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SPACE MANUFACTURING UNIQUE TO ZERO GRAVITY ENVIRONMENT

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16. Abstract

Manufacturing processes are reviewed and three categories are established: (1) processes which work in orbit, (2) processes which work much better in orbit, and (3) processes which work only in orbit. Two unique process groups are discussed; (1) buoyancy and thermal convection sensitive processes and (2) molecular forces controlled processes. The range of recommended products includes heterogeneous radiation shielding, isotope fuels, high strength fittings, high purity reactor casings, hollow precision balls, ultra thin membranes for "solid state chemistry," optical components, multilayer curved components, and controlled density materials. These products have unique new features and can be made only in extended zero "g" environment.

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SUMMARY

Manufacturing processes are reviewed and three categories are established:

1. Processes which work also in orbit.

2. Processes which work much better in orbit.

3. Processes which work only in orbit.

The uniqueness of the last category rests on utilization of the low and zero gravity environment and two unique process groups are discussed:

A. Buoyancy and thermal convection sensitive processes.

B. Molecular forces controlled processes.

Some basic physical data are shown and seven basic processes are described. Examples of unique products are given for each of the process groups. The range of recommended products includes heterogeneous radiation shieldings, isotope fuels, high strength fittings, high purity reactor casings, hollow precision balls, ultra thin membranes for "solid state chemistry," optical components, multilayer curved components like bullet proof windows, and controlled density materials for armor plates, turbine blades, high temperature structures, and sonar components. All these products have unique new features and can be made only in extended zero "g" environment; this means these are not cost trade-off cases of terrestrial versus orbital processing.

Some philosophy is offered by comparing the discovery of the vacuum during the 17th Century with the space age achievement of a permanent zero gravity environment in orbit. While the possibility of producing a vacuum within our "Ocean of Air" opened the technical period of the steam engine and vacuum tube, one can state that the new possibility of escaping from our highest order environment, the "Ocean of Gravity," will open a new phase in our technical history.

INTRODUCTION

The development of the capability to manufacture products in space can be approached in the same manner we use on earth, as depicted in Figure 1. The lower portion of Figure 1 shows the potential markets or customers for manufacturing in space. Space maintenance, repair, modification and assembly are one of the objectives frequently mentioned to support our projected long term operations in space.

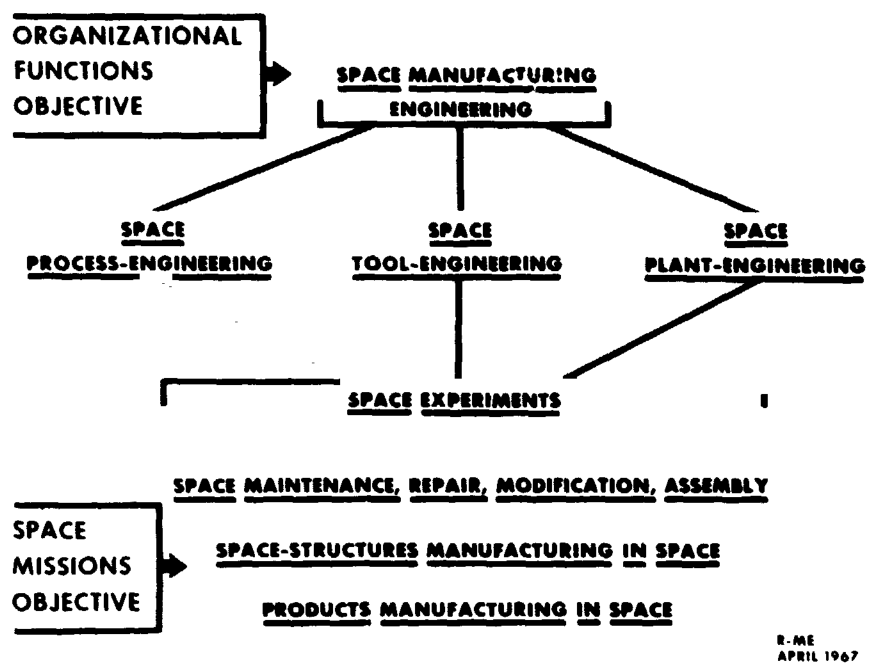

Fig. 1

The manufacture or erection of structures in space is another objective which is considered to support our operations. A third, new objective is to produce unique products in space for use on earth. In other words, produce a product to sell to a customer. Which processes can be developed in space to produce these unique products? Which products should be made? These are questions we need to answer first. Therefore, in this presentation I will rather concentrate on space process engineering and try to demonstrate that unique products can be manufactured in space. Only at the end I will mention some general views about space tool and space plant engineering and outline the plans for development of these new areas of technology.

SPACE PROCESS ENGINEERING

To get a better understanding of the processes that might be used in space, we reviewed the terrestrial manufacturing processes. There are about a dozen basic processes with subgroups as shown in Figure 2.

TERRESTRIAL MANUFACTURING PROCESSES

CASTING	EXTRUDING	FORGING	SINTERING	FORMING	MATERIAL REMOVAL
MOLDING	HOT	CLOSED DIE	POWDER METALLURGY	COLD WORKING	MACHINING
DIE CASTING	COLD	OPEN DIE	PLASTICS	HIGH VELOCITY	ELECTRO CHEMICAL
CENTRIFUGAL		UPSETTING	COMPOSITES	FILAMENT WINDING	ELECTRO DISCHARGE
CONTINUOUS		COLD HEADING	HOT PRESSING	VAPOR DEPOSITION	ABRASIVE
				ELECTRO FORMING	CHEM-MILLING
				GAS PRESSURE BONDING	VAPORIZATION-EMR
				PLASMA ARC SPRAYING	ULTRASONIC

HEAT TREATING	SURFACE FINISHING	STERILIZATION & CLEANING	JOINING	ASSEMBLY
VACUUM FURNACE	COATING	HEATING	WELDING	GAGING
ELECTRON BEAM	PLATING	CHEMICAL	DIFFUSION BONDING	INSPECTION
INFRARED	VAPOR DEPOSITION	MECHANICAL	ADHESIVE BONDING	NON DESTRUCTIVE TESTING
LASER	VACUUM METALLIZING		MECHANICAL	ALIGNMENT
	ELECTRO DEPOSITION		ELECTROMAGNETIC	

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Figure 2

In screening these processes for space manufacturing applications, you can divide them into categories as shown in Figure 3.

SPACE MANUFACTURING PROCESSES

CATEGORY I
APPLICATION OF EXISTING TERRESTRIAL PROCESSES FOR SPACE MANUFACTURING
(WORKS ALSO IN ORBIT)

CATEGORY II
OPTIMIZATION OF TERRESTRIAL MANUFACTURING PROCESSES TO THE SPACE ENVIRONMENT
(WORKS MUCH BETTER IN ORBIT)

CATEGORY III
DEVELOPMENT OF UNIQUE SPACE MANUFACTURING PROCESSES
(WORKS ONLY IN ORBIT)

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Figure 3

The first category concerns all the processes which would work in orbit as well as they do on earth. The second category concerns all processes which would work much better in orbit because of the environment. The third category of processes are actually the interesting ones, and these are the ones which will be emphasized.

CATEGORY I

APPLICATION OF EXISTING TERRESTRIAL PROCESSES FOR SPACE MANUFACTURING

- EVALUATION FOR SPACE USE
- SELECTION OF THE MOST PRACTICAL CANDIDATES

EXAMPLES:
ELECTRON BEAM WELDING EXPERIMENT
EXOTHERMIC TUBE BRAZING EXPERIMENT
HIGH ENERGY CUTTING AND FORMING EXPERIMENT
BONDING EXPERIMENT
DIFFUSION BONDING EXPERIMENTS
VAPOR DEPOSITION EXPERIMENTS
LASER WELDING, CUTTING, AND DRILLING EXPERIMENTS

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Figure 4

Category I, as shown in Figure 4, is the application of existing terrestrial processes for space manufacturing. These processes would be evaluated for space use and the most practical candidates would be selected for flight experiments. Processes like electron beam welding, exothermic tube brazing and high energy cutting were selected because they have a high assurance of working. These are in fact approved experiments for the Workshop mission. Bonding experiments, diffusion bonding experiments, and vapor deposition are all experiments which are under consideration. They were selected because we would not expect any problem with these processes working in the space environment. Actually the purpose of such experiments is to verify that these processes will work in space and to gain the operational capability for Space Maintenance, Repair and Modification tasks.

