October 21, 1965

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Materials in Space Exploration

Abstract

This paper presents a general review of major structural alloys that have been used in liquid rockets and space vehicles, the current state-of-the-art as applied to the Apollo launch vehicle system, and discusses some materials currently under development for future requirements in vehicles for space exploration. Some aspects of the importance of corrosion resistant materials and suitable protective measures are discussed, as applied to both flight hardware and associated ground support equipment.

"Materials in Space Exploration" presented by Mr. C. E. Cataldo at the South Central Regional National Association for Corrosion Engineers Conference in New Orleans, La., on October 21, 1965.

Materials in Space Exploration

It is a pleasure to have the opportunity to speak to this session of the NACE Conference and to tell you something about the work being done at the MSFC and by associated contractors for the Saturn-Apollo space vehicle program. Although my subject is rather encompassing, I would like to set the stage for my remarks this morning by considering that manned planetary travel is a little further into the future than the planned lunar landing, the major mission that has been assigned to NASA. Therefore, my remarks will center largely around this particular mission and the vehicles and associated materials and hardware that will be used to accomplish this mission.

It is very doubtful if any monumental breakthrough in materials echnology will occur within the time frame allotted for the Apollo moon mission and even less likely that it would be of any use in such a short time period. So, we're going to have to use what we have in most cases. We are certain, however, that this mission will result in considerable advances in materials technology that will be of great benefit to future planetary travels and certainly to American industry as a whole. Many of you are very familiar with the history of large space launch vehicles, but I would like to review briefly the past, with respect to major structural alloy use, from Redstone to Saturn. The Redstone seemed to be very large in its day, but now it is somewhat dwarfed by Saturn V.

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This slide compares the size of several vehicles that have been developed under the Marshall Space Flight Center. The first stage of Saturn I consists of a cluster of nine tanks, all made from 5456-H343 aluminum; eight tanks of the Redstone diameter surrounding one Jupiter size tank. Four external tanks plus the center tank hold liquid oxygen, and the other four outside tanks are for RP-1 fuel, similar to kerosene. The Saturn I used eight H-1 engines with a total thrust of 1,500,000 pounds. The second stage, designated as S-IV, is a hydrogen-oxygen stage and develops 90,000 pounds of thrust with six RL-10 engines. The S-IV is 22 feet in diameter, 60 feet long and is constructed of 2014-T6 aluminum. The Saturn I has been fired successfully 10 times and has been used to place the three Pegasus meteorite satellites into orbit. The last Saturn I was fired in July of this year with a 10 for 10 success for the vehicle.

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The Saturn IB is an uprated Saturn I being now assembled in this area by Chrysler. Some weight reductions have been made and the H-1 engines uprated from 188,000 pounds to 200,000 pounds thrust each. The second stage is the DAC S-IVB, with one J-2 engine of 200,000 pounds thrust. This vehicle will be fired sometime early in 1966 and will be used for practicing many maneuvers in space that will be necessary for the later moon flight with the Saturn V.

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The Saturn V consists of three stages and has a capability of allowing manned lunar missions in one flight. The first stage is known as the S-IC and will be very familiar to the Boeing representatives present here today. This stage is approximately 138 feet long and 33 feet in diameter. It weighs about 280,000 pounds empty and 4,400,000 pounds loaded with liquid oxygen and RP-1. The five engines, designated as F-1 engines, each develop 1.5 M pounds of thrust for a total of 7.5 M pounds of thrust. The major structural alloy is 2219-T87 aluminum.

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The second stage is known as the S-II made by S&ID, NAA, and measures about 82 feet long and 33 feet in diameter and has five J-2 engines, totaling 1.0M pounds of thrust. This stage is fabricated from 2014-T6 aluminum.

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The third stage again is the S-IVB that will be used also on the S-IB, having one 200,000 pound J-2 engine. On top of these stages is the brains of the vehicle, the instrument section, and the payload, the Apollo capsule - for a total height of about 350 feet. To date, each of the stages has been static fired, but no mating has yet taken place, and no flight of any has been made.

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This next slide is a more detailed view of the S-IC. The skin of the vehicle is also the propellant tank wall. This stage has separate bulkheads for the two propellant tanks instead of a common bulkhead. This is an all welded assembly.

