AEROSPACE
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SOME MAJOR IMPACTS OF THE NATIONAL SPACE PROGRAM

IV. Impacts of New Materials Technology

Prepared for:

I.P. HALPERN
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
WASHINGTON, D. C.

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Principal Investigator: Arthur E. Bayce

Project Manager: John G. Meitner

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FOREWORD

This is the fourth in a series of task reports within a brief study of "Some Major Impacts of the National Space Program."

Within this investigation, many candidate impacts were first screened and those that appeared (a) minor or (b) not likely to yield to sufficient study within the short time available were eliminated. The remaining impacts were subjected to further study and each is separately reported within this series.*

The results of this study are the first concrete assays within a welter of conflicting, incomplete, exaggerated, and frequently unsupported information. Stanford Research Institute considers their objective study an important task and is looking forward to extend the scope of this study in the future by application of the background, methodologies, and initial results obtained to date.

John G. Meitner
Project Manager

* The titles are: "Economic Impacts," "Identification of New Occupations," "Impacts of New Materials Technology," "Impacts Upon Aviation and Aeronautics," "Impacts Upon Health, Biology, and Medicine," "Some Total Impacts of NASA Capability," "The Impact of the Space Program Upon Science--1. Astronomy."

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INTRODUCTION AND SUMMARY

The overall purpose of this study was to examine the contributions of NASA to selected areas of materials technology and their impact upon the economy of the nation as a whole. Quantitative as well as qualitative measures were to be obtained so that an estimate could be had of the proportion of the NASA effort in relation to the total national effort in the same areas.

The determination of the technical contributions of NASA both as to amount and degree was accomplished with the design and utilization of a specific literature search technique. The procedure included the use of a console/computer arrangement, which had access to a linear file of citations of reports including those abstracted in STAR (Scientific and Technical Aerospace Reports) of NASA. This made it possible to obtain a listing of the accession numbers of all entries in STAR for each of 33 seelected materials technology areas over the period 1962 to 1967. The quantitative measure that was selected for this study was the proportion of NASA vs all contributions of literature entries in STAR for each one of these materials areas. Eight out of the 33 materials technology areas had a significant percentage of NASA reports referenced in STAR and were studied in greater detail. The survey covered the significant technical contributions and the ensuing and potential applications to sectors of the economy outside the space program. The source material included the NASA-sponsored reports that were sorted out from the computer listings, other materials literature, and discussions with experts in the various fields. Evaluation of the eight areas indicated that each had an impact on sectors of the economy outside of the space program itself. The nature of the impact together with a listing of items transferred to other sectors of the economy are summarized in Table 1 below for each of the eight materials areas.

Even though the scope of the present study was limited, sufficient data and information were generated to show that the contributions by NASA in the materials technology areas were not only significant in proportion to the total national effort but also that the impacts on the national economy as a whole were considerable and varied. This variety is shown in Table 2, which depicts to which of four major sectors of the nation's economy--power generation, communications, transportation, health care--each of the eight materials technology areas has contributed significant innovations or improvements.

Further extension and refinement of the techniques developed here could be applied readily to a larger sampling of the materials technology areas. In this way, the considerable nature of NASA's contributions to

Table 1

IMPACT OF NASA-SPONSORED WORK

Materials Areas Selected	Impact by NASA*	Transfer to Other Sectors of Economy
Electroforming	+	• Stress-free components
		• Improved nickel-cadmium batteries
		• Tooling and dies
		• Solar concentrators
		• Complex parts
		• Artificial limbs
Fuel cell	++	• Deep ocean technology
		• Silver-zinc batteries
		• Dry tape battery
		• Electric automobiles
		• Life support system
Nickel-cadmium battery, Silver-cadmium battery, Silver-zinc battery	+++	• Economical, compact hearing-aid batteries
		• Electric automobile
		• Battery systems of improved reliability and energy density
		• Deep submergence vehicles and submarines
		• Life cycle testing
Refractory alloy	+++	• Power generation systems
		• High temperature, ductile alloys
		• Oxidation resistant coatings
		• Plasma spraying
		• Welding techniques
		• Jet turbine engines
Solar cell	+	• Weather prediction (satellite)
		• Communication (satellite)
		• Remote area power generation
		• Emergency telephone systems
		• Improvement in solar cell systems for all uses
		• Establishment of standards
Stress-corrosion of titanium alloys	+++	• Supersonic aircraft
		• Rapid, reliable, low cost stress-corrosion cracking test procedure
		• Helicopters
		• Deep submergence vehicles
		• Desalination plants
		• Chemical processing industry
		• Medical implants

* +++ Heavy impact
++ Moderate impact
\+ Light impact

materials technology and the transfer of this knowledge to benefit the nation as a whole in many sectors are clearly indicated. It is recommended that consideration be given to extending the work that was initiated in this study so that the full measure of the NASA contribution can be identified and recognized.

Table 2

MATERIALS IMPACTS IN MAJOR SECTORS OF NATION'S ECONOMY

Materials Areas	Power Generation	Communication	Transportation	Health Care
Electroforming	X	X	X	X
Fuel Cell	X	X	X	
Nickel-cadmium battery	X	X	X	X
Silver-cadmium battery	X	X		
Silver-zinc battery	X	X	X	
Refractory alloy	X		X	
Solar cell	X	X		
Stress-corrosion of Titanium alloys	X		X	X

DISCUSSION OF METHODOLOGY

Objective

The objectives of this study were to (1) develop an information search method that would identify the NASA contribution to each of several selected areas of materials technology; (2) assess the impact of the NASA contribution within a selected sample of materials technology areas; and (3) point out how the past and future applications of NASA-sponsored developments that were originally oriented toward the space program would benefit other sectors of the national economy more related to daily living. These objectives were designed to show the feasibility of such a search method to identify those areas of materials technology to which NASA has made a significant contribution and extension of knowledge. This study was designed to develop quantitative as well as qualitative measures of the contribution of NASA to the state of the art of selected materials technology areas, particularly with respect to the total contribution by all government agencies and the private sector over the same time period (1, 2)*. This study does not attempt to look at all materials areas in depth but only to sample some of the promising areas to verify the suitability of the search method and to determine where refinements of the technique would be useful in future studies of this kind.

Selection of Materials Technology Areas

The complete list of index terms for STAR, CSTAR, and IAA as used at the NASA Scientific and Technical Information Facility and as compiled in the Subject Authority List of September 1967 was surveyed. Items relating to materials and materials fabrication techniques were extracted together with the total number of documents indexed by this term for publication purposes. Then, a sample of 33 index terms was selected from a total of 399. The sample index terms are listed in Table 3 (shown hereafter). The selection of the 33 terms was based on a survey of the materials literature, discussions with experts in the field, and scientific judgment as to which areas would have the best potential to show a significant NASA controbution relative to the total effort in those areas (1-6).

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* Numbers in parentheses refer to References listed at the end of report.

Table 3

INDEX TERMS SELECTED FOR MATERIALS STUDY

Beryllium	Graphite
Boron	Lubricant
Boron alloy	Magnetic forming
Boron polymer	Nickel-cadmium battery
Ceramics	Nondestructive testing
Chemical milling	Polymer
Composite material	Refractory alloy
Corrosion	Silver-cadmium battery
Cryogenic insulation	Silver-zinc battery
Electrochemical machining	Solar cell
Electrohydraulic forming	Spin forging
Electron beam welding	Stress-corrosion
Explosive forming	Stress-corrosion of titanium alloys
Fiber	Titanium
Fracture mechanics	Titanium alloy
Fuel cell	
Gallium arsenide	

To obtain a rapid, accurate, and uniform assessment of published information, arrangements were made to use the on-line teletype console, located at NASA Headquarters in Washington, D.C., which has access to the linear file of citations of reports located at the Lockheed computer facility at Sunnyvale, California.

This console/computer arrangement did not have the search and print-out capability of the College Park, Maryland, facility. One of the shortcomings was the inability of the system to sort the items into NASA and non-NASA groupings. The computer was programmed to select items from STAR only; the unclassified and unlimited distribution reports on NASA and DOD-supported work. The IAA items were not selected since this publication is devoted to periodicals and symposia and translations. Also there is strong evidence that technological progress is first reported in contract progress reports in a preliminary form and then repeated in periodicals and symposia.

With the use of the computer, a listing of accession numbers for items in STAR for each of the 33 index terms for the period 1962 through 1967 was obtained. Since no breakdown could be achieved between NASA and non-NASA items by the computer print-out, the items were manually separated into these categories by reference to the published annual indexes of STAR where NASA-sponsored items are identified by an asterisk after the accession number. Because of the extremely large volume of items for some of the categories, a sample of up to a maximum of 100 most recent items in each pertinent category was separated into NASA and non-NASA groupings, and the percentage of NASA entires in the sample was determined. A summary showing the total number of entries for the time period 1962 to 1967, with the total number and percentage of NASA entries in the sample, is given in Table 4.

Since only the most significan items were to be surveyed for this study, a criterion for eliminating all but a few items had to be established. If one considers the distribution of federal obligations for research and development for the year 1967, the contribution of NASA was 30% (7). Then, if the ratio of entries of items in STAR that were supported by NASA were above that percentage, it was considered significant for this study. The 40% level was the selection criterion. In addition, a minimum of at least 40 total entries for the period 1962 to 1967 for each category was established before the category was considered for the survey of contributions. The following eight categories of materials technology met the above criteria:

Electroforming
Fuel cell
Nickel-cadmium battery
Refractory alloy
Silver-cadmium battery
Silver-zinc battery
Solar cell
Stress-corrosion of titanium alloys

Survey of Materials Technology Areas

For each of those eight materials technology items shown above, every accession number that referred to a NASA item in the sample was checked and the abstract in STAR was reviewed for content. For each category, a list was prepared giving the contract number, contractor, and title of the report. In certain cases, there was a series of abstracts extending over a period of time covering the same contract number and the same project. In these cases, only the final report--or the latest report of a series when a final report had not yet appeared--would be listed. Each of these listings of NASA-sponsored work is given in a table at the end of the discussion of each individual materials technology area.