CATEGORY II

OPTIMIZATION OF TERRESTRIAL MANUFACTURING PROCESSES TO SPACE ENVIRONMENT

- QUALITY IMPROVEMENT THROUGH
  - HIGHER REFINEMENT
  - SMALLER PROCESS VARIATIONS
  - SMALLER TOLERANCES
- PROCESSING COST SAVINGS THROUGH
  - SIMPLER FACILITIES
  - SIMPLER TOOLING
  - SMALLER PAYLOAD VOLUME FOR IN ORBIT MANUFACTURED STRUCTURES BECAUSE OF SAVING OF MECHANICAL DEPLOYMENT SYSTEMS
  - NO SIZE LIMITATION OF PRODUCTS BY THE GIVEN PAYLOAD DIMENSIONS

EXAMPLES
VACUUM MELTING AND CASTING
LEVITATION MELTING
HEAT TREATMENT WITH PRECISE HEATING AND CHILLING RATES
VAPOR DEPOSITION, ELECTRICAL AND CHEMICAL, FOR SOLID STATE ELECTRONICS
CRYSTAL AND WHISKER GROWING
THIN FILMS SURFACE TENSION DRAWING FOR THERMAL PROPERTIES
SEMI-CONDUCTORS, MICRO-ELECTRONICS
EXTRUSION OF LARGE THIN SHAPES FOR ONE PIECE SPACE STRUCTURES
WIRE FENCE WEAVING MACHINE FOR ONE PIECE LARGE SPACE CAGES

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Figure 5

Category II processes, as shown in Figure 5, are those processes which would work much better in orbit because of the space environment. Manufacturing processes requiring a hard vacuum are naturals for the space environment. The vacuum of space, of course, is clean and of unlimited volume. Processes such as vacuum melting, casting, levitation melting and vapor deposition are all processes which work on earth, and we know the capabilities and restraints. Levitation melting is on earth only usable for very small amounts of conductive materials.

LEVITATION MELTING AT 1g

POSITION CONTROL AT 0g

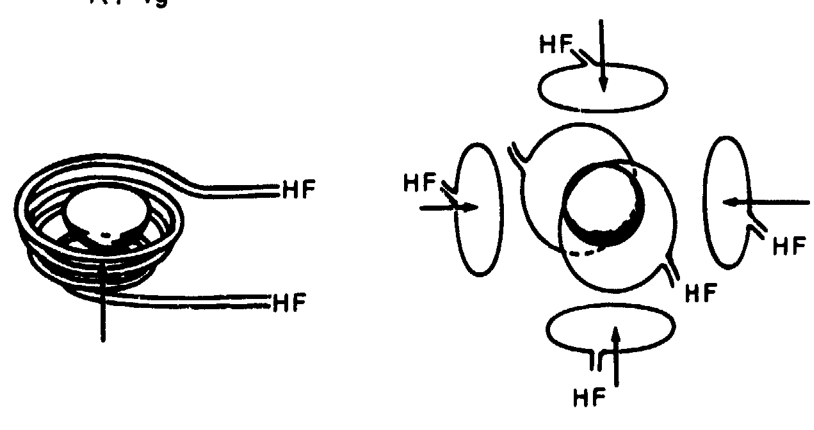

Figure 6

Figure 6 shows how this process is adaptable to the zero gravity environment, where the high frequency coils serve as positioning control only. We know that cooling rates play an important role and also the contamination factor is limiting in our terrestrial processes. Included in these processes are crystal and whisker growing, and indications are that these processes will work much better in the zero gravity environment. Basically all of these processes must be traded off for cost effectiveness, and this is quite difficult to do at this point. For building space structures, there are such things as extrusion of structural shapes. For example, glass may be extruded into large and long pipes for components in space structures. Another possibility would be a wire weaving machine, which would enable us to weave inclosures of large size in space. This may be easier than fabricating them on earth and then being faced with the problem of packaging and deploying them. These are trivial examples of well-known terrestrial processes which may be used. They are mentioned to indicate that we need not look just at the complicated processes but should try to look for the simple, practical processes.

CATEGORY III

DEVELOPMENT OF UNIQUE SPACE MANUFACTURING PROCESSES

- LOW AND ZERO GRAVITY PROCESSES
  - A BUOYANCY AND THERMAL CONVECTION SENSITIVE PROCESSES
    - 1 BLENDING OF MATERIALS OF DIFFERENT DENSITY IN PLASTIC MATRIX
    - 2 CONVERSION OF COMPACTED POWDERS AND COMPOUNDS INTO CASTINGS
    - 3 COMPOSITE CASTING
  - B MOLECULAR FORCES CONTROLLED PROCESSES
    - 1 COHESION OR SURFACE TENSION CASTING
    - 2. ADHESION OR LAYER CASTING
    - 3 BLOW CASTING
    - 4 CONTROLLED DENSITY CASTING
  - C COMBINED PROCESSES A AND B
- OTHER UNIQUE SPACE PROCESSES

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Figure 7

The Category III processes, as shown in Figure 7, are the truly unique ones. They are unique and cannot be duplicated on earth because they involve primarily processing in low and zero gravity conditions. Looking at the low and zero "g" environment, we can compare our situation now to what happened during the 17th Century with the discovery and development of vacuum processes. Until then every process was at or above one atmosphere air pressure. The development of vacuum processes was actually delayed because of the Horror Vacui philosophy. Once this philosophy was overcome, such technological developments as the steam engine and the vacuum tube were made possible.

The discovery of the vacuum or rather of the fact that we can escape our "Ocean of Air" belongs to the history changing events. With the development of rockets which enable us to get into a steady environment of lower than one "g", we can extend and improve on free fall processes which on earth cannot last longer than a few seconds. Processes using less than one "g" are not new. For instance, to make shot during the Middle Ages liquid lead was poured through a screen, and as the droplets fell little lead spheres were formed in this free fall process. Today Minnesota Mining uses a free fall process to form the little glass spheres used in reflecting color for traffic signs and the glass micro balloons. There are other processes using free fall to make metal powders for example. The problem is that there is no practical way of extending this low gravity condition for longer than a few seconds on earth. With our capability to go into orbit, where we can escape from our highest order environment, the "Ocean of Gravity", we can readily see that any process affected by gravity could be drastically improved in space. An amendment of major environmental factors as shown in Figure 8 can rightfully be postulated.

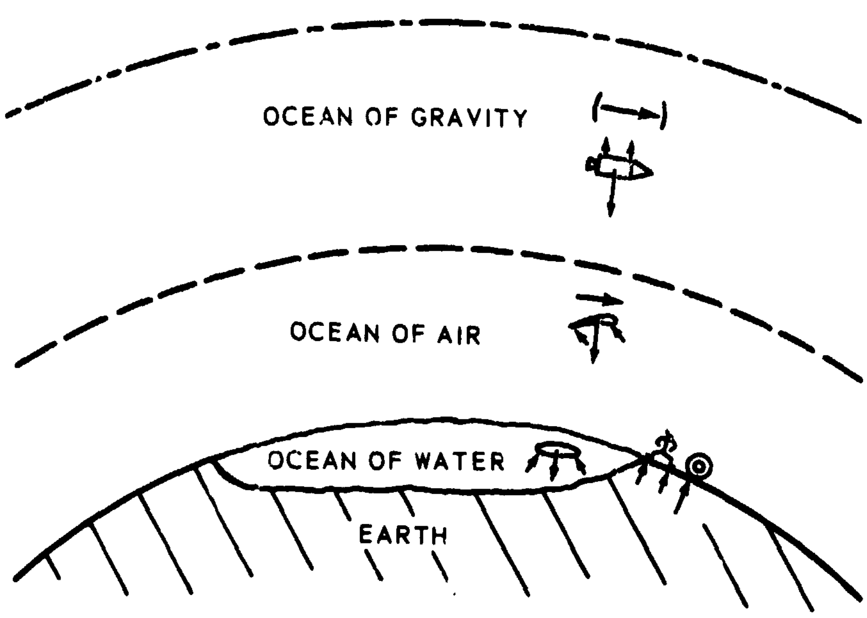

Figure 8

Processes sensitive to buoyancy and thermal convection would without doubt be basically changed and secondly in the absence of gravity molecular forces come into play and would become major processing factors. Figure 9 shows how different sand in water behaves. Figure 10 shows that a candle does not sustain burning, and Figure 11 demonstrates that the gravity field changes any thermal imbalance into a velocity field as is best seen at a cloud. Such very often violent mixing actions are ever-present at any phase change, like during the solidification of materials.

