Development of Cryogenic Insulations for Launcher Upper Stages

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AIRBUS D&S, Bremen has executed a program for development of cryogenic insulations for application on upper stages for future launchers. Insulations under consideration are those applied inside the hydrogen tank as well as external surfaces of hydrogen and oxygen tanks. Currently a status of TRL 3 has been achieved and the next phase has been commenced heading for TRL 4/5. Until TRL 3 the foam basic material has been developed and down-selected to the most appropriate ones for internal and external applications. The chemical composition and structure as well as the cell morphology have been frozen. Parameters for manufacturing have been investigated on lab scale as well in very detail and have been preliminarily frozen. Comprehensive characterization and qualification has been done for LN2 conditions for physical, mechanical and thermal properties. For the most important properties a first characterization has been performed under LH2 conditions. All the measurements and tests performed so far exhibit excellent and promising results. Now for the next phase (IWTI = ~1 year. ETI = ~2 years) the insulation concepts will be established incorporating such components/aspects as liners, substructure fixation and NDI methods. Detailed characterization/qualification under LN2 and LH2 is intended on sample as well as on building block level. This paper refers to the achievements of the development performed so far and will discuss the development approach for the next maturation phase.

Nomenclature

A5ME	=	ARIANE 5 Midlife Evolution
CT	=	Computer Tomography
CTE	=	Coefficient of Thermal Expansion
DLR	=	German Space Agency
IWTI	=	Inner Wetted Thermal Insulation
ETI	=	External Thermal Insulation
ESA	=	European Space Agency
FLPP3	=	Future Launcher Preparatory Program # 3
He	=	Helium
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
LN2	=	Liquid Nitrogen
Mfg	=	Manufacturing
NDI	=	Non Destructive Inspection
NDT	=	Non Destructive Testing
PBI	=	Polybenzolimide
PI	=	Polyimide
PU/PUR	=	Polyurethane
PVC	=	Polyvinylchloride
RT	=	Room Temperature
TRA	=	Technology Readiness Assessment
TRL	=	Technology Readiness Level
US	=	Ultra-Sonic
α	=	Thermal Expansion Coefficient
ρ	=	Density
σ	=	Tensile Strength
E	=	Young's Modulus
ε	=	Elongation Coefficient
λ	=	Thermal Conductivity

I. Introduction

AIRBUS D&S; Bremen has a strong heritage in developing and applying all types of space insulations ranging from cryogenic (LH2/He temperature) up to very high temperature applications for re-entry missions (~ 2000°C).

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All kinds of concepts have been developed in the past using vacuum super insulations, foams, fibers, microspheres, multi-layer (MLI) vacuum insulations with the full spectrum of materials like several metals, PUR, PVC, PI, PBI, KEVLAR, NOMEX, SILICA, several ceramics et cetera. The full spectrum of missions ranging from planetary (Mars/Moon), outer space, LEO, entry and re-entry has been considered.

For more than 8 years AIRBUS D&S has specialized also on the development of cryogenic insulations to be used on launcher tanks. AIRBUS D&S is doing those developments within the frame of national (DLR) projects (C3B, SUCCESS) or on company funded basis together with partner institutes and companies. The detailed development is done from the perspective of the upper stage responsible taking into account all the constraints/requirements coming from the prime contractor role. However, AIRBUS D&S has gained a broad knowledge even in the technical details of cryogenic insulations ranging from specification, directing of suppliers/partners, evaluating, attending and performing development and testing activities.

Recently two concepts for future launchers one for the applications inside LH2 tanks called IWTI (internal wetted tank insulation) and the other one for application on external surfaces named ETI (external tank insulation) based on closed cell PU-foam material have been developed. Both materials/concepts have been newly developed by AIRBUS D&S. This offers the advantage (compared to current concepts which use off-the shelf materials) that this materials/concepts have been specifically established for the envisaged use and can be adapted and modified according to requirements evolving during the development process. Both insulations have gathered a maturity corresponding to TRL 3.

Detailed information on the foam material development can be found in the previous ICES paper [4].

The current paper deals mainly with the insulation concept and reviews the status achieved so far for both external and internal insulation and provides an overview about the activities currently on-going and such planned for the near future.

