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UNUSUAL SPACECRAFT MATERIALS

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0.0 ABSTRACT

For particularly innovative space exploration missions,
unusual requirements are levied on the structural
components of the spacecraft. In many cases, the
preferred solution is the utilization of unusual
materials. This trend is forecast to continue. Several
hypothetical examples are discussed in this paper.

1.0 SAILS, SUNGRAZERS, AND ICESHIPS

For particularly innovative space exploration missions,
unusual requirements are levied on the structural
components of the spacecraft. Titanium and carbon-carbon
have become materials of choice, the Lunar Excursion
Module's thermal protection blanket was literally
gold-plated, and so on. But this trend is likely to
continue, straining the ingenuity of space engineering,
construction, and operations capabilities.

To list three examples: (1) solar sail missions require
extremely lightweight, reflective, flexible deployment
of very large surface areas, as discussed by Clarke
(ref. 3) and Anderson (ref.1); (2) Starprobe is a
mission being considered at NASA-JPL which would send a
spacecraft close to the sun, and future follow-on
Sungrazer missions may go even further: into the corona
of the sun, requiring structural stability at extreme
temperatures; (3) unmanned interstellar probes, as
outlined by Jaffe (ref. 5) and Mallove (ref. 9), powered
by nuclear fusion require a minimum deadweight ratio
(fraction of non-payload mass remaining after all fuel
is expended) and minimum molecular weight of exhaust
material.

In many cases, the preferred solution is the utilization of unusual materials. In the three examples above, solutions include: (1) monatomic layer ion sputtered deposition of metal on a substrate subsequently etched or sublimed away as described by K. Eric Drexler (ref. 4); (2) tungsten carbide, rhenium, and other extreme refractory materials for the structural components of Starprobe successors; (3) The fuel and the structural components of a fusion probe being one and the same. Among contenders, beryllium (molecular weight 8) is rather difficult to vaporize, leaving the prime choices as either water ice (molecular weight 18) or lithium (molecular weight 6) stiffened by boron (molecular weight 11) or carbon (molecular weight 12) fibers, being vaporized, ionized, and expelled as reaction mass until no structural components remain besides the payload and now-useless engine.

In the last case, recent analysis by J. B. Stephens et. al. at NASA-JPL and this author, as popularized by Moser (ref.12), suggests that even hydrogen ice (molecular weight 2) can be stiffened by admixture of fibrous or particulate material far beyond its normal pliability -- about the same as butter. Hydrogen ice can also be adequately protected against sublimation by very modest insulation. A one meter radius sphere of Hydrogen ice, insulated by a centimeter of low-density Hydrogen ice fluff and one centimeter of layered reflector, can last ten years in Earth orbit.

Each of these cases, all feasible within the next 30 years, raises further material-related concerns.

(1) What is the best metal for solar sail deposition in strength/weight tradeoff of ultra-thin films, and to what extent can weight be further reduced by perforation with holes smaller than the wavelength of light? What is the ideal disposable substrate? How can enormous numbers of microscopic holes best be engineered? Aluminum has been recommended, but additional analysis is required.

Dr. Robert L. Forward assumed aluminum could be used for a laser-propelled round-trip interstellar lightsail (ref. 7). But, as Geoffrey A. Landis pointed out (ref. 10), achievable thrust is limited by the maximum acceptable temperature that the sail attains by inadvertant absorption of light.

Landis ignores reflectivity and high-temperature tensile
strength for sail metals, using a figure of merit of
melt temperature divided by density, normalized for
aluminum (T = 940°K, density = 2.7 grams/cm^3) as Al=1.
Other metals have superior figures of merit, including
boron (3.6), beryllium (2.8), scandium (2.1), and
titanium (1.5). Richard Feynman (ref. 6) pointed out
that scandium was hitherto unique among elements in
having NO known useful applications. Beryllium and
scandium are also of perversely low relative abundance
in the Solar System -- see the zig-zag graph in New
Scientist, (ref. 13). Since beryllium (T = 1550°K,
density = 1.8 grams/cm^3) is also very reflective, Landis
considers it the best metallic sail material.