The discussions of the work performed under NASA auspices were based on the abstracts of the contracts, reports on NASA authorization hearings before congressional committees, NASA Special Publications, review articles, other publications, and discussions with persons knowledgeable in the various materials technology--new with respect to both innovations and advancement and improvement.

Table 4

STATISTICS ON INDEX TERMS USED IN STUDY

Index Term	Total No. of All Entries for 1962-1967	Years Covered by Sample	Sample Size	Total NASA Entries in Sample	Percent NASA Entries in Sample	Selected for Analysis
Beryllium	1,199	1967*	100	17	17%	
Boron	918	1967*	100	24	24	
Boron alloy	19	1962-1967	19	5	26	
Boron polymer	3	1962-1967	3	0	0	
Ceramics	901	1967*	100	20	20	
Chemical milling	15	1962-1967	15	4	27	
Composite material	331	1967*	100	36	36	
Corrosion	1,963	1967*	100	20	20	
Cryogenic insulation	50	1962-1967	50	15	30	
Electrochemical machining	7	1962-1967	7	0	0	
Electroforming	43	1962-1967	43	26	60	X
Electrohydraulic forming	9	1962-1967	9	2	22	
Electron beam welding	74	1962-1967	74	16	22	
Explosive forming	41	1962-1967	41	14	34	
Fiber	1,022	1967*	100	25	25	
Fracture mechanics	141	1965*-1967	100	24	24	
Fuel cell	328	1966*-1967	100	56	56	X
Gallium arsenide	203	1965*-1967	100	19	19	
Graphite	1,278	1967*	100	12	12	
Lubricant	600	1966*-1967	100	31	31	
Magnetic forming	12	1962-1967	12	7	58	
Nickel-cadmium battery	168	1965*-1967	100	87	87	X
Nondestructive testing	270	1966*-1967	100	26	26	
Polymer	2,087	1967*	100	21	21	
Refractory alloy	163	1964*-1967	100	67	67	X
Silver-cadmium battery	81	1962-1967	81	66	82	X
Silver-zinc battery	95	1962-1967	95	76	80	X
Solar cell	362	1966*-1967	100	75	75	X
Spin forging	4	1962-1967	4	1	25	
Stress-Corrosion	181	1965*-1967	100	39	39	
Stress-Corrosion of titanium alloys	217	1965*-1967	100	45	45	X
Titanium	2,101	1967*	100	20	20	
Titanium alloy	636	1967*	80†	15	19	

* Only a portion of the entries for that year were required to make up the total of 100 for the sample.

† Only the 80 most recent references were supplied by the console-computer system for this index term.

ANALYSIS OF NASA CONTRIBUTIONS TO SELECTED AREAS OF MATERIALS TECHNOLOGY

Each of the eight materials technology areas that met the selection criteria for this study is discussed in greater detail in the text that follows. The coverage includes a brief description of the operation or application where required to clarify or place in proper perspective the contributions by NASA. The discussion generally concentrates on those items elicited by the limited sample taken for this study and is not intended to be all-inclusive of the entire body of work done by NASA. Generally, the period covered is 1962 through 1967 as entered in STAR--or the last 100 items where the total number of entries is large--in which case only the last year or two is covered. The statistics are shown in Table 4 and are repeated at the end of the discussion for each materials area. A brief list summarizes the major categories covered by the literature items. A table listing all of the pertinent contracts, grants, and in-house projects within the sample by contract number, contractor, and title concludes each discussion.

Electroforming

Electroforming is the production or reproduction of an article by electrodepositing a metal layer over a mandrel that later is removed from the deposited metal by etching or melting out (8). The process is used in the manufacture of such aerospace components as precise metal mirrors that reflect sunlight for auxiliary power for space vehicles (NAS1-6218, NAS7-100, NAS1-4105, NAS1-3309, NAS7-86, NAS1-5743, Table 5).* Other aerospace components such as antennas and radiation shields are also fabricated by electroforming (9), (NAS5-10187, Table 5).

The electroforming process is not new in itself; it has been around since the 1830s (10). Current production parts range from giant missile bulkheads to portable appliances and builders' hardware (11). However, the precise nature of some of the aerospace applications has required refinements in the processing techniques and studies of the fundamental nature of the process.

There are such problems as nonuniform thickness from noneven current distribution and high residual stresses in the deposit, which are the major causes of splitting and distortion (12).

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* NASA contract numbers included in parentheses are referenced in the corresponding table for each materials technology category.

Experimental studies were performed on cylindrical and spherical shells, which were formed by the electroforming process and contained a known imperfection. Theoretical buckling loads were computed for imperfect shells, and the computations showed the same trends as the experimental studies. The test results obtained suggest that test performance is related to the nature and severity of flaws or imperfections and that low buckling pressures can be correlated with the presence of severe flaws or nonuniformities (NsG-18-59, NsG-630, Table 5).

One of the major problems is in making parts that are stress-free. The higher stresses might not be critical in heavier sections, but would be critical in foil-thick hollow sections in space applications with wall thicknesses down to 0.001 inch (9). Studies of the various factors that influence stresses include current density, bath composition, temperatures, and impurities. The development of a sensor that permits accurate monitoring of the density has made it possible to produce distortion-free mirrors ranging from 2 to 120 inches in diameter (13) (NAS7-100, NAS1-4105, Table 5).

The development of large-internal-surface-area nickel-metal plaques by electroforming is being pursued for incorporation into improved nickel-cadmium batteries (NAS3-6003, Table 5). This has been a continuing program over several years.

A program was initiated to demonstrate the capability of uiltizing electroforming techniques in the design and fabrication of liquid propellant rocket motor injectors (14), (NAS9-6177, Table 5). The results showed that the techniques are capable of producing injectors having complex internal propellant flow passages and incorporating fewer components and subassemblies devoid of press fits, welds, and brazes with demonstrated reproducible hydraulic characteristics.

Electroforming has been used for many years in making injection dies for producing phonograph records. It also has been used in toy manufacture, and more recently in the medical field, in the production of artificial limbs (11). Wave guides, with their requirements for fine internal surfaces and close tolerances, have been produced by electroforming (10). The use of nickel electroforms in tools and dies is under consideration by automotive companies (11).

The potential of electroforming has been increased by NASA-sponsored work. The important areas are the development of techniques to electroform stress-free parts, the improvement of electrodes for nickel-cadmium batteries, the carry-over of techniques needed to fabricate large diameter solar concentrators, and the techniques for making complex parts as exemplified by the electroformed injectors.

The survey of the reports in STAR yielded a total of 43 entries for the years 1962-67. Out of these, a total of 26 (60% of all items) were reports of NASA-sponsored contracts, grants, and in-house research. These entries covered the following subject areas:

1. Determination of buckling stress of cylindrical and spherical shells formed by the electroformed process.

2. Electroforming of solar concentrators.

3. Research and development of electroforming process.

4. Use of electroforming process in fabrication of large diameter mirrors.

5. Development of large-internal-surface-area nickel-metal plaques.

6. Development of electroforming techniques for fabrication of injectors.

7. Microcircuit masking techniques.

8. Development of a process for fabrication of spherical cryogenic storage containers.

A complete list of the projects found in the survey of reports on electroforming is given in Table 5.

Fuel Cell

The fuel cell is characterized as a continuously operating battery consisting of a nonconsumable anode and cathode with the reactants fed continuously to the cell and the reactant products continously removed along with any heat produced by the reaction. The free energy of the reactants is converted directly to electrical energy. Since any oxidation-reduction reaction may be a potential fuel cell, the suitability of a material is partially determined by the thermodynamic data for the overall reaction. However, it is also necessary to consider the kinetics, which in turn are influenced by factors such as temperature and pressure of the reactants (15). To be considered, the system must be favorable from an economic point of view. It must be capable of high conversion efficiencies from chemical energy to electrical energy (over 50% for fuel cells) (15, 16), be compact, and have few or no moving parts.

Materials used as oxidizers and fuels include oxygen, which can be reacted with hydrogen, ammonia, methyl alcohol, bottled gas, or even metals such as zinc. In the last case, the zinc-oxygen battery may be regarded as a hybrid fuel cell/storage battery (17, 18). Hydrogen peroxide, nitric acid, and compounds of chlorine and fluorine may be reacted with fuels like hydrazine in fuel cells for specialized applications. The reactant products are principally water with some carbon dioxide and other nonpollutant compounds.

Table 5

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF ELECTROFORMING

Contract No.	Contractor	Title
NAS1-6218	Electro-Optical Systems, Inc. Pasadena, Calif.	Research and Development of Magnesium/Aluminum Electroforming Process for Solar Concentrators
NAS7-100	General Electric Co. Philadelphia, Pa.	9½-Foot Diameter Master and Mirror
NAS1-4105	General Electric Co. Philadelphia, Pa.	9.5-Foot Paraboloidal Master and Concentrator
NAS5-10187	Electro-Optical Systems, Inc. Pasadena, Calif.	Lightweight Solar Panel Interconnections
NAS3-6003	Battelle Memorial Institute Columbus, Ohio	Development of Large-Internal-Surface-Area Nickel-Metal Plaques
--	General Dynamics/Convair San Diego, Calif.	Evaluation of Electroformed Nickel to 301 Stainless Steel Resistance Spotwelds at 78°F. and -423°F
NAS9-6177	Camin Labs., Inc. Brooklyn, N. Y.	Development of Electroforming Techniques for the Fabrication of Injectors
NASA Order H-76715	NASA-Marshall Space Flight Center, Huntsville, Ala.	The Making of Nickel and Nickel-Alloy Shapes by Casting, Powder Metallurgy, Electroforming, Chemical Vapor Deposition, and Metal Spraying
NAS8-20094	Electro-Optical Systems, Inc. Pasadena, Calif.	Development of an Electrodeposition Process for the Fabrication of a Spherical Cryogenic Fluid Storage Container

Table 5 (concluded)