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The fuel tank assembly is shown in this slide. The transverse section shows the integral skin - stringer designs which are made from two inch thick plate and mechanically milled.

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The Apollo spacecraft, as shown in this diagram, consists of several units with a total fueled wt. of about 90,000 pounds. It is approximately 80 feet tall and 13 feet in diameter and consists of a Lunar Excursion Module, a Service Module, and a Command Module for a three man crew and a launch escape system.

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I would like to now review briefly the major structural alloys being used in the vehicles I have just described. This chart represents both a learning curve as far as manufacturing techniques are concerned and a development curve for high strength aluminum alloys. Both parent metal mechanical properties and weld properties have shown considerable increase in the last decade. At the time of the Redstone missile, 5052 aluminum alloy was the most accepted weldable alloy considered for such structures. The newer and higher strength alloy, 5086, became available about that time, and this material was used in the Jupiter C missile in section thicknesses up to approximately 3/4 of an inch. This same material was also used in the Jupiter, although 5456 alloy was considered for a late model of the Jupiter which was never built. The 5456 alloy in the H343 temper, however, is used in the first stage of Saturn I and IB. Several years ago, 2014 was considered practically unweldable; however, new techniques in welding have provided the opportunity to use this high strength alloy in the as-welded condition in very large structures. 2014-T6 is used in the second stage of Saturn I and also in the second and third stages of Saturn V. In the first stage of Saturn V, however, the section thicknesses of one-half inch or more caused us to select 2219 with a slightly lower strength than 2014 for this structure. We encounter less welding problems in 2219 than in 2014 in these very thick sections. The 2219 alloy was, as you know, developed initially for high temperature service, but early tests at Marshall indicated the suitability of this material also for low temperature applications such as cryogenic propellants. The 7000 series alloys have been used to a large extent in unpressurized areas where no welding is required and fastening can be done mechanically, such as the interstage area between tanks, for certain forgings and fittings, and for the anti-slosh baffling inside the propellant tanks. Although we consider aluminum as the major structural

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alloy in these stages, this next slide shows that there are many other materials in one of these vehicles. These are the materials used in the Saturn V vehicle.

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Let us take a look at the rocket engines in use or being developed for the Saturn vehicles. There are two families of engines shown here; both the H-1 and the F-1 burn kerosene type fuel and liquid oxygen, developing 188,000 and 1.5 million pounds of thrust respectively. The RL-10 and J-2 engines burn liquid hydrogen and liquid oxygen. The next slide shows an

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overall view of the F-1 engine. The thrust chamber on this engine, as are those on the other engines shown, is the regeneratively cooled type; that is, the chamber is made up of many small diameter tubes through which the fuel passes before it enters the injector through a common manifold. Thus, the chamber walls are cooled to prevent melting by the extremely high heat produced in the combustion zone, and the fuel is preheated before passing into the chamber. In the case of the F-1, these tubes are made of Inconel X with about 20 thousandths of an inch nominal wall thickness and 1 inch in diameter at the exit end. They are brazed together in a hydrogen atmosphere furnace using an Ag-Pd-Mn (75-20-5) braze alloy for the primary braze cycle and a secondary braze cycle using Nioro (85-Au-15-Ni). Needless to say, several pounds of precious metals are used in each of these thrust chambers. The chambers in the early H-1 engines were pure nickel and were hand brazed, but the later ones use 347 stainless steel and are furnace brazed. The RL-10 and J-2 engines also use 347 stainless steel; most of them being brazed with silver solder of from 90 to 100% silver. Many high temperature alloys, as well as low temperature alloys, are used in these engines. With liquid oxygen at -320°F and liquid hydrogen at -423°F coming in at one end and a flame of 5000°F plus coming out the other, the thermal stresses existing during firing are quite severe, and these are coupled with large shock stresses and thrust loads. Materials such as Rene' 41, Haynes Stellite, the Hastelloys, Inconel, and stainless steels are used extensively in high temperature areas, such as for gas generators, heat exchangers,

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turbines, thrust chambers, exhaust ducts, etc. This next slide shows what one might find in a typical rocket engine with respect to relative amounts of materials.