Provocatively, Landis compares transparent nonmetallic
dielectric materials, which can be deposited as
quarter-wavelength thin-film reflectors. Forward
suggested an 8-layer stack alternating diamond [T >
3500°K] with vacuum, as per Forward (ref. 8). Materials
with good figures of merit include diamond (2.41),
silicon carbide (2.65), zinc sulfide (2.35), tantalum
pentoxide (2.5), zirconium dioxide (2.15), and silicon
dioxide. Furthermore, if the incident laser light is
infrared or ultraviolet instead of visible, then silicon
(3.5 at 1200 nm) and lithium fluoride (1.45 at 130 nm)
become viable candidates. silicon carbide is judged to
be best, but any of these materials offers accelerations
"orders of magnitude higher than those achievable with
metal films":

Diamond, SiC, ZnS, Ta$_2$O$_5$, ZrO$_2$, SiO$_2$, Si, LiF

Diamond thin-film can be made by glow-discharge
decomposition of methane; tantalum pentoxide, zirconium
dioxide, and zinc sulfide are commonly deposited as
thin-film for optical coatings by electron beam
evaporation; silicon carbide is currently grown by
epitaxial deposition on silicon, with the silicon
substrate capable of being "etched away to leave a
free-standing film ... eminently suitable for a
small-scale demonstration" according to Landis (ref.
10). It isn't clear if LiF would make a suitably strong
free-standing film.

The solar sail concept represents a spacecraft which
needs no fuel, as fictionalized by Clarke (ref. 3), and
has historical/ political significance as shown by

Anderson (ref. 1) and Uphoff and Post (ref. 18). Refinements to the concept give it an almost poetic elegance, as in the unique presentation co-authored by Ray Bradbury and this author (ref 2).

(2) What are the optimal refractory materials for Starprobe successors, and how can they best be combined and engineered? Some particular materials can be easily manufactured from in situ regolith on the lunar surface:

Al_2O_3, CaO, MgO, TiO_2, SiO_2, Ti_5Si_3, Cr_2O_3, K_2TiO_3

Problems remain to be solved. What are the optimal mixtures of these materials (and others, such as the spinels)? Is the moon an appropriate site for materials extraction and processing for near-sun spacecraft components? How may passive refractory insulation and dynamic cooling best be combined? What is the optimum refractory geometry? Robert Waldron (ref. 19) suggests a sharply tapered wedge pointing toward the sun for optimal combination of reflection angle and radiator surface area.

(3) What are the structural limits of fiber-stiffened water ice, hydrogen ice, and lithium? Is it preferable to filter out the fibers, adding them to the deadweight, or to add engine weight to allow them to also be ionized and added to the exhaust? And, in the case of a water-ice fusion spacecraft, can we legitimately refer to this as the ultimate steamship?

2.0 HYDROGEN ICESHIP: DETAILED EXAMINATION

This section of the paper concentrates on the hydrogen ice spacecraft concept, and consists of an introduction, thermal analysis, experimental results, conclusions, and suggestions for future research.

Much of this analysis was contributed by James Salvail, of SETS, Inc. Honolulu.

Rather than having astronauts perform extravehiclular activity to chip off chunks of hydrogen ice for fuel, we visualize a spacecraft made of a structural cluster of hydrogen ice spheres which can be robotically detached, one at a time as needed, and melted or slushified in a conventional fuel tank. I have expounded on this at greater length, with an extended bibliography on

hydrogen ice and slush in another paper (ref. 15).

2.1 Hydrogen Iceship: Introduction

Visualize a bunch of grapes. Replace each grape with a cocktail onion. Our configuration for a hydrogen ice spaceship (the bunch) can be modelled as a cluster (connected to a common stem) of concentric metal spheres (onions) each of which has hydrogen ice (onion pulp) filling the spaces between its spherical surfaces (onion skins).

Most of the mass of the spacecraft is composed of these spheres, with the mass of the engine, avionics, payload, and so on comprising a much smaller fraction. The spheres are designed to provide some structural capability and to maintain fuel in solid form until needed; then they are liquefied or slushified for propellant usage. This is conceptually similar to the scene in the Marx Brothers' film "Go West", where Groucho, Harpo, and Chico feed the furnace of a steam locomotive with boxcar slats, and then demolish and burn the caboose.

