CRYOGENIC INSULATION SYSTEMS

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ABSTRACT

The results of a comparative study of cryogenic insulation systems performed are presented. The key aspects of thermal insulation relative to cryogenic system design, testing, manufacturing, and maintenance are discussed. An overview of insulation development from an energy conservation perspective is given. Conventional insulation materials for cryogenic applications provide three levels of thermal conductivity. Actual thermal performance of standard multilayer insulation (MLI) is several times less than laboratory performance and often 10 times worse than ideal performance. The cost-effectiveness of the insulation system depends on thermal performance; flexibility and durability; ease of use in handling, installation, and maintenance; and overall cost including operations, maintenance, and life cycle. Results of comprehensive testing of both conventional and novel materials such as aerogel composites using cryostat boil-off methods are given. The development of efficient, robust cryogenic insulation systems that operate at a soft vacuum level is the primary focus of this paper.

1. INTRODUCTION

Cryogenics is fundamentally about energy, and thermal insulation is about energy conservation. The technological developments of this century have led to insulation systems that have approached the ultimate limit of performance. More technologies and markets forecast for rapid expansion into the 21st century will require, in many cases, not superinsulations but more efficient systems for a wide variety of cryogenic applications. Although bulk storage and delivery of cryogens such as liquid nitrogen, argon, oxygen, hydrogen, and helium are routinely accomplished, cryogenics is still considered a specialty. As ice usage was a specialty in the 19th century (not becoming commonplace until the 20th century), our goal is to make cryogen usage commonplace in the early 21st century. To make liquid nitrogen "flow like water," superior methods of thermal insulation are needed. The development of efficient, robust cryogenic insulation systems that operate at a soft-vacuum level is the focus of this paper and the corresponding research.

2. PRINCIPLES, PRACTICES, AND PROBLEMS (AN OVERVIEW)

A brief technical history and overview of modern practices are needed to properly explain the phrase *cryogenic insulation systems*. The first definition of the word *insulate* (from the Latin *insulatus*, made like an island) is "to set apart, detach from the rest, isolate." Any cryostat device, therefore, could be called a high-performance cryogenic insulation system.

2.1 Energy Considerations

It is understood that much heat (energy) is required to produce a little cool. The fact that thermodynamics is essentially about money and is a tradeoff between refrigeration (energy bill) and the refrigerator (capital cost) was pointed out by Flynn (1997). In addition to the energy required to liquefy the gases, much energy is expended in the extraction or separation of these desired gases. Any product losses during storage and transfer can therefore be directly equated to monetary losses. As an example, consider 100 liters of liquid nitrogen (LN_2) saturated at its normal boiling point. An energy input of only about 10 kW-hr is required for evaporation and warming to ambient temperature, while the energy required to liquefy that same amount is on the order of 100 kW-hr.

For the original ice businesses, the energy expended was the human effort to cut the ice out of lakes and then handle, store, and transport the massive blocks. Competitive methods to ice were nonrefrigerated preservative methods such as salt or smoke. The Freon-based refrigeration system was the enabling technology that allowed refrigeration to enter every home, along with low-cost production and distribution of electricity. Likewise, the wide-scale proliferation of nitrogen and carbon dioxide (CO_2) as refrigerants is dependent on low-cost production, distribution, storage, and end-use application systems. Assume a nominal case where the total cost of LN_2 to the end-user is 15¢ with production at 5¢, distribution and storage at 5¢, and application at 5¢ per 1 cubic meter of gas at standard conditions.

Dramatic savings can be achieved with technological advancements in each of these three areas. Industrial gas companies and independent suppliers must continually invest heavily for improvements in cryogenic production and equipment. Novel ideas for liquefied air usage, for example, could reduce costs by 30 to 40 percent compared to LN_2. Savings in the distribution and storage area are driven by high-vacuum and insulation system advances, software for efficient route modeling, and remote telemetry options for monitoring.

