APPLICATIONS OF
AEROSPACE
TECHNOLOGY

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# REFLECTIVE SUPERINSULATION MATERIALS

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# REFLECTIVE SUPERINSULATION MATERIALS

## TABLE OF CONTENTS

## INTRODUCTION

How does new knowledge, acquired for one purpose, develop into useful technology having significant impact and benefits to society? This is one case study in a series of detailed investigations tracing the origins of new knowledge developed to solve specific problems of manned space exploration, and its subsequent modification and application to commercial needs.

What differences exist between the technology required for space exploration and the requirements for application to earthly problems? What factors determine the time required to convert new knowledge into viable economic benefits? Various case examples disclose differing patterns of technological development. By comparing the common and contrasting findings, it may be possible to understand better how new knowledge generates real benefits.

Starting from a specific "knowledge contribution" previously identified from an analysis of astronaut life support requirements, the origins, adaptations, and eventual significance of the new technology are presented.

## REFLECTIVE SUPERINSULATION MATERIALS

### Knowledge Contribution Previously Identified

Multilayer reflective "superinsulations" developed primarily for cryogenic applications were widely used for insulating spacecraft and lunar equipment. To protect the astronauts from temperature extremes, these thin, flexible thermal shields were, for the first time, incorporated in the garments used for extravehicular activities. The essential features of flexibility and multilayer spacing were achieved without significant increase in weight or bulk.

Fabrication techniques for superinsulations were developed and perfected. Differential pattern grading to insure proper spacing, textile bonding, lamination, and seaming methods were pioneered. The thermal performance of these new insulations was evaluated over a wide range of conditions--including the critical ±250° F requirement for lunar exploration.

Reflective superinsulation films are gradually being adapted for use in civilian thermal products. As the properties and performance of reflective insulation materials are more generally appreciated, a wide range of applications in emergency equipment and lightweight clothing has become practical.

### I. What They Are

"Superinsulations" developed originally for thermal insulation of liquid hydrogen or liquid helium handling equipment, are thin, reflective, metallized plastic films designed to virtually eliminate radiant heat transfer. Radiation-reflecting shields, in multiple layers, separated by low conductivity spacers, provide superior efficiency as cryogenic insulation. As used in the vacuum of space, reflective superinsulations become a thousand times more effective than conventional insulations. A graphic appreciation of this thermal performance comes from NASA technicians, who point out that only a 1/2-inch thickness of this new insulation can keep an ice cube from melting for more than 3 years!

In addition to many applications for super cold insulation, the materials have found increasing uses in industry, consumer products and microwave communications. Reflective insulation materials have now been incorporated into garments and blankets that afford protection to the user from extremes of cold or heat.

## II. Development History

The evolution of today's reflective insulations can be traced to scientific discoveries in the late 19th century with the first production of liquid air in the laboratory. This was the start of what is now the cryogenics industry. The first liquid air plant in the United States was built by Linde in 1907. Unitl the 1930's, the main problems were concerned with developing efficient processes to produce liquefied gases. Since that time, emphasis has shifted to finding better ways to store, transport and use cryogens on a larger scale.

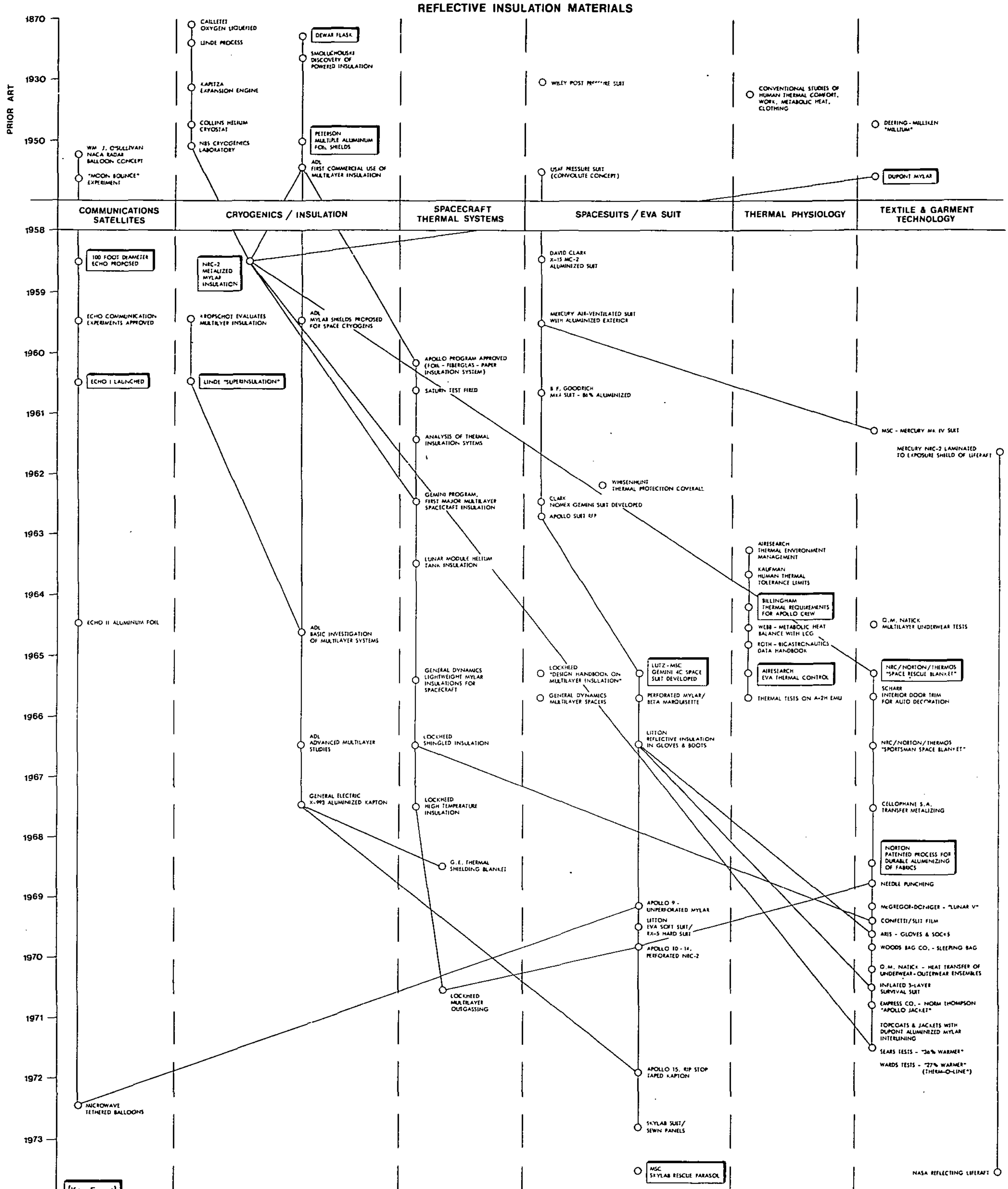
Insulation technology underlies all of cryogenics. The object in insulating liquid gases is to reduce their intense evaporation. To keep outside heat from flowing into storage containers usually requires three steps: minimizing *solid conduction* paths, evacuation to eliminate *gas conduction*, and reducing *thermal radiation*.

