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THE INFLUENCE OF NUCLEAR RADIATION ON MATERIALS TECHNOLOGY FOR SPACE APPLICATIONS

by

Lowell K. Zoller *25 Oct. 1963 21p refs*

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ABSTRACT

The extension of man's presence into the realm of "space" continually necessitates dramatic developments in materials technology to meet the unique environments and constraints imposed by the space vehicles and by "space" itself. The fundamental interest in deep space exploration has made the use of nuclear power sources attractive for space vehicles. The presence of such a copious source of nuclear radiation, in addition to the indigenous space radiation, however, further restricts the applicability of materials, necessitates extensive multiple-environment testing, and demands the development of new, more environment-resistant materials. It is intended in this discussion to define the various material categories and the associated combinations of environments which must be investigated and to consider some imposed modifications of accepted test methods including radiation dosimetry.

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MATERIALS DIVISION
PROPULSION AND VEHICLE ENGINEERING LABORATORY

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SUMMARY

A

The extension of man's presence into the realm of "space" continually necessitates dramatic developments in materials technology to meet the unique environments and constraints imposed by the space vehicles and by "space" itself. The fundamental interest in deep space exploration has made the use of nuclear power sources attractive for space vehicles. The presence of such a copious source of nuclear radiation, in addition to the indigenous space radiation, however, further restricts the applicability of materials, necessitates extensive multiple-environment testing, and demands the development of new, more environment-resistant materials. It is intended in this discussion to define the various material categories and the associated combinations of environments which must be investigated and to consider some imposed modifications of accepted test methods including radiation dosimetry.

AUTHOR

This paper was presented at the Sixty-Sixth Annual Meeting of the American Society for Testing and Materials held in Atlantic City, New Jersey, June 23-28, 1963.

INTRODUCTION

During the last decade, and due largely to the stringent demands of the missile/space industry, dramatic and significant advances have been realized in nearly all aspects of material technology. However, in order to meet our national objectives and commitments relative to the serious scientific exploration of space, it will be necessary to rapidly extend the state-of-the-art of materials science and engineering to solve the problems with which we are constantly confronted--problems which result largely from the unique environments, or combinations of environments, which are introduced by "space" and the space vehicles themselves. One of the problem areas which demands our attention is the electromagnetic and particulate radiation from space indigenous sources and from on-board nuclear sources. Considering the deficiencies in the definition of the indigenous space radiation environment and the expense and difficulty in simulating the environmental factors of space, it is not strange that there exists a paucity of radiation effects data for the design of space vehicles. It is my opinion, therefore, that the service which symposia, such as the Symposium on Space Radiation Effects, render to the industrial community is to create additional appreciation for the problems which are inherent in the design and operation of space vehicles and, as a result, to further stimulate interest in investigating the effects of the various environments which are encountered by materials in space.

MATERIALS

To augment the aforementioned objective of elucidating design considerations for space vehicles, it is appropriate to delineate some of the types of materials which are typically used in construction of launch vehicles and space craft and the environments to which these materials are subjected. In Table I, I have compiled a summary of typical material applications for space vehicles. Obviously, this list is neither exhaustive nor universally applicable; nevertheless, it illustrates the diversity required in the materials technology for space applications, since it is evident that the entire spectrum of materials--metals, inorganics, and organics--is brought to bear on the problems.

To provide greater appreciation for the types and quantities of materials which are being used in today's large launch vehicles, a weight breakdown for the SA-2, Saturn I vehicle is given in Table II. The SA-2 booster was a two stage vehicle consisting of the 1.5 million pound thrust S-I stage and a dummy S-IV stage which was constructed largely of steel. The category indicated as "Engines (Mixed Metals)" includes the

TABLE I

SUMMARY OF MATERIALS APPLICATIONS

APPLICATION	METALS	INORGANICS	ORGANICS
STRUCTURAL MATERIALS	X		X
FASTENERS, FITTINGS, etc.	X		
PLUMBING, TUBING, etc.	X	X	X
ELECTRICAL CONDUCTORS	X		
THERMAL INSULATIONS		X	X
THERMAL CONTROL COATINGS		X	X
ELECTRICAL INSULATORS		X	X
SEALS, GASKETS, etc.	X		X
ADHESIVES			X
LUBRICANTS		X	X
POTTING COMPOUNDS			X
WORKING FLUIDS		X	X

TABLE II

SATURN (SA-2)

MATERIAL	POUNDS
ALUMINUM	71,459
STEEL	17,987
MAGNESIUM	82
REINFORCED PLASTICS	2,974
RUBBER	18
WOOD	17
PAINT & SEALER	382
WIRE/CABLES	2,650
ENGINES (MIXED METALS)	16,814
MISCELLANEOUS	3,152
TOTAL	115,535

eight H-1 engines of the S-I stage. These mixed metals consist mostly of steel and superalloys as shown in Table III. The weights given in this table are for a considerably larger engine than the H-1 which is currently under development; the distribution of materials is, however, about the same as for the H-1 engine.

