umami, texture, and aroma? This is not only about technology. It is a philosophical question about how humanity can have the joy of living among the stars.

We will use synthetic biology technology for food production for our long-term space missions. Food ingredients will no longer come from natural crops or animals. Instead, proteins, fats, and other nutrients will be designed at the DNA level and produced in bioreactors in food factories. Houses or restaurants will combine these base materials to design their own unique tastes. For this reason, NOVA has developed the Space Cooker, a device to prepare our meals. Inside the NOVA colony, a cooking contest is held every month, and household chefs present

their original meals (example in Appendix 2). This event is celebrated as Space Food Culture Day, one of the most joyful festivals held throughout the entire spaceship. From these dishes, a new culinary culture is gradually born. A food tradition that belongs not to one nation or region, but to humanity in our new home among the stars.

6.0. Infrastructure for Cell-Free and Cell-Based Meals: Space Cooker

Protein, fat, and carbohydrate will be integrated into both industrialized and home-cooking systems, as it is shown in Figure 3. Dedicated production lines for protein and carbohydrate, or fat will be created. After synthesis and purification, these components are freeze-dried into powder for long-term storage and easy use as cooking ingredients. Meanwhile, in each household, a Space Cooker device that resembles a pipe organ allows residents to design their own recipes with unique flavors and textures. Recipes are sent to the Food Control Center, ingredients are mixed and delivered to each home through a tube system, and they are automatically stored. Residents combine the powdered mix with liquid to form dough or batter, and food is made using a 3D printer. A robotic cooking arm completes the dish by cooking it under the most optimized conditions of temperature, timing, and method.

Fresh vegetables are grown in a hydroponic cultivation unit like a refrigerator. The robotic arm selects the freshest vegetables for salads and side dishes. All these operations are fully automated.

The Space Cooker will create new flavors, aromas, and textures from a combination of proteins, carbohydrates, fats, minerals, and vitamins. A monitor displays cooking information, calories, and macronutrient contents. The tabletop functions as a large touch-panel computer connected to an AI system to design daily meals based on personalized health data. Buttons on both sides of the monitor allow for manual fine-tuning of ingredient ratios and cooking parameters. The wing on each side has sensory modules, so users can experience the taste, aroma, and

texture of a dish while still in preparation. For example, when making a soup, a small “taste window” opens on the module, dispensing a “sampling” cup. Users can taste the AI-generated flavor before the actual meal. This creates new flavors and new experiences at home for the near future.

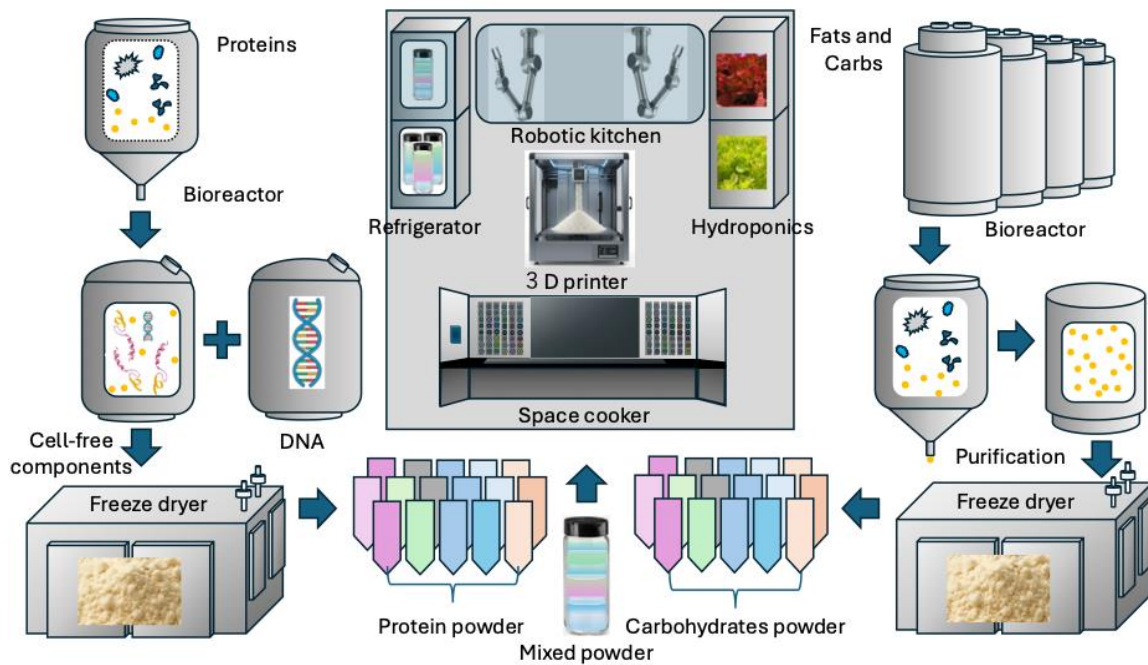


Figure 3. Space Cooker.

