PLANTS FOR HUMAN LIFE SUPPORT IN SPACE: FROM MYERS TO MARS

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ABSTRACT

Bioregenerative life support systems have been discussed since the writings of Tsiolkovsky in the early 20th century. Central to the concept is the use of photosynthetic organisms to regenerate air and food. Bioregenerative research expanded rapidly in the 1950s and 60s through the work of Jack Myers and colleagues, and focused largely on algal systems. Testing even included space flight experiments by Herb Ward in the 1960s, but bioregenerative research in the USA decreased soon after this. In contrast, the Russian BIOS projects led by Josef Gitelson and Henry Lisovsky maintained a steady pace of bioregenerative research from the 1960s through the 1980s, including tests with human crews lasting up to several months. Around 1980, NASA initiated its Controlled Ecological Life Support Systems (CELSS) Program, which focused on higher plant (crop) testing. In the late 1980s through the 1990s, findings from university CELSS researchers were used to conduct tests at NASA's Kennedy Space Center in a large, atmospherically closed chamber. Related tests with humans and regenerative life support systems were subsequently conducted at NASA's Johnson Space Center in the mid 1990s, and a large-scale bioregenerative test bed called BIO-Plex was planned but never completed. A likely scenario for implementing bioregenerative life support might start with a small plant growth unit to produce some fresh foods for the International Space Station or early lunar missions. The plantings might be expanded for longer duration lunar missions, which would then provide an opportunity to assess concepts for Mars missions, where bioregenerative life support will play a more crucial role.

Perhaps the earliest description of "life support" capabilities of plants was by Joseph Priestley when he noted that placing a sprig of mint in a bell jar could sustain a candle's flame and "was not at all inconvenient to a mouse" (Rabinowich, 1945). About a century later, the novelist Percy Greg wrote of an Earth traveler taking plants along on a voyage to Mars to help with waste recycling (Greg, 1880, reprinted 2006). The Russian scientist Konstantin Tsiolkovsky (1926) took this notion beyond fiction and proposed how humans and plants might co-exist inside closed environments in space. Nearly 20 years later, Willy Ley (1948) noted that if the space journey is sufficiently long, growing plants would be an alternative to stowing oxygen and suggested pumpkins for this role.

With this fascination of plants and humans co-existing in space, serious testing of bioregenerative life support capabilities began with Jack Myers and colleagues during the 1950s (Myers, 1954; Miller and Ward, 1966). The basis for this work can be summarized by comparing the general metabolic equations for human respiration and photosynthesis (Myers, 1954; Gouleke and Oswald, 1964) (Fig. 1). These equations show that biomass (CH_2O) and oxygen (O_2) can be generated through photosynthesis, while waste CO_2 from human respiration can be removed (Galston, 1992; Ferl et al., 2002). By choosing appropriate species, e.g., crops, a portion of this biomass can be food. A less obvious but equally valuable contribution is that waste water could be recycled to plants and the transpired water vapor then condensed as clean water (Wolverton et al., 1983).

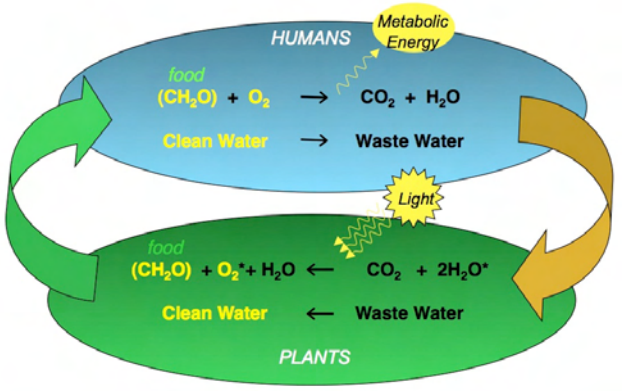

Figure 1. *Simplified equations showing photosynthesis (top) and human respiration (bottom). The products of photosynthesis are oxygen (O_2) and carbohydrate (CH_2O), which can be used as food. Through the process of transpiration, plant systems (including root-zone microflora) can be used to purify waste water, where the transpired humidity can then be condensed as clean water.*