2.2 Origins and History of Thermal Insulation

From the beginning of history, humankind has made use of thermal insulation (e.g., animal furs to keep warm or cellars lined with straw to keep perishable foods cool). The measure "R-value" comes from the heat resistance of a 1-inch-thick oak board (Emmer, 1996). Before John Gorrie invented the first icemaking machine around 1850, ice farms were started in Massachusetts where large slabs were cut, stacked in thick-walled warehouses, and packed in sawdust for later export. Ice shipments were made to hotter countries around the world. At times, the demand for ice was high enough to raise the price to an exorbitant $1.25 per pound in Florida in 1855 (Flynn, 1997)! The industrial revolution brought increased demands for energy efficiency in boilers and metalworking processes, and thus thermal insulation development was started. As the industry proceeded to a chemical and process revolution, corresponding to the first liquefaction of key gases during the period 1877 to 1908, development of insulation for low temperatures began.

The development of insulation for modern cryogenic storage tanks can be traced through three patents issued in the United States. The first, "insulated container for liquefied gases and the like" filed by Dana (1939), gave details for a double-walled tank with the annular space evacuated to the range of 10^{-3} torr up to 4 torr and filled with finely divided solid material. The second patent, "radiation shield supports in vacuum insulated containers" filed by Cornell (1947), gave details for radiation shielding of containers by use of multiple polished tank walls within the outer tank. The third patent, "thermal insulation" filed by Matsch (1956), outlines the fundamental approach to MLI, which is now the industry standard. Reducing these three patents to large-scale processes, MVE, Inc., optimized MLI and fiberglass material combinations for cryogenic bulk storage systems. Coined as "composite insulation" in 1993, this new insulation system replaced perlite as the industry standard.

2.3 Insulation Methods and Materials

Conventional insulation materials for cryogenic applications can be divided into three levels of apparent thermal conductivity (k-value): around 30 mW/m-K for materials at ambient pressure, about 1.5 mW/m-K for bulk fill materials at good vacuum, and below 0.1 mW/m-K for MLI at high vacuum. Systems using evacuated powders or fibers require a good vacuum level (below 10^{-3} torr) to be fully effective. Evacuated powder systems have the tendency to settle and compact due to vibration or thermal cycling, which in turn leads to degradation of thermal performance and possible structural damage. The reference case boundary temperatures for all k-values in this paper are approximately 80 and 300 kelvin (K) unless otherwise noted. Some representative experimental k-values for different materials are given in Table 1.

Table 1: Experimental apparent thermal conductivity values for different materials.

Material System	K-Value (mW/m-K)		Vacuum (torr)		Reference
Cellular glass foam, 128 kg/m³ (190 K)	33		760		Vendor data
Polyurethane foam, 32 kg/m³ (190 K)	21		760		13
Fiberglass, 16 kg/m³	2	14	10^{-4}	1.0	Vendor data
Perlite powder, 128 kg/m³ (190 K)	1.5	16	10^{-4}	1.0	1
Aerogel/fiber composite, 125 kg/m³	0.55	3.3	10^{-4}	1.0	8
Microspheres, uncoated, 73 kg/m³	0.59		10^{-6}		5
Vacuum, polished surfaces	0.5 to 5.0		$<10^{-5}$		9
MLI, foil and paper, 60 layers @ 2.8/mm	0.08		6×10^{-5}		3
MLI, foil and paper, 50 layers	0.06	18	4×10^{-5}	1.0	10
MLI-ultimate	~0.02		$<10^{-5}$		2

Standard MLI systems, such as those using aluminum foil and fiberglass paper spacers, represent the benchmark for comparison. MLI or superinsulation requires a vacuum level below 10^{-4} torr to be effective. Other drawbacks of MLI are that it is highly anisotropic, is sensitive to compressive loads and edge effects, requires careful attention during installation, and is often limited in application by awkward structural complexities. Furthermore, the steps of evacuation, heating, and vacuum retention are costly and time consuming. Thermal performance degrades rapidly for vacuum levels above 10^{-3} torr. It is important to recognize that there are three levels of thermal performance: ideal, laboratory, and industrial. Industrial (or actual) performance is typically several times worse than the laboratory performance and often 10 times worse than the ideal (Nast, 1998). The heat leak for the overall mechanical system can in turn be several times more than that estimated for the insulation system alone.

3. ECONOMICS AND SYSTEM DESIGN CONSIDERATIONS

The appropriate choice of a thermal insulation system depends on matching the performance level with the overall cost. That is, the performance must justify the cost.