NEUTRAL BUOYANCY

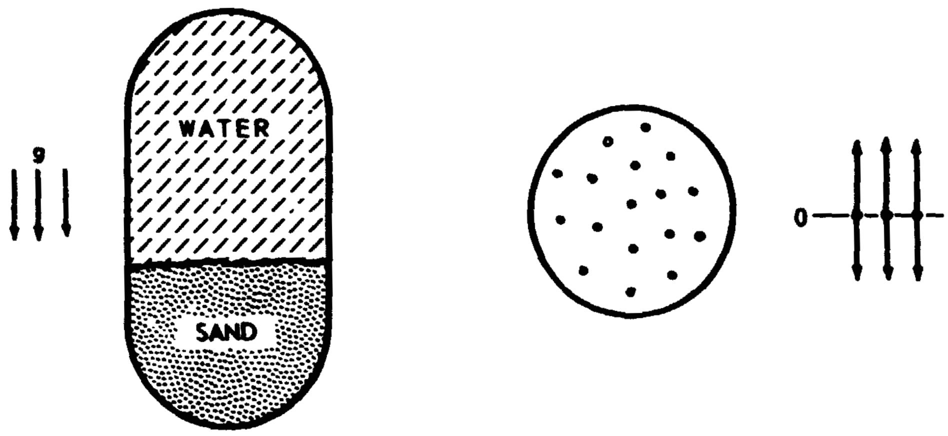

Figure 9

THERMAL CONVECTION

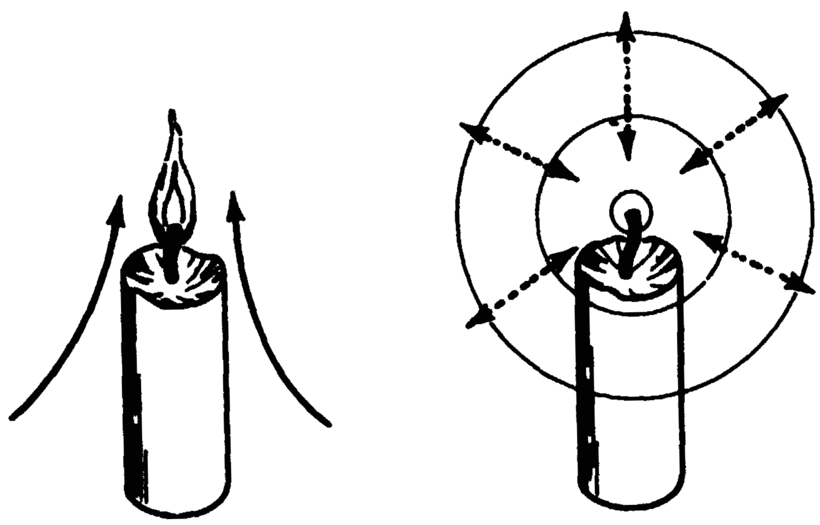

Figure 10

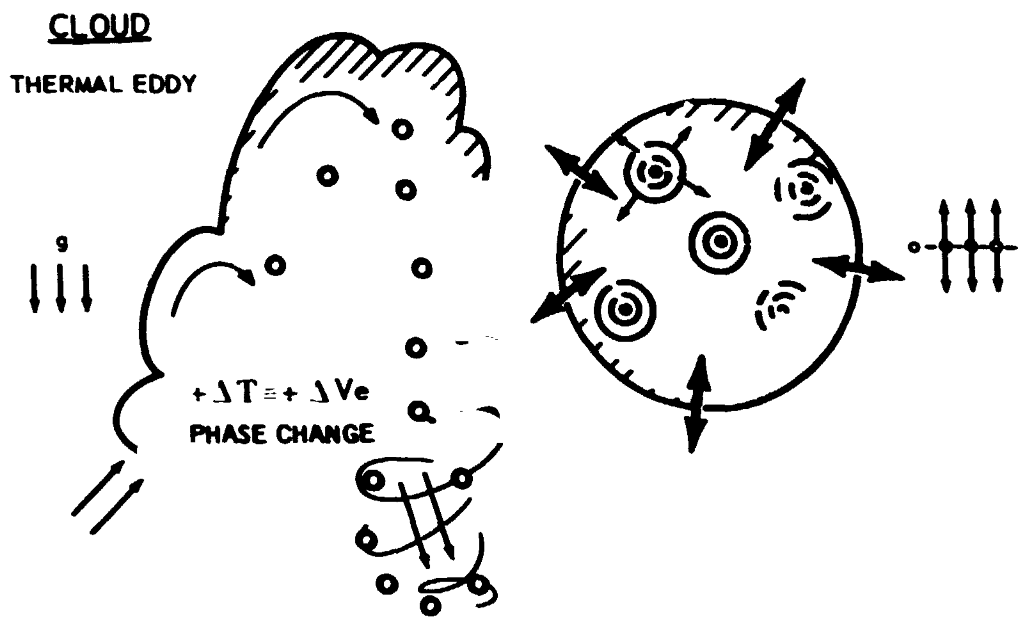

Figure 11

Before we can fully exploit the possibilities for processing in a reduced gravity environment, we must understand the implications. For instance, in our one "g" environment we melt metals and the low density material comes to the top. This is an advantage in purifying the metals. On the other hand, solidification and crystallization are irregular because of buoyancy and thermal disturbances so that the cast material is not good enough for many applications. We build factories to refine these irregular crystals by hot rolling, cold rolling, forging, etc., and then we machine the material to get it into the shape and size wanted. This of course requires a large investment and in fact is the major investment in industry, which can also be interpreted as a penalty for living in our "Ocean of Gravity". Now, if we can mix something into the liquid metal and we can use the zero gravity effect of no buoyancy and no thermal convection, it may be possible to obtain full properties in a cast metal. These are consequences which sound simple but could be far reaching.

In looking at some well-known facts found in physics books, we can see the possibilities of processing in zero "g". Figure 12 shows that the viscosity of water and liquid metals is of the same order of magnitude. Liquid lead is only twice as viscous as water, whereas a drop of engine oil is two thousand times as viscous as water. This chart shows that the surface tension of iron increases by a factor of 20 over that of water. We can also get an idea how fast liquid materials contract in zero gravity to form perfect spheres. A drop of water contracts from an irregular shape to a perfect sphere with a surface velocity of about 150 miles per hour. In the case of liquid iron, the velocity is nearly that of sound. This means that the molecular forces of surface

MATERIALS DATA FOR THE LIQUID STATE

MATERIAL	TEMPERATURE °C	SURFACE TENSION α DYN/CM	VISCOSITY IN POISE η DYN SEC/CM^2	DEFORM. RATE INDEX α/η CM/SEC	
WATER	18	73	0.011	0.7×10^4	150 MPH
MERCURY	20	465	0.021	2.2×10^4	
TIN	232	526	0.020	2.6×10^4	
LEAD	327	452	0.029	1.6×10^4	
COPPER	1131	1103	0.038	2.9×10^4	
IRON	1420	1500	0.040	3.7×10^4	
ENGINE OIL	20	15-30	10-20	1.5 – 3.0	
GLYCERIN	20	(20)	15	1.3	

DEFORMATION RATE V FOR A BODY OF THE SURFACE AREA A AND A DISTANCE BETWEEN SURFACES H.

$$\frac{dv}{dh} = \frac{F}{\eta A} = \frac{\alpha}{\eta}$$

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Figure 12

tension versus viscosity are so powerful that materials will assume the equilibrium shape of a sphere almost instantly. Of course this is valid only for small droplets because mass forces can be neglected. The message of this chart is clear that molecular forces become significant in the zero gravity environment of space. Since the molecular forces can be used as a means of processing material, we would expect that tolerances will be improved by several orders of magnitude. To machine something within ten thousandths or maybe 25 millionths of an inch is quite expensive. Because we are talking about molecular forces and sizes, we may be able to produce spheres in zero "g" that are accurate within angstrom units.

Figure 13 shows the relations in a soap bubble or pressure vessel between the pressure which can be contained, the hoop stress and the diameter. The smaller the diameter, the higher the pressure capability if the wall thickness is kept constant. In the case of a very small pressure vessel like a droplet of water 10^{-6} centimeters in diameter, the hoop stress is produced by the surface tension of water. This is very small but still in such dimensions produces a large internal pressure of 5,000 psi. This is another indication of the powerful nature of the forces available for processing. In a droplet of iron the increase in surface tension by a factor of 20 would yield a reaction pressure of 100,000 psi. Looking at the possibilities from an engineering viewpoint, we try to determine how these phenomena can be used in manufacturing.

INTERNAL REACTION PRESSURE CAUSED BY SURFACE TENSION

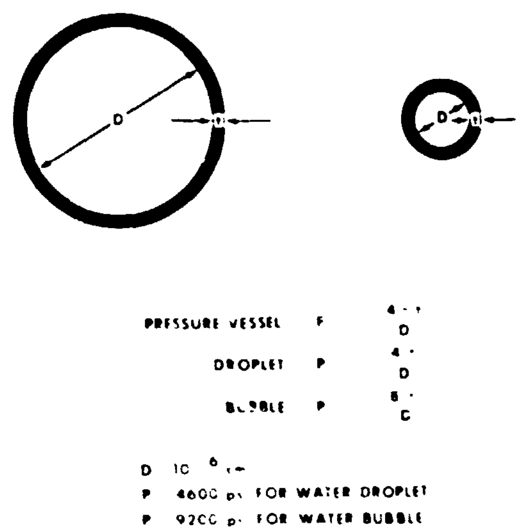

Figure 13

In addition to these molecular forces, we have other possibilities which may be helpful. One is in the solidification of metals. Solidification mechanics is a big and complicated science. In Figure 14 we show some basic concepts that may be possible in zero gravity. First of all we can cool materials without the disturbing convection currents and we can eliminate contamination by keeping the materials in a free floating condition. Secondly, we may be able to supercool a liquid metal because there is no disturbance. Third, we may be able to control nucleation by the dispersion of powders within the liquid metal. We have shown that liquid metals are as thin as water, and to be able to mix particles in a liquid metal on earth is as hopeless as mixing sand in water under one "g" conditions.