Concentric spheres (within a single "onion") are connected to each other by at least two rods made of a material that has very low thermal conductivity, such as hard rubber. This is necessary so that the spheres above the instantaneous level of the subliming ice surface do not move relative to each other. The outer shells are made of a highly reflective material, such as aluminized (more easily ionized in propulsion: lithium-ized) mylar, thick enough to provide reasonable structural integrity. The inner spheres are made of the same materials, but much thinner (<<0.1 cm), as they are merely radiation shields.

The radiation shields and outer hulls must contain enough sufficiently sized holes or pores so that sublimed hydrogen molecules are quickly lost into space. The evacuated spaces between the slowly receding ice surface and the outer hulls thus have negligable gaseous heat conduction because the gas is very rarified. Gas flux is small enough (barring close flyby of the sun, nuclear explosions, or laser heating) that heat convection is also negligible. Under the listed abnormal operating conditions, gaseous conduction/convection would still be much smaller than radiative heat

transfer.

The effects of varying sphere radii, radiation shield number/spacing, outer hull albedo, and external environment are investigated to optimize the design for cost, size, and lifetime.

2.2 Hydrogen Iceship: Thermal Analysis

Thermal analysis consists of temperature calculations for outer hull, radiation shields, fixed radii from centers, and (crucially) at ice surfaces. Hull and shields are sufficiently thin and heat conductive as to be effectively isothermal through their thicknesses.

The energy balance at the outer hull consists of incoming solar radiation, emitted radiation from both sides, incoming radiation from the adjacent lower surface, and downward gaseous heat conduction. The two sides of the outer hull have, in general, different albedos and emissivities (i.e. painted black externally for visual stealth, as the low temperature already offer IR-stealth). These effects are described by:

$$E_m Sb\, T_{i,j}^4 + E_b Sb\, T_{i,j}^4 - f_b (1-A_m) E\, Sb\, T_{i-1,j}^4 - K\frac{dT}{dr} = \frac{(1-Ab)Sc}{4R^2}$$

Where E_m is the emissivity of the natural metallic surface, E_b is the emissivity of the outer surface (possibly black), unsubscripted E is the emissivity of the adjacent lower surface. If the lower adjacent surface is a radiation shield, then $E=E_m$. If the lower adjacent surface is the ice surface, then $E=E_h$, the emissivity of the ice. A_m is the albedo of the natural metallic surface. T is temperature, with subscripts i and j denoting depth and time. f_b is a geometric factor accounting for the smaller area of the adjacent inner surface. Sb is the Stefan-Boltzmann constant. Sc is the solar constant at 1 AU (Astronomical Unit). K_g is the gaseous thermal conductivity of hydrogen. r is the radial coordinate (from the center of the ice sphere). R is the heliocentric distance in AUs. The factor 4 in the right hand solar insolation term reflects the assumption of rapid rotation. Constant values are given in section 2.3. This equation, and a related one for the moving ice surface (with an energy balance including upward radiation from the ice surface, downward radiation from the adjacent metal surface, heat conduction into the ice, and the latent heat energy due to sublimation) are the basis for the results of section 2.3.

2.3 Hydrogen Iceship: Computer Simulation Results

Computer simulation based on the preceding analysis calculated temperature at outer surface, radiation shields, surfaces and interior of the hydrogen ice. Ice surface temperature allowed derivation of hydrogen gas flux and radial position of the receding ice surface as a function of time, and thereby deriving hydrogen ice lifetime. Various runs determined the effects of radiation shields, outer albedo, and outer hull radius, in normal conditions and in a simulated nuclear blast. Kirchoff's law was assumed for metallic and ice surfaces. Parameter values are as listed below:

Property/Parameter		Value
A	Vapor pressure constant	6.17×10^9 dynes/cm^2
B	Vapor pressure constant	$149.44\ ^\circ K$
A_m	Albedo of metal	0.95
A_h	Albedo of hydrogen ice	0.65
E_m	Emissivity of metal	0.05
E_h	Emissivity of hydrogen ice	0.35
C_h	Specific heat of hydrogen ice	2.7×10^7 erg/g-$^\circ K$
D_h	Density of hydrogen ice	7.06×10^{-2} g/cm^3
K_h	Thermal conductivity of ice	1×10^7 ergs/cm-s-$^\circ K$
H_s	Latent heat of hydrogen ice	6.2×10^9 ergs/g
S_c	Solar constant at 1 AU	1.3928×10^6 ergs/cm^2-s
T_i	Initial temperature of ice	$5^\circ K$
M	Molecular weight of hydrogen	2.0 g/g-mole
Sb	Stephan-Boltzmann constant	5.6×10^{-5} ergs/cm^2-s-$^\circ K$
R_u	Universal gas constant	8.315×10^7 ergs/mole-$^\circ K$