Contract No.	Contractor	Title
--	NASA-Manned Spacecraft Center Houston, Texas	Microcircuit Masking Techniques
NsG-18-59	NASA Washington, D. C.	The Effect of Initial Imperfections on the Buckling Stress of Cylindrical Shells
NsG-18-59	California Inst. of Tech. Pasadena, Calif.	The Buckling of Cylindrical Shells
NsG-630	Stanford University Stanford, Calif.	An Experimental Study of the Buckling of Complete Spherical Shells
NASr-112	United Aircraft Corp. East Hartford, Conn.	Research on the Collision Probabilities of Electrons and Cesium Ions in Cesium Vapors
--	NASA-Langley Research Center Langley Station, Va.	Status of Solar Energy Collector Technology
NAS7-10	Electro-Optical Systems, Inc. Pasadena, Calif.	Research and Development Techniques for Fabrication of Solar Concentrators
NAS1-3309	General Electric Co. Philadelphia, Pa.	Electroforming Aluminum for Solar Energy Concentrators
NAS7-86	Electro-Optical Systems, Inc. Pasadena, Calif.	Research and Development of High Efficiency Lightweight Solar Concentrators
NAS1-5743	General Electric Co. Philadelphia, Pa.	Electroforming Aluminum Composites for Solar Energy Concentrators
--	NASA-Langley Research Center Langley Station, Va.	Geometric Efficiency of an Electroformed Nickel Solar Concentrator

In applications directed to the space program, such as the Apollo and Gemini spacecraft, where high power density and reliability are prime considerations, the reactants are oxygen and hydrogen, and the product water will be used by the astronauts (19). The fuel cell research and development now sponsored by NASA to assist in life support in the sealed environment of spacecraft will be directly applicable to supporting life in the ocean depths (2). In a sealed environment, the fuel cell can (1) contribute potable water to reduce the fresh water supply requirements, (2) utilize exhaled breath from the cabin atmosphere as a source of oxygen to reduce the overall required fresh oxygen supply, and (3) concentrate the carbon dioxide that must otherwise be taken up on absorbers (NAS9-4107, NAS3-7638, NAS5-10241, NAS9-5080, Table 6).

The ability of miniature hydrogen/oxygen fuel cells to consume the gases generated in silver-zinc batteries allows the use of completely sealed batteries with no danger of overpressurization or venting into the cabin atmosphere (NAS5-9594, Table 6).

In the regenerative type of fuel cells, the product formed is dissociated to regenerative the reactants so that they can be reused. Regenerative-type cells, when incorporated into systems utilizing solar cells, will be especially useful (NAS3-2781, Table 6). The solar cells can function during sunlight periods to supply power and regenerate new reactants from the fuel cell products so that reactants will be available for the fuel cell to operate during periods of darkness (20).

A novel variation of the fuel cell is the dry tape battery where the electrodes and an encapsulated electrolyte are contained in a plastic film or tape. As the tape is passed through feed rollers that crush the electrolyte capsules, the electrochemical reaction proceeds and thus generates electric power. The advantages of such a system are easy storage of the reactants, light weight, high power, long shelf life, and portable applications (16, 18, 21).

Another area in which NASA is supporting work on fuel cells gives the spacecraft or submersible the option of using the oxidizers and fuels on board to perform an active mission of work and travel or to support the life of the crew while awaiting reassignment or rescue. The combination of hydrogen peroxide and hydrazine is an example that has been cited in presentation of this concept of flexibility (NAS3-4175, Table 6).

NASA was the first U.S. federal agency to specify a fuel cell as part of a required power system (15). The agency invited bids for fuel cells for auxiliary power requirements for some space projects, and multimillion dollar appropriations have been made to further this effort. The first applications will naturally be in space technology, but its impact on the general public should be significant.

Of most immediate interest to the consumer is the consideration being given to fuel cells for powering electric automobiles (NsG-316, Table 6). Allis-Chalmers has already demonstrated a farm tractor powered by fuel cells using hydrocarbons and air (15). The increased impetus given to fuel cell research should hasten the day when the cells may be used for passenger automobiles. The application of fuel cells to automobiles may supply an economic transition to cleaner air in our cities (without requiring the disestablishment of our petroleum distribution network of refineries and service stations) by providing battery-charging facilities convenient to the drivers (2).

The survey of the reports in STAR yielded a total of 328 entries from the years 1962-67. From the most recent 100 items--covering part of 1966 and all of 1967--there were a total of 56 items (56% of all items) that were reports of NASA-sponsored contracts, grants, and in-house research. These entries covered the following subject areas:

1. Fundamental chemistry of fuel cells.
2. Discovery and characterization of catalysts for fuel cells.
3. Selection and characterization of reactants for fuel cells.
4. Selection of materials and design of electrodes.
5. Selection and characterization of electrolytes.
6. Geometry of cells.
7. Regeneration of fuel cells.
8. Removal of water from fuel cells.
9. Purification and use of water from fuel cells.
10. Use of cabin atmosphere as an oxygen source for fuel cells.
11. Development of fuel cells with higher power output, longer life, improved reliability, lower weight-to-power ratios, and volume-to-power ratios.
12. Design and characterization of fuel cells for applications such as Gemini and Apollo.

A complete list of the projects found in the limited survey of reports on fuel cells is given in Table 6.

Nickel-Cadmium, Silver-Cadmium and Silver-Zinc Batteries

Battery systems have been widely used over a long period of time. The nickel-cadmium cell was developed in 1900, with the silver-zinc cell following in about 1930 and silver-cadmium in the 1950s. The nickel-cadmium cell was already in limited commercial use for powering rechargeable flashlights, power tools, and other portable items before NASA's

Table 6

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF FUEL CELL

Contract No.	Contractor	Title
NsG-325	Pennsylvania University Philadelphia, Pa.	Studies in Fundamental Chemistry of Fuel Cell Reactions
NASw-1233	Tyco Labs, Inc. Waltham, Mass.	Development of Electrocatalysts for Use in Low Temperature H_2O_2 Fuel Cells with an Alkaline Electrolyte
NASw-1527	Monsanto Research Corp. Everett, Mass.	Test Evaluation of Fuel Cell Catalysts
NASw-1577	Catalyst Research Corp. Baltimore, Md.	Test Evaluation of Fuel Cell Catalysts
NsG-496	Massachusetts Inst. of Tech. Cambridge, Mass.	Mixed-Feed Methanol-Oxygen Fuel Cells
NAS3-4175	Monsanto Research Corp. Everett, Mass.	Study of Fuel Cells Using Storable Rocket Propellants
NAS5-10247	Union Carbide Consumer Products Co. Parma, Ohio	Secondary Zinc-Oxygen Cell for Spacecraft
NAS8-2696	Allis-Chalmers Mfg. Co. Milwaukee, Wis.	Research and Development on Fuel Cell Systems
NASA Order W-12300	Bureau of Mines Pittsburgh, Pa.	Development of an Improved Oxygen Electrode for Use in Alkaline H_2-O_2 Fuel Cells

Table 6 (continued)

Contract No.	Contractor	Title
NAS3-6477	American Cyanamid Co. Stamford, Conn.	Development of High-Performance Light-Weight Electrodes for Hydrogen-Oxygen Fuel Cells
NAS3-8524	American Cyanamid Co. Stamford, Conn.	See NAS3-6477 above
NAS3-9430	Union Carbide Corp. Cleveland, Ohio	Development of Fuel Cell Electrodes
NGR-10-005-022	Florida Univ. Gainesville, Fla.	A Study of Gas Solubilities and Transport Properties in Fuel Cell Electrolytes
NAS7-326	United Science Associates, Inc.,Pasadena, Calif.	Gaseous Electrolytes for Batteries and Fuel Cells
NAS7-437	United Science Associates, Inc. Pasadena, Calif.	See NAS7-326 above
NAS3-2781	Electro-Optical Systems, Inc. Pasadena, Calif.	Hydrogen-Oxygen Electrolytic Regenerative Fuel Cells
--	NASA-Lewis Research Center Cleveland, Ohio	Use of a Fluidic Oscillator as a Humidity Sensor for a Hydrogen-Steam Mixture
NASA order T-31248-G	Aerospace Medical Research Labs. Wright-Patterson AFB,Ohio	Effects of Oral Administration of a Fuel Cell Product Water to *Macaca Mulatta*
NAS9-4107	IIT Research Inst. Chicago, Ill.	Purification of Gemini Fuel Cell Water by Ion-Exchange Chromatography

Table 6 (continued)

Contract No.	Contractor	Title
NAS3-7638	TRW Equipment Labs. Cleveland, Ohio	Carbon Dioxide Concentration System
NAS5-10241	Gulton Industries, Inc. Metuchen, N.J.	Characterization of Recombination
NAS9-5080	Midwest Research Inst. Kansas City, Mo.	Purification of Fuel Cell Gases
NAS8-2696	Allis-Chalmers Mfg. Co. Milwaukee, Wis.	Development of 2KW Fuel Cell Power Systems
NAS8-5392	Allis-Chalmers Mfg. Co. Milwaukee, Wis.	Research and Development of Open-Cycle Fuel Cells
--	NASA Manned Spacecraft Center Houston, Tex.	Electrical Power and Sequential Systems
--	NASA Lewis Research Center Cleveland, Ohio	Apollo Fuel Cell Condenser Heat Transfer Tests.
NAS3-2787	Vickers, Inc. Torrance, Calif.	Development of a Hydrogen-Oxygen Space Power Supply System.
NAS5-9594	Douglas Aircraft Co., Inc. Newport Beach, Calif.	Small Fuel Cell to Eliminate Pressure Caused by Gassing in High Energy Density Batteries.
NAS8-2696	Maryland Univ. College Park, Md.	Vent Subsystem-Development Plan
--	Allis-Chalmers Mfg. Co. Milwaukee, Wis.	Fuel Cell Module Development Plan-Activity 145-2[illegible]5

Table 6 (concluded)

Contract No.	Contractor	Title
		Reactant Control and Conditioning Subsystem-Development Plan Activity 190
		Fuel Cell Reliability Assessment
NAS9-3349	Lockheed-California Co. Burbank, Calif.	A Transient Heat Transfer and Thermodynamic Analysis of the Appolo Service Module Propolsion System. Vol. 1, Phase 1: Transient Thermal Analysis
NsG-316	Pennsylvania Univ. Philadelphia, Pa.	The Electric Automobile - Its Future
--	NASA Washington, D.C.	An Introduction to Fuel Cells

work in this area (16). However, further research, spurred by the space program, with its requirements of higher energy density and reliability, has led to better products for the consumer market. Some items that have been mentioned are compact hearing-aid batteries that would operate at a cost of almost one-hundredth of those in present use. The electric automobile has been mentioned frequently as being feasible, especially for short range distances for city and commuter driving. If specially designed nickel-cadmium cells were used, a range of 200 miles might be achieved (16). Automobile manufacturers are considering the use of the improved batteries, along with fuel cells, as alternatives for the internal combustion engine because of the air pollution problems. Any improvements in batteries developed for the space program will lead to improvements in battery systems already in general use. Techniques of research, new knowledge of electrode chemistry, and other items to be discussed later will result in improved batteries of all types--not just limited to the three discussed here.