ZERO G SOLIDIFICATION CONCEPTS

1 CONTROLLED RADIATION COOLING WITHOUT THERMAL EDDIES

2 SUPER COOLING OF LIQUID PHASE

3 NUCLEATION CONTROL THROUGH SOLID POWDER DISPERSION

Figure 14

Now we will go into the Category III processes in more detail, Figure 15, giving examples of processes and product groups which may be developed.

CATEGORY	PROCESSES	PRODUCTS GROUPS
III A1 BLENDING	HIGH DENSITY PARTICLES IN PLASTIC MATRIX	HIGH ALTITUDE RADIATION SHIELDING FOR AIRCRAFT ELECTRONICS
	SOLID COMPOUNDS IN NON METAL MATRIX	NUCLEAR AND THERMAL HETEROGENEOUS SHIELDING STRUCTURE
III A2 POWDER CONVERSION	PARTIAL MELTING OF PRECOMPRESSED POWDERS AND COMPOUNDS	ISOTOPE FUELS
III A3 COMPOSITE CASTING	DISPERSION OF SOLID COMPOUNDS AND FIBERS IN METAL MATRIX	COMPLEX HIGH STRENGTH FITTINGS
		HIGH TEMPERATURE STRUCTURES
		HIGH STRENGTH BRAZING ALLOYS
		CERMETS
III B1 COHESION CASTING	FREE CASTING	SOLID SPHERES FOR BALL BEARINGS, OPTICAL COMPONENTS
	INERTIA CASTING	ELLIPSOIDAL AND OTHER BODIES OF REVOLUTION
	ELECTROSTATIC FIELD CASTING	HYBRID COMPUTER COMPONENTS
		STANDARDS FOR SHAPES
		LARGE OPTICAL BLANKS
		HIGH PURITY NUCLEAR REACTOR CASINGS

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Figure 15

The first group of processes concerns the blending of different density materials in either a plastic or metal matrix. An example of a product in this category came from General Dynamics. They have a requirement for shielding electronic components from the radiation environment to which the F-111 or any high flying aircraft is exposed. The radiation shielding is provided by a layer of fine metal powder. Because of the high density of the metal powder, it cannot be painted on, dipped on, or sprayed because it demixes from solution. Their solution was to make a tape and wrap the components. This is a very troublesome, unreliable and costly process. It looks like that under zero gravity a cost effective process for dipping or spraying such components could be developed. It is also possible that components of heterogeneous materials could be developed for nuclear and thermal shielding. These are unique applications of things which are not possible on earth.

The powder conversion process could be improved under zero gravity conditions, and processes such as the dispersion of fibers in metal matrix and the production of new types of isotope fuels would be possible.

A third category is composite casting, where high strength fittings and parts for high temperature structures could be cast directly, and novel configurations which cannot be machined can be achieved.

Figure 16 shows how cohesion acts on a liquid in zero gravity environment. Cohesion casting processes may be developed to free cast materials allowing them to assume perfect spherical shapes for ball bearings, spherical standards, etc. The surface conditions, dimensional accuracies and properties may be superior to those produced under terrestrial conditions. We reach a new level of precision. In this free floating condition it may be possible to spin the molten material to form perfect bodies of revolution or the shape of the material can be influenced with electrostatic fields to produce irregular but repetitive shapes.

COHESION - SURFACE TENSION

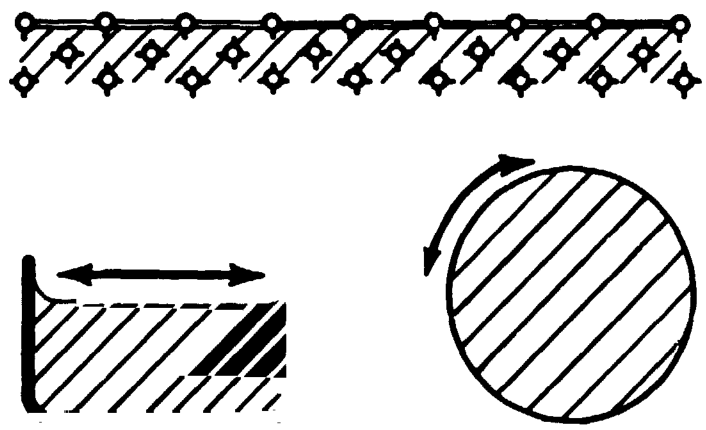

Figure 16

Figure 17 shows the principles of cohesion casting. Such bodies could possibly be used for standard shapes for hybrid computers to reproduce functions, to transform coordinate systems, etc. mechanically rather than electronically. The last two examples shown on the chart are probably more realistic at this point. The production of optical blanks larger than 35 to 40 inches in diameter by inertia or electrostatic casting would be feasible. Optical glass produced or processed under zero gravity conditions may exhibit lower inner stresses thus improving the performance. The machining or grinding of optical lenses is complex but may not be as critical in affecting the performance as induced stresses in the glass. This example was pointed out by Douglas, who is engaged in an Air Force project to develop large lenses for satellites. They are of the opinion that under zero gravity conditions it would be easier to support the glass and control the cooling process without inducing stresses. It may be feasible to return such lenses in the command module. A similar case is the casting of casings for nuclear fuel elements. If you have a perfect sheet of metal for a container, and you form it, you rearrange the molecular

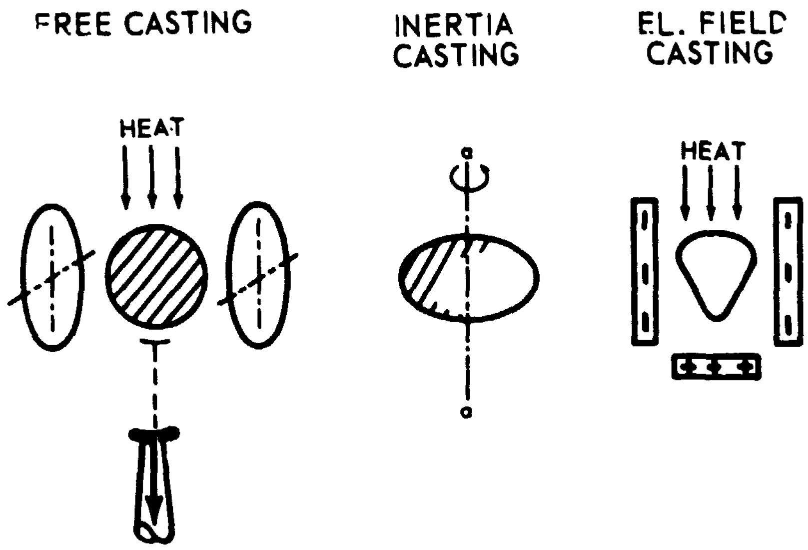

Figure 17

structure and the radiation lifetime goes down by an order of magnitude. Under zero "g" conditions, the casing material could be cast and you would increase the lifetime a hundred times. Casings for such fuel elements are not necessarily large and could be recovered with available equipment. Another novel process in combination with the free suspended super-cooled material is the shaping and directional solidification as shown in Figure 18.

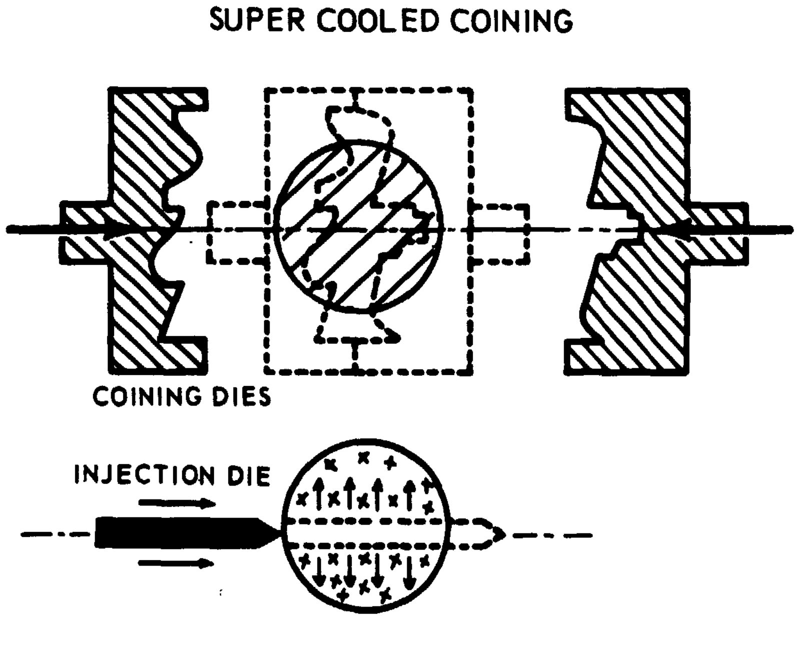

Figure 18

Adhesion casting and blow casting processes are shown in Figure 19. Figure 20 shows how adhesion between a liquid and a solid body acts in zero gravity environment. Adhesion casting may be described simply by the example of soldering. Under one "g" conditions if you apply too much solder it will drip off. Under zero gravity conditions relatively thick layers of material can be built up and would remain in place because of the adhesive forces.