First, a 1 meter radius sphere with 50 radiation shields spaced 2 centimeters apart and natural metallic surface was simulated. The ice remained nearly isothermal at the initial temperature of $5^\circ K$, with a negligible temperature gradient and a near-constant mass flux of 17.3 nanograms/cm^2-sec. The outer hull remained at a temperature of $236^\circ K$ at 1 AU from the sun. After a simulated 10 years, the sphere had shrunk to 21 cm in radius, and the total lifetime was roughly 12 years.

Reducing the radiation shields from 50 to 10 had no effect. Painting the outer surface black (albedo = 0 for stealth) gave a tripled mass flux of 53.8 nanograms/cm^2-sec, a surface temperature of $5.2^\circ K$, and a reduced lifetime of 4.2 years.

At 0.1 AU from the sun a 50-shield 1 meter shiny sphere stays at $5.81^\circ K$, with a mass flux of 1.06 micrograms/cm^2-sec, and a lifetime of 75 days. With 10

shields, a 1 meter shiny sphere stays at $6.39^{O}K$, with a mass flux of 10.5 micrograms/cm^2-sec, and a lifetime of 35 days. Hence radiation shields are important for larger thermal loads, such as would occur if the hydrogen iceship mission began with a gravity assist swingby close to the sun.

The thermal effects of nearby nuclear detonation were simulated as a temporary change in heliocentric distance from 1.0 AU to 0.01 AU (where the radiative equilibrium temperature for a black body is $2808^{O}K$) for 20 seconds. If the outer metallic coat doesn't melt at the maximum temperature attained ($2361^{O}K$), then the hydrogen ice adjacent to the outer surface peaks at $8.73^{O}K$, with a gas flux of 4.7 milligrams/cm^2-sec, decreasing after 10 minutes to $5.85^{O}K$ (ten shields) or $5.79^{O}K$ (fifty shields), at which time the ice has receded 2.5 cm.

All other things being equal, the lifetime of a hydrogen ice sphere was found to be directly proportional to the first power of the the initial radius. Thus, a 2 meter radius sphere has a 24 year lifetime at 1 AU, and 2 years at 0.1 AU. For deep space missions, loss becomes rather small for spheres several meters in radius.

Similar thermal analyses have been performed by Hustvedt for slab and cylindrical geometries (ref. 9).

2.4 Hydrogen Iceship: Summary of Concepts

The greatest advantage for a hydrogen ice spacecraft is obtained if the craft is an unmanned monolithic composite solid cryogen with embedded insulation and superconducting avionics. As disclosed by J. Stephens at JPL (who generated the original concepts in 1984 and 1985, while in communication with this author), the primary intellectual properties for patent purposes are:

(1) Ice embedded insulation,
(2) Vapor cooled insulation,
(3) Isomer conversion catalyst integral with insulation (activated carbon),
(4) IR photon reflective and vapor conductive insulation (variable mesh cloth multi-layer insulation),
(5) Vapor cast crystalline hydrogen ice using nuclear magnetic resonance heating of non-crystalline ice,
(6) Self-forming filamentary insulation from dispersed particles in the ice that cohere due to ice cleaning.

Attributes of the primary intellectual properties are:

(1) Unitized design; ice is the cryogen, structure,
    propellant, shielding, absorber, power source,
    window, and insulation support during launch,
(2) Superconducting temperature cryostat (<5 $^{\circ}$K for
    Hydrogen),
(3) Self-insulating solid cryogen,
(4) Long lifetime in earth orbit,
(5) Low cost materials (<$10/lb),
(6) Low cost fabrication (casting process),
(7) Low launch cost (withstand high acceleration
    forces),
(8) Low cost operation (efficient superconducting
    solid-state system),
(9) Acoustically quiet (no moving parts) so good for
    very accurate optics or interferometry,
(10) Thermally stable (large thermal capacity well
    insulated),
(11) High density ice vapor cast and used at same
    temperature avoiding shrink stresses in
    insulation and components embedded in ice.