7.0. Conclusion

We propose a revolutionary system to produce healthy and diverse meals for 10,000 people during long-term interplanetary travel by using cell-free protein and cell-based synthetic biology. By using the most advanced technologies, we developed a novel platform to design combinations of nutrients to make unique meals, supporting both health and the enjoyment of food in space.

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BioBits®: Central Dogma (classroom kit) miniPCR bio. miniPCR bio.

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Appendix Table 1:

Protocol to Check the Stability of BioBits Pellets at -20°C (Figure 2):

The BioBits Central Dogma Lab Kit (KT-1102-01) was used to check the stability of BioBits pellets, which contain the cell-free components for protein synthesis. A set of pellets was stored at -20°C for 11 months, and another set (newly purchased pellets) represented the 0-month condition. Water and DNA A were added to the tubes according to Appendix Table 1. Fluorescence was then observed using the P51 viewer, a fluorescence viewer with an orange filter.

Protocol to Check the Stability of Pellets at -20°C
(Figure 2)

	Tube 1	Tube 2
DNA A	none	4 μl
Water	8 μl	4 μl

Appendix 2:

Example of rice using the Conventional Method and the Synthetic Biology Method using our Space Cooker.

In the synthetic biology method, nutrient powders are mixed and shaped with a 3D printer before cooking.

Procedure in the space cooking device:

1-Select Input Mode

- (1) Check either “Automatic” or “Manual.”
- (2) Automatic: Uses pre-programmed nutrient powders for cooking.
- (3) Manual: Enter quantities for each nutrient to design a custom mixed powder.

2. Cooking (Example: Rice)

3. Serving (Example: 3 portions)

4. Types (Example: Koshihikari)

All ingredients needed for rice are entered into the Space Cooker, and the food center receives an order for the required powders.

Traditional Rice for 3 people

Food	Quantity (cups)	Quantity (g)
Rice	1.5	300

Rice ingredients prepared using synthetic biology for 3 people

Input Method (Manual input) >Cooking (Curry rice) >Servings(3)>Ingredience(Rice)>Types(Koshihikari)				
Ingredient	Category of Nutrition	Quabty:g (per 100g)	Taret amount (g)	Required quantity (g)
Rice (per 100g)		100	0	450
	[Carbohydrates (g)]	76.6	76.6	344.7
	Starch	75	75	337.5
	Dietary Fiber	0.9	0.9	4.05
	Sugars	0.7	0.7	3.15
	[Protein (g)]	6.3	6.3	28.35
	Glutelins	4.5	4.5	20.25
	Albumins & Globulins	1.5	1.5	6.75
	Proamins	0.3	0.3	1.35
	[Fats (g)]	1.5	1.5	6.75
	Unsaturated Fatty Acids	1.2	1.2	5.4
	Saturated Fatty Acids	0.3	0.3	1.35
	[Vitamins]	(mg)		
	Thiamin	0.12	0.12	0.54
	Riboflavin	0.02	0.02	0.09
	Niacin	1.4	1.4	6.3
	Vitamin B6	0.12	0.12	0.54
	Folate	10	10	45
	Pantothenic Acid	0.67	0.67	3.015
	Biotin	3.3	3.3	14.85
	Vitamin E	0.1	0.1	0.45
	[Minerals]	(mg)		
	Sodium	1	1	4.5
	Potassium	89	89	400.5
	Calcium	5	5	22.5
	Magnesium	23	23	103.5
	Phosphorus	97	97	436.5
	Iron	0.8	0.8	3.6
	Zinc	1.4	1.4	6.3
	Copper	0.22	0.22	0.99
	Manganese	1.05	1.05	4.725
	Selenium	1.1	1.1	4.95