The battery evaluation program is especially important. To improve life and reliability of operational batteries, NASA initiated a program of long term life-cycle tests (charge-discharge cycling) which were run on cells that had passed the normal acceptance, which entails only inspection and short-time testing (22) (NASA Order W-11252-B, Tables 7, 8, 9). The main failure mechanisms were identified. For example, in the first year of life-cycle testing on 660 nickel-cadmium cells, there were 191 failures. Over 100 of these were caused by internal short circuits that were attributed to separator breakdown. Other major causes of failures were other separator problems, electrolyte leakage, and poorly welded connections. Identification of the major failure areas has led to work to correct the deficiencies. This program has for the first time given complete details on causes of battery failures under controlled experimental conditions. The technique and information gained in these programs should lead to improved battery reliability and establish new design criteria.

Another significant improvement was the addition of an auxiliary electrode (23) that served two functions: (1) to produce a reliable electrical signal with nickel-cadmium cells to indicate when recharging is complete, thus preventing overcharging or undercharging and increasing the operating life of a battery, and (2) to avoid build-up of excessive pressure caused by high rates of charge and overcharge (24), (NASr-191, Table 7; NAS5-2817, NAS5-3669, Table 8). The auxiliary electrode causes the oxygen to recombine as fast as it is produced, thus preventing pressure build-up and resulting in lighter and more reliable batteries.

Other work has included better seals for longer life and greater reliability (20, 25), and the development of a battery to withstand the high temperature sterilization requirement for planetary landing vehicles (26) (NAS7-100, Tables 7, 8, 9).

There is a continuing program to improve battery energy density in addition to the cycle life. The nickel-cadmium battery has a high recharge rate, is capable of operating for tens of thousands of recharge cycles, and has a good overcharge capacity; however, it has a comparatively low realizable energy density. In turn, the silver-zinc battery has the highest energy density, but it has a limited recycle life of only a few hundred recharges and poor overcharge capacity. The silver-cadmium cell lies somewhere between the two others (22). Aside from desired improvements in the nickel-cadmium cell, the direction of research was obviously directed toward the silver-zinc cell. The problem areas causing poor recycle life were soluble electrodes, separators that were not inert to their environment, and the fact that the zinc electrode was subject to dendritic growths (27, 28). An example of work in one of these problem areas was the development of an inorganic type of separator, which shows great promise (26, 29), and the major failure problem of the silver-zinc cell is no longer the separator. Work is continuing on the other problems. With present improvements, the silver-zinc batteries have found usage in deep submergence vehicles and submarines (30).

Although the preceding coverage of three major battery types--nickel-cadmium, silver-cadmium, silver-zinc--was given in a single discussion because of their similarities, the report literature survey is divided into separate sections

Nickel-Cadmium Battery

The survey of the reports relating to nickel-cadmium batteries in STAR yielded a total of 168 entries for the years 1962-67. From the most recent 100 items--covering part of 1965 and all of 1966-67--there were a total of 87 items (87% of all items) that were reports of NASA-sponsored contracts, grants, and in-house research. These entries covered the following subject areas:

1. Life cycle tests and analysis of results.
2. Improvements of cadmium and nickel electrodes.
3. Improvement of overdischarge and overcharge characteristics.
4. Development of auxiliary electrodes.
5. Heat sterilization studies.
6. Effects of radiation.
7. Control of electrolyte level.
8. Computer methods for analysis of battery data.
9. Development of auxiliary electrode instrumentation.

A complete list of the projects found in the li. ited survey on the nickel-cadmium battery is given in Table 7.

Table 7

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF NICKEL-CADMIUM BATTERY

Contract No.	Contractor	Title
NASA Order W-11252-B	Naval Ammunition Depot Crane, Ind.	Life Cycle Tests
		Space Cell Test Program
		Evaluation Program for Secondary Spacecraft Cells (Includes acceptance tests of Sonotone Corporation, General Electric Company, and Gulton Industries of 3.0 to 20 ampere-hour Nickel-Cadmium Cells under various arrangements.)
NASA Order S-23404-G	Naval Ammunition Depot Crane, Ind.	Space Cell Test Program
NAS5-9073	Cook Electric Co. Dayton, Ohio	Testing and Evaluation of Nickel-Cadmium Spacecraft-Type Cells
NAS5-9586	General Electric Co. Schenectady, N. Y.	Study of Nickel-Cadmium Cells
NAS3-7636	General Electric Co. Gainesville, Fla.	Development of Improved Cadmium Electrodes for Sealed Secondary Batteries
NAS5-3477	General Electric Co. Schenectady, N. Y.	Characterization of Nickel-Cadmium Electrodes
NAS5-3707	General Electric Co. Gainesville, Fla.	Development of a Nickel-Cadmium Storage Cell Immune to Damage from Overdischarge and Overcharge
NAS5-3667	Gulton Industries, Inc. Metuchen, N. J.	Hermetically Sealed Cells Capable of Overdischarge as well as Overcharge

Table 7 (continued)

Contract No.	Contractor	Title
NAS5-3813	Electric Storage Battery Co. Raleigh, N. C.	Research and Development on Cells with Bellows Controlled Electrolyte Levels
NASr-191	Pennsylvania University Philadelphia, Pa.	Study Papers on the Auxiliary Electrode
NAS3-7620	Gulton Industries, Inc. Metuchen, N. J.	Investigation of Battery Active Nickel Oxides
NAS3-6003	Battelle Memorial Institute Columbus, Ohio	Development of Large-Internal-Surface-Area Nickel-Metal Plaques
NGR-33-006	Polytechnic Institute of Brooklyn Brooklyn, N. Y.	Calorimetric Study of the Thermodynamic Properties of the Nickel-Cadmium Cell
NASw-1001	Radio Corp. of America Princeton, N. J.	Correlation of Data from Tests on Nickel-Cadmium Batteries
NASA Order S-12730-G	Marine Engineering Lab. Annapolis, Md.	Shunt Voltage Regulator Circuit for Nickel-Cadmium Cells with Auxiliary Electrodes
		Nickel-Cadmium Battery Reconditioner
NAS1-5708	Gulton Industries, Inc. Metuchen, N. J.	Investigation of Sterilization of Secondary Batteries
NAS7-100	TRW Systems Redondo Beach, Calif.	Nickel-Cadmium Cell Heat Sterilization Test Program, Phase I
		Heat Sterilized Nickel-Cadmium Cell Failure Analysis Program, Phase II
		Heat Sterilized Nickel-Cadmium Electrical Performance Investigation, Phase III

Table 7 (continued)

Contract No.	Contractor	Title
NAS7-100	Atomics International Canoga Park, Calif.	Effects of High-Energy Protons on Selected Cells
NAS5-9226	Sonotone Corp. Elmsford, N. Y.	Procurement and Development Program for Nickel-Cadmium Cells to Specification S-615-P-2
NAS5-10241	Gulton Industries Metuchen, N. J.	Characterization of Recombination and Control Electrodes for Spacecraft Nickel-Cadmium Cells
NAS5-10261	General Electric Co. Gainesville, Fla.	Characterization of Recombination and Control Electrodes for Spacecraft Nickel-Cadmium Cells
NAS5-10105	American University Washington, D. C.	Research into Fundamental Phenomena Associated with Spacecraft Electrochemical Devices-Calorimetry of Nickel-Cadmium Cell
NAS5-10160	Gulton Industries, Inc. Metuchen, N. J.	Development of Pile Type, High Discharge Rate Nickel-Cadmium Squib Batteries
NAS5-3027	Martin Co. Baltimore, Md.	Nickel-Cadmium Battery Test Project Relationship between Operation, Life and Failure Mechanism Volume 1: Experimental Procedure
NAS1-4289	Gulton Industries, Inc. Metuchen, N. J.	Design and Fabrication of 100 Ampere-Hour Nickel-Cadmium Battery Cells
NAS5-3839	Gulton Industries, Inc. Metuchen, N. J.	Prototype Nickel Cadmium Cells for a Future Meteorological Spacecraft
NAS5-10213	Dayrad Lab. Dayton, Ohio	Testing and Evaluation of Nickel-Cadmium Spacecraft-Type Cells

Table 7 (concluded)

Contract No.	Contractor	Title
NAS5-10203	Mauchly Systems, Inc. Montgomeryville, Pa.	Computer Methods for the Reduction Correlation and Analysis of Space Battery Test Data
		NiCd Space Battery Test Data Analysis Project
--	Jet Propulsion Lab. Pasadena, Calif.	Energy Storage
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Use of the Absorption Hydrogen Electrode and the Oxygen Fuel-Cell Electrode in Nickel-Cadmium Cells
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Auxiliary Electrode Instrumentation for Nickel-Cadmium Cells
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Analysis of Cadmium-Cadmium Coulometers Used for Charge Control in Nickel-Cadmium Space Batteries
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Some Factors to Consider in Determining the Capacity of a Nickel-Cadmium Cell
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Computer Program for Analyzing Battery Performance Data

Silver-Cadmium Battery

The survey of the reports relating to silver-cadmium batteries yielded a total of 81 entries for the years 1962-67. There were a total of 66 items (82% of all items) that were reports of NASA-sponsored contracts, grants, and in-house research. These entries covered the following subject areas:

1. Life cycle tests and analysis of results.

2. Silver-cadmium development program.

3. Design and development of a hermetically sealed cell in a nonmagnetic metallic case.

4. Study of the use of auxiliary electrodes.

5. Research and development of battery separators.

6. Study of the electrochemical process in silver-cadmium secondary cells.

7. Solid state circuit development.

8. Study of radiation effects.

9. Heat sterilization studies.

A complete list of the projects found in the survey on the silver-cadmium battery, is given in Table 8.