Chorella: The initial candidate

Algae, and in particular *Chlorella pyrenoidosa*, quickly became the preferred organism for life support studies in the 1950s and 60s (Sorokin and Myers, 1953; Krauss, 1962; Eley and Myers, 1964; Miller and Ward, 1966). *Chlorella* was hardy, relatively easy to culture, could be moved within reactors (e.g., chemostats) by pumping a liquid medium, and light sources such as fluorescent lamps could be embedded directly in the vessels, thereby providing near-total absorption of the light (Sorokin and Myers, 1953; Krall and Kok, 1960; Matthern and Koch, 1964; Miller and Ward, 1966; Taub, 1974). The *Chlorella* studies provided estimates of the mass and energy requirements for life support ranging from <10 kW to ~100 kW of electrical power and ~5 to ~50 m^2 surface area to produce enough oxygen for one human (Miller and Ward; 1966). But many of these studies were relatively short and it was difficult to assess the long-term

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reliabilities. Other algae and cyanobacteria studied during this time included *Anacystis*, *Synechocystis*, *Scenedesmus*, *Synechococcus*, and *Spirulina* (Miller and Ward, 1966; Taub, 1974).

Initially the interest in photosynthetic organisms for space was only for O_2 production and CO_2 removal (Gouleke and Oswald, 1964; Miller and Ward, 1966; Taub, 1973), and the US Navy even sponsored algal studies for air regeneration on submarines (Office of Naval Res., 1956). But as researchers began to consider long-duration space missions, the issue of food became increasingly important. A number of studies examined the food potential of algae, but converting the algal biomass to palatable foods proved challenging (Krauss, 1962; Karel et al., 1985; Nakhost et al, 1987). Many algae were too rich in protein for a balanced diet and contained large amounts of indigestible cell wall materials (Gouleke and Oswald, 1964; Karel et al., 1985). Other challenges with algae included liquid / gas phase mixing and separation, especially in µ-gravity (Gouleke and Oswald, 1964), and the production of phytotoxic volatiles by some species, which compromised some life support studies in the BIOS projects in Russia (Gitelson et al., 1975; Fong and Funkhouser, 1982).

"Higher Plants"

Higher plants (crops) have been used for food by humans for centuries and of course plants provide the same atmospheric regeneration functions as algae (Myers, 1954). Not long after NASA was formed in 1958, a symposium was held at Wright Patterson Air Force Base to generate a list of crops for space missions; this list included: lettuce, Chinese cabbage, cabbage, cauliflower, kale, turnip, Swiss chard, endive, dandelion, radish, New Zealand spinach, tampala, and sweetpotato (Boeing Comp., 1962; Gouleke and Oswald, 1964). Selection criteria included the ability to grow under low light intensities, compact size, high productivity, and tolerance to osmotic stress. Despite these recommendations, with a few exceptions (Mansell, 1968), testing with crops for life support in the US space program went dormant for the next 10 to 15 years.

In contrast, bioregenerative testing with algae and plants flourished in Russia throughout this period as part of the BIOS projects in Krasnoyarsk, Siberia (Gitelson et al., 1976, 1989; Salisbury et al., 1997). These tests included studies with human crews who grew much of their own food and provided atmospheric regeneration with crops, while recycling wastes (such as urine) back to the plants. At one point, nearly 100 researchers and staff worked on the BIOS team in Krasnoyarsk (J. Gitelson, per. com.). Later, other groups started bioregenerative life support research in Europe (Skoog, 1987; Gerbaud et al., 1988; Daunicht and Brinkjans, 1992), Japan (Nitta and Yamashita, 1985; Oguchi et al., 1987), and Canada (Grodzinski, 1992; Stasiak et al., 1998), and reviews of some of these efforts are presented in this issue (Tako et al., 2010; Lasseur et al., 2010).

Plant Research in NASA's CELSS and Advanced Life Support Programs

Following a series of conferences to identify challenges for long duration life support, NASA revived its bioregenerative research with the start of the Controlled Ecological Life Support Systems, or CELSS Program ca. 1980 (Moore et al., 1982). Key issues included food production, nutrition and food processing, waste processing, system engineering, and closed system ecology (Mason and Carden, 1982). Other workshops focused on what crops might be appropriate, and targeted nutritional needs, harvest index (ratio of edible to total biomass), food processing, and horticultural requirements (Hoff et al., 1982; Tibbitts and Alford, 1982). Crops common to many of these lists included: wheat, soybean, potato, rice, sweetpotato, lettuce, and peanut. NASA testing with algae and cyanobacteria also continued in the 1980s (Averner et al., 1984; Smernoff et al., 1987; Fry et al., 1987), but to a lesser degree than with plants.