From the foregoing tables, it should be obvious that very significant quantities of a wide variety of materials are used in space vehicles. The diversity in the types of materials is, of course, necessitated by the requirements for maximization of properties and minimization of weight. Because of their unique properties, many thousands of pounds of organic and inorganic materials are used in vehicle construction in addition to the primary structural alloys. It must be recognized, however, that the weight of a given material is not necessarily indicative of its importance to the successful operation of the stage, as evidenced by the fact that the organic materials constitute only 3-4% of the total SA-2 vehicle dry weight.

ENVIRONMENTS

In selecting materials which may be used in a space vehicle, the basic mechanical and physical properties of the potential materials are necessary but not sufficient criteria. In the final selection, the insured survival of the material in the expected environments is the dictating factor. The environments to which a space craft is subjected are many and varied. Singularly, they are generally severe; in combination, they may be synergistically disastrous. Table IV lists some of the environmental factors which may be detrimental to the successful operation of a space vehicle. With the exception of the nuclear radiation, the environments listed in this table are common to most space vehicles. As might be anticipated, each of these environmental factors tends to limit the number of materials which are apropos for space vehicle design. When these factors are superimposed, one is restricted to a rather select group of materials.

The interest in deep space exploration and high specific impulse vehicles has made the use of nuclear power sources attractive for both electrical power generation and primary propulsion in space applications. The use of such sources, nuclear reactors in particular, however, creates additional environmental problems in the form of nuclear radiation damage and radiation heating. The indigenous space radiation, both electromagnetic and particulate, is generally degrading to coatings and components on the exterior of the space craft. Despite the extremely high energies of the charged particle radiations in space, the relatively low flux levels are generally less detrimental to the space vehicle materials than

TABLE III

A ROCKET MOTOR

MATERIAL	POUNDS
ALUMINUM	1,691
STEEL	4,358
SUPER ALLOYS	8,450
COPPER & BRASS	247
SOLDER	127
RUBBER & PLASTICS	17
MISCELLANEOUS	1,000
TOTAL	15,890

TABLE IV

SUMMARY OF ENVIRONMENTAL CONSIDERATIONS

ENVIRONMENT	METALS	INORGANICS	ORGANICS
PRE-LAUNCH CORROSION	X		
VIBRATION	X	X	X
SHOCK	X	X	X
EXTREME TEMPERATURES	X	X	X
REACTIVE CHEMICALS	X	X	X
MICROMETEOROIDS	X	X	X
THERMAL CYCLING	X	X	X
FRICTION	X	X	X
NUCLEAR RADIATION	X	X	X
INDIGENOUS RADIATION			X
VACUUM			X

the radiation from an on-board nuclear reactor. The radiation, particularly the nuclear radiation, is an environment which can induce severe, if not total, degradation of properties in all materials under the appropriate conditions. Particularly sensitive are the semi-conducting and organic materials which are usually incorporated in high critical applications on space vehicles. Since the nuclear radiation is a very detrimental and restrictive environment, especially when combined with other environmental factors which were listed in Table IV, an attempt has been made in Table V to show some potential problem areas for some typical combined radiation environments for space applications. It should be recognized that although this table may be somewhat illustrative, it is difficult, and perhaps fallacious, to make generalizations about the combinations of environments that present materials problems. Therefore, some detailed explanation of this table is in order.

Radiation/Elevated Temperatures

Elevated temperatures in space vehicles can result from several sources. Vehicle components and structures may operate at temperatures up to 300° - 400°F due to aerodynamic heating, solar heating, nuclear radiation heating, impingement of engine exhaust plumes, etc. Reactor components and materials, of course, may operate at temperatures as high as 4000° - 5000°F. Displacement reactions in some metallic materials at elevated temperatures result in a reduction in the mechanical properties which could endanger the structural integrity of the component.

Since destruct systems are usually sensitive to elevated temperatures and since nuclear radiation can induce changes in detonation characteristics, care must be exercised in the use of pyrotechnics on nuclear space vehicles.

Radiation/Cryogenic Temperatures

Cryogenic temperatures occur in nuclear space vehicles through the use of cryogens, such as liquid hydrogen, for propellants. Much of the propellant storage and transfer systems for a nuclear stage utilizing LH_2 would operate at temperatures in the vicinity of -423°F. Studies by the General Dynamics Corporation (Ref. 1) and the work being done at NASA's Plum Brook Reactor Station (Ref. 2) signal a potential degradation of mechanical properties in structural alloys due to irradiation at cryogenic temperatures.