Silver-Zinc Battery

The survey of the reports relating to silver-zinc batteries yielded a total of 95 entries for the years 1962-67. There were a total of 76 items (80% of all items) that were reports of NASA-sponsored contracts, grants, and in-house research. These entries covered the following subject areas:

1. Life cycle tests and analysis of results.

2. Design of standard nonmagnetic, sealed silver-zinc cells.

3. Feasibility of dry tape battery concept.

4. Study of the use of auxiliary electrodes.

5. Investigation and improvement of zinc electrodes.

6. Study of alkaline battery separators.

7. Heat sterilization studies.

8. Study of the reactions pertaining to zinc-silver batteries.

9. Use of a small fuel cell to eliminate pressure caused by gassing in high energy density batteries.

A complete list of the projects found in the survey on the silver-zinc battery is given in Table 9.

Table 8

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF SILVER-CADMIUM BATTERY

Contract No.	Contractor	Title
NASA Order W-11252B	Naval Ammunition Depot Crane, Ind.	Life Cycle Tests
		Evaluation Program for Secondary Spacecraft Cells
		Space Cell Test Program
NAS5-1318	Eagle-Picher Co. Joplin, Mo.	Design and Development of Silver-Cadmium Storage Batteries.
NAS5-1431	Telecomputing Corp. Denver, Colo.	Silver-Cadmium Development Program
NAS5-2155	Yardney Electric Corp. New York, N.Y.	Design and Development of a Hermetically Sealed 12 Ampere-Hour Silver-Cadmium Cell in a Non-Magnetic Metallic Case
NAS5-2155	Boeing Co. Seattle, Wash.	Evaluation of Silver-Cadmium Batteries
NAS5-2452	Yardney Electric Corp. New York, N.Y.	Research and Development Study of the Silver-Cadmium Couple for Space Application
NAS5-2817	General Electric Co. Schenectady, N.Y.	Research Study on the Use of Auxiliary Electrodes in Sealed Silver-Cadmium Cells
NAS5-3669	General Electric Co. Schenectady, N.Y.	Study of Use of Auxiliary Electrodes in Silver Cells
NAS5-3452	Yardney Electric Co. New York, N.Y.	Research and Development of the Silver-Cadmium Couple for Space Application

Table 8 (continued)

Contract No.	Contractor	Title
NAS5-3467	Borden Chemical Co. Philadelphia, Pa.	Research and Development of Separators for Silver Oxide-Cadmium Cells for Spacecraft Application
NAS5-9107	Borden Chemical Co. Philadelphia, Pa.	Improved Separators for Silver Oxide-Zinc and Silver Oxide-Cadmium Cells for Spacecraft Application
NAS5-9168	General Electric Co. Schenectady, N.Y.	Electrodeposited Inorganic Separators
NAS5-9106	Yardney Electric Corp. New York, N.Y.	Research and Development of the Silver Oxide-Cadmium Electrochemical System
NAS9-6470	Boeing Co. Seattle, Wash.	Development and Fabrication of Advanced Battery Energy Storage System
NASA Order S-70008-C	National Bureau of Standards Washington, D.C.	A Study of Electrochemical Processes in Silver-Cadmium Secondary Cells
NAS9-1307	Lockheed-California Co. Burbank, Calif.	Study for on On-Board Electrical Power System for a Manned Orbital Space Station
--	Marine Engineering Lab. Annapolis, Md.	Solid-State Circuit Development
NASA Order S-23404-0	Electrochimica Corp. Menlo Park, Calif.	Four Ampere-Hour Silver Cadmium Cells Program
NAS7-100	Atomics International Canoga Park, Calif.	Radiation Effects on Silver and Zinc Battery Electrodes V
		Effects of High-Energy Protons on Selected Cells

Table 8 (concluded)

Contract No.	Contractor	Title
NAS7-100	Idaho State Univ. Pocatello, Idaho	The Reactions Pertaining to Zinc-Silver and Cadmium-Silver Batteries
NAS7-100	Electric Storage Battery Co. Yardley, Pa.	Heat Sterilizable, Impact Resistant Cell Development
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Use of a Sealed Silver Cadmium Battery on Explorer XII
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Two Level Voltage Limiter
NASw-401	IIT Research Inst. Chicago, Ill.	Space Battery Hand Book

Table 9

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF SILVER-ZINC BATTERY

Contract No.	Contractor	Title
NASA Order W-11252-B	Naval Ammunition Depot Crane, Ind.	Space Cell Test Program Life Cycle Tests
NAS5-1607	Electric Storage Battery Co. Raleigh, N. C.	Design of a Standard Line of Non-Magnetic Sealed, Low Rate Silver-Oxide-Zinc Cells for Space Applications
NAS3-2777	Monsanto Research Corp. Everett, Mass.	Feasibility Proof of Dry Tape Battery Concept
NAS5-3669	General Electric Co. Schenectady, N. Y.	Study of the Use of Auxiliary Electrodes in Silver Cells
NAS5-9591	Leesona Corp. Great Neck, N. Y.	The Improvement of Zinc Electrodes for Electrochemical Cells
NAS5-3873	Yardney Electric Corp. New York, N. Y.	Investigation and Improvement of Zinc Electrodes for Electrochemical Cells
NAS3-8513	Douglas Aircraft Co., Inc. Newport Beach, Calif.	Improved Zinc Electrode
NAS8-5493	Eagle-Picher Co. Joplin, Mo.	Investigations Leading to the Development of a Primary Zinc-Silver Oxide Battery of Improved Performance Characteristics
NAS5-3351	Yardney Electric Corp. New York, N. Y.	Development of a 12 Ampere-Hour Sealed Silver Zinc Cell for Satellite Applications

Table 9 (continued)

Contract No.	Contractor	Title
NAS5-2860	Electric Storage Battery Co. Yardley, Pa.	Alkaline Battery Separator Study
NAS5-3467	Borden Chemical Co. Philadelphia, Pa.	Improved Separations for Silver Oxide-Zinc and Silver Oxide-Cadmium Cells for Spacecraft Application
NAS5-9107	Borden Chemical Co. Philadelphia, Pa.	Improved Separations for Silver Oxide-Zinc and Silver Oxide-Cadmium Cells for Spacecraft Application
NAS3-6007	Douglas Aircraft Co., Inc. Santa Monica, Calif.	Inorganic Separator for High Temperature Silver-Zinc Battery
--	NASA-Goddard Space Flight Center, Greenbelt, Md.	Separator Materials for Silver-Oxide Zinc and Silver Oxide-Cadmium Electrochemical Cells
NAS3-7639	Douglas Aircraft Co., Inc. Newport Beach, Calif.	Program to Develop an Inorganic Separator for a High Temperature Silver-Zinc Battery
NAS7-100	Radiation Applications, Inc. Long Island City, N.Y.	Fabrication and Test of Battery Separator Materials Resistent to Thermal Sterilization
NAS7-100	Monsanto Research Corp. Everett, Mass.	Separator Development for a Heat Sterilizable Battery
NAS7-100	Monsanto Research Corp. Dayton, Ohio	Silver-Zinc Battery Separator Material Development
NAS7-100	Westinghouse Electric Corp. Pittsburgh, Pa.	Separator Development for a Heat Sterilizable Battery

Table 9 (continued)

Contract No.	Contractor	Title
NAS7-100	Whittaker Corp. Los Angeles, Calif.	Separator Development Phase of Heat-Sterilizable Battery Development Program
NAS7-100	Electric Storage Battery Co. Yardley, Pa.	Heat Sterilizable, Impact Resistant Cell Development
--	Jet Propulsion Lab. Pasadena, Calif.	Sterilizable Battery
--	NASA-Lewis Research Center Cleveland, Ohio	Alternate Approaches to Sterilizable Power Sources
NAS7-100	Atomics International Canoga Park, Calif.	Radiation Effects of Silver and Zinc Battery
NAS7-100	Yardney Electric Corp. New York, N.Y.	Design of Sealed Secondary Silver Zinc Battery
NAS7-100	Idaho State University Pocatello, Idaho	The Reactions Pertaining to Zinc-Silver and Cadmium-Silver Batteries
NAS7-100	Jet Propulsion Lab. Pasadena, Calif.	Development of an Electrochemical Energy Source for the Mariner II Spacecraft
NAS7-100	Brigham Young University Provo, Utah	Studies of Reaction Geometry in Oxidation and Reduction of the Alkaline Silver Electrode
NAS5-9594	Douglas Aircraft Co.,Inc. Newport Beach, Calif.	Small Fuel Cell to Eliminate Pressure Caused by Gassing in High Energy Density Batteries

Table 9 (concluded)

Contract	Contractor	Title
NAS2-3819	Douglas Aircraft Co., Inc. Newport Beach, Calif.	Development of One Ampere-Hour Heat Sterilizable Silver-Zinc Cell
--	NASA-Lewis Research Center Cleveland, Ohio	Centaur Electrical System Problems, Related Work, and Solutions
--	NASA-Goddard Space Flight Center Greenbelt, Md.	The Atmosphere Explorer-B Solar Array (AE-B)
--	NASA-Goddard Flight Center Greenbelt, Md.	Silver Zinc Batteries Power Supply for the Atmosphere Explorer-B Spacecraft (AE-B)
NASw-401	IIT Research Inst. Chicago, Ill.	Space Battery Hand Book

Refractory Alloys

The operating temperature limits of components of aircraft and aerospace vehicles have expanded radically in recent years. On the high temperature scale, we had the piston engine operating at a maximum of 1000°F in the 1930s, the introduction of the jet engine with operating temperatures up to about 1500°F in the early 1940s, and the rocket engine with temperatures up to 5000°F in the middle 1950s and estimated to be up to around 6000 F by 1970 (31, 32). If re-entry vehicles are considered, the upper temperature of interest is extended to about 15,000°F. No material is able to withstand the re-entry temperatures for any length of time, and the concept of ablation--the gradual vaporization of the surface to protect the main body of the material--must be used.