In 1892, Sir James Dewar first applied the principle of reflective insulation to reduce radiant heat transfer in his silvered vacuum flask. The common Thermos bottle uses all three of these basic insulation techniques. For more than 50 years, the brightly polished vacuum jacket would be considered the ultimate in thermal insulation.

The development, over the following 80 years, of vastly improved insulations shows few, if any, startling breakthroughs. Instead, a steady progression of advances and practical innovations paces the history of insulation systems--culminating in today's multilayer radiation shields.

Key events and major lines of development and use of the current reflective materials are shown in Figure 1. Five fields of development are highlighted for clarity of presentation. Two fields--CRYOGENIC INSULATION and SPACECRAFT THERMAL SYSTEMS--represent the basic uses for which reflective insulations were originally devised. EVA SUITS for space, COMMUNICATIONS SATELLITES and TEXTILES AND GARMENTS are applications that branched off from the main development trends, and are based in part upon characteristics of the reflective films beyond their primary insulation function. More detailed documentation of these five fields of development is contained in the chronology sections.

## REFLECTIVE INSULATION MATERIALS



Growing applications for gases and cryogenic liquids in the 1930's demanded larger equipment having more efficient insulation. Cool-down losses during filling tanks, and boil-off losses in storage are expensive. Yet the construction of large tanks for cryogen storage presents many difficult problems. The vacuum jacket walls must be strong enough to withstand atmospheric pressure without buckling. Support pads of low conductivity material are often used within the vacuum jacket to help support the outer wall. These supports conduct heat through the jacket, lowering the insulation value. To minimize radiation, the metal surfaces must be brightly polished or silver plated--a difficult and costly process.

The first major improvement in insulation for large cryogenic tanks came in 1937 with the introduction of evacuated powder insulations. Filling the jacket with fine powders of low thermal conductivity gave significantly lower heat transfer, and also reduced the degree of evacuation that was needed in the jacket. But most powders were partly transparent to thermal radiation. Powder insulation usually had to be 6 to 10 inches thick for good efficiency. These systems were adequate for liquid oxygen or nitrogen, but were not efficient enough for use with liquid hydrogen or helium.

When the National Bureau of Standards in 1952 established its Boulder, Colorado, laboratory exclusively for cryogenics research, an important task was the development and evaluation of improved insulations. The concept of placing multiple reflective shields within the vacuum jacket originated in 1951 with Peterson at the University of Lund, Sweden. Placing and supporting many polished shields inside the walls of the vacuum jacket was regarded as practical only for small laboratory equipment.

By 1956, the U.S. Air Force had started development of liquid hydrogen fueled rocket engines; and the following year saw the test firing of the liquid oxygen powered Atlas that soon would boost the first U.S. astronauts into orbit.

NASA programs planned to use enormous tonnages of liquid oxygen, and would eventually use one-half of total U.S. production of liquid hydrogen. Highly efficient insulation was essential for booster propellants, for helium and oxygen storage in manned spacecraft, and for specialized equipment such as hydrogen bubble chambers.

## III. Space Requirements--Contributions

Compared to the problems of insulating cryogenic vessels on earth, the requirements for space flights were vastly more demanding for efficient insulation. Weight penalties associated with boil-off losses of stored cryogens could not be tolerated. For large tanks, the outer jacket wall could not be made heavy enough to withstand air pressure, so that solid supports had to be used inside the insulation jacket. Rocketry, prior to the manned space programs, often had to accept thermal compromises--limitations that were largely overcome before the first lunar landings. Major requirements for space insulation systems are summarized in Table 1.

New, high-efficiency, reflecting multilayer insulations were commercially developed just as the NASA programs began. The Metallized Products Division of National Research Corporation became interested in the potential of low emissivity, vacuum metallized plastic films, and approached NASA for a study contract. This work culminated in NRC-2,* crinkled, aluminized Mylar film, only 0.00025 inches thick. Similar research by Linde created a series of insulations dubbed SI-62** (for "Superinsulation"). The Linde insulations comprised thin aluminum foils supported by unbonded glass fiber sheets. Use of these types of multilayer radiation shields would play an important part throughout many space programs.

Displaying a classic pattern of technological progress as the reflective insulation concept gained wider recognition, development work diverged sharply. The central thrust followed two lines--basic studies to learn the properties of multilayer insulations, and practical design and fabrication of insulating systems for space. At the same time, other applications developed that had little to do with cryogenics.

### A. Echo Satellites

One of the earliest, and perhaps the most spectacular, uses of metallized superinsulation by NASA, involved not the thermal characteristics of these films, but their electrical properties, strength and light weight--the Echo Communications Satellites.

Originally, William O'Sullivan proposed a Mylar air density balloon in the same year that Mylar film first became available in ultrathin gages for use as a packaging and laminating material. When these films were aluminized to provide thermal reflection, passive communications satellites became an exciting possibility. The problems that had to be solved were many: fabricating a 100-foot sphere; packing the material into a small canister; and providing the gentle inflation needed to swell the balloon when warmed by solar radiation.

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* U.S. Patent 3,018,016.

** U.S. Patent 3,007,596.

TABLE 1

MAJOR REQUIREMENTS FOR SPACE THERMAL INSULATION

- High initial thermal performance
    - Low conductance (K)
    - Low bulk density ($\rho$)
    - Lowest $K\rho$ product
- Low insulation flight weight
- Minimum insulation thickness
- Ease of fabrication; low cost
- Load bearing insulation
- Maintenance and repair
- Reliability of insulation after repeated use
- Avoid condensation from atmosphere
  Permit long prelaunch ground holds
- Withstand launch G-forces
- Withstand aerodynamic heating during launch

Extremely valuable knowledge about the behavior of metallized films in the thermal vacuum of space was gathered. The radar reflectivity, thermal emissivity, and durability in the harsh space environment was tested. This knowledge and confidence led to the use of superinsulation films for a variety of uses quite apart from their primary function as spaced multilayer insulation.

