APPLICATIONS OF AEROSPACE TECHNOLOGY

REFLECTIVE SUPERINSULATION MATERIALS

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for Technology Utilization Office

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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.
# REFLECTIVE SUPERINSULATION MATERIALS

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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. Until 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

COMMUNICATIONS / INSULATION
SPACECRAFT THERMAL SYSTEMS
SPACESUITS / EVA SUIT
THERMAL PHYSIOLOGY
TEXTILE & GARMENT TECHNOLOGY

[Diagram with various events and time periods, including '1970', '1971', '1972', and '1973']
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.

** U.S. Patent 3,007,596.
TABLE 1

MAJOR REQUIREMENTS FOR SPACE THERMAL INSULATION

- High initial thermal performance
  - Low conductance (K)
  - Low bulk density (ρ)
  - Lowest KP 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 metalized 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>
<thead>
<tr>
<th>Multilayer Assembly</th>
<th>Thickness, inches</th>
<th>Density $\text{lb/ft}^3$</th>
<th>Heat Flux $\text{Btu/hr/ft}^2$ $(+55^\circ \text{ to } -423^\circ \text{ F})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 layer crinkled Aluminized Mylar No spacers</td>
<td>0.385</td>
<td>1.2</td>
<td>0.87</td>
</tr>
<tr>
<td>10 Aluminum shields, 0.002-in. H-19 11 layers 50% open glass fiber mat</td>
<td>0.300</td>
<td>13</td>
<td>0.20</td>
</tr>
<tr>
<td>95 layer Aluminized Mylar 96 layer 0.001-in. glass fabric</td>
<td>0.800</td>
<td>20</td>
<td>0.43</td>
</tr>
</tbody>
</table>

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

## Reflective Insulation Materials

<table>
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<tr>
<th>Requirements</th>
<th>Space Program Contributions</th>
<th>Advances</th>
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<tbody>
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<td>- Cryogenic Propellants</td>
<td>Spaced Multilayer Reflector Spacers, Foams</td>
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<td>Low Emittance/Nontarnishing</td>
<td>- Spacecraft Thermal Systems</td>
<td>Skewed Wrapping</td>
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<td>Lightweight/Thin/Flexible</td>
<td>- Space Suits</td>
<td>Emissometers</td>
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<td>Minimum Flammability</td>
<td>- Apollo Suit</td>
<td>Metalized Lightweight Fabrics</td>
</tr>
<tr>
<td>Breathable</td>
<td>- Echo</td>
<td>Silver, Aluminized 2 Sides, Gold, SiO Coatings</td>
</tr>
<tr>
<td>Withstand Solar Ultraviolet</td>
<td>- ALSEP Space Walks</td>
<td>.00025 in. Mylar, NRC-2</td>
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<tr>
<td>Fabricate to Fit Complex Shapes</td>
<td>- Cryogenic Tanks Suits and Gloves</td>
<td>Nonwoven Laminates</td>
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<td></td>
<td></td>
<td>Kapton, Beta Marquisette,</td>
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<td></td>
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<td>Laminates to High Temperature Fabrics</td>
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<td></td>
<td></td>
<td>Teflon Coated Beta Covers</td>
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<td></td>
<td></td>
<td>Perforation, Shingling, Needle Bonding, &quot;Confetti&quot;</td>
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<tr>
<td></td>
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<td>Long-Term Test Data</td>
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<td></td>
<td></td>
<td>Thermal Vacuum Outgassing</td>
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<td>Cryogenic Adhesives</td>
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<td>Differential Patterns</td>
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<td>Spaced Seams</td>
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<td></td>
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<td>Rip Stop Taping</td>
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<tr>
<td></td>
<td></td>
<td>Sewn Panels</td>
</tr>
</tbody>
</table>
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
MACHINE WINDING OF MULTILAYER INSULATION

COURTESY OF LINDE DIV. OF UNION CARBIDE

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**

<table>
<thead>
<tr>
<th>THERMAL</th>
<th>REFLECTIVE</th>
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<tr>
<td>JACKETS AND COATS</td>
<td>SOLAR ENERGY CONCENTRATORS</td>
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<tr>
<td>BLANKETS</td>
<td>HEAT PROXIMITY SUITS</td>
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<tr>
<td>DRAPERIES</td>
<td>FIRE FIGHTING SUITS</td>
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<tr>
<td>SLEEPING BAGS AND LINERS</td>
<td>WELDING SCREENS AND SHIELDS</td>
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<tr>
<td>GLOVES AND SOCKS</td>
<td>HEAT SHIELD CURTAINS</td>
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<tr>
<td>SPACE SUITS</td>
<td>BOOTS</td>
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<tr>
<td>SURVIVAL SUITS</td>
<td>GLOVES</td>
</tr>
<tr>
<td>CRYOGENIC INSULATION</td>
<td>HOODS, APRONS</td>
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<tr>
<td>STORAGE TANKS</td>
<td>LEGGINGS</td>
</tr>
<tr>
<td>LIQUID NATURAL GAS TANKERS</td>
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<tr>
<td>TRANSFER LINES</td>
<td>DECORATIVE</td>
</tr>
<tr>
<td>TRANSPORTERS</td>
<td>AUTO DOOR TRIM</td>
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<tr>
<td>SUPER CONDUCTORS</td>
<td>CLOTHING</td>
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<td></td>
<td>ELECTRICAL</td>
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<tr>
<td></td>
<td>MICROWAVE COMMUNICATIONS</td>
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<td>RADAR CHAFF</td>
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<td>LIFE RAFT AND BEACONS</td>
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</table>
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 multi-layer 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 multi-layer 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
<table>
<thead>
<tr>
<th>APPLICATIONS</th>
<th>REQUIREMENTS</th>
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<tbody>
<tr>
<td>CLOTHING</td>
<td>THERMAL RADIATION BARRIER</td>
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<td>LOW EMITTANCE</td>
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<tr>
<td></td>
<td>FLEXIBLE</td>
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<td>SPACED MULTILAYER</td>
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<td>MINIMUM FLAMMABILITY</td>
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<td>WITHSTAND SOLAR ULTRAVIOLET</td>
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<td>NONTARNISHING</td>
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<td>BREATHABLE/PERFORATED</td>
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<td></td>
<td>ANTHROPOMORPHIC SHAPE</td>
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<td></td>
<td>TEAR RESISTANT</td>
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</table>

Figure 5 - Reflective Supersilation 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 metalized 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.
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 or 25-liter liquid helium container; University of Chicago, 145-liter liquid hydrogen bubble chamber.


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.


- 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.


- 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.


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.


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

CHRONOLOGY

SPACE SUITS/EVA SUITS

SUPERINSULATION

- 1955: ILC pressure suit for USAF, first use of balanced convolute concept.
- 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-
  - 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.
- 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.


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


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.


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

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-
■ 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.


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


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


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


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.


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


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


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.


- 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."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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