The area of interest for this discussion lies from about 2000°F to above 5000°F, the operating range of the rocket engines. The useful range of the superalloys--containing nickel or cobalt--extends only to about 2200°F. If one needs to go to higher temperatures as in propellant rocket nozzles, it is necessary to consider a new class of materials--the refractory materials (33, 34). There are only four metals with melting points above 4000°F that are readily available. These are columbium, with a melting point of 4470°F; molybdenum, which melts at 4750°F; tantalum at 5400°F; and tungsten at 6170°F. If one groups the refractory metals according to their strength and ductility, one finds that tungsten and molybdenum have the best high temperature strength but tend to become brittle at low temperatures. On the contrary, tantalum and columbium have excellent low temperature strength.

Efforts are being directed toward improvement of the properties of the refractory metals by alloying. For example, a tantalum alloy has been prepared by adding about 10% tungsten and 2.5% hafnium, which has an increase of high temperature strength of four to five times over tantalum alone, with retention of good ductility properties (35, 36, 37). The ductility of tungsten has been improved by addition of small amounts--around 3%--of rhenium (31).

A major problem with all refractory metals is that they readily oxidize even at temperatures of a few hundred degrees Fahrenheit. In this case, alloying has not proved successful in reducing oxidation rates without severely decreasing high temperature strength and low temperature ductility at the same time. Another approach to the oxidation problem is to provide suitable oxidation resistant coatings. One coating process that has been of particular interest is plasma spraying (31). In this case, the coating material in powder form is carried in a gas stream through an electric arc and sprayed on to the piece to be coated. The various parameters of the process have been studied, and significant improvements have been made.

The fabricability of the refractory alloys has been studied with particular attention to welding (38). Special procedures have been derived to minimize contamination and to control welding variables including complete cleaning of the materials before welding and working in very clean vacuum (NAS3-2540, Table 10).

Another application area for the refractory materials has been in liquid-metal technology (NASA in-house, Table 10). Liquid metals, with their highly desirable heat transfer characteristics, have been used successfully in jet turbine engines to cool turbine blades (39, 40). Another use has been as working fluids in electric power generating systems. A typical system is a Rankine cycle power system where the liquid metal is first heated to a vapor that is passed through a turbine. The turbine converts the energy to mechanical energy that becomes electrical energy via the electric generator. This is very similar to the operation of a steam power plant. By using potassium as the working fluid, the efficiency of power plant operation is increased over that by using conventional fluids such as water.

The choice of container material for use with liquid metals depends on the use temperature. For the alkali liquid metals--sodium, potassium, and sodium-potassium mixtures--refractory metals must be used above 1800° F (39). Again, for optimum corrosion resistance, refractory metal tory alloys were evaluated in test loops that permitted long-time testing under operating conditions (NAS3-2547, NAS3-6474, Table 10). A substantial part of the effort in refractory alloys has been directed toward potassium Rankine system technology (NASA in-house, Table 10). All of the previously mentioned areas of research--oxidation, structural properties including creep strength, fabricability, and corrosion--are also being pursued for liquid metal technology applications.
metal technology applications.

The efforts will culminate in the first real refractory components typical of advanced Rankine power systems (41). The principal objectives are for space applications, but the resulting systems could just as easily be developed for nuclear and conventional power systems to feed into our national power network.

The survey of the reports in STAR yielded a total of 163 entries for the years 1962-67. From the most recent 100 items--covering part of 1964 and all of 1965-67--there were a total of 67 items (67% of all items) that were reports of NASA-sponsored contracts, grants, and in-house research. The subject areas that were covered are given in the following list:

1. Determination of the weldability and elevated temperature stability of refractory metal alloys.

2. Elevated temperature fatigue data in ultra-high vacuum.

3. Long time creep data at elevated temperatures.

4. Advanced refractory alloy corrosion loop programs.

5. Cavitation damage in liquid metals.

6. High strain rate behavior.

7. High temperature extrusion.

8. Development of fabrication process for refractory metal alloy fibers.

9. Studies of solubilities of refractory metals and alloys in alkali metals.

10. Growth of refractory carbide single crystals.

A complete list of the projects found in the limited survey on refractory alloys is given in Table 10.

Solar Cells

The use of solar cell power systems outside of space applications are at present limited because of their high cost. However, the satellite applications are important to our daily living--observation of our environment for prediction of weather changes and other natural phenomena and the relay of electromagnetic radiations allowing us to communicate on a global scale with radio and TV broadcasting and enabling ships (and at a future date aircraft) to navigate with precision (2). On Earth, applications are currently limited to remote sunny places where solar cells are more economical than other methods. For example, emergency telephone systems along certain freeways are powered by solar cells (16). The development of a truly low-cost solar cell power system should open up new application areas.

The emphasis of work on solar cells has been to increase their efficiency over wider temperature ranges, increase resistance to radiation, and decrease cost and weight. In practical situations, the solar cells have been capable of converting solar energy to electricity with 10% system efficiency (20). Silicon and gallium arsenide are among the most promising single-crystal solar cell materials being investigated (42, 43).

One of the main problems with solar cells is their sensitivity to radiation damage. The substitution of "n-on-p" type solar cells for the "p-on-n" type brought a great improvement with respect to susceptibility to damage from radiation. However, the "n-on-p" type solar cell is less efficient than the "p-on-n" type so that research is continuing in these areas (16, 20), (NAS5-3805, NAS5-9131, NAS5-9580, NAS7-289, Table 11.) Some additional improvements have been effected by eliminating certain impurities from the cell materials (21). Use of cover glasses (made from glass, quartz, or sapphire) have also reduced radiation damage (21). Improvements have been directed toward reducing the thickness and weight of protective glass shielding (NAS5-10236, Table 11). The addition of lithium has been found to increase radiation resistance since lithium migrates to and repairs damaged areas, but further work is needed to determine whether lithium will eventually evaporate under such environmental conditions as the high vacuum in space (26) (NAS5-9131, Table 11).

Table 10

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF REFRACTORY ALLOYS

Contract No.	Contractor	Title
NAS3-2540	Westinghouse Electric Corp. Astronuclear Lab. Pittsburgh, Pa.	Determination of the Weldability and Elevated Temperature Stability of Refractory Metal Alloys
NAS3-2545	TRW Equipment Labs Cleveland, Ohio	Generation of Long Time Creep Data on Refractory Alloys at Elevated Temperatures
NAS3-2547	General Electric Co. Cincinnati, Ohio	Potassium Corrosion Test Loop Development
		Material and Process Specifications for Refractory Alloy and Alkali Metals
NAS3-4172	Hydronautics Inc. Laurel, Md.	Cavitation Damage in Liquid Metals
NAS3-6010	TRW Equipment Labs, Cleveland, Ohio	Determination of Elevated-Temperature Fatigue Data on Refractory Alloys in Ultra-High Vacuum
NAS3-6012	General Electric Co. Cincinnati, Ohio	Studies of Alkali Metal Corrosion on Materials for Advanced Space Power Systems
		Compatibility of Biaxially Stressed D-43 Alloy with Refluxing Potassium
NAS3-6270	Hughes Research Labs. Malibu, Calif.	Surface Ionization Studies on Refractory Metals and Metal Alloys
NAS3-6272	Hughes Research Labs. Malibu, Calif.	Alloy Ionizer Fabrication

Table 10 (concluded)

Contract No.	Contractor	Title
NAS3-6474	General Electric Co. Cincinnati, Ohio	Advanced Refractory Alloy Corrosion Loop Program
NAS3-7906	General Electric Co. Cleveland, Ohio	Development of Fabrication Process for Metallic Fibers of Refractory Metal Alloys
NAS3-8506	Hydronautics, Inc. Laurel, Md.	Cavitation Damage in Liquid Metals
NAS3-8507	Atomics International Canoga Park, Calif.	Solubility of Refractory Metals and Alloys in Alkali Metals
NAS9-4905	Marquardt Corp. Van Nuys, Calif.	Investigation of High Strain Rate Behavior of Refractory Alloys and Coatings
NASr-49(19)	Stanford Research Institute Menlo Park, Calif.	Study of Growth Parameters for Refractory Carbide Single Crystals
--	NASA,Lewis Research Center Cleveland, Ohio	Potassium Rankine System Materials Technology
--		Space-Power-System Material Compatibility Tests of Selected Refractory Metal Alloys with Boiling Potassium
--		Summary of the Potassium-Refractory Metal Corrosion Capsule Program at NASA Lewis Research Center.
--		Progress in Superalloys
--		Extrusion at Temperatures Approaching 5000^{o}F
--		Materials

Gallium arsenide solar cells show higher resistance to radiation damage than the silicon type (NAS2-2600, NAS2-3613, Table 11).

The development of flexible thin film solar cells showed promise for reducing weight and permitting mounting on flexible surfaces. The feasibility of large area arrays required for high power solar cell systems was established with increased emphasis on problems relating to package deployment and reducing weight (24) (NAS7-1000, NAS3-6466, NAS3-8502, NAS5-9658, Table 11). The refinement in packaging techniques has resulted in a flexible roll-up type of construction that can easily be expanded to high power arrays (NAS7-100, Table 11).

A significant accomplishment has been the establishment of standards for space applications and calibration for solar cells by launching solar cells to 80,000 feet atop balloons. Before the work by NASA, there were no accurate criteria, since measurements were made on the ground where there is no consistency in available solar energy (24).

Work is continuing on increasing the high temperature performance of solar cells to improve the operation at distances close to or far away from the sun. There is work on solar power systems where solar cells operate until they are close enough to the sun where the heat affects their operation so that they are automatically covered up, and the thermionic power system (electricity generated by heat--in this case the sun) takes over. At distances further from the sun, the opposite process takes place (24), (NAS2-2600, NAS2-3613).

Solar cells have been the main source of electric power on about one-half of the spacecraft. Solar cell-powered electric propulsion systems show promise of increased payloads to distant planets compared with conventional chemical propulsion vehicles (26).