Multilayer reflective insulations show the highest insulation efficiency per pound of any known cryogenic insulation. Table 2 compares three types of multilayer systems for liquid hydrogen tanks. Not only are these insulations light in weight, but they permit reducing the thickness of the insulation layer to about 1/2 inch, versus 5 to 10 inches thick for comparable powder insulations.

In 1959, when manned space programs started, the problems of insulation systems for space were well known, and new materials basically capable of meeting stringent requirements were available. However, carrying the reflective insulation concept through to practical use would require a host of innovations as shown in Table 3.

B. Spacecraft Thermal Control

The contributions and advances made during the following decade were chiefly those involved in developing the technology of using multilayer reflective materials in the most effective manner. Specific developments and improvements introduced by space contractors and NASA are indicated in Table 4. The thermophysical properties of the new metallized plastic films were imperfectly understood. The two commercial types of insulations were relatively fragile and variable in performance. Fabrication and application techniques were developed and repeatedly improved as experience was gained. Testing procedures were devised that permitted critical evaluation of different approaches. By the mid-1960's, sufficient development had been performed to permit accurate analysis and modeling of complex insulation systems. Design handbooks reduced the task of evaluating alternative types of spaced, multilayer configurations.

Throughout this period, a variety of practical advances were achieved. Low emissivity radiation shields made it possible to eliminate costly polishing of the jacket walls. Adhesives giving good bonds at ultralow temperatures were developed. Foams and honeycomb materials were used together with reflective shields to form highly effective composite insulations. Virtually every aerospace contractor added to the knowledge about these versatile insulation systems. Figure 2 shows the machine application of reflective multilayer insulation. NASA field centers made numerous

TABLE 2

MEASURED PERFORMANCE OF MULTILAYER INSULATIONS FOR LIQUID HYDROGEN

| Multilayer Assembly | Thickness, inches | Density lb/ft$^3$ | Heat Flux Btu/hr/ft$^2$ (+55° to -423° F) |
|---|---|---|---|
| 20 layer crinkled Aluminized Mylar No spacers | 0.385 | 1.2 | 0.87 |
| 10 Aluminum shields, 0.002-in. H-19 11 layers 50% open glass fiber mat | 0.300 | 13 | 0.20 |
| 95 layer Aluminized Mylar 96 layer 0.001-in. glass fabric | 0.800 | 20 | 0.43 |

For comparison:
Bare liquid hydrogen tank has a typical heat flux of 3,600 Btu/hr/ft$^2$.
Polished Dewar vessel has a typical heat flux of 3 Btu/hr/ft$^2$.

TABLE 3

REFLECTIVE INSULATION MATERIALS

| REQUIREMENTS | SPACE PROGRAM CONTRIBUTIONS | ADVANCES |
|---|---|---|
| THERMAL RADIATION BARRIER | ● CRYOGENIC PROPELLANTS | SPACED MULTILAYER REFLECTOR<br>SPACERS, FOAMS<br>SKEWED WRAPPING |
| LOW EMITTANCE/NONTARNISHING | ● SPACECRAFT THERMAL SYSTEMS<br>SPACE SUITS | EMISSOMETERS<br>METALIZED LIGHTWEIGHT FABRICS<br>SILVER, ALUMINIZED 2 SIDES, GOLD, SiO COATINGS |
| LIGHTWEIGHT/THIN/FLEXIBLE | ● SPACE SUITS | .00025 in. MYLAR, NRC-2<br>NONWOVEN LAMINATES |
| MINIMUM FLAMMABILITY | ● APOLLO SUIT | KAPTON, BETA MARQUISETTE, LAMINATES TO HIGH TEMPERATURE FABRICS<br>TEFLON COATED BETA COVERS |
| BREATHABLE | | PERFORATION, SHINGLING, NEEDLE BONDING, "CONFETTI" |
| WITHSTAND SOLAR ULTRAVIOLET | ● ECHO<br>ALSEP<br>SPACE WALKS | LONG-TERM TEST DATA<br>THERMAL VACUUM OUTGASSING |
| FABRICATE TO FIT COMPLEX SHAPES | ● CRYOGENIC TANKS<br>SUITS AND GLOVES | CRYOGENIC ADHESIVES<br>DIFFERENTIAL PATTERNS<br>SPACED SEAMS<br>RIP STOP TAPING<br>SEWN PANELS |

TABLE 4

SPACE ADVANCES AND CONTRIBUTIONS - REFLECTIVE INSULATIONS

- Conceptual
  - Eliminate need for polished walls
  - Performance independent of wall spacing

- Theoretical Analysis and Modeling
  - Thermophysical properties of insulations
  - Computer thermal analysis
  - Mathematical models cost-effective design
  - Weight optimization
  - Cool-down/Boil-off tradeoffs

- Test and Evaluation
  - Commercial calorimeters
  - Improved emissometer

- Spacers and Supports
  - Crinkled wrap, embossed pattern
  - 60 spacer materials
  - Discrete shield clamps
  - Constrictive wrap
  - Radial bumper, discrete shields
  - Load bearing multilayers
  - Perforations for outgassing

- Fabrication and Maintenance
  - Self-evacuating, sealed, removable panels
  - Cryogenic adhesives
  - Flexible vacuum jackets (MAAM laminate)
  - Internal, unidimensional insulation
  - 3-D fiber reinforced foams
  - Gas purged insulation
  - Sealed honeycomb panels
  - Shingled application