CATEGORY	PROCESSES	PRODUCTS GROUPS
III B2 ADHESION CASTING	FLOATING OF LAYERS OF METALS AND NON-METALS INSIDE OR OUTSIDE A MOLD	MULTILAYER COATED ISOTOPES OPTICAL COMPONENTS SOLID STATE ELECTRONICS COMPONENTS
III B3 BLOW CASTING	EXPANSION OF INERT GAS INCLUSION IN CONTROLLED PRESSURIZED ENVIRONMENT (GASEOUS OR LIQUID)	HOLLOW SPHERES FOR BALL BEARINGS IN LARGE RADAR ANTENNAS, TILT WINGS, JET ENGINES OPTICAL COMPONENTS
	INJECTION OF GAS INTO MOLTEN MATERIAL IN CONTROLLED PRESSURIZED ENVIRONMENT	ULTRA THIN MEMBRANES FOR FILTERS AND SEA WATER DESALTING
	INERTIA AND ELECTROSTATIC FREE FORMING AFTER BLOWING	HOLLOW BODIES OF REVOLUTION AND OTHER SHAPES
	PARTIAL BLOWING THROUGH DIE CUTOUTS	CURVED SHAPES AND MEMBRANES
	COMBINATION WITH ADHESION CASTING	MULTILAYER SHAPES FOR DISTORTION FREE, RADIATION PROOF, BULLET PROOF WINDOWS AND STRUCTURES SOLID STATE CHEMISTRY COMPONENTS

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Figure 19

ADHESION - CAPILLARY FORCE

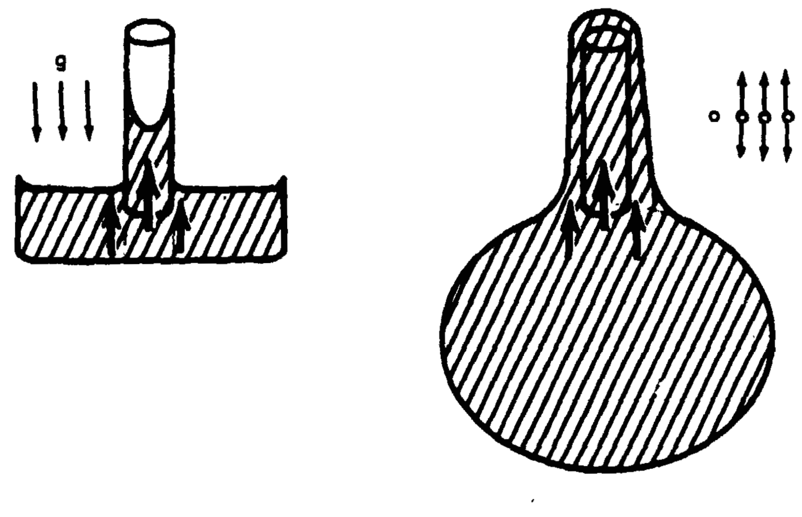

Figure 20

The implication is that it may be possible to float layers of metals and non-metals inside or outside a mold to produce parts, as shown in Figure 21. Adhesion casting processes may be applied to the coating of nuclear isotopes and optical components. The production of thin layer materials for solid state electronics may also be an important application of this process.

ADHESION CASTING

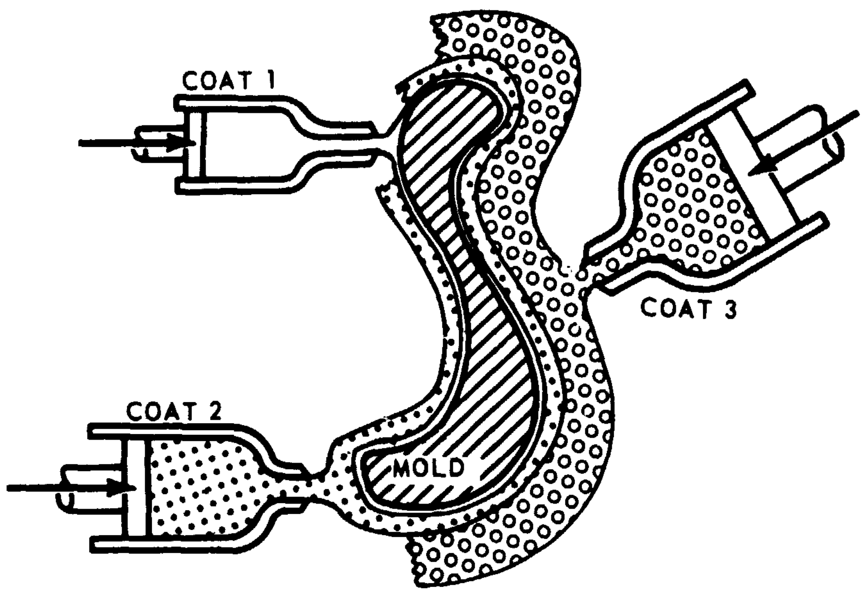

Figure 21

Blow casting is an area which may yield some interesting products. Basically we are talking about the production of bubbles from metals or non-metals as illustrated in Figure 22.

BLOW CASTING

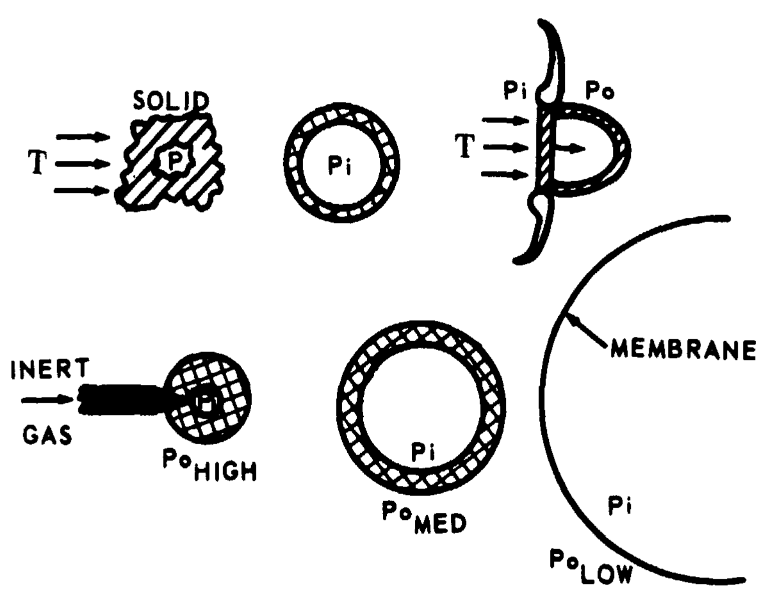

Figure 22

A soap bubble blown on earth is not stable because the liquid between the outer and inner surface tension layers drains under gravity, the surface tension layers touch and you have a brittle fracture case. Under zero gravity conditions stability is achieved, and you can blow bubbles from steel or any other material. The hollow steel sphere, for example, would fill a need of the Air Force, who has been looking for hollow ball bearings. These hollow balls are needed to reduce the mass inertia, to compensate for temperature gradients, and to increase bearing lifetime. It may also be possible to blow large thin wall bubbles three molecular layers thick to produce membranes of metals, glass or other inorganics.

Utilizing the adhesive and the cohesive forces, the liquid material can be drawn to thin wires, tubes and membranes free of crucible and draw die contamination. Figure 23 shows this in principle. These membranes would be extremely fragile but could be stacked up in layers to produce membranes for such things as sea water desalting. It may even be possible to develop "solid state chemistry", that is to reproduce functions with inorganics that the human body produces with organic materials.