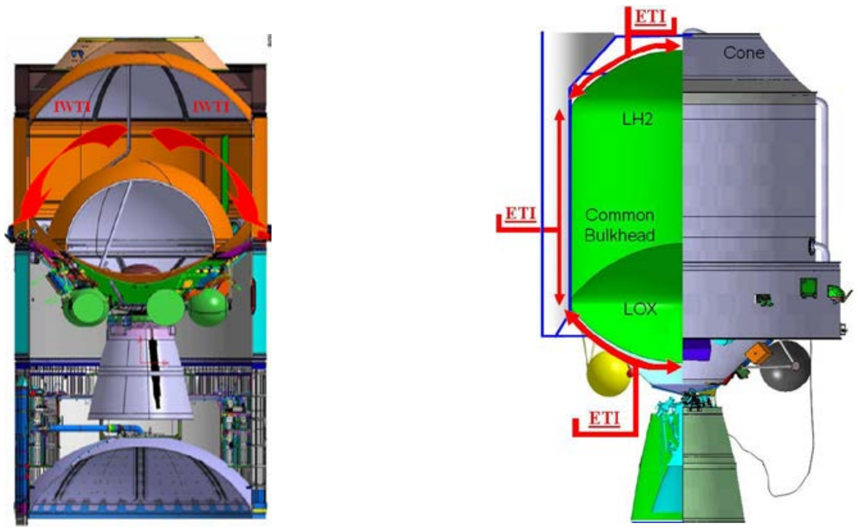

Figure 1 . Locations of IWTI & ETI Insulation on current LH2 & LOX Tank Configurations for Upper Stage

II. Cryogenic Insulation Development Statii

A. IWTI Status

Major part of the IWTI concept is the polyurethane (PU) insulation foam which has been *newly and specifically* developed for low (LH2 temperature regime) cryogenic conditions.

The foam insulation has been *especially designed* for an optimum chemistry and cell structure morphology in order to achieve *superior mechanical and thermal performance* under these exceptional conditions.

Compared to current state-of-the-art solutions where already *on the market existing materials* had been chosen, this approach offers excellent possibilities to find an *optimized solution* and to adapt the fundamental properties even during the course of the further maturation whenever deemed to be necessary.

During the development of recent years this PU cryogenic insulation foam has achieved a maturity of TRL=3. *Excellent thermal as well as mechanical performance* have been demonstrated down to LH2 temperatures.

Verification of major environments (e.g. storage at low cryogenic (LH2) temperatures, temp.-cycle, -shock et cetera) has been executed with superior results.
With the excellent thermal performance of the AIRBUS D&S foam material the demanding low boil-off rate requirement for new upper stages (A5ME) can be *already fulfilled* provided the to be developed LH2 barrier will confirm the expected characteristic. The currently proposed A5ME cryogenic insulation is by a factor of approx.imately 5 higher than the requirement.
The current baseline is to apply this material as spray-on foam with all the advantages concerning *simpler processing and cost reduction*. The nature of the material allows this even for large structures where current solutions are very limited (glued as single tiles) and tend to form unacceptable cracks during the tank filling process.
For application on the inner tank structure the insulation has to provide sufficient barrier properties in view of permeation of LH2 (He) molecules. Currently two liner variants are considered for further maturation of the IWTI insulation concept. One is a metallic liner i.e. aluminum foil glued on the foam. The feasibility of such metallic liner has been already demonstrated for SATURN IV upper stages and the ENERGIA rocket. However, the *most promising solution* is thought to be a *polymeric liner (nano-particles filled).* A most recent AIRBUS D&S R&T study performed until end of 2013 has demonstrated good LH2-barrier capabilities more than sufficient for a 6h flight (re-ignition) and also good compatibility to the PU foam. The polymeric liner is the preferred solution since it offers *low cost* (spraying process) and *low mass* liner (650 µm) application especially for complex insulation geometries.
NDI methods for identification of possible defects (lab & field scale) have already been identified and demonstrated successfully on substrates/foam samples with artificial defects. As a lab scale method computer tomography has been identified and for field measurements the so-called Terra-Hz method which is a imaging procedure has been chosen (see also descriptions in para. IV).
Comprehensive information about the IWTI foam material characterization can be found in the previous ICES paper on this subject [4] and in [2] & [3]. Table 1 and Figure 2 show some major mechanical and thermal characteristics presented in those references.