3.1 Optimization and Design of Insulation Systems

The actual operating conditions must first be considered. An analysis of the total heat leak of the mechanical system is needed to determine the insulation requirements. Often only a common-sense thermal review of the system is needed to ascertain which level of insulation material should be selected. The performance level will dictate the insulation materials and mechanical support structures or joining devices to be used. The main factors to consider are: (1) operating conditions of the system, (2) total heat leak of the mechanical system, (3) material properties such as density and compatibility, and (4) method of testing and evaluation. Attention should also be given to offering advantages such as easier installation, maintenance, and modification where possible.

3.2 Insulation Economics

The complete economics picture for an insulation system depends upon the energy tradeoff for the system life cycle. For example, durability is a critical factor for foam systems because performance can degrade dramatically over time if proper attention is not given to environmental exposure and thermal cycling. Product losses for a 2-year-old foam-insulated pipe installation have been reported to exceed that of a bare pipe. For the cost of a bulk storage container (with standard MLI), more than 25 percent is attributed to the insulation. The materials are only a small fraction of this cost; but the heating, vacuum pumping, testing, material handling, and other steps necessary in manufacturing a high-vacuum vessel are costly. In summary, the overall effectiveness of the system of insulation depends on: (1) thermal performance, (2) versatility and durability, (3) ease of use in manufacturing and installation, and (4) costs of operations and maintenance.

3.3 Market and Applications

Today's choice is generally between a k-value of ~0.1 mW/m-K (R1440) or ~30 mW/m-K (R4.8). Many applications call for intermediate level of thermal performance or perhaps a lower performance with longer life. Or when examining a system design from a total energy standpoint, superinsulation may be excessive. A great potential for improvement in the applications area is the offering of "soft vacuum" (1 to 10 torr range) insulation systems at low cost with performance several times better than conventional foam systems. Whether it is an affordable piping system or new advanced containers, the present opportunity is to bridge the gap between R5 and R1500 in terms of both cost and performance. A soft vacuum system with R30 or better performance has numerous advantages. The ability to commercialize an insulated product at vacuum levels near those produced by high-volume vacuum packaging equipment presents tremendous potential for cost-competitive, high-efficiency products. In evaluating life-cycle costs, the repair or modification of a system is far easier under soft vacuum than at high vacuum.

Markets of interest extend from cryogens to other fluids such as CO_2, ammonia, chilled water, oil, and steam up to about 480 K. Finally, by initially focusing on higher value applications such as LN_2 or CO_2 piping, the industry is able to match low volume with higher cost while the more exotic insulating materials such as aerogels are developed. As volumes increase and costs fall, applications for the new materials and methods will grow. Ultimately, large-scale applications such as home insulation or appliances may be cost competitive as production methods for the advanced insulations are employed to satisfy the higher demand levels.

4. INSULATION TESTING AND RESULTS

A unique cooperative research program, "Comparative study of cryogenic vacuum insulation systems," was performed under the Space Act Agreement between MVE, Inc., and NASA Kennedy Space Center (KSC-NON-054). The main goal was to develop a new soft vacuum system (1 to 10 torr) that provides an intermediate level of performance (k-value below 4.8 mW/m-K). Liquid nitrogen boiloff methods were used to test conventional materials, novel materials, and certain combinations. The test articles included combinations of aluminum foil, fiberglass paper, polyester fabric, silica aerogel composite blanket, fumed silica, silica aerogel powder, and syntactic foam.

4.1 Cryostat Test Method

The cryostat test apparatus is a liquid nitrogen boiloff calorimeter system for direct measurement of the apparent thermal conductivity at a fixed vacuum level between 5×10^{-5} and 760 torr. The system is further described by Fesmire and Augustynowicz in the paper, "Insulation testing using cryostat apparatus with sleeve," 1999 Cryogenic Engineering Conference, Montreal. Continuously rolled materials are installed around a cylindrical copper sleeve (or cold mass) using a 1-m wide wrapping machine built by the Cryogenics Test Laboratory at KSC. The sleeve is slid onto the vertical cold mass of the cryostat. Sensors are placed between layers of the insulation to obtain temperature-thickness profiles. The temperatures of the cold mass (maintained at 77.8 K), the sleeve [cold boundary temperature (CBT)], the insulation outer surface [warm boundary temperature (WBT)], and the vacuum chamber (maintained at 313 K by thermal shroud) are measured. The measurable heat gain for this apparatus is from 0.2 to 20 watts; the surface area for a typical 25-mm-thick insulation test article is 0.63 m^2. The steady-state measurement of k-value is made when the vacuum level, all temperatures, and the boiloff flow are stable.