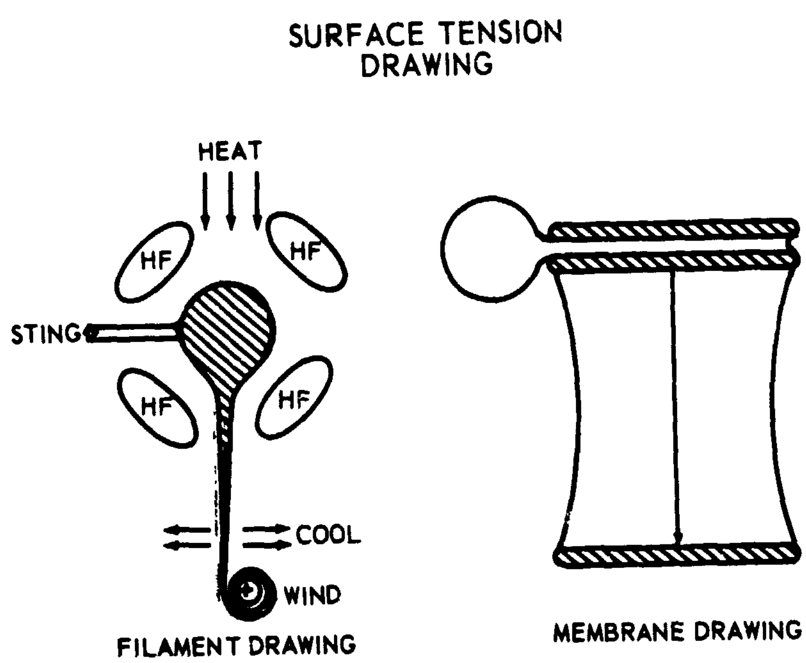

Figure 23

The last category, as shown in Figures 24 and 25, is called controlled density casting. By controlled density casting we are talking about foam materials or variations of foam materials. The stability of foam is determined by the same criteria as a soap bubble, so if we can eliminate the gravity effects which drain the liquids from around the gas, we can produce stable foams and can control the packaging density. Balsa wood and hickory are basically the same material but with different packaging densities. Nature grows things with inherited

CATEGORY	PROCESSES	PRODUCTS GROUPS
III B4 CONTROLLED DENSITY CASTING	CONTROL OF "PACKAGING DENSITY" BY DISPERSION OF INERT GAS INCLUSIONS PREPRESSURIZATION BEFORE DISPERSION DETERMINES BUBBLE SIZE SOLID COMPOUNDS DETERMINE DISTRIBUTION PATTERN CONTROL OF BUBBLE DISTRIBUTION BY INERTIA CASTING	STRUCTURES WITH A NEW OPTIMUM IN. STRENGTH TO WEIGHT RATIO TEMPERATURE COMPATIBILITY DUCTILITY HOMOGENEOUS PROPERTIES AND FRACTURE MECHANICS ARMOR PLATES, VESTS, HELMETS BULK FOAM MATERIALS FOR TERRESTRIAL EXPANSION VARYING DENSITY-TURBINE BLADES SONAR TRANSDUCER MATERIALS BOUYANT STRUCTURES FOR SHIPS

R-ME
5-27-68

Figure 24

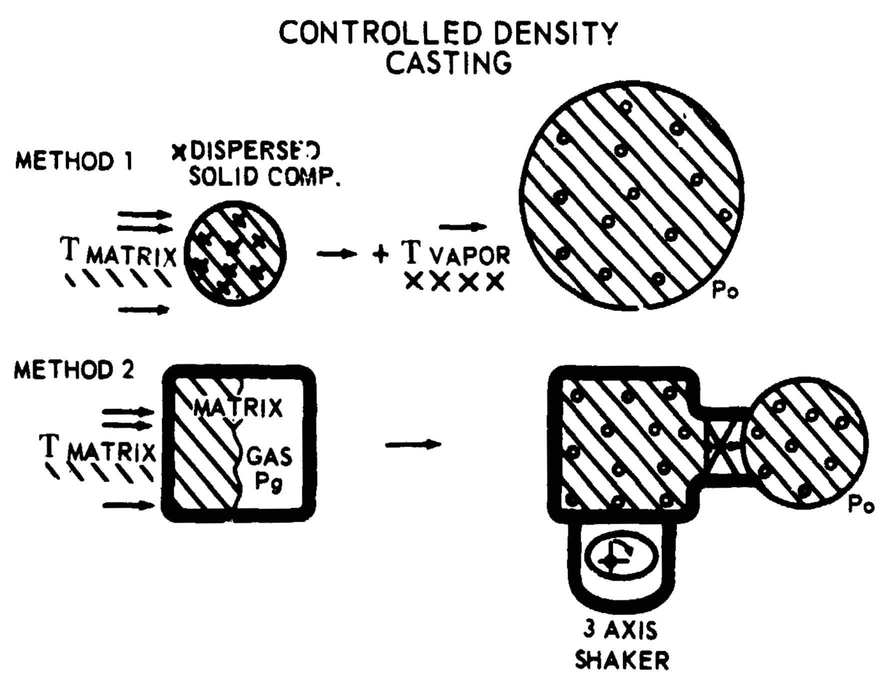

Figure 25

molecular patterns. Anything which is not alive comes in one density, like steel 7.8, but if you go into zero gravity you can control the density by inducing gas bubbles into the material. It may be possible to produce a material that would have the same low density as balsa wood and have the high temperature, high strength properties of steel. It would have the same strength-to-weight ratio in tension but in compression there would be a big gain because of the cross section. The ductility of materials could be influenced; for example, Beryllium could be foamed and would withstand more deflection because of the stresses in the bubbles. Problems such as crack propagation and stress corrosion would be alleviated by the little bubbles. It would be similar to the practice of stop drilling a crack. The production of superior armor materials may be possible because of these features. Another possibility exists in lowering the density of materials to that of less than water and make it float for use in deep submersible structures.

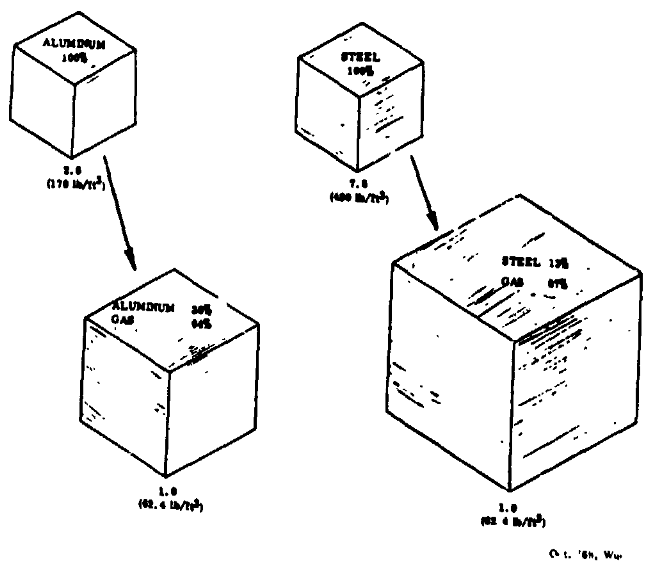

Figure 26

The dispersion of the perfectly spherical gas inclusions should be so fine that a high equilibrium pressure is maintained. Figure 26 shows the volume ratio required for aluminum and steel in order to make these materials buoyant in water. It may also be possible to vary the density of material over the length by applying centrifugal force to a batch of material containing uniform size bubbles and freezing the material when the desired density distribution is attained. The material could then be cut and used for components such as for equal stress and cross section compressor blades for jet engines, as shown in Figure 27. Another potential application is for sonar transducer material. Figures 28 and 29 summarize once more the previously described processes, experiments and potential applications.

VARYING DENSITY COMPOSITE

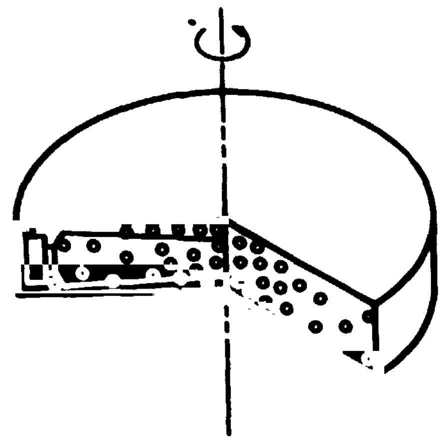

Figure 27

SUMMARY (First Cut)	SPACE PROCESSES UNIQUE TO LOW AND ZERO GRAVITY ENVIRONMENT	

1. Free Melting, Refining, Forming.
2. Single and Multiple Matrix Casting.
   (2-State Casting; Liquids + Solids)
3. Supersaturated Alloy Casting.
4. Multilayer Coating and Casting.
5. Controlled and Varying Density Casting.
6. 3-State Casting.
   (Liquids + Solids + Gases)
7. Liquid State Blow Forming.
8. Liquid State Drawing.
9. Super-Cooled Coining.
10. Free Solidification.
    (Control of Nucleation)

xx.

xx.
Earth Magnetic Field Isotope Separation.

xx.
Ultra-Centrifugal Separation of Macro-Molecules.

xx.

__Conclusion:__ These Processes yield a first generation of novel Space Products, forming the building blocks for a next higher level technology.