Ancillary intellectual properties enabled by the
primary concepts are:

(1) Vapor cooled refractory insulation,
(2) Neutron absorbing cryogen (Hydrogen),
(3) Microwave absorbing ice/insulation,
(4) Microwave reflecting ice/insulation.

The advantages of the ancillary concepts are:

(1) Laser tough shielding,
(2) Neutron tough shielding,
(3) Neutral and charged particle beam tough shielding,
(4) Radar stealth,
(5) Superconducting phased array radar.

Concepts enabled by Cryostat primary and secondary
concepts are:

(1) Propulsion and electric power systems:
    (a) Solar powered ion rocket and superconducting
        magnet power generator and storage system,
    (b) Magnetohydrodynamic detonation wave ion rocket
        and superconducting magnet power generator and

storage system (detonate layers of solid
oxygen alternated with solid hydrogen);
(2) Guidance and control:
    (a) Superconducting computer,
    (b) Superconducting gyroscope,
    (c) Superconducting magnet attitude control,
    (d) Superconducting radio and antenna;
(3) Launch forces resistant structure:
    (a) fiber reinforced composite ice;
(4) Remote sensing synersensory systems in phased arrays
in Cryostats orbiting in formation:
        (a) Synthetic aperture superconducting phased
array radar,
        (b) Synthetic aperture superconducting phased
SQUID array Magnetic Anomaly Detection,
        (c) Synthetic aperture superconducting phased
SQUID array Gravimeter,
        (d) Synthetic aperture superconducting phased
array Altimeter,
        (e) Blue-Green synthetic aperture
superconducting phased array lidar,
        (f) Thermal IR telescope spectrometer.

This astonishingly rich set of concepts of Jim Stephens
is only moderately challenged by demands of the
interplanetary or interstellar regime, as opposed to the
near-Earth applications originally envisioned.

Individual hydrogen ice spheres can be cheaply orbited
by small boosters (or electromagnetic propulsion, most
recently discussed by Wallich, ref. 20), and later
assembled into a large spacecraft. Solid hydrogen is
inherently safer than liquid hydrogen.

The spheres can have embedded avionics, providing
distributed redundant capability for the spacecraft at
superconducting temperatures.

Once assembled, the low accelerations typical of an ion,
fission, or fusion propulsion would not endanger the
inherently low tensile strength of hydrogen ice as a
structural material. The hydrogen ice spheres would be
between the crew (or payload) and the nuclear
propulsion, providing neutron-absorbant shielding at no
extra cost.

Space exploration applications include:

(1) Sungrazer,

(2) Outer planet explorer,

(3) 1000 AU mission (TAU),

(4) Subterranean radar mapping of planets,

(5) Manned Mars Mission,

(6) Propellant transfer and storage for Space Station refueling depot (ref. 15),

(7) Interstellar mission.

2.5 Hydrogen Iceship: Future Research

Future areas of hydrogen iceship analysis include:

(1) Comparisons of fiber-stiffened water ice, carbon dioxide, lithium, or other alternatives to hydrogen ice;

(2) Experimental determination of strength, stiffness, etc. for hydrogen ice with various fiber compositions (boron, carbon);

(3) Structural design optimization for various types of propulsion system;

(4) Exploration of the concept of detonation wave propulsion/attitude control with alternating layers of hydrogen ice and oxygen ice, or solid ozone with an ISP of 494 according to Stwalley (ref. 16);

(5) Sensor capabilities of phased arrays of embedded cryogenic detectors in a fleet of coorbiting iceships;

(6) Relativistic kinematics of multi-staged interstellar iceships, following the mathematical treatments of Jaffe (ref. 5), and other papers as compiled by Mallove (ref. 9);

(7) Extension of hydrogen ice concepts to hydrogen metal, which might remain solid at low pressures and have an ISP in the thousands, taking into account results announced by Peterson (ref. 14), Stwalley (ref. 16), and Thierschmann (ref. 17).

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