After this review of past and present usage of materials in the space vehicles, let's take a brief look now at some of the more recent developments in materials that have resulted from aerospace research and developments or advanced technology that offers considerable promise in such structures. The Marshall Space Flight Center, in the belief that useful alloys can be developed having higher strength and better weldability than is now attainable and having strong convictions that a material should be tailored for the use made of it, is sponsoring a program at Alcoa to develop an aluminum alloy with a tensile strength of 75,000 psi, a yield strength of

65,000 psi, 10% elongation, and notched to unnotched ratio of 1.0 at room temperature and 0.9 at -423°F. Two very attractive alloys have resulted from this program to date and are designated as X2021, which is an aluminum copper alloy, and X7007, an aluminum-zinc-magnesium

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alloy. The next slide shows that the X2021 differs from 2219 primarily by the addition of cadmium and tin and that X7007 is a modification of the X7106, with respect to content of copper, magnesium, and zinc. The

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next slide compares the mechanical properties of these alloys with established goals and with several other commercial alloys. It appears that these alloys will meet our strength and toughness criteria. Weldability tests and stress corrosion tests, although encouraging, are inconclusive at this time. Other than these very high strength alloys, the new 7000 series alloys, such as 7139, 7002, and 7106 look very promising for a variety of structural applications. The Alcoa 7106 and the Kaiser 7039 or 7139 and the Reynolds 7002 materials have favorable low temperature properties. They are weldable and have better general corrosion resistance than the 2000 series alloys. Although the parent metal strength is somewhat lower than in the 2000 series, the as-welded strength is superior.

Many aluminum castings have been used in the Saturn vehicles, and other castings could be used if better alloys were available. In a contract with Battelle Memorial Institute, including considerable in-house evaluation at MSFC, we have developed a heat treatable aluminum casting alloy of very

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high strength and toughness at cryogenic temperatures. In this next slide, the chemical composition of this alloy which has been designated M-45 is compared with several other high strength aluminum casting alloys. The alloy is very similar to the commercial 195 alloy but is different with respect to cadmium, silicon, and iron contents. The alloy is based on a high purity base alloy. In the next slide, the mechanical properties of -T6 temper of the alloy are compared with those of other aluminum casting alloys. The alloy is also comparable to 195 in castability. It can be welded to itself and to wrought aluminum alloys such as 2219. Some very recent Saturn configuration castings made from this alloy have had ultimate tensile strengths of 59 ksi, yield strengths of 52 ksi, and elongation of 3 percent. The next slide shows a recent casting made from this alloy which is a rather complex casting and yet was of very high quality with respect to radiographic soundness. Different heat treatments have yielded even higher strengths than those I just reported; however, it has been found that the stress corrosion resistance of the alloy is decreased considerably with the higher strength heat treatments that have been developed so far. The material is not yet advertised commercially, but it can be obtained from ingot suppliers on special orders.

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Titanium alloys have been used to a limited extent for cryogenic tankage, but the higher strength alloys do not have sufficient toughness at cryogenic temperatures, and even in the alpha alloys the interstitial content must be maintained at a fairly low level to give adequate toughness, and this results in a corresponding reduction in strength. Titanium is much too reactive with liquid oxygen to use where there is danger of a local ignition source. Also, to use titanium in the liquid oxygen container, especially in thin sections in a situation where there is a possibility of puncture or any sudden application of energy, constitutes an extreme hazard. Titanium will see, however, increased use in advanced aerospace structures, possibly in fuel container structures and general structural applications.

Many applications have already been made of the magnesium-lithium alloys which are the lightest structural metals commercially available. Battelle has developed for us two alloys, LA-141 and LAZ-933, which are compared in this next slide. Mechanical properties are shown in this next slide. Our initial interest was for structures in a space environment where corrosion would not be a problem; however, these alloys are now being used for a variety of applications in the earth environment. The Saturn V Instrument Unit uses about 70 pounds of LA-141, and many military missiles and other space vehicles use a considerable amount of magnesium-lithium in certain applications. It is probable that even greater use will be made of these light-weight alloys, particularly if somewhat higher strength can be attained and better coatings are developed.