4.2 Dewar Test Method

The dewar test apparatus provides a means of determining the "real world" performance of an insulation system, with consideration given to the fabrication, quality control, testing, and operation of the cryogenic tank. This method gives a direct measure of actual system performance as a func-

tion of cold vacuum pressure (CVP). The dewars were 10-liter vacuum-jacketed aluminum vessels (Lab10 by MVE Inc.). A custom built 0.5-m wide wrapping machine was used for installing continuously rolled materials onto the inner vessel. A vacuum pumping station with a shutoff valve and bake-out system with a temperature controller were connected during test preparations. Capacitance manometers connected to the vacuum port were used for measuring vacuum levels from $5x10^{-5}$ to 100 torr. A transfer standard mass flowmeter with a thermal conditioning coil was connected to the dewar. The entire setup was mounted on a precision weight scale for the primary test measurement. The ambient conditions (temperature, barometric pressure, and humidity) were also monitored. The weight loss due to the boiloff of nitrogen gas is proportional to the total heat leak into the inner vessel.

4.3 Cryostat Test Results

A total of 142 tests of 17 different insulation systems were performed using the cryostat method. The installed thickness of all test articles ranged from 0.75 to 1.25 inches (except the syntactic foam, which was 2 inches). All tests were run with the same copper sleeve outfitted with six surface temperature sensors. The CBT was constant at around 80 K. The outer heat shroud was maintained at approximately 313 K, which gave WBT ranging from 290 K (at high vacuum levels) down to about 190 K (for near ambient pressure). The residual gas is nitrogen for all tests. Further details regarding the test method and layer temperature distributions are given in the paper by Augustynowicz and Fesmire, "Cryogenic insulation system for soft vacuum," 1999 Cryogenic Engineering Conference, Montreal. A summary chart of k-value as a function of vacuum level for some of the more important material systems is given in Figure 1. The MLI standard (C108) is composed of a reflective shield (aluminum foil, 0.00724 mm) and spacer (fiberglass paper, 0.061 mm) at a density of 1.8 layers/mm. A number of the presented systems have k-values better than the target 4.8 mW/m-K (R30) at 1 torr CVP. For example, layered composite C107 gave superior performance of 2.4 mW/m-K (R60) at 1 torr (about 4 times better than the MLI standard). Performance of C107 was also found to be comparable to C108 at high vacuum (0.09 versus 0.08 mW/m-K).

4.4 Dewar Test Results

A total of 59 tests of 22 different insulation systems was performed using the dewar method. Figure 2 shows the effect of CVP on the rate of total heat leak to the inner vessel. The average line is an excellent representation of the classical S-curve, showing the transition from radiation to gas conduction dominated heat transfer, which occurs at about $5x10^{-2}$ torr. Note also the cluster of data points around 10^{-3} torr with a performance comparable to those dewars operating below 10^{-5} torr, which shows an significant improvement from the manufacturing point of view. The dewar tests served to verify the practicality of fabricating production tanks with the new layered composites.

5. CONCLUSION

Two test methods are needed to adequately describe the overall thermal performance of an insulation system. The cryostat method provides the apparent thermal conductivity values for the material combination while the dewar method gives the actual performance for the mechanical system. The performance of a given cryogenic insulation system has as much to do with engineering and manufacturing as it does with materials and heat transfer properties. This research study was entitled "comparative" to acknowledge that all test methods (from installation, to preparation, to testing sequences) must be performed as close to the same way as possible all the time. A new layered composite is being developed into a family of cryogenic insulation systems. The performance level for LN_2 and 1-torr conditions was measured to be 2.4 mW/m-K (R60). This system is targeted for low-cost, intermediate performance uses but offers advantages for high-vacuum superinsulation applications as well. Performance at LN2 and 10^{-4} torr conditions was 0.09 mW/m-K, which is near that of the benchmark MLI. The actual performance of the more robust composite could exceed

that of the highly evacuated MLI when the factors of edge effects and compression are considered. The "vacuum burden" of fabricating 1-torr systems versus 0.0001-torr systems is accordingly reduced. The layered composite insulation should benefit any industry that deals in the storage, transfer, or handling of different temperature fluids, by lowering the manufacturing costs and the life-cycle costs for equipment. These insulation systems should also allow for more flexibility in the overall design and implementation of cryogenic systems, a key benefit to the cryogenic equipment on Earth and in Space.