CELSS research in the 1980s and early 1990s occurred largely at universities (Fig. 2) and included testing with wheat (Goyal and Huffaker, 1986; Bugbee and Salisbury, 1988; Bugbee and Monje, 1992), soybean (Tolley-Henry and Raper, 1986; Raper et al., 1991), lettuce (Knight and Mitchell, 1983, 1988; Barta and Tibbitts, 1991), potato (Wheeler and Tibbitts, 1986; Wheeler et al., 1991a; Cao and Tibbitts, 1994), sweetpotato (Mortley et al., 1991, Bonsi et al., 1992), rice (Bugbee et al., 1994; Goldman and Mitchell, 1999), cowpea (Ohler and Mitchell, 1996), peanut (Mackowiak et al., 1998; Mortley et al., 2000), tomato (Gianfagna et al., 1998), and onion (Jasoni et al., 2004). Experiments were typically carried out in growth chambers under electric lighting and used either hydroponics or solid growing media. Thus these approaches were most applicable to planetary surface settings where gravity could assist water delivery and drainage (Bugbee, 1995a). But testing of watering concepts for µ-g was also conducted to prepare for early spaceflight opportunities (Wright et al., 1988; Dreschel and Sager, 1989; Morrow et al., 1993). Because the candidate crops were all C_3 photosynthetic types, CO_2 enrichment was commonly used to increase growth (Wheeler et al., 1991a; Bugbee and Monje, 1992; Mortley et al., 1996; Monje and Bugbee, 1998; Jasoni et al., 2004). Extensive tests on crop responses to temperature, humidity, mineral nutrition, light level, photoperiod, and even light spectral quality were conducted as part of the CELSS program (Bonsi et al., 1994; Bugbee and Monje, 1992; Cao and Tibbitts, 1991, 1994; Dougher and Bugbee, 2001; Frantz et al., 2000; Grotenhuis and Bugbee, 1997; Knight and Mitchell, 1983, 1988; Mortley et al., 1993; Wheeler et al., 1986a; 1991b).

Many of the university findings were then used to conduct tests in the Biomass Production Chamber (BPC) at NASA's Kennedy Space Center, FL from 1988-1998. The BPC provided a 20-m^2 growing area inside a closed volume of 113 m^3, which allowed a "scale-up" test of the