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MACHINE WINDING OF MULTILAYER INSULATION

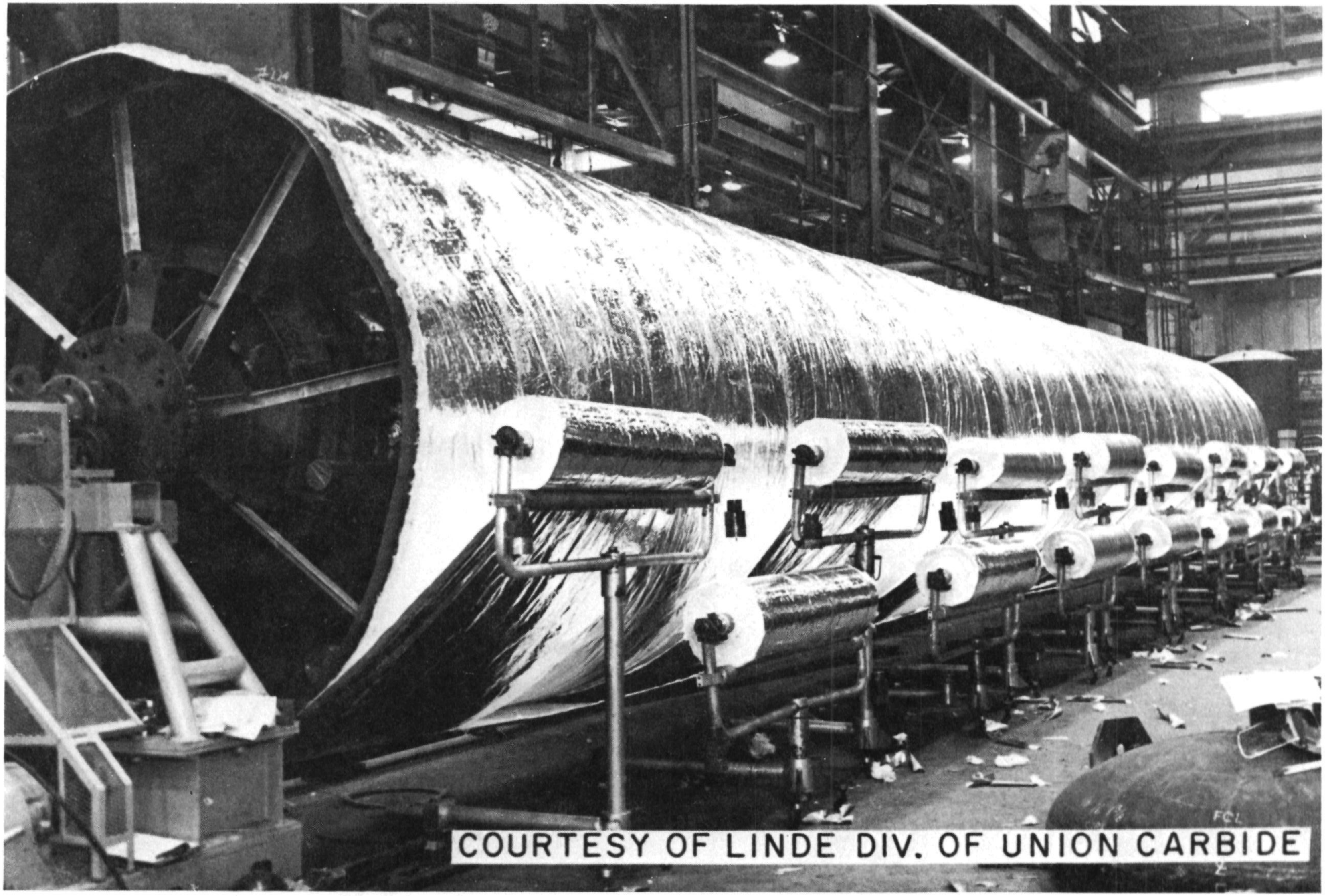


Figure 2

contributions, so that eventually the high efficiency reflective materials became standard, state-of-the-art approaches for handling liquid hydrogen, helium, and other cryogens--reliably and predictably. The cumulative effect was that systems could be designed, analyzed, fabricated and tested to performance levels virtually impossible a few years earlier.

### C. Space Suit Thermal Insulation

Clothing is one of the most important and common types of insulation. For suits that could insulate astronauts from the temperature extremes in space, it was logical to consider the reflective films that were proving so effective in other space uses. The decision to perform the first U.S. space walk as early as the spring of 1965, greatly speeded up EVA suit work. Development of the GT-4 space suit for EVA required learning how to blend the technology of multilayer insulation with the traditional craftsmanship of garment making. There were almost no data from which to predict the performance of reflective films around the complex shape of the human body. The lightweight metallized films had not generally been used like fabrics, or combined with textile materials. Six years of continual interplay between clothing manufacture, thermal physiology and space insulation materials eventually led to substantial improvements in the comfort, reliability and performance of each succeeding generation of space suits.

## IV. Subsequent Applications - Their Requirements

The reflective insulation films were so widely used during the late 1960's that thousands of technicians learned to appreciate the performance of these new materials. As more experience was gained in fabrication and use of superinsulations, a broad range of earthly uses became apparent.

Detailed studies of work loads and thermal comfort had shown that a significant fraction of metabolic heat is lost by radiation from the normally clothed body. By 1966, various manufacturers realized the potential offered by reflective insulating films. A wide variety of garments, safety products and sporting goods were devised and marketed. Just as with space systems, there were some false leads and blind alleys in the development of commercial products. Eventually, many of the same practical techniques of handling reflective insulations that were mastered for spacecraft and EVA suits were incorporated into the successful insulating consumer products. Current applications of reflective insulation materials are listed in Table 5.

Representative products being marketed currently are shown in Figure 3. Ultralight sports jackets, topcoat liners, industrial heat

TABLE 5

APPLICATIONS OF REFLECTIVE INSULATION MATERIALS

THERMAL

- JACKETS AND COATS
- BLANKETS
- DRAPERIES
- SLEEPING BAGS AND LINERS
- GLOVES AND SOCKS
- SPACE SUITS
- SURVIVAL SUITS

CRYOGENIC INSULATION

- STORAGE TANKS
- LIQUID NATURAL GAS TANKERS
- TRANSFER LINES
- TRANSPORTERS
- SUPER CONDUCTORS

REFLECTIVE

- SOLAR ENERGY CONCENTRATORS
- HEAT PROXIMITY SUITS
- FIRE FIGHTING SUITS
- WELDING SCREENS AND SHIELDS
- HEAT SHIELD CURTAINS
- BOOTS
- GLOVES
- HOODS, APRONS
- LEGGINGS

DECORATIVE

- AUTO DOOR TRIM
- CLOTHING

ELECTRICAL

- MICROWAVE COMMUNICATIONS
- RADAR CHAFF
- LIFE RAFT AND BEACONS

Figure 3 - Consumer and Industrial Products
Based on Reflective Insulations

Source: Midwest Research Institute

shields, reflective fabric laminates, thermal blankets, heavy-duty materials used in fire fighting suits, compact backpacking gear, and steel workers' safety clothing are illustrated.