The ductile or elastomeric properties of organic materials are extremely important in space vehicle design. Under the individual conditions of cryogenic temperatures and nuclear radiation, most engineering materials have a tendency to embrittle. Irradiation of organic materials

TABLE V

TYPICAL COMBINED RADIATION ENVIRONMENTS

ENVIRONMENTS	ILLUSTRATIVE PROBLEM AREAS
RADIATION / ELEVATED TEMPERATURE	HEAT TRANSFER SYSTEM DESTRUCT SYSTEMS REACTOR STRUCTURAL MATERIALS
RADIATION / CRYOGENIC TEMPERATURE	PROPELLANT SYSTEM STRUCTURE PROPELLANT TRANSFER SYSTEM ELECTRICAL INSULATIONS THERMAL INSULATIONS
RADIATION / REACTIVE CHEMICALS / TEMPERATURE	THERMOCONDITIONING SYSTEM PROPELLANT STORAGE SYSTEM REACTOR HEAT TRANSFER SYSTEM PROPELLANT TRANSFER SYSTEM
RADIATION / VIBRATION / TEMPERATURE	THERMAL INSULATION ELECTRICAL INSULATION
RADIATION / VACUUM / TEMPERATURE	THERMAL CONTROL COATINGS ELECTRICAL INSULATIONS THERMAL INSULATIONS SEALANTS LUBRICANTS

at cryogenic temperature, therefore, might be expected to introduce failures in seals, gaskets, etc. Another potential problem in the irradiation of organics at cryogenic temperatures relates to the formation of free radicals which are immobilized by the low temperature. If the material is allowed to warm subsequent to irradiation, the exothermic reaction of the free radicals may be catastrophic.

The embrittlement of organic materials such as might be used for cryogenic insulation or for electrical insulation of conductors immersed in the propellant tanks may lead to failure of the part if the coefficient of thermal expansion of insulation is significantly different from that of other parts--an electrical conductor or tank wall, for example.

Radiation/Reactive Chemicals/Temperature

Propellants for nuclear propulsion systems or for attitude control systems are necessarily highly reactive chemicals. Being reactive, the chemicals are relatively unstable and are subject to dissociation by nuclear radiation which can change the combustion characteristics. Secondary propellants, such as the monopropellant hydrogen peroxide or a bipropellant such as one of the hydrazine family of fuels and nitrogen tetroxide, are often contained in organic bladders which are used to disperse the propellants. In addition to the chemical degradation of the fuels, the nuclear radiation can render the bladder and, hence, the engine inoperative.

The example of the thermo-conditioning unit was included because of a specific problem on nuclear stages. Frequently, Freon, or dichlorodifluoromethane, is used as a refrigerant in launch vehicle stages. Freon, unfortunately, is subject to chemical decomposition at relatively low radiation doses. In addition to altering the thermal properties of the refrigerant, the halogen gases which are formed in the chemical decomposition of Freon are highly corrosive to the other elements of the thermo-conditioning unit.

Heat transfer fluids, both liquids and gases, which are used in nuclear reactors are often corrosive or erosive to the reactor core materials. This is particularly true if the nuclear radiation or elevated temperatures have made the materials more susceptible to corrosive attack.

Radiation/Vibration/Temperature

Brittle materials, such as ceramics, organic foams, and refractories, are particularly susceptible to damage from the vibrations and shocks which are inherent in the launching and operation of a space vehicle. This susceptibility to damage is greatly increased if the material is operated at cryogenic temperatures, if the material is further embrittled by nuclear radiation, or if the binders or adhesives are made less effective by the radiation.

Radiation/Vacuum/Temperature

The items which are listed in this category have been discussed in Ref. 3. The space vacuum, as has been pointed out, is very detrimental to organic materials. If the nuclear radiation breaks down polymeric structures into lower molecular weight fragments, the vapor pressures of the organic materials are increased and the material properties can be significantly altered by the out-gassing.

TESTING

From the foregoing discussion, it is evident that a great many materials must be proven in a number of environments. It is obvious, however, that neither time nor money will permit the testing of all materials under all conditions. One must, therefore, be very selective in the combination of environments to be studied and the properties to be measured. Furthermore, it must be recognized that the experiment has to be planned and executed in sufficient detail to segregate the separate and synergistic effects of the various environments. The problems of radiation effects testing are rather unique in that all of the testing must be done under remote handling conditions. The testing of materials in the suggested combinations of environments is difficult; it is expensive; it is time consuming; it requires elaborate facilities; and it is sometimes hazardous; but, it must be done.