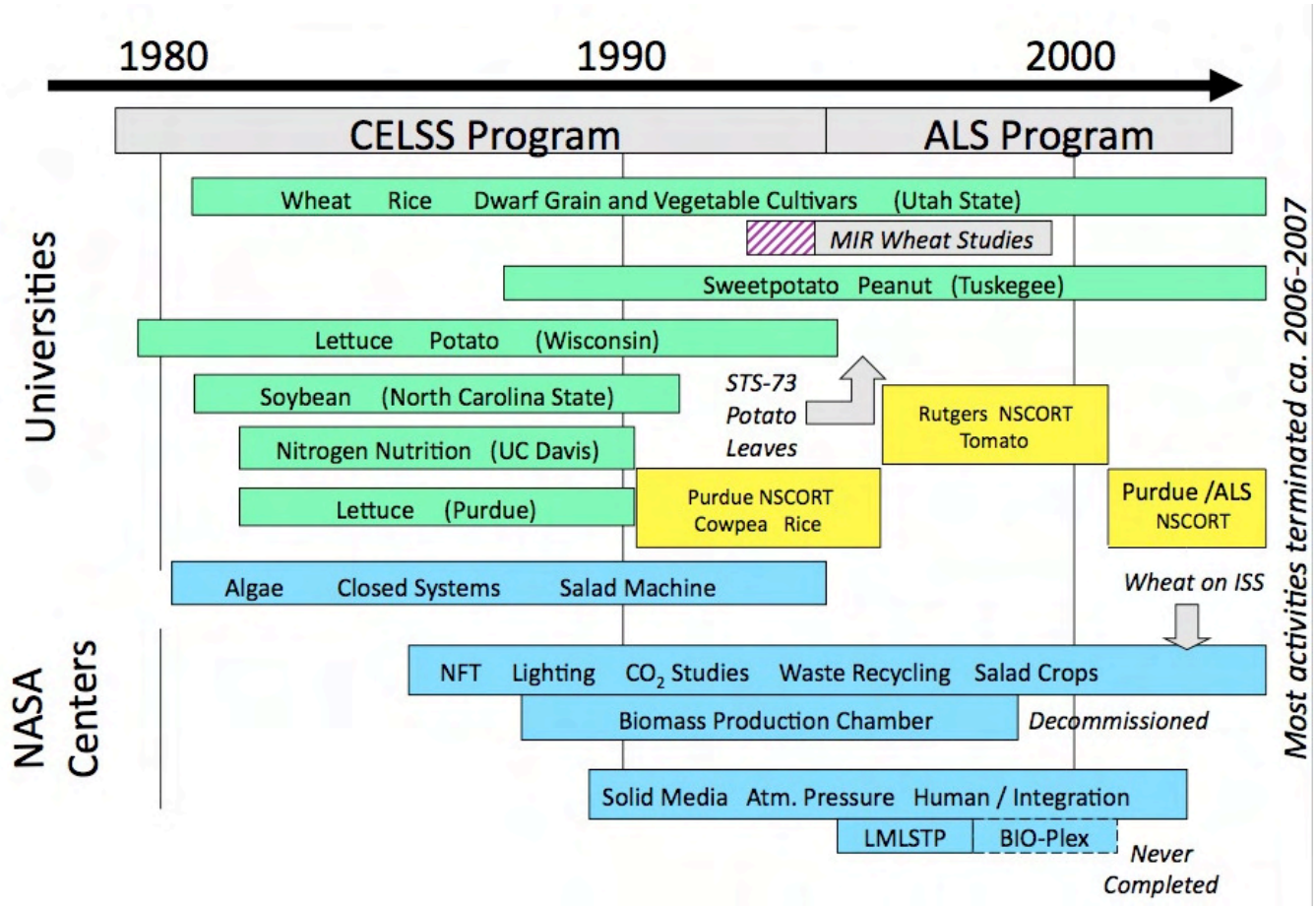

Figure 2. *NASA's Controlled Ecological Life Support (CELSS) and Advanced Life Support (ALS) Program activities.*

fundamental findings, as well as a chance to assess the effects of a tightly closed atmosphere on crop growth (Fig. 3). Although yields from the BPC tests were good, they were typically less than yields measured in smaller chambers (Wheeler et al., 1996). This was an important observation and may have been related to 1) more pronounced edge-effects or side lighting in smaller chambers, which can inflate yield estimates (Went, 1957); 2) the inability to provide close attention to individual plants in larger plantings; and/or 3) possible injurious effects of volatile organic compounds in a tightly sealed BPC atmosphere (Batten et al., 1995; Wheeler et al., 2004).

As with the Russians, NASA also developed integrated, bioregenerative life support test capabilities for humans in closed systems. During this time, the NASA program became known as the Advanced Life Support Program (Fig. 2). Tests began at NASA's Johnson Space Center in the mid 1990s and showed that one human's oxygen needs could be provided by 11 m^2 of wheat grown at high light intensity (Edeen et al., 1996) (Fig. 4). These tests were followed by others using a four-person crew living in a closed chamber, including one test in which the chamber was connected to a plant growth chamber (Barta and Henderson, 1998). The oxygen produced by the 11 m^2 of wheat again supported the air exchange needs for roughly one human, while the needs of the other three crew members were supplied by physico-chemical life support equipment and stowage (Edeen et al., 2000). In addition, a small growth chamber was placed in the human living habitat to allow the crew to grow fresh lettuce as a supplement to their stored foods (Barta and Henderson, 1998). The next step in this test sequence was to build a larger facility called BIO-Plex, that would ultimately supply most of the life support needs for human crews using plants (Barta et al., 1999), but this was never completed.

Figure 3. *Lettuce plants growing inside NASA's Biomass Production Chamber located at Kennedy Space Center. NASA researchers Neil Yorio and Lisa Ruffe are shown in the photo.*

What Have We Learned?