Wuenscher, R-ME-DIR
November 1, 1968

Figure 28

2 TO 3 YEARS	1975 - - - -
EXPERIMENTS IN ZERO 'g' - VERIFICATION & EVAL.	APPLICATION - MANUFACTURING IN ZERO 'g'
Cast	
Metals	Solid Precision Spheres High Purity Reactor Castings
Metal-Matrix Composites	High Performance Materials Cermets Complex High Strength Components Armor Plates Turbine Blades
Glasses, Ceramics, Pl... s-Composites	Large Optical Blanks and Precision Shapes Radiation Shielding
Supersaturated Alloys	Thermoelectric Material (Telluride-Lead)
Multilayer Coatings and Components	Solid State Electronics (Layers) Optical Composites Multilayer Coatings
Controlled-Density Metals and Glasses	Buoyant High Strength Deep Submergents Sonar Magnetostrictive Transducers Super Strength to Weight Ratio Material Armor
Varying-Density Composites	Optimum Equal-Stress Turbine Blades
Draw Membranes and Filaments from Liquified Material	Inorganic Membranes for Chemical Processes High Purity Refractory Wires and Filaments
Blow and Form Hollow Shapes from Liquified Materials	Hollow Precision Spheres and Shapes Hollow Ball Bearing Balls
Control Nucleation for Crystallization or Amorphous Solidification of Materials	New Type Glasses, Semi-Conductors Single Crystal Components

H. Wuenscher, R-ME-DIR
October 23, 1:68

Figure 29

Let me make the statement that all these potential products are only a very bashful beginning of exploiting our new access to zero gravity. If one would have asked Toricelli (the inventor of the vacuum pump in 1650) what his vacuum was good for, and if he would have answered that this opens the age of radio and television, nobody would have understood. We are presently in a similar situation with respect to our new access to extra-terrestrial production environment. We have to understand further, as another by-product of low gravity gradient environment, that the size of process equipment can increase by many orders of magnitude because of the diminishing dead weight deflections. This means access to processes which need large dimensions, high precision and vacuum of the universe in order to take place. As mentioned at the bottom of Figure 28, future process development such as isotope production and new separation methods might be the avant-garde for "cosmic production" of non-terrestrial materials.

SPACE TOOL ENGINEERING

A typical "Space Manufacturing Machine Tool" can be seen in Figure 30, where a "Space Foundry Machine" is shown as it was specified by the author in July 1966.

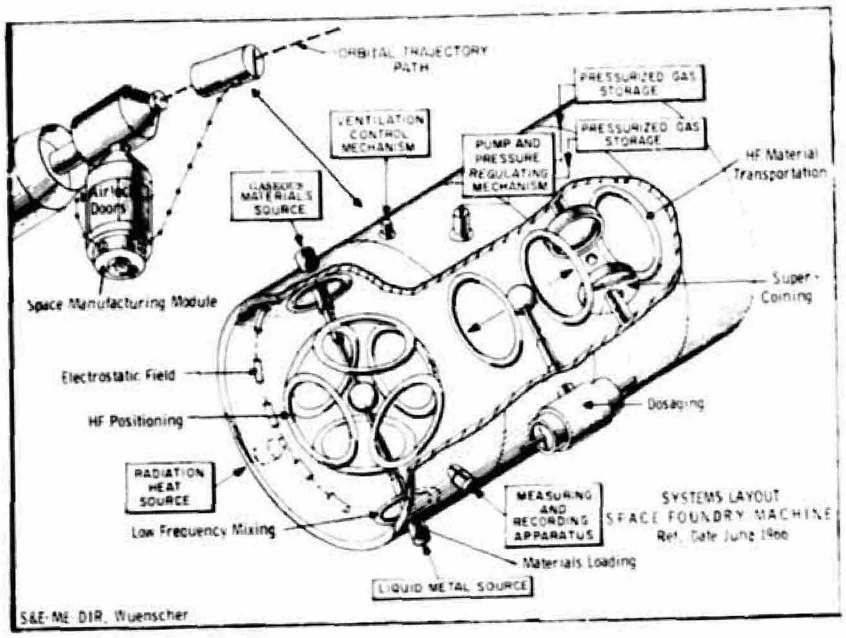

Figure 30

One has to remember that the consequences of weightlessness are abstract facts to us and therefore the most practical solutions to the space manufacturing engineering problems may appear very strange at first.

Zero "g" processing will take advantage of the free floating liquid material, which becomes now an object in its own right. The liquid will immediately take the basic "cosmic" configuration of the perfect sphere. The interaction of free suspended liquid materials with solid and gaseous materials is a new field of science and engineering which has to be developed now and will provide the in-depth backup for the Space Tool Engineer. Space processing will differ from terrestrial manufacturing mainly because the operations are achieved by "Energy Management" and not by hard tooling such as drop hammers, milling machines, and cranes. One can postulate that space manufacturing consists of areas such as:

1. Energy management for heating and cooling.
2. Field (electric and inertia) management for positioning and forming.
3. Gravity gradient field management during processing.
4. Gas management for the internal materials configuration.
5. Others, such as trajectory management for positioning the Space Manufacturing Machine in the Earth Magnetic Field or the Van Allen Belt, Earth Shadow, Libration Points and Orbital Drop areas for shipment down to earth.

SPACE PLANT ENGINEERING

We have concerned ourselves over the past years with the consequences of zero gravity to a terrestrial type factory. The most remarkable change must be seen in the disappearance of the function of the floor, which serves the location and translation of men and materials. In an orbital plant, mechanical means such as we are presently developing in the Serpentuator will take over these tasks. Furthermore the doors, which have to be big air locks in a space station, must still be developed. It looks like most of the manufacturing will go on outside the actual "manned quarters", and the tools or processing units will float around outside and be brought inside the station for loading and servicing.

Figure 31 shows our latest developed Serpentuator, which can cover a spherical motion volume of 40-foot radius around its attachment point, and Figure 32 shows a preliminary configuration for a "Space Manufacturing Development Module" which could be considered a building block for a future space plant.