One of the classic ways that information gained for space exploration is translated for use on earth, is illustrated by the emergency suit for subzero weather survival shown in Figure 4. The insulating principle can also be applied to many other thermal applications. The garment is composed of three layers of aluminized plastic film with the edges sealed for suit-wall inflation. The plastic zipper down the front makes it easy to put on, and permits adjustment of heat loss from the suit.

The garment was designed to be stowed as part of a survival kit for motorists in the northern regions. Weighing only 11 ounces, the package readily fits a pocket or glove compartment, ready for use over ordinary light clothing. When the two separate layers are inflated, the suit wall is about 3/4 inch thick, and affords protection down to temperatures of -45° F.

Much of the knowledge acquired while developing Litton's space suits was directly applied by D. L. Curtis in designing and testing this survival suit. In subzero weather, a person waiting quietly for assistance produces about 450 Btu per hour in metabolic heat. The suit was designed to provide thermal equilibrium at -40° F. Radiation losses from the multilayer aluminized insulation average 210 Btu per hour, while breathing and suit conduction losses amount to 240 Btu per hour, just balancing the heat generated by a stationary person. Lightly clad test subjects reported that the suit kept them comfortable to +10° F without inflation. After inflating the suit walls, tests verified good thermal protection against moderate winds with temperatures ranging from -20° F down to -45° F for the last half hour.

Many of these later uses were based on requirements that are similar to those of aerospace applications. Few of these uses needed vacuum stability, and only a limited number could take advantage of spaced multilayer radiation heat shielding. As shown in Figure 5, many of the basic performance characteristics had already been demonstrated in space programs.

## V. Impact/Significance

A dozen years have passed since the first reflective metallized insulation films became available. Techniques for their effective use have been refined to meet space requirements. The applications of superinsulation materials have been extensive and impressive. But, what has been the long-term impact and significance of these advances?

Figure 4 - Emergency Survival Suit of
Reflective Insulating Films

Source: Curtis-Le Vantine & Associates

| REQUIREMENTS | CLOTHING | BLANKETS | DRAPERIES | SLEEPING BAGS AND LINERS | SPACE SUITS | HEAT PROXIMITY SUITS | CRYOGENICS | REFLECTIVE SHIELDS | GLOVES AND SOCKS | FIRE FIGHTING GARMENTS | SURVIVAL SUIT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| THERMAL RADIATION BARRIER | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| LOW EMITTANCE | ● | ● | | ● | ● | ● | ● | ● | ● | ● | |
| LIGHTWEIGHT / THIN | ● | ● | | ● | ● | | | | ● | | ● |
| FLEXIBLE | ● | ● | ● | ● | ● | ● | | | ● | ● | ● |
| SPACED MULTILAYER | | | | | ● | | ● | | | | ● |
| MINIMUM FLAMMABILITY | ● | ● | | ● | ● | ● | | ● | | ● | |
| WITHSTAND SOLAR ULTRAVIOLET | | | ● | | ● | | | | | | |
| MINIMUM OUTGASSING | | | | | ● | | ● | | | | |
| NONTARNISHING | ● | ● | ● | | | ● | | ● | | ● | |
| BREATHABLE/PERFORATED | ● | | | ● | | | | | ● | | |
| ANTHROPOMORPHIC SHAPE | ● | | | | ● | ● | | | ● | ● | ● |
| TEAR RESISTANT | ● | ● | | ● | ● | ● | | | ● | ● | ● |

Figure 5 - Reflective Superinsulation Material Applications/Requirements

Users and suppliers agree that reflective insulation materials and their fabrication techniques have now become one of the standard or routine alternatives that the engineer considers in solving thermal control problems. Performance advantages as well as limitations are more generally appreciated. Perhaps the impact of the knowledge gained since 1960 is best gauged by the pervasiveness with which reflective materials are employed for both difficult and sophisticated thermal control, and for less demanding applications where convenience or light weight justifies their use.

A. Communications

Although active communications satellites quickly superseded the passive Echo type inflatable satellites, the impact of Echo I cannot be minimized. As much as any space program of the early 1960's, Echo convinced the public that satellites were real--and could serve useful purposes. Echo left a substantial legacy. The program influenced ground station technology and radio-propagation experience; tracking facilities were improved, and the tracking beacon system was developed. Echo proved that microwave transmissions through the ionosphere were adequately understood--there would be no surprises or unexpected phenomena. The feasibility of new techniques for ultrasensitive ground receivers was proved. In a few short months, Echo dramatically demonstrated the promise of communication satellites.

Today, in developing nations, tethered balloons covered with aluminized Mylar can be used to relay communications and educational programs to remote villages. It is certainly no coincidence that the manufacturer of these passive communications balloons first learned to work with metallized plastic films in making space suits that incorporated seven spaced layers of superinsulation films.

B. Cryogenics

Because efficient insulation is basic for cryogenics, it is inevitable that the technology, materials and designs created to meet space requirements are finding increasing use in the production, transport, storage, handling and use of cryogenic liquids. The significance of this field can only be indicated by the spectacular increase in use--in 1972, cryogen shipments exceeded $850 million. Some fraction of the growing benefits associated with cryosurgery, superconductivity, shipment and storage of liquid natural gas, oxygen steel making and advanced waste water treatment must be attributed to the increased ease and efficiency of handling cryogenic liquids.

C. Industrial and Consumer Products

By about 1967, a small but growing number of commercial products using the thermal retention and reflective properties of metallized films became available. Industrial safety equipment, sportswear, fire fighting and emergency rescue products, lightweight camping equipment, plus life rafts and radar reflectors to locate victims at sea have been marketed. According to leading suppliers, sales for 1973 probably amounted to approximately $18 million. The real significance of these products lies more in the improved levels of safety and convenience that users now enjoy. Recent emphasis on industrial safety under the Occupational Safety and Health Administration (OSHA) indicates that "hot-suits" will be much more widely used. Currently, 37 firms throughout the U.S. produce protective garments utilizing metallized films to provide a low emittance, heat reflecting surface.

D. Skylab

In May of 1973, when Skylab was placed in orbit, the entire mission was jeopardized by loss of the thermal-meteoroid shield. Unprotected from solar radiation, the workshop temperatures rose excessively. Some areas of the spacecraft were too hot to touch. Stored food, photographic film and medical supplies could soon spoil.