The limited survey of reports in STAR on solar cell research and development yielded a total of 362 entries from the years 1962-67 and showed that NASA is supporting a major portion of research in this area. From the most recent 100 items--covering part of 1966 and all of 1967--there were 75 reports (75% of all items) of NASA-sponsored contracts, grants, or in-house research. The subject areas that were covered are:

1. Efficiency, improvement and characterization of gallium arsenide solar cells.

2. Efficiency, improvement, and characterization of silicon solar cells.

3. Efficiency, improvement, and characterization of cadmium sulphide cells.

4. Improvement in the energy/density ratio of solar cells.

5. Flexible large area solar arrays.

Table 11

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF SOLAR CELL

Contract No.	Contractor	Title
--	NASA, Goddard Space Flight Center Greenbelt, Md.	The Relay I Radiation Effects Experiment
--	NASA, Lewis Research Center Cleveland, Ohio	The Performance of N/P Silicon and CdS Solar Cells as Effected by Simulated Micrometeoroid Exposure
--	NASA, Goddard Space Flight Center Greenbelt, Md.	Solar Cell Calibration Evaluation
--	Radio Corp. of America Mountaintop, Pa.	Materials Development for Solar Cell Applications
--	NASA, Lewis Research Center Cleveland, Ohio	Effect of Moisture on Cadmium Sulfide Solar Cells
--	NASA, Lewis Research Center Cleveland, Ohio	Thermal Cycling of Thin-Film Cadmium Sulfide Solar Cells
--	NASA, Lewis Research Center Cleveland, Ohio	Mechanism of Cadmium Sulfide Cell
NAS3-7631	Harshaw Chemical Co. Cleveland, Ohio	Research and Development in CdS Photovoltaic Cells
NAS5-10187	Electro-Optical Systems, Inc. Pasadena, Calif.	Lightweight Solar Panel Interconnections

Table 11 (continued)

Contract No.	Contractor	Title
NAS7-100	Jet Propulsion Lab. Pasadena, Calif.	Multikilowatt Solar Arrays
--	NASA, Lewis Research Center Cleveland, Ohio	Theoretical Performance of Solar Cell Space Power Systems Using Spectral Dispersion. I:Dispersion by Prism Reflector
--	NASA, Lewis Research Center Cleveland, Ohio	Theoretical Performance of Solar Cell Space Power Systems Using Spectral Dispersion. II:Dispersion by Diffraction Gratings
NAS7-1000	Ryan Aeronautical Co. San Diego, Calif.	Deployable Large Area Solar Array Structure
		Design and Fabrication of a Deployable Large Area Solar Array Supporting Structure
NAS7-100	Fairchild Hiller Corp. Germantown, Md.	Fabrication Feasibility Study of a 30-Watt-Pound Roll-Up Solar Array
NAS7-100	General Electric Co. Philadelphia, Pa.	Feasibility Study - 30 Watt per Pound Roll-Up Solar Array
NAS3-6466	Radio Corp. of America Princeton, N. J.	Materials and Methods for Large-Area Solar Cells
NAS3-[illegible] 2	Clevite Corp. Cleveland, Ohio	Study of Thin Film Large Area Photovoltaic Solar Energy Converter
NAS5-9658	Fairchild Hiller Corp. Rockville, Md.	Positive Deployable Solar Array Development Program
NAS7-428	Electro-Optical Systems, Inc. Pasadena, Calif.	Development of Lightweight Rigid Solar Panel

Table 11 (continued)

Contract No.	Contractor	Title
NAS7-100	Boeing Co. Seattle, Wash.	Large Area Solar Array
NAS3-6464	Harshaw Chemical Co. Cleveland, Ohio	Development of Optical Coatings for CdS Thin Film Solar Cells
NAS5-10236	Ion Physics Corp. Burlington, Mass.	Solar Cel Cover Glass Development
NAS5-3559	Texas Instruments, Inc. Dallas, Texas	Development of Epitaxial Structures for Radiation Resistant Silicon Solar Cells.
NAS5-9609	Texas Instruments, Inc. Dallas, Texas	Advancement of the State of the Art in the Production of Drift Field Solar Cells.
NAS5-0612	Electro-Optical Systems, Inc. Pasadena, Calif.	Advancement of the State of the Art in the Production of Drift Field Solar Cells
NAS5-10272	Textron Electronics, Inc. Sylmar, Calif.	Development and Fabrication of Radiation Resistant High Efficiency Solar Cells
NsG-6	Rice Univ. Houston, Texas	A Distributed Parameters Model for Solar Cells
NAS3-7920	Westinghouse Electric Corp. Lima, Ohio	Development of a 3400 Watt Programmed DC Power Supply Providing Static and Dynamic Solar Cell Array Simulation
NAS7-100	Jet Propulsion Lab. Pasadena, Calif.	A method for Predicting Solar Cell Current-Voltage Curve Characteristics as a Function of Incident Solar Intensity and Cell Temperature

Table 11 (continued)

Contract No.	Contractor	Title
--	NASA-Goddard Space Flight Center Greenbelt, Md.	Spectral Response Measurements of Solar Cells
NAS2-2564	Philco Corp.,WDL Div. Palo Alto, Calif.	The Feasibility of a Programmed Heat Shield for Solar Cell Performance Control
NAS7-409	Philco Corp.,WDL Div. Palo Alto, Calif.	Experimental Study of Coatings for Temperature Control of Solar Cells
NAS5-9668	Radio Corp. of America Princeton, N. J.	Nimbus-B Solar-Conversion Power Supply Sub-System
--	NASA,Marshall Space Flight Center Huntsville, Ala.	The Electrical Power System for the Pegasus Satellite
--	NASA,Goddard Space Flight Center Greenbelt, Md.	Solar Power Systems for Satellites in Near-Earth Orbits
NAS2-2600	Radio Corp.of America Princeton, N. J.	Application of Gallium-Arsenide Solar Cells to Solar Probe Power Systems
NAS2-3613	Electro-Optical Systems Pasadena, Calif.	Silicon Solar Cells for Near-Sun Missions
NAS3-7920	Westinghouse Electric Corp. Lima, Ohio	Power Conditioning and Control System for an Ion Thrustor
NAS5-9178	TRW Systems Redondo Beach, Calif.	Study and Analysis of Satellite Power Systems Configurations for Maximum Utilization of Power

Table 11 (concluded)

Contract No.	Contractor	Title
NAS7-100	Electro-Optical Systems, Inc. Pasadena, Calif.	Planetary Solar Array Development
NASw-417	Bellcomm, Inc. Washington, D.C.	The Effect of Launch Time on the Performance of a Solar Array/Battery Electrical Power System
JPL-951144	Hughes Aircraft Co. El Segundo, Calif.	Solar-Powered Electric Propulsion Spacecraft
--	Jet Propulsion Lab. Pasadena, Calif.	Spacecraft Power
NAS5-3805	TRW Systems Redondo Beach, Calif.	Charged Particle Radiation Damage in Semiconductors. XII: Effects of High Energy Electrons in Silicon and Silicon Solar Cells
NAS5-9131	Radio Corp. of America Princeton, N. J.	Analysis of Radiation Damage in Silicon Solar Cells and Annealing or Compensation of Damage by Impurities
NAS5-9580	Princeton Research and Development Co. Princeton, N. J.	A Theoretical and Experimental Study of Radiation Damage in Drift-Field Solar Cells
NAS7-289	General Dynamics Corp. San Diego, Calif.	Radiation Effects on Silicon
--	NASA, Goddard Space Flight Center Greenbelt, Md.	Early Results from the Solar Cell Radiation Damage Experiment on ATS-1
--	NASA, Goddard Space Flight Center Greenbelt, Md.	ATS-1 Solar Cell Radiation Damage Experiment: First 120 Days

6. Extendible large area solar arrays.

7. Improvements in coatings and cover glass for solar cells.

8. Production techniques for solar cells.

9. Ground testing of solar cell arrays.

10. Thermal balance of solar cell arrays.

11. Design of solar cell arrays for applications in satellites.

12. Analysis of future applications for solar cell arrays.

13. Radiation effects on solar cells.

A complete list of the projects found in the limited survey of reports on solar cells is given in Table 11.

Stress-Corrosion of Titanium Alloys

Titanium and its alloys have been receiving considerable attention because of the combination of low density, high strength, and toughness over a wide temperature range with excellent corrosion resistance for most applications. The strength-to-weight ratio of titanium is higher than that of either steel or aluminum over a temperature range from -400°F to about 600°F, above which steel has better strength-to-weight properties. These properties make titanium more desirable for most aerospace applications including cryogenic tanks, boosters, and supersonic aircraft. However, titanium is not being used to its fullest extent since it is a new material, and it has several problem areas that must be solved to achieve a better understanding and better utilization of the materials (31, 44, 45).

One of the major problems with titanium and its alloys are their susceptibility to failure under the combination of stress and corrosive conditions. While strengthening of titanium is achieved by alloying, the cracking resistance of the titanium alloys is reduced substantially by some of the alloying elements. Modification in alloying and change in heat treatment have brought a reduction in the cracking tendency (31).

Studies of the fundamental physics and electrochemistry of the corrosion processes, together with practical knowledge, are being used to attack these problems (NASA Order R-130, Table 12). In one procedure, the process of corrosion is followed by using a radioactive salt (44), (NASA Order R-124, Table 12). In another, a series of different titanium alloys is tested in various corrosive environments to determine which alloy is least affected (NAS7-488, NAS7-489, NAS9-6015, Table 12).

Work being done on titanium in hot salt environments has brought out the possibility that the production of hydrogen could result from the reaction between titanium and the salt, and therefore the cracking could result from hydrogen embrittlement (NAS Order R-124, Table 12). Further studies tend to confirm this hypothesis (46).

Another environment studied was nitrogen tetroxide, which had caused failures of titanium tanks (47, 48), (NASA in-house, Table 12). This is the oxidizer used in propulsion and control systems of spacecraft. In this case a fast, reliable, and economic test technique that originally had been developed by NASA to study the stress-corrosion problems in the supersonic transport was used to study the many variables of the new problem (48). The data from the test specimens and some of the service failure data showed remarkable correlation. Tests showed that titanium alloys in nitrogen tetroxide that contained dissolved oxygen were immune to cracking, while further work tended to show that chlorine impurities might well be the cause (46).

Investigation of fatigue cracking of many titanium alloys that had failed at low loads in a short time showed that titanium sheets with very small fatigue cracks will withstand high loads indefinitely in air, but if salt water gets into the cracks, the material will fail rapidly, even at low loads (47).