IWTI - CR87											
Testing temperature	Density ρ	Exp. Coeff. $\alpha_x \times 10^{-6}$	Compressive characteristics[1)]						Tensile characteristics[2)]		
			σ_{cz}	σ_{cx}	E_{cz}	E_{cx}	ε_{cz}	ε_{cx}	σ_{tx}	E_{tx}	ε_{tx}
[K]	[kg/m³]	[K⁻¹]	[MPa]	[MPa]	[MPa]	[MPa]	[%]	[%]	[MPa]	[MPa]	[%]
77 (LN2)	81.8[1)] 82.6[2)]	57.7	1.99	1.40	30.2	16.8	6.5	8.2	1.67	38.2	4.7
296 (RT)			0.73	0.45	16.4	10.0	5.5	6.2	0.96	18.5	10.43

Table 1 . Major properties of IWTI

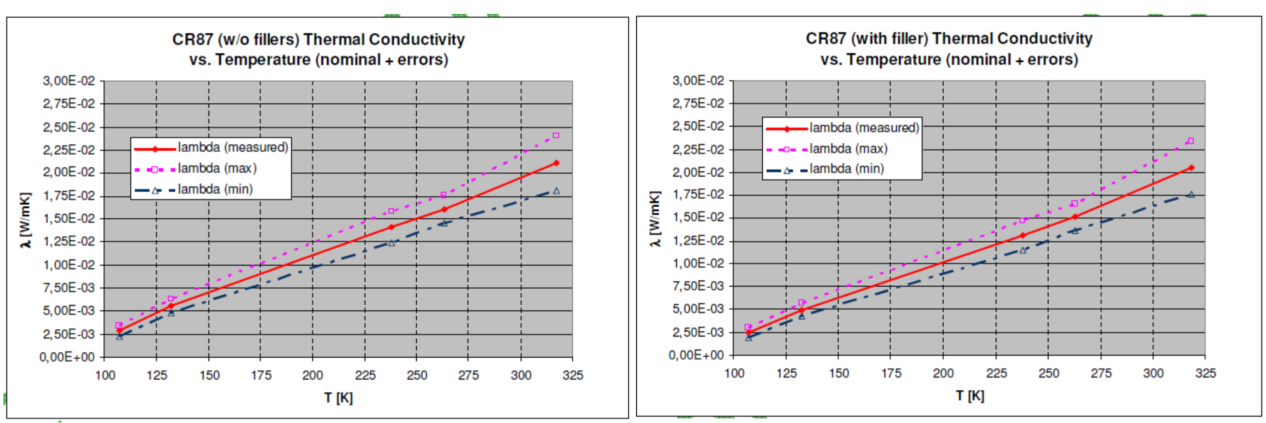

Figure 2 . Thermal Performances of IWTI (bare and with microsphere filler)

B. ETI Status

Major part of the ETI concept is the polyurethane (PU) insulation foam which, as for IWTI, has been newly and specifically developed for low (LH2 temperature regime) cryogenic conditions. The ETI foam chemistry and morphology is quite different from those of the IWTI.

Also this foam insulation has been especially designed for an optimum chemistry and cell structure morphology in order to achieve superior mechanical and thermal performance under these severe conditions.

Compared to current state-of-the-art solutions where already on the market existing materials had been chosen, this approach, as used for IWTI, offers excellent possibilities to find an optimized solution and to adapt the fundamental properties even during the course of the further maturation whenever deemed to be necessary.

During the development of recent years this ETI PU cryogenic insulation foam has achieved a maturity of TRL=3. Excellent thermal as well as mechanical performance had been demonstrated down to LH2 temperatures. Verification of major environments (e.g. storage at low cryogenic (LH2) temperatures, exposure to aero-thermal fluxes, temp.-cycle, -shock et cetera) has been executed with superior results. Some mechanical and thermal properties are shown in the table and figure of this para. Below. For further detailed results please refer to [4].

Compared to the IWTI the ETI has to bear also relatively high aero-thermal fluxes on the outer surface due to protuberances which may occur in specific areas. For ETI therefore a so-called gradient foam concept has been established with good shear properties at the tank wall superior thermal insulation properties in the middle layer and good resistance against high thermal loading at the outer surface. Sufficient performance under such loads had been already demonstrated in cone-calorimeters.

The current baseline is to apply this material as spray-on foam with all the advantages concerning simpler processing and cost reduction. The nature of the material allows this even for large structures where current solutions are very limited (glued as single tiles) and tend to form unacceptable cracks due to thermal expansion coefficient differences between tank structure and insulation.

NDI methods for identification of possible defects (lab & field scale) have been already identified and demonstrated successfully on substrates/foam samples with artificial defects. Same methods as for IWTI (see above) have been applied.