Launch of the first Skylab crew was delayed for 10 days to see whether a plan could be devised to save the Skylab missions. Various types of sun shields were improvised by contractors and by three NASA centers. Within 6 days, specialists at the Johnson Spacecraft Center in Houston had developed a "space parasol" that could be extended through the 8 x 8-inch opening of the scientific airlock. The essential solar shield was a 22 x 24-foot laminate of aluminized Mylar and lightweight nylon. Astronauts Conrad and Weitz deployed the thermal shield over the workshop and successfully reduced Skylab's temperature.

Was the vital, $2.5 billion Skylab program salvaged by a hastily assembled low emittance thermal barrier? Not really. A crucial ingredient was the knowledge and confidence acquired through 10 years of testing and using these materials in space and on the lunar surface.

## CHRONOLOGY

## CRYOGENICS/INSULATION

1877: Cailletet and Pictet succeeded in liquefying measurable quantities of oxygen.

1892: Sir James Dewar independently invented and perfected the silvered vacuum flask that bears his name.

1895-
1907: Linde developed the Joule-Thompson effect process for liquefaction of air and the separation of oxygen and nitrogen. In 1907, Linde installed the first liquid air plant in America.

1910: Smoluchowski showed that thermal insulators, much more effective than air, could be made from fine powders in a moderate vacuum.

1934: Peter Kapitza developed the first multiple expansion engine for liquefaction of helium.

1937: Evacuated powdered insulation introduced. Resulted in significant reduction in heat transfer to stored cryogens.

1947: S. C. Collins developed the Collins helium Cryostat at MIT.

1951: Peterson (University of Lund, Sweden) found that multiple thin shields of polished aluminum foil, spirally wound with glass fiber spacers, showed remarkable insulating qualities.

1952: National Bureau of Standards Cryogenic Laboratory (Boulder, Colorado) established solely for research in cryogenics.

1954: Black, Fowle, Glaser (ADL) investigated use of radiation shields for a 2,000-liter liquid hydrogen transport dewar.

1958: Development of high-efficiency "superinsulation" made possible additional reductions in the amount of heat transferred to stored cryogens.

1959: M. P. Hnilicka (NRC Equipment Corporation) describes NRC insulation. Patent was still pending. First nonclassified use by MIT for S. C. Collins on 25-liter liquid helium container; University of Chicago, 145-liter liquid hydrogen bubble chamber.

1960: R. H. Kropschot et al., (NBS), "Multiple Layer Insulation." Compared aluminum foil and aluminized films. Advances in Cryogenic Engineering, 5, (1960).

1960: Black, Fowle, Glaser (ADL) mention metallized Mylar as a possible alternative to thin aluminum foils for radiation shields. Advances in Cryogenic Engineering, 5, 182. 0.00025-in. Aluminized Mylar; also, 0.002-in. Aluminized Mylar.

■ 1960-1962: C. R. Lindquist (Linde Company), "Superinsulation Applied to Space Vehicles." Revised December 1962.

1961: L. C. Matsch (Linde), "Thermal Insulation." U.S. Patent 3,007,596, November 7, 1961. Application filed July 16, 1956.

■ 1964: I. A. Black (ADL), basic investigations of multilayer insulation systems. NASA-CR-54191.

■ 1966: Ruccia and Hinkley (ADL), "Advanced Studies on Multilayer Insulation Systems," NASA-CR-54929, NAS-3-6283. Emissivity of 1/4-mil DuPont type polyester film metallized with 250 Å thickness of Al, Au, Ag, Cu, and SiO. Improved emissometer developed for rapid measurement of total hemispherical emittance of insulation materials.

## CHRONOLOGY

### SPACECRAFT AND STRUCTURES
### THERMAL SYSTEMS

- 1960: Apollo program recommended by House Committee on Science and Astronautics. Apollo Cryogenic Gas Storage System (CGSS) consisted of tanks insulated with layers of foil, Fiberglas and Dexiglas paper.

- 1960: Gray, Gelder and Cochran bonded and sealed external insulations for liquid hydrogen fuel tanks. NASA-TN-D-476 (1960).

- 1961: Ehrenfeld and Strong (ADL), analysis of thermal protection systems for propellant storage during space missions.

- 1961: The Saturn launch vehicle was test fired. This was the first space vehicle using liquid hydrogen and liquid oxygen as propellants.

- 1962: Gemini program officially started. Cryogenic gas storage system for 14-day mission, used multilayer aluminized Mylar insulation.

- 1962: Hinckley (ADL), "Liquid Propellant Losses During Space Flight." NAS-5-664.

- 1962: Miller, et al., (Lockheed), "Properties of Foams, Adhesives and Plastic Films at Cryogenic Temperatures." Ind. Eng. Chem., (December 1962).

- 1963: Apollo Lunar Module CGSS used aluminized Mylar for helium tank insulation.

- 1965: Getty, Clay, Kremzier and Leonhard (General Dynamics), experimental evaluation of selected lightweight superinsulation for space vehicles.

- 1965: Swalley and Nevins, "Practical Problems in Design of High-Performance Multilayer Insulation Systems for Cryogenic Stages," Advances in Cryogenic Engineering, **10**, (1965).

- 1965: R. T. Parmley (Lockheed), "Handbook of Thermal Design Data For Multilayer Insulation Systems." NASA-CR-67353, NAS-8-11347.

- 1966: Parmley (Lockheed), "Shingled" multilayer insulation for space vehicles, Advanced Cryogenic Engineering, **2**, 15-25.

- 1967: A. R. Cunnington (Lockheed), performance of multilayer insulation systems to 700° K. NASA CR-907.

- 1967: E. Fried and G. Heiser (General Electric), measurement of thermal conductance of multilayer and other insulation materials. NAS-9-3685. Tested 1/2-mil Kapton--Betaglass marquisette insulation material made by Schjeldahl. Seven layers X-993 Aluminized Kapton/Beta marquisette crinkled, also, gold 1/4-mil Mylar.

- 1968: General Electric. Development of thermal shielding blankets for Jet Propulsion Laboratory. Made of DuPont Kapton gold, metallized polyimide film.

- 1970: Glassford (Lockheed), outgassing behavior of multilayer insulation materials. NAS-8-20758, MSFC.

- 1970: NASA/AEC, "Thermal Insulation--a Compilation." NASA-SP-5930(01) (1970).