The results of most multiple-environment testing to date indicate a definite preference for dynamic or in-pile testing as opposed to pre- and post-irradiation testing where the test results are susceptible to other influences such as handling. The impact of dynamic testing is best appreciated by considering the variety of material properties which are required for space vehicle design. Table VI suggests some of the types of properties which are used by designers in the selection and application of the various categories of materials. Providing remotely operated testing equipment which is suitable for use in environments such as hard vacuum, elevated and/or cryogenic temperature, and vibration is a difficult and challenging task. It is also obvious that a wide variety of equipment and instrumentation is necessitated. The running of meaningful tests under all of the suggested contingencies requires the utmost in care, insight, and imagination in developing the test sequence and procedure. For example, the radiation dosimetry has become relatively routine at most nuclear research facilities. The conducting

TABLE VI

DESIRED ENGINEERING PROPERTIES

MATERIALS	PROPERTIES
STRUCTURAL MATERIALS	TENSILE PROPERTIES
	MECHANICAL / THERMAL SHOCK RESISTANCE
ADHESIVES	LAP SHEAR STRENGTH
LUBRICANTS	COEFFICIENT OF FRICTION
SEALS, GASKETS, etc.	COMPRESSION SET
	MODULUS OF ELASTICITY
THERMAL CONTROL COATINGS	ABSORBTIVITY
	EMISSIVITY
THERMAL INSULATIONS	THERMAL CONDUCTIVITY
	MECHANICAL / THERMAL SHOCK RESISTANCE
	PERMEABILITY
	COEFFICIENT OF EXPANSION
DIELECTRIC MATERIALS	DIELECTRIC STRENGTH
	MECHANICAL / THERMAL SHOCK RESISTANCE
	ADHESIVE STRENGTH

of multiple-environment tests, however, demands some modification of the routine dosimetry practice. If the radiation field is to be measured in a vacuum, it is imperative that the dosimeter material have a low vapor pressure since volatilization would certainly change the calculated dose or flux and might also contaminate the vacuum system. Moreover, it is important that the temperature limitations of the detector be factored into the installation design since heat generated in the detector can be dissipated only by thermal radiation in the vacuum and by conduction through the mounting bracketry. The response of the dosimeter as a function of temperature must also be determined for elevated temperatures, as might be experienced in the above example, as well as for reduced temperatures, such as would be experienced in a cryogenic environment. The response of neutron activation foils at cryogenic temperatures must be taken into account since errors of several orders of magnitude may be introduced by incorrect assessment of the average neutron energy and the appropriate reaction cross section value. In at least one experiment which was reported recently in the literature, nitrous oxide (N_2O) dosimeters were used for determinations of the gamma ray dose at liquid hydrogen temperatures (about -423°F). Obviously, the nitrous oxide would be solidified at these temperatures and the dissociation rate of the N_2O, if any, would be greatly diminished, resulting in totally erroneous calculated doses.

CONCLUSIONS

As I indicated at the beginning of this paper, it is my belief that the demands for reliable engineering design data from multiple-environment tests require more vigorous and creative attention to insure the fulfillment of our space objectives and programs. The paucity of essential environmental data is not peculiar to the space radiation effects data; deficiencies exist in many areas. These deficiencies invite, even demand, pre-eminence in ingenuity, thoroughness, and insight to develop test programs, equipment, instrumentation, procedures, and analytical techniques.

As was stated before, one cannot expect to test all materials under all conditions. It is imperative, therefore, to optimize the data output with respect to both time and money. The first step in this process is to give very critical and analytical consideration to the determination of test materials, environments, and properties. Furthermore, one must determine what control tests are required to analyze the multiple-environment data. With very few exceptions, the data from tests involving several competing environments are worthless without adequate control data and thorough documentation of such fundamentals as: the specimen definition, preparation, and history; the exact and detailed test procedure; and details of all environmental influences.

One aspect of the data optimization can and should be the responsibility of organizations such as the American Society for Testing and Materials (ASTM). Obviously, it is difficult to ceremoniously adhere to current standards when conducting tests in combined environments, particularly when nuclear radiation or reactive and hazardous chemicals preclude the use of standard laboratory equipment and instrumentation. The impracticality of establishing multiple-environment "Standards" that would be universally applicable at this point in time is also obvious. Nevertheless, the rate at which materials technology is being developed and applied in areas such as the aerospace industry and the nuclear industry has reached the point, I believe, where the traditional and methodical approach to developing "Standards" is seriously deficient in meeting the needs of the industry. I would propose that organizations develop not "Standards," but recommended practices and procedures which could be used as guides for planning and running combined environment tests and for developing appropriate equipment and instrumentation. The need for guidelines related to nuclear radiation and other space environment testing is urgent if the technology is to be developed rapidly enough to permit the timely determination of material behavior and the development of more environment-resistant materials for space applications.

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