The importance of light. NASA's testing demonstrated repeatedly that light was key to controlling crop yields, which in turn affected the area of crops required to sustain the crew (Salisbury, 1991). Lab-scale and large chamber studies showed near linear effects of light on photosynthetic rates and biomass production across the low to moderate intensities (Bugbee and Salisbury, 1988; Knight et al., 1988; Wheeler et al., 1991a). Depending on the crop, edible biomass also increased by extending the photoperiod and hence total light (Wheeler and Tibbitts, 1986a; Bugbee, 1995b). But this was not always effective for some short day species and more testing is needed to develop day-neutral lines for crops like potato, soybean, and rice (Wheeler and Tibbitts, 1986b).

The pursuit of efficient electric light sources to reduce power needs included testing lamps with narrow spectra, e.g., low-pressure sodium lamps and light emitting diodes-LEDs (Guerra et al., 1985; Barta et al., 1992). Plants grown under these narrow spectrum sources were often leggy or showed morphological abnormalities, but providing sufficient blue light could offset this (Barnes and Bugbee, 1992; Wheeler et al., 1991b; Goins et al., 1997). Recent LED studies suggest that red and blue light should be adequate for most crops, but that adding a small amount of green light would be helpful for visual assessment of crop health (Kim et al., 2007; Massa et al., 2008; Morrow, 2008).

Hydroponic advances. Although hydroponics was well established, NASA research expanded the use of hydroponic approaches to agronomic species such as wheat, soybeans, and rice (Bugbee, 1995), and even subterranean crops such as potato and peanut (Wheeler et al., 1990; Mackowiak et al., 1998). The research provided valuable data on crop water use, nutrient use, and solution pH maintenance, which in turn provided assessment of system costs and reliabilities (Bugbee, 1995; Wheeler et al., 1999a; Drysdale, 2001).

New limits to yields. Controlled environment testing with plants is not new (Went, 1957; Downs, 1975), but bioregenerative life support testing extended it to more traditional field crops. Findings showed that world-record yields could be surpassed in controlled environments using high light and CO_2 enrichment (Bugbee and Salisbury, 1988; Tibbitts et al., 1994; Wheeler, 2006). Studies at Utah State University showed that hydroponically-grown wheat could tolerate remarkably high irradiance (e.g., continuous light at ~2000 µmol m^{-2} s^{-1} PPF), which in turn produced remarkable yields (Bugbee and Salisbury, 1988; Bugbee, 1995b). Such findings were especially important for systems modelers, who had to assess the costs of growing volume and other constraints for space life support (Drysdale, 2001; Drysdale et al., 2003).

Figure 4. *Nigel Packham of NASA's Johnson Space Center living inside a closed chamber where wheat plants provided all of his oxygen and removed all of his exhaled carbon dioxide (photo courtesy of NASA's Johnson Space Center).*

Canopy gas exchange data. Plant testing also included measurements of canopy (stand) photosynthetic rates for life support calculations (Gerbaud et al., 1988; Knight et al., 1988; Bugbee and Monje, 1992; Wheeler et al., 1993b). These measurements directly tracked stand growth, which could quickly revealed perturbations or stresses to the crops (Wheeler et al., 1993b; Wheeler, 2006). Canopy gas exchange also allowed measurement of assimilation quotients (CO_2 fixed / O_2 evolved; Krall and Kok, 1960), with lipid/protein-producing soybean plants having an lower AQ values than a carbohydrate producing rice plants (Tako et al., 2001, 2010). Systems with closed atmospheres could also track the production of biogenic gases (Batten et al., 1996). NASA studies were perhaps the first to document ethylene production throughout growth and development of normal, healthy crop stands, with production rates being highest during rapid vegetative growth for many species (Wheeler et al., 2004). Allowing this ethylene to accumulate proved harmful to some species (Edeen et al., 1996; Levinskikh et al., 2000) and testing at Utah State showed that chronic ethylene exposures even as low as 25 ppb had negative effects on some species (Klassen and Bugbee, 2004).