CHRONOLOGY

SPACE SUITS/EVA SUITS
SUPERINSULATION

- 1955: ILC pressure suit for USAF, first use of balanced convolute concept.
- 1958: David Clark Company, Forrest Poole used aluminized exterior on MC-2 suit for X-15.
- 1959: Mercury (MSC), air ventilated suit MC-2 for Mercury with metallized exterior surface; B. F. Goodrich.
- 1960-1961: B. F. Goodrich, MA-9, MK-4 suit. Mercury suit used 86 percent reflectivity aluminized coated nylon, as the outside surface to protect from reentry heat. Surface temperature expected to reach 180° on reentry. Ed Vail at Pensacola tested thermal properties.
- 1962: G. B. Whisenhunt and R. A. Knezek (LTV), thermal protection systems for EVA space suits. ARS paper 2472-62; NAS-9-7519.
- 1962-1965: Freedman, McBarron, and C. C. Lutz (MSC) had been working on a "Moon Suit" for 2-1/2 years prior to decision to accelerate the first extravehicular activity on Gemini 4.
- 1962: David Clark Company, Gemini suit development. Gemini used hatch ejection as escape mode. Nomex garments. Considered gold-coated protective film on outside of suit to protect from fireball in event of abort.
- 1962: Apollo suit RFP, Hamilton Standard prime; ILC subcontractor.
- 1965: F. H. Goodnight, R. O. Pearson and R. J. Copeland, (LTV), thermal performance tests of the A-2H Apollo Extravehicular Mobility Unit. NASA-CR-65856.
- 1965: C. C. Lutz et al., (MSC) development of Gemini 4C EVA suit. 0.00025-in. aluminum Mylar, dacron spacer, 250 Btu/hour suit heat-leak requirement.
- 1965: Apollo suit design competition, ILC design selected. Of all suits submitted and tested, one was judged significantly superior--"No second choice."

- 1965: EVA suit problems: Venting was poor, needed better spacers. Found necessary to perforate the Mylar film.

- 1965-1967: D. L. Richardson (Aerospace Medical Laboratory, Wright Patterson, AFB), "Study and Development of Materials and Techniques for Passive Thermal Control of Flexible Extravehicular Space Garments." AMRL-TR-65-156-67-128.

- 1965-1968: F. J. Turnbow and J. T. Bevans (TRW Redondo), "Thermal Properties of Selected Space Suit Materials." NASA-CR-65678, NAS-9-3670.

- 1966: Joseph Kosmo (Litton), improved reflective insulation in gloves for soft EVA suit.

- 1966: L. Sheppard (ILC), convolute restraint was made of aluminum-coated nylon, laminated to 3-M, super abrasion resistant aluminized film. Putnam Mills supplied fabric.

- 1966: Roger Copeland (LTV) developed: gloves and boots, October 12; visor, September 6; and, gloves and boots, September 30.

- 1969: Apollo 9 suit used unperforated aluminized Mylar in thermal layers.

- 1969: John F. Royfield and Pierre Brosseau. Litton develops EVA soft suit and RX-5 hard suit. Seven layers of aluminized Kapton.

- 1969-1971: Apollo 10-14 suits used Beta fabric outer garment. Perforated NRC-2, nonwoven Dacron spacers.

- 1971: Apollo 15 suit used rip-stop taped metallized Kapton outside layer; inner layers not taped.

- 1972-1974: Skylab suits (ILC), used sewn panels; reflective films do not require special perforations.

CHRONOLOGY

THERMAL PHYSIOLOGY

1948-
1960: Traditional studies of human thermal comfort zones, exposure, clothing, etc. Roughly 26 percent of metabolic heat radiated from normally clothed body.

■ 1963: W. C. Kaufman, human tolerance limit for some thermal environments of aerospace.

1963-
■ 1965: Burris and Wortz, (Airesearch), a. Internal thermal environment management program, b. EVA suit thermal and atmospheric control.

■ 1964: Billingham (MSC) estimates of metabolic rates, thermal balance and water requirements for Apollo crew members.

■ 1964: Bio Astronautics Data Book, thermal control.

■ 1964: J. F. Crocker and P. Webb, metabolic heat balances in men wearing LCG and sealed clothing.

■ 1965: P. J. Berenson (Airesearch), general analysis of human thermal comfort.

## CHRONOLOGY

## TEXTILES, LAMINATES, CLOTHING

Prior to 1950: Deering-Milliken Company, "Millium," metallized fabric introduced as drapery lining material to reduce damage due to sunlight.

1957: DuPont Mylar polyester film available in commercial quantities for packaging uses. First 0.00025-in. film produced and metallized in 1958.

■ 1961: Mercury splashdown life raft. NRC-2 laminated to rip-stop nylon exposure shield to protect astronaut at sea and reflect search radar.

■ 1962: G. B. Whisenhunt and R. A. Knezek, thermal coverall to protect workers in space. 1963 (same), thermal protection system for extravehicular space suits.

1964: Hodge and Fonseca (Natick), thermal conductivity of multilayer sample of underwear material under a variety of conditions.

1965: Metallized Products Division, NRC/NORTON/THERMOS, space rescue blanket introduced. Edge strengthened 1/2-mil, NRC-2

1965-1974: Scharr Industries. High reflectivity metallized films for industry. Mostly decorative uses, especially automotive trim.

1966: NRC/NORTON/THERMOS, Sportsman's space blanket introduced. Crinkled NRC-2 laminated to fabric. 56 x 84-inch grometed sheet; two films 0.00125-in., one aluminized, one clear. Norton tried use for tents, sleeping bags, garments, but material was difficult to sew and non-breathable.

1967: Gentex Corporation, (Carbondale, Pa.). Developed aluminized film significantly more durable than conventional aluminum coatings. Dual mirror coating resists molten metal splashes. Higher reflectivity and extended life. Forty-four companies use in manufacturing clothing.

■ 1967: NASA, Kennedy Space Flight Center, fire suit for liquid hydrogen handling crews.

1967-1971: U.S. Patent 3,589,962, metallization of fabrics, assigned to Cellophane S. A. Paris. Transfer from plastic film to adhesive-coated fabric.

■ 1968: Needle perforated metallized films for sleeping bags (Apollo and Skylab). Perforated Teflon-coated Beta fabric sleeping bags.

1968-
1969: Norton developed process for vacuum metallizing of woven fabrics with protective coating to improve durability and permit washing. The fabric is breathable and has low emissivity. Eighty percent of body radiation is returned so that jacket is reportedly 30 percent warmer.