In some cases, work was done to help solve unexpected problems. Titanium tanks that had been pressure tested with methanol experienced catastrophic failures. Test specimens were obtained from unused, unstressed material and from the remnants of two Apollo service propulsion system fuel tanks that failed while containing methanol under pressure. The investigation showed that methanol and the stressed titanium alloy are incompatible because of a stress-corrosion mechanism (NASA in-house, Table 12). Further work has shown that water contaminants in methanol may act as an inhibitor to prevent failure (46).

These examples of the work being done on the stress-corrosion problems of titanium indicate the heavy contribution that NASA is making in this area.

The importance of titanium is indicated by the fact that the aerospace industry takes about 94% of the output. The breakdown for 1967 shows 54% for jet engines, 34% for airframes (26% military), 6% for space and missiles, and 6% for nonaerospace (49). The supersonic transport is the most promising application. Since the proposed SST will be flying at three times the speed of sound (Mach 3), the skin temperature may locally reach temperatures between 500° F to 600° F. Above 350° F, aluminum loses strength rapidly, so that titanium alloys are the most logical choice (31). It is reported that some 130,000 pounds of titanium will be used in each supersonic transport, not including some 9,000 lb of titanium fasteners (49).

Other areas of application include rotor hub forgings for helicopters and hardware for the Saturn rocket (49). The undersea applications of titanium should increase as that area receives increased attention. Present interest is in deep submergence vehicles.

Because of the many problems with copper and nickel alloys in condenser and evaporator tubing to handle brines and saline, brackish, and contaminated water, titanium is receiving increased consideration. Desalination plants yielding 50 million gallons of water per day could take up to 5,000 tons of titanium. Because of its excellent nonreactive properties, titanium has been used for such medical applications as body implants. For example, more than 4,000 of the heart valves in service are essentially titanium (49).

With the strong efforts toward understanding and solving the corrosion and stress-corrosion problems of titanium and its alloys, both space and nonspace applications should continue to grow rapidly.

The survey of the reports in STAR yielded a total of 217 entries from the years 1962-67. From the most recent 100 items--covering part of 1965 and all of 1966-67--there were a total of 45 items (45% of all items) that were reports of NASA-sponsored contracts, grants, and in-house research. These entries covered the following subject areas:

1. Mechanics of stress-corrosion of titanium alloy 8-1-1.

2. Elevated temperature stress-corrosion of high strength sheet materials.

3. Long term stress tests on supersonic transport structural alloys.

4. The role of chloride in hot salt stress-corrosion cracking.

5. Study of variables--heat treatment effects, velocity in various solvents, electrochemical kinetics--in stress-corrosion cracking of a titanium alloy.

6. Evaluation of fasteners and fastener materials.

7. Stress-corrosion of titanium in nitrogen tetroxide.

8. Stress-corrosion of titanium in methanol.

9. X-ray measurement of residual stresses in titanium.

10. Study of hydrogen embrittlement.

A complete list of the projects found in the limited surveys on stress-corrosion of titanium alloys is given in Table 12.

Table 12

GRANTS AND CONTRACTS IN STAR UNDER THE SUBJECT HEADING OF STRESS CORROSION OF TITANIUM ALLOYS

Contract No.	Contractor	Title
NASA Order R-130	National Bureau of Standards Washington, D. C.	The Mechanisms of Stress-Corrosion of the Titanium Alloy Ti 8-1-1 Exposed to Salt Environments at Elevated Temperatures
NASr-50	Materials Research Lab., Inc. Richton Park, Ill.	Elevated Temperature Stress-Corrosion of High Strength Sheet Materials in the Presence of Stress Concentrations
NASw-921	North American Aviation, Inc. Los Angeles, Calif.	Investigation of Long-Term Exposure Effects Under Stress on Supersonic Transport Structural Alloys
NASw-1233	Tyco Labs., Inc. Waltham, Mass.	Development of Cathodic Electrocatalysts for Use in Low Temperature H_2/O_2 Fuel Cells with an Alkaline Electrolyte
NASA Order R-124	E.I. du Pont de Nemours and Co. Aiken, S. C.	Stress-Corrosion Cracking of Titanium Alloys. Role of Chloride in Hot Salt Stress-Corrosion Cracking of Titanium-Aluminum Alloys
NAS3-6474	General Electric Co. Cincinnati, Ohio	Advanced Refractory Alloy Corrosion Loop Program
NAS7-488	Douglas Aircraft Co., Inc. Newport Beach, Calif.	Stress-Corrosion Cracking of Titanium Alloys of Ambient Temperature in Aqueous Solutions
NAS7-489	Boeing Scientific Research Labs. Seattle, Wash.	Stress-Corrosion Cracking of Titanium Alloys: Heat Treatment Effects, SCC Velocity in Various Solvents and Electrochemical Kinetics with Ti 8-1-1 Alloy

Table 12 (continued)

Contract No.	Contractor	Title
		Stress-Corrosion Cracking of Titanium Alloys: Electrochemical Mass-Transport-Kinetic Model, Metallurgical and Mechanical
		Effects and Proposed Relation of Electrochemical, Metallurgical and Mechanical Effects
NAS8-11125	Standard Pressed Steel Co. Jenkintown, Pa.	Evaluation of Fasteners and Fastener Materials for Space Vehicles
NAS8-20029	Battelle Memorial Inst. Columbus, Ohio	A Study of Hydrogen Embrittlement of Various Alloys
NAS9-5422	Southwest Research Inst. San Antonio, Texas	Analysis of Nitrogen Tetroxide Samples
NAS9-6015	Aerojet-General Corp. Sacramento, Calif.	Investigation of Environmental Effects on Specially Heat-Treated Ti-6Al-4V Alloy
--	NASA,Langley Research Center Langley Station, Va.	Salt Stress Corrosion of Residually Stressed Ti-8Al-1Mo-1V Alloy Sheet After Exposure at Elefated Temperatures
--	NASA,Langley Research Center Langley Station, Va.	Salt Stress-Corrosion of Ti-3Al-1Mo-1V Alloy Sheet at Elevated Temperatures
--	NASA, Manned Spacecraft Center Houston, Texas	A case History of Titanium Stress-Corrosion in Nitrogen Tetroxide
--	NASA, Langley Research Center Langley Station, Va.	X-Ray Measurement of Residual Stresses in Titanium Alloy Sheet

Table 12 (concluded)

Contract No.	Contractor	Title
--	NASA, Manned Spacecraft Center Houston, Texas	Stress-Corrosion Cracking of Ti-6Al-4V Alloy in Methanol
--	NASA, Marshall Space Flight Center Huntsville, Ala.	Stress-Corrosion
--	NASA, Langley Research Center Langley Station, Va.	NASA Research on Materials Applicable to Supersonic Transports

CONCLUSIONS

- NASA is a heavy contributor in the materials technology areas encompassing battery systems (nickel-cadmium, silver-cadmium, and silver-zinc), refractory alloys, and stress-corrosion of titanium alloys. The impact of each of these areas was concentrated mostly in similar applications outside of the space program. These included improvements in reliability and higher energy density for battery systems in every day use; application to power generation systems for refractory alloys; and applications of titanium alloys to the SST program, deep submergence vehicles, and chemical processing plants.

- NASA is a moderate contributor to the area of fuel cells, where the potential applications outside the space program were somewhat broader--smog-free electric automobiles, life support systems, and deep ocean technology.

- NASA is a heavy contributor to the solar cell program, but the applications in this case were more exclusive with fewer direct applications outside of space. However, some of the space applications--mainly weather and communication satellites--have indirect benefits such as improved weather prediction and better radio and TV transmission and reception.

- NASA has also made a contribution to electroforming, where the applications were more diffuse--covering such items as improved batteries, tooling and dies, solar concentrators, and production of complex parts.

- NASA has contributed significantly to the knowledge in different areas of materials technology. These have included breakthroughs in processing techniques such as electroforming and pioneering of new materials such as new refractory alloys.

- The impact of NASA work in materials technology has been considerable. Many of the new materials developments by NASA have been applied to other sectors of the nation's economy than the space program. These include the major economic sectors such as power generation, transportation, communications, and health care.

- The literature search method devised for and used in this preliminary survey has proven to be a valuable technique in locating and separating items pertinent to specific areas of materials technology.

RECOMMENDATIONS

- Extension and refinement of the literature search technique developed for this study is warranted since more complete information may be gained with considerably less effort.

- It is recommended that the work initiated in this study be extended so that the real worth of the NASA contribution to materials technology and the full impact of those contributions to the nation's economy can be detailed and documented.

FUTURE STUDY PROGRAM

The results of this survey have shown, from the samples of selected materials technology areas, that the work performed by NASA has had significant impacts on the nation's economy. From this promising first step, continuation and extension of the study of the impacts of new materials technology is warranted.

From the experience gained from the feasibility study, a more desirable arrangement for searching the literature files would be to use the SRI information access channel to the NASA Scientific and Technical Information Facility at College Park, Maryland. The batch process would be used, and the retrieval of information as to content and print-out would be subject to the limitations of the computer alone and not the limitations of a console/computer combination. In this way, separations into NASA and non-NASA items with print-out would be performed by machine and preclude the necessity of manual operations for those steps In addition, the print-out of Citations for each item would provide sufficient information to eliminate the need for the complete abstracts as printed in STAR (50).

By surveying the list of print-outs, it would be possible to identify the groupings of items under contract number and to select those items on the basis of technical content and advancement of the state of the art. The analysis of the technical contributions and resulting impacts would then have the advantage of more complete coverage. Many more of the index terms, which did not meet the high percentage of NASA entries per sample criterion used for the preliminary survey, would then be analyzed. Many of the items in the original listing of 33 items were assumed to have high impacts, but would have to await a more extensive survey of the materials technology areas.

In addition, a more complete study would cross-reference pertinent contracts to NASA forms 1122 to obtain dollar values for the selected samples and determine the dollar volume of the NASA support to the total effort in each of the materials technology areas.

By the more detailed survey procedure described above, a complete and impressive study could be made of the substantial contribution that NASA has made to the advancement of materials technology.

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