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Beryllium is presently used in the inertial guidance system of the Saturn V, approximately 165 pounds per vehicle. These are gyroscopic parts which are extremely accurate dimensionally, and the parts must be capable of being polished to very high surface finishes of four micro-inches or better and be extremely free from corrosion. The properties of beryllium as shown in this slide make it an excellent material for this

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application. Several other applications for beryllium have been considered, primarily in general structural components, but none have been implemented yet, primarily because of the extreme brittleness of the material. A somewhat more attractive material for structural applications is the recently developed beryllium-aluminum composite containing 20 to 40 percent aluminum. This material has a much better capability of being fabricated by various means and is becoming available commercially.

A class of material with perhaps more potential currently than any other for aerospace structures is composite materials. The application of sandwich composite materials in missiles and rocket systems are not as many as in aircraft structures; however, this situation is changing as we learn more about using these materials efficiently. The next

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slide shows some major applications of sandwich materials in Saturn V. As you can see, there is a rather wide application because this type of material can be tailored to utilize the most favorable properties of each element of the composite. Notice first the heat shield of the S-IC stage of Saturn V which protects the tail of the vehicle from radiative

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and convective heat loads from the rocket exhaust plume. This is a stainless steel honeycomb filled with an insulating material.

The heat shield on the S-II stage is also a composite structure consisting of two layers of fiberglass honeycomb and filled with a resin plus microballoons.

The S-IVB stage and the S-II stage, second and third stages, respectively, of Saturn V, each have two major applications of sandwich materials that

I will discuss briefly. These are the common bulkheads separating the liquid hydrogen and the liquid oxygen and also the insulation of the liquid hydrogen tanks. The applications differ slightly between the vehicles but are generally the same. In this next slide, a cutaway of the S-II stage shows both of these applications. The fiberglass phenolic honeycomb core in the common bulkhead is about 4" thick over most of the bulkhead with a cell size of about 3/16 of an inch. It is bonded to the aluminum faces by means of high temperature adhesive HT 424. Aluminum faces, which are 2014-T6, are made of welded gore segments. This bulkhead is about 33 feet in diameter.

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A recent insulation development at the Marshall Space Flight Center is a double seal insulation concept which was developed to insulate the liquid hydrogen stage of the S-II stage. This composite consists of a layer of Mylar honeycomb with a Mylar film bonded to one side and aluminum foil bonded to the other so that each cell of the honeycomb is sealed as is shown in the next slide. To this layer is bonded a perforated phenolic fiberglass honeycomb core and finally aluminum film is bonded to the exterior. The complete composite is bonded to the tank wall. The liquid hydrogen evacuates the sealed cells of Mylar honeycomb by cryopumping which is condensing and solidifying and thus provides the insulation. The external layer is designed to stand temperatures up to 425°F which may be encountered in aerodynamic heating as the vehicle passes through the atmosphere. By being perforated, it can be purged with helium to protect

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the Mylar core from condensed oxygen with which it would be incompatible. The thermal gradient across this material may be more than 800°F.

Another recent and significant development in composite materials is that of brazed aluminum honeycomb material. In a contract with Aeronca, sponsored by MSFC, some honeycomb composites of the new 7000 series alloys have been made wherein they were solution treated and quenched from the brazing temperature with exceptionally high strength for this type of structure. A small section of such a structure is shown in

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this slide.

Another type of composite material in which we have great interest currently is metal fiber or wire reinforced aluminum and/or aluminum castings. Harvey Aluminum, under contract to Marshall Space Flight Center, is working currently on a wire reinforced 5000 series aluminum

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plate in the manner shown here similar to the reinforced concrete concept by using high strength NS 500 steel wires with about 25 percent density to produce tensile strengths on the order of 170,000 psi without too great a sacrifice in overall density. In another contract with MSFC, North American Aviation is exploring the potential use of a variety of composite concepts with combinations of aluminum sheet, fiberglass cores,

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titanium, aluminum reinforced with steel wires, and various other materials that may be suitable for liquid oxygen tankage, fuel tankage, and general structural applications for aerospace hardware. One big problem in using composite materials concerns the joining of these materials for pressure type vessels. To weld such a system would require considerable ingenuity;

however, there is a variety of joining techniques that can be explored and that may be suitable for joining composite materials.