1969: Aris Gloves, space gloves and socks made of Lurex metallized yarn plus wool, cotton and nylon. Marketed through sporting goods shops for last 5 years.

1969: Woods Bag Company, (Onondaga, New York), introduced sleeping bags using Norton reflective insulation.

1969: McGregor-Doniger, Inc. Introduced reflective fabric called "Lunar V" for ski parkas, jumpsuits and other clothing. 1969 sales $3.8 million.

1969: Small areas of reflective film (called "confetti") applied over fabric surface. (See shingled Mylar insulations.)

1970: U.S. Steel Company, specifications for metal workers hot suit. Must withstand 2 pounds molten steel splash.

1970: Empress Corporation (Norm Thompson), produce "Apollo Jacket," using aluminized film bonded to nylon fabric.

■ 1970: George Fonseca (Natick), heat-transfer properties of 10 underwear-outerwear ensembles.

1970: Alpha Associates, A-24 polyester nonwoven, needle punched laminated to 1/2-mil aluminized polyester film.

1971: Sears/Wards, simultaneously market men's topcoats and jackets using DuPont aluminized Mylar interlining. Sears tests, 36 percent warmer, Therm-o-Line; Wards tests, 27 percent warmer.

■ 1971: Curtis (Mechanics Research, Inc.), "An Emergency Survival Suit," a three-layer suit covering the entire body, and inflated with air, or with Freon. Designed to protect the wearer from arctic exposure to temperatures of -45° F. Earlier, Curtis was responsible for development of space suits and gloves for Litton. NASA-SP-302.

1972: Thermaliner, reflective, permeable nylon fabric for insulated products introduced by Carroll George, Inc.

■ 1973: NASA Radar Reflecting Life Raft.

■ Activity linked to aerospace requirements.

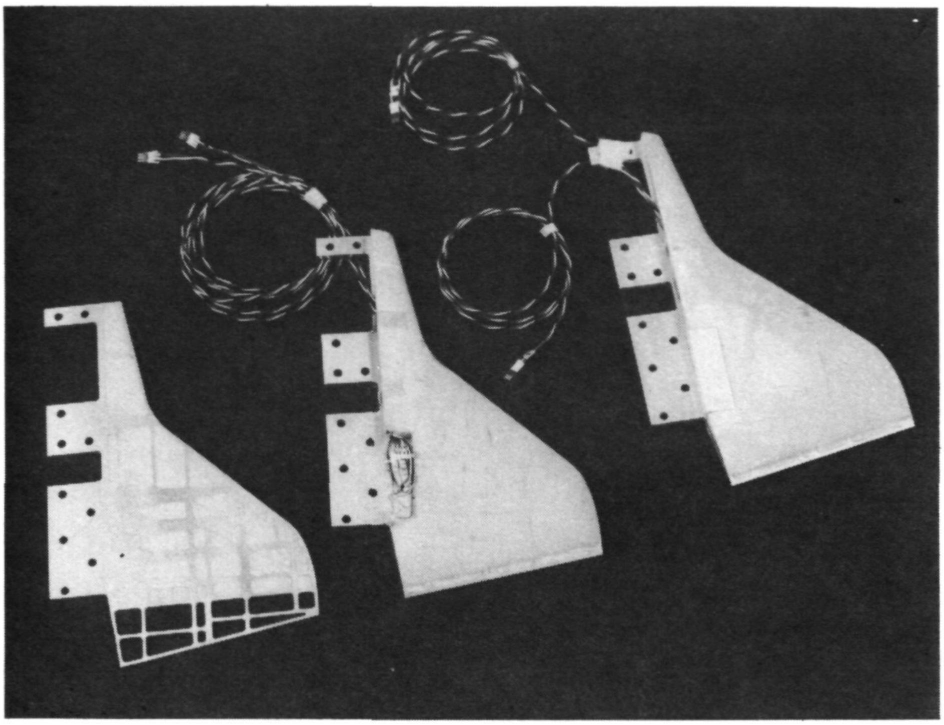

Figure 3.— Details of Wing Model Construction

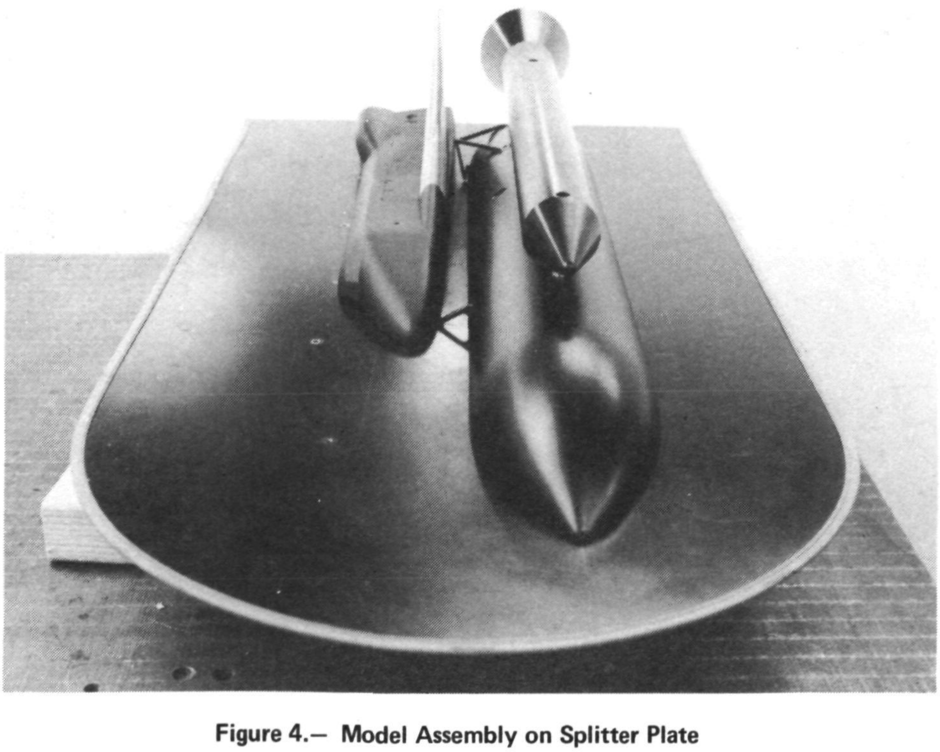

Figure 4.— Model Assembly on Splitter Plate

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*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

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