Stomatal opening at "super-elevated" CO_2. Increasing CO_2 concentrations from typical Earth-ambient (~400 ppm or 0.04 kPa) to ~1000 ppm (0.10 kPa) resulted in the expected gains in C_3 plant growth, while reducing transpiration (Wheeler et al., 1993b; Monje and Bugbee, 1998; Wheeler, 2006). But super-elevating the CO_2 to levels such as 5000-10,000 ppm, which can occur in spacecraft, sometimes had negative (toxic) effects on growth or seed yield in some species (Bugbee et al., 1994; Grotenhuis and Bugbee, 1997). In addition, these very high CO_2 concentrations unexpectedly increased stomatal conductance and water use in several dicot species, and the explanation for this is still unknown (Wheeler et al., 1993b; 1999b).

Spaceflight Tests with Plants for Life Support

In comparison to the number of studies of µ-gravity effects on plants, testing of plants specifically for life support applications in space has been limited (Ferl et al., 2002; Musgrave, 2007). One of the earliest demonstrations of plants removing CO_2 and producing O_2 in space was carried out by Ward et al. (1970) using giant duckweed (*Spyrodela polyrhiza*). Several decades later, spaceflight studies with wheat and potato also documented photosynthetic gas exchange (Brown et al., 1997; Monje et al., 2000) and the successful production of edible biomass in space (Croxdale et al., 1997; Levinskikh et al., 2000; Salisbury et al., 2003). The initial experiments with wheat on the Russian Mir Space Station failed to develop seed due to elevated ethylene levels (Levinshkikh et al., 2000; Salisbury, 2003) and there are still concerns of dealing with ethylene and providing adequate gas exchange to developing embryos and seeds in µ-g settings (Musgrave et al., 1997). An elegant demonstration of plant gas exchange occurred in the PESTO experiment, which tracked CO_2 uptake through successive plantings of wheat on the International Space Station (Stutte et al., 2005). This sequence of experiments showed virtually no difference between ground- and space-grown plants when given similar light, water, and nutrients (Monje et al., 2005)

"Salad machine" concept. Because of volume and power limitations, near-term testing of plants for life support in space will be limited to subsystem or component tests. But growing a small number of plans to supplement the crew's diet is feasible even for early missions and this idea has commonly been referred to as a "salad machine" (Kliss and MacElroy, 1990; MacElroy et al., 1992). A salad machine could provide fresh foods on a continual basis and add diverse colors, textures, flavors, and bioavailable

nutrients to the crew's diet. Video footage presented by Gail Bingham (Utah State Univ.) at the 2001 ASGSB meeting showed the last cosmonauts on the Russian Mir Station harvesting and tasting fresh mustard (*Brassica*) greens from the SVET plant growth unit. Their comments documented the enjoyment of seeing and tasting these greens, and suggests that plants could have a positive impact on humans in confined environments (Ulrich and Parsons, 1992; Sadler, 1995).

On to Moon and Mars!

Demonstrating sustained plant production in a salad machine on the ISS would be a good first step toward implementing bioregenerative life support for the future (MacElroy et al., 1992). Lessons learned from salad machine operations on ISS would be directly applicable to Mars transit missions, and valuable for early lunar or Mars surface missions, where relatively small plant production systems could provide supplemental foods for the space travelers. As the infrastructure expands for surface outposts, additional plant growth modules might be added to provide more food and off-load other life support equipment; alternatively, an entire logistics module might be adapted to grow plants after it has been emptied of its stowed goods and equipment. But numerous challenges remain: Can electric lighting efficiencies improve to reduce the costs of crop production? Will there be nuclear power available to power these lamps (Miller and Ward, 1966)? Can solar light be collected and conveyed to the plants, thereby eliminating the power requirements for electric lamps (Cuello et al., 2000)? Can the plants grow and reproduce at the reduced atmospheric pressures and reduced oxygen partial pressures projected for future missions (Mansell, 1968; Daunicht and Brinkjans. 1992; He et al., 2007). Can the plants withstand the higher radiation levels in exposed surface structures, and if not, how much shielding will be needed (Bücker and Horneck, 1975)? Can we use modern tools of genetic engineering to fit the plants to the environment, rather than fit the environment to the plants? As we solve these challenges, I am convinced we will eventually take plants with us into space, just as pioneers like Jack Myers envisioned in the 1950s. Perhaps then we will be able to conduct the ultimate Priestly experiment, where the plants might "not at all be inconvenient" to their human companions.

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