6. NOMENCLATURE

k-value apparent thermal conductivity (mW/m-K)   MLI multilayer insulation
R   thermal resistivity per inch (hr-ft^2-degF/Btu-inch)   CBT cold boundary temperature
CVP   cold vacuum pressure   WBT warm boundary temperature

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SYSTÈMES D'ISOLATION CRYOGÉNIQUES

RÉSUMÉ: Les résultats d'une étude comparative des systèmes d'isolation cryogénique sont presentés. Les aspects clés de l'isolation thermique se rattachant à la conception, la mise à l'essai, la fabrication et l'entretien d'un système cryogénique sont expliqués. Un survol du développement de l'isolation selon une perspective de conservation de l'énergie est également présenté. Les matériaux conventionnels d'isolation pour les applications cryogéniques procurent trois niveaux de transport thermique. La performance thermique réelle de l'isolation à couches multiples (MLI) est grandement inférieure à la performance en laboratoire et souvent 10 fois moindre que la performance idéale. Le rapport coût-efficacité du système d'isolation dépend de la performance thermique ; de la flexibilité et de la durabilité ; de la facilité de manutention, d'installation et d'entretien ; et du coût total y compris l'exploitation, l'entretien et la durée de vie. Les résultats d'une étude approfondie utilisant des méthodes d'évaporation par cryostat sur des matériaux conventionnels et nouveaux tels que les composites aérogel sont présentés. Le développement de systèmes d'isolation cryogénique efficaces et economiques qui fonctionnent sous vide moderé constitue le sujet principale de cette étude.
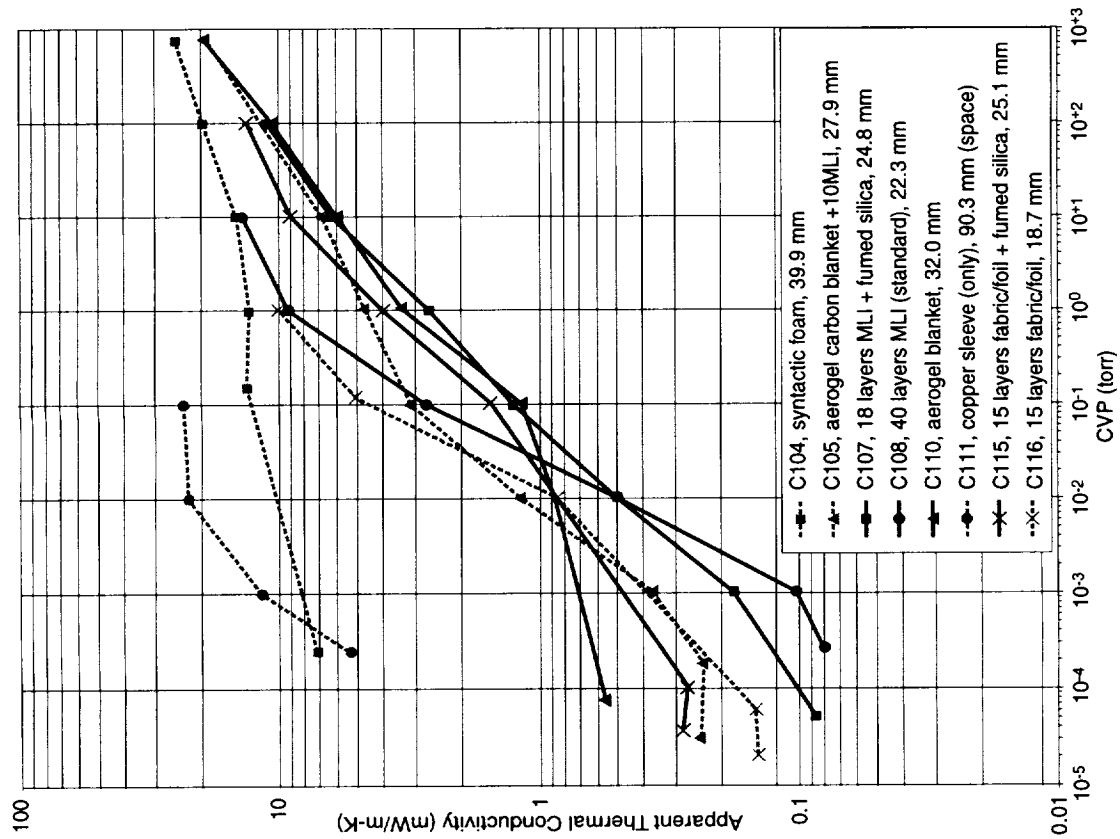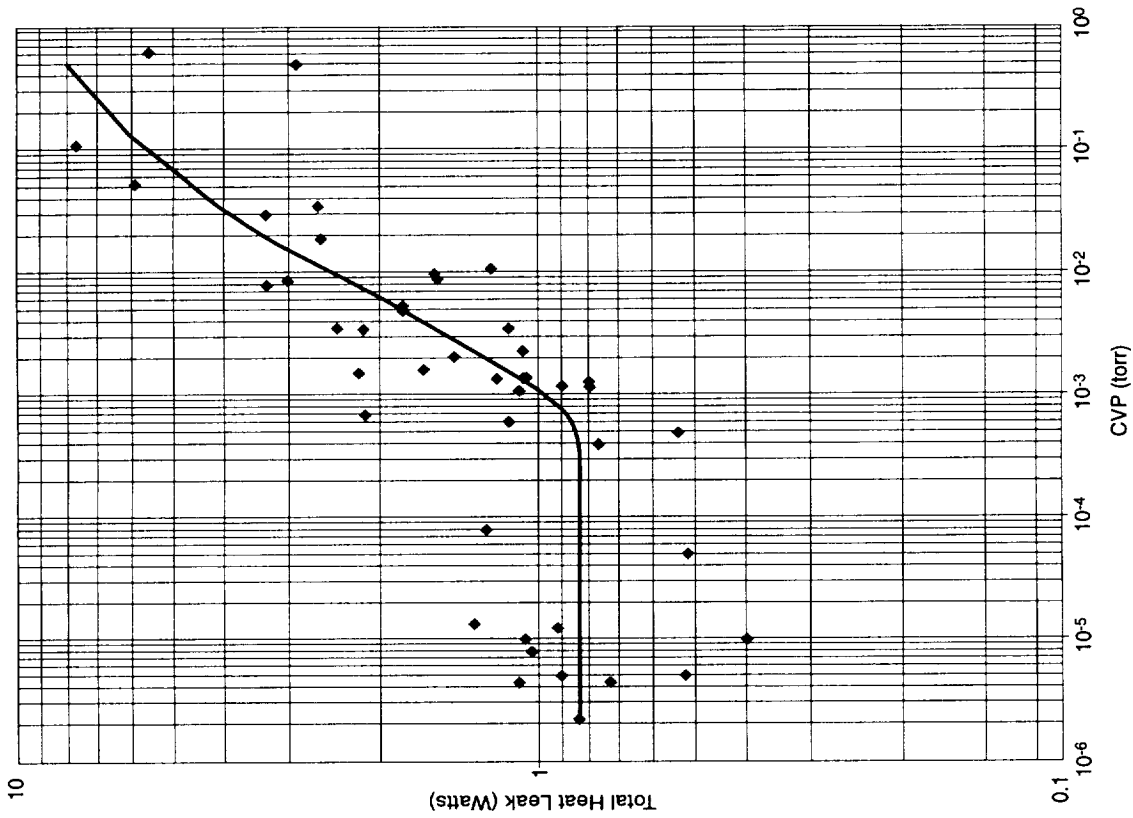
Figure 2. Lab10 dewar test summary: variation of total heat leak with CVP

Figure 1. Cryostat test summary: variation of apparent thermal conductivity with CVP

Legend (Figure 1):
- C104, syntactic foam, 39.9 mm
- C105, aerogel carbon blanket +10MLI, 27.9 mm
- C107, 18 layers MLI + fumed silica, 24.8 mm
- C108, 40 layers MLI (standard), 22.3 mm
- C110, aerogel blanket, 32.0 mm
- C111, copper sleeve (only), 90.3 mm (space)
- C115, 15 layers fabric/foil + fumed silica, 25.1 mm
- C116, 15 layers fabric/foil, 18.7 mm