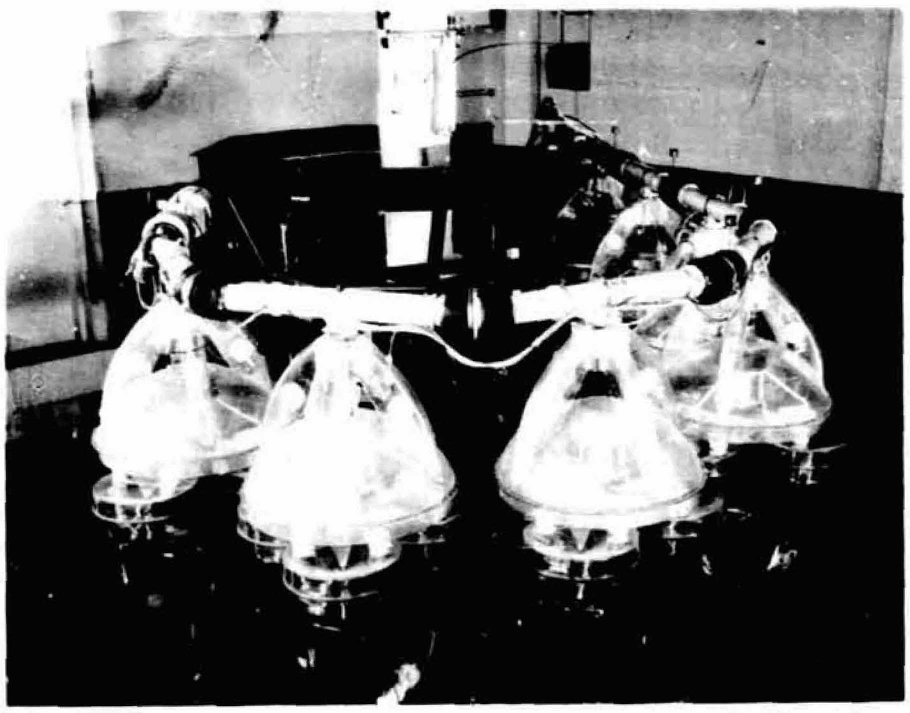

Figure 31

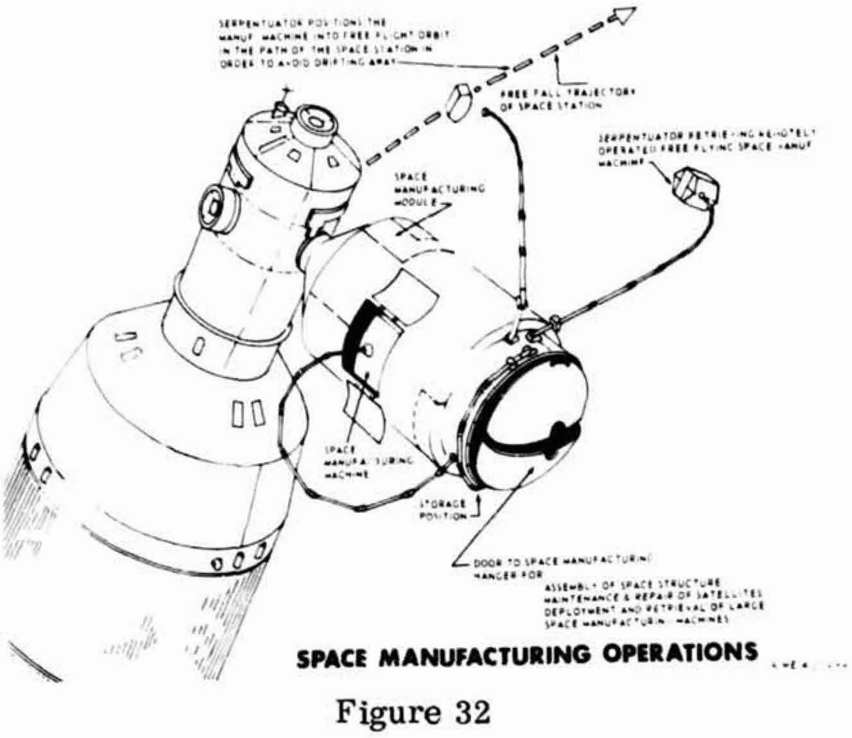

Figure 32

The Space Manufacturing Development Module will be separately launched and docked at the space station. The interfaces to its launch vehicle, the orbital transfer vehicle for accomplishing the docking and to the space station systems and operations are to be determined in such a way that no duplication of systems and operations functions exists. The module provides the facility for an environmentally controlled volume inside the basic structure. It consists of (a) a laboratory portion equipped for shirt-sleeve operations (but does not contain any facilities such as living quarters, eating and sleeping equipment, etc.), (b) a storage portion for experiment materials and products with its own docking port for logistics vehicles, and (c) a shop and air-lock portion providing full cross-sectional access to the outside. In addition, an outside manufacturing operations range is provided by positioning and handling systems such as Serpentuators and manipulators. The outside range covers a spherical motion volume of about 100-foot radius.

The basic arrangement of an inside and an outside operations range provides the flexibility for permanent attachment of the module at nearly any place on the outside envelope of the space station. The creation of the outside range enables positioning of the manufacturing equipment into the proper location with respect to the required gravity gradient limitations of the specific process. The experiment, or manufacturing equipment, has to be designed for operation in the outside vacuum either staying attached to the Serpentuator and maintaining the power and monitoring interfaces with the shirt-sleeve operations control room of the module or the complete experiment package can be released and operate as a free flying satellite and be retrieved by the Serpentuator after completion of the process. This outside operational capability solves furthermore problems with respect to energy management, because the heat radiation does not burden the internal space station systems. Another important advantage is in the safety aspects and enables experimental development of processes where the failure and hazard level is difficult to predict or prohibitive for inside operation. A very important advantage is in elimination of free flying requirements for the complete module, which would provide extremely difficult operations problems. The Serpentuator system can also serve as remote inspection and repair equipment for the whole space station and also as a mechanically closed logistics system transferring man and material.

The role of man in the presently visualized manufacturing process development is essentially as an observer. Two astronauts are necessary on a full-time basis, sharing the supervision of the Space Manufacturing Development Module. The products manufacturing operations are automated and remotely controlled from the manufacturing laboratory where the astronaut is working in shirt-sleeve environment. Most of the experiments will be attached in the shop or air-lock zone to the Serpentuator. After closing the inner air-lock door, the experiment is moved out and the manufacturing operation is remotely conducted a safe distance from the module and space station. Other satellites are moved into the shop or air lock for repair and are repaired and modified in shirt-sleeve environment. There is a second smaller air lock in the laboratory portion for the outside operation of small experiments.

The inspection of the space station for the purpose of maintenance and repair is also done remotely by sensor packages which are attached to the tip end of a Serpentuator. Corrections and repairs are basically done by remote tooling attached to the Serpentuators.

A far-out configuration of an orbital factory is shown in Figure 33.

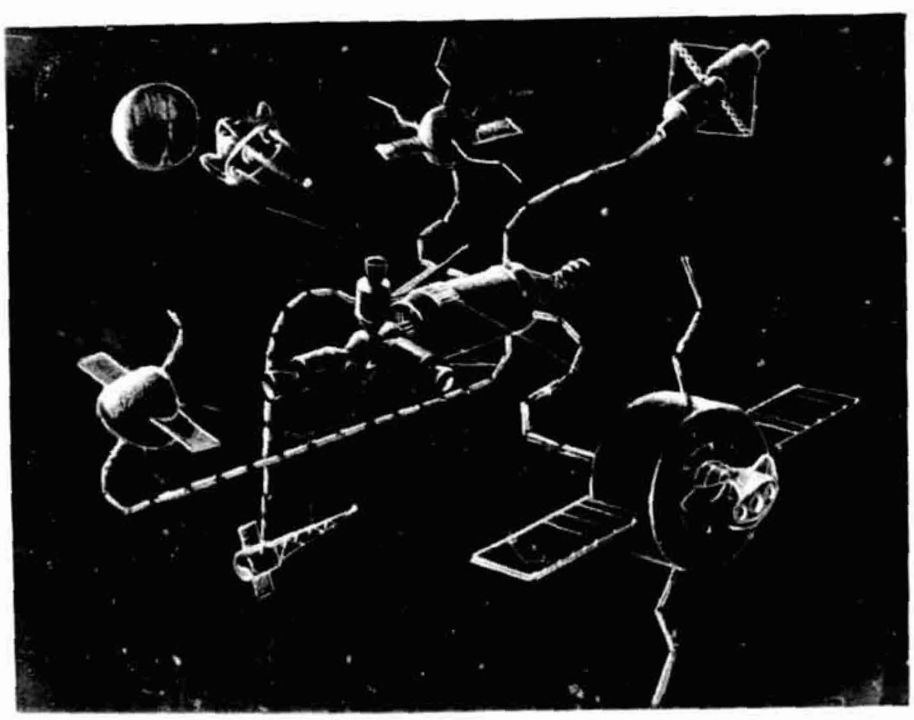

Figure 33

DEVELOPMENT OUTLINE FOR SPACE MANUFACTURING

The selection of space manufacturing projects must be targeted toward efficient, early accomplishment of significant results. The past activity, as previously shown, has yielded a first set of ideas, recommendations and proposals for experiments. From this, two basic categories of space manufacturing activity can be cited:

1. Utilization of the buoyancy and thermal convection free environment for processing of unique materials.

2. Utilization of the molecular forces of the materials during liquid state for shaping and configuration control of unique products.

Space Manufacturing Experiments for AAP-2 Mission

The Space Manufacturing Experiment M512 has been updated to cover some potential materials development of category 1. Included is a number of zero gravity melting and solidification samples of unique materials. Part of these samples are electron beam melted and of about 1/4-inch diameter. They are located on a supporting bracket or sting. Other samples are processed in a closed crucible or capsule by exothermic heating. The samples cover metallurgical and crystallization aspects of metals and pre-mixed composite materials. Also the formation and configuration of free surfaces will be studied. The updated implementation plan has been submitted and is in general accepted.

Space Manufacturing Project for the Follow-on Mission

The next space manufacturing experiment will progress into category 2. processes. An experiment proposal for "Zero-g Casting" is presently in preparation. This Free Casting Module will allow for free suspension of the materials during melting and cooling and will provide for controllable inert gas pressure environment and inertia and electrical force fields for free forming.

The following experiment groups are then accessible for process development:

1. Making solid precision bodies by free, inertia and electrostatic field casting.

2. Making hollow precision bodies as above and development of bubble centering processes.

3. Novel nucleation controlling solidification processes with the completely free suspended materials by super-cooling. The following materials and configurations can be accomplished with the Free Casting Module:

Materials
Supersaturated alloys for thermoelectric and super-conductive application
New type glasses
Prestress free blanks for lenses
Single crystals
High purity metal standards (centrifugal cleaning)

Configurations
Precision balls for bearings
Precision hollow balls for bearings
Optical components
Density controlled metal configurations with unique properties, structurally, electrically, and thermally (three-state casting)

Space Manufacturing Projects for the 1975 Permanent Space Station

Large quantities of novel materials, such as 50 pounds or more, will be processed in the Manufacturing Development Module and serve as baseline for industrial product applications.

Supporting Research and Development

Research and development studies have been released and are planned to continue in order to establish the in-depth physical and mathematical verification for the proposed processes and the daily influx of new processes and applications. Also, an encouraging industry response has developed, and a number of industry-sponsored experiments are presently underway.

LISTING OF KEY PAPERS CONCERNING THE UNIQUE UTILIZATION OF ZERO GRAVITY ENVIRONMENT PRIOR TO NOVEMBER 1968

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SPACE MANUFACTURING UNIQUE TO
ZERO GRAVITY ENVIRONMENT

By Hans F. Wuenscher

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This document has also been reviewed and approved for technical accuracy.

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