I have mentioned a few of the many materials developments related to the aerospace industry, particularly those that I am familiar with. There are many, many more, of course, in both metals and non-metals, but too, there are still requirements for new advances. Our ever increasing knowledge of the space environment continues to dictate specific material property requirements and several forthcoming NASA space experiments are designed specifically to study in detail certain materials characteristics in the space environment.

What are some of the materials problems on current and past vehicles that will dictate certain improvements for the future? I cannot begin to discuss these in detail this morning, but perhaps refer to them in general terms. Our quest for lighter weight structures and associated high strength-to-weight ratio materials often results in the selection of materials having less than desirable ductility or toughness. Consequently, a slight mistake in processing or in design can often make a difference in failure or success of a component. Fortunately, most errors of this sort are quickly identified in qualification tests. Unfortunately, this is not quite true of failures due to corrosion, and specifically, stress corrosion.

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This slide shows, in general, the conditions attributing to stress corrosion cracking. Stress corrosion failures cannot be predicted, currently, to the point that the materials engineer can relax in this respect. There are many things that can be done, however, to minimize the danger of

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stress corrosion failures, and some of these are listed on this next slide. I might point out, at this point, that in the Saturn I vehicle program, two firing schedule delays were caused by stress corrosion failures; one in AM-355 stainless steel fittings and the other in 7079-T6 aluminum forgings. In the case of the stainless steel, a slight change in heat treatment solved the problem; in the aluminum, a complete alloy change was made to 7075-T73. As a result of these two failures, the Marshall Center instituted a thorough review of materials in Saturn components that were known to be somewhat susceptible to stress corrosion. Also, several research programs were initiated to attempt to develop new alloys or tempers of alloys more resistant to stress corrosion and to study the more fundamental aspects of the mechanism of stress corrosion cracking. It is hopeful that this work will lead to a better understanding of this problem and consequently to stress corrosion resistant materials for the future.

In addition to flight type hardware and associated space environments, some of the biggest problems confronting the materials engineers are found in ground support equipment. Due to the usual proximity of launch support equipment to seacoast environments, corrosion protective measures have received a great deal of attention. We are constantly working on improvement of both organic and inorganic coatings, platings, and corrosion resistant materials. Some of the critical high pressure systems necessary have dictated the use of higher strength materials than are conventionally used in general structural applications, and such high strength materials give rise to both general and stress corrosion problems. It is extremely important that ground equipment be reliable, and with the advent of increasingly complex space vehicles, these systems must necessarily be of more complex design also. Additionally, we are concerned, in many instances, with extremely large structures such as the

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big Saturn V crawler, shown in this slide. A mobile vehicle of this size begins to challenge the state-of-the-art in many respects. For instance, some of you may recall the recent publicity concerning the failure of anti-friction roller bearings in this crawler.

In conclusion, I want to emphasize the importance of developing

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materials sophistication, so to speak, particularly in the field of rocketry. Our metallurgists need to tailor the material for the application, not compromise the requirement for what is readily available. This is not merely wishful thinking; there are many cases to show that the research dollars spent have paid big dividends in increased reliability, performance, and longer life materials in specific applications.

Not considering the need for a large number of specialty materials,

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I have summarized on this last slide some of the demands for metals for aerospace structures. We need materials with higher strength-to-weight ratios, gained either by the use of higher strength light metal alloys such as aluminum, magnesium, beryllium, or titanium, or by reducing the density of the higher strength alloys through combinations into composite structures. Higher strength aluminum alloys are needed that are weldable, corrosion resistant, and have good low temperature toughness. Ductile beryllium alloys, beryllium-aluminum combinations, and beryllium composites may have applications. Strengthening techniques, such as wire or fiber reinforcement of both wrought materials and castings will find some requirements. And last, high quality general structural aluminum and steel are needed for large ground support equipment.

In the particular interests of you who are here today, and of primary importance to us, are the requirements for improved protection methods for all of these materials. A great deal of work is needed in this area. I think we need to make a strong effort to convince everyone concerned that we can't solve all of our corrosion problems with buckets of paint alone.