Comprehensive information about the ETI foam material characterization can be found in the previous ICES paper on this subject [4] and in [2] & [3]. Table 2 and Figure 3 show some major mechanical and thermal characteristics presented in those references.

ETI - CRE 210S											
Testing temperature	Core density ρ	Exp. Coeff. $\alpha_x \times 10^{-6}$	Compressive characteristics						Tensile characteristics		
			σ_{cz}	σ_{cx}	E_{cz}	E_{cx}	ε_{cz}	ε_{cx}	σ_{tx}	E_{tx}	ε_{tx}
[K]	[kg/m³]	[K⁻¹]	[MPa]	[MPa]	[MPa]	[MPa]	[%]	[%]	[MPa]	[MPa]	[%]
77 (LN2)	47.0	55.3-63.0	-	-	-	-	-	-	0.88	16.8	4.56-5.81
296 (RT)			0.24	0.25	6.53	5.83	-	-	0.49	8.00	15.9

Table 2 . Major properties of ETI

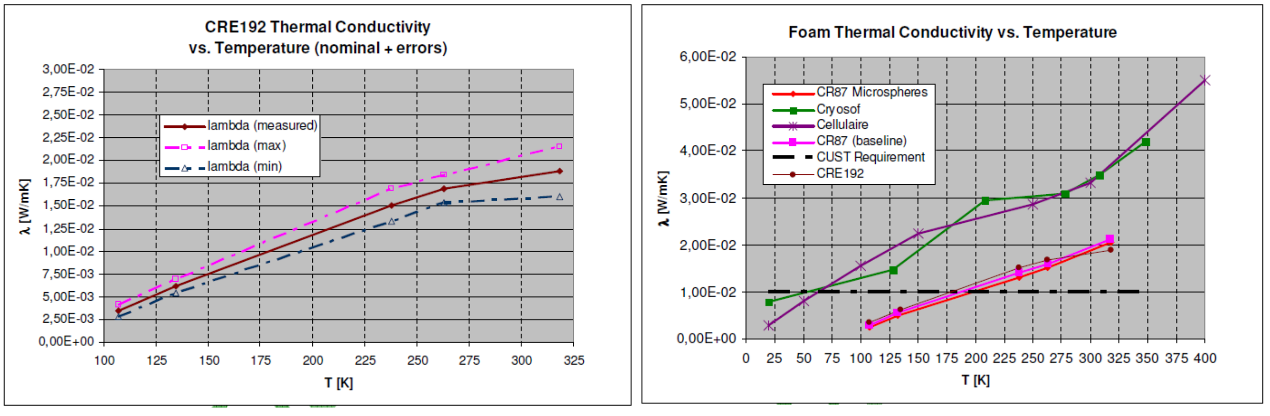

Figure 3 . Thermal Performances of ETI (CRE 192 and comparison with current foams)

III. Next Phase Development Approach

A. Development Approach IWTI

Emphasis will be on the development of the IWTI concept and concept components and on extensive verification of the thermal and mechanical performance under LH2 conditions.

In addition, the devopment of an effective barrier against LH2 and He permeation into the PU-foam is a major task of the next phase.

The following major activities are foreseen to be accomplished during the development of IWTI during the coming phase to gain in the end a TRL of 4.

- Finalization of the foam material development for IWTI
- Development of LH2/He sealing components or barriers (polymeric/metallic liners)
- Study of manufacturing parameters and freezing of them
- Manufacturing of bread board samples with substrate simulating the tank wall for characterization tests
- Comprehensive characterization testing of performance parameters under LH2 conditions
- Investigation of NDI methods for both lab and field scale application and verification on samples with artificial typical defects
- Investigation of next steps to gain TRL5
- First loop assessment for an industrialization concept for IWTI

Detailed performance targets for the IWTI concerning functional, mechanical and thermal aspects are given in [4] and summarized also in [4]. The bulk of mechanical and thermal properties are generated by the foam material itself and are considered as already achieved in previous development phases [4]. Functional performances are related to the IWTI concept, e.g. LH2 barrier function by the liner. Functional performance demonstration is a major subject of the described development of the coming phase.

B. Development Approach ETI

The ETI development will concentrate on establishment of the concept and of concept components and on extensive verification of thermal and mechanical performance under LH2 conditions on specimen and building block level.

The following major activities are foreseen to be executed during the development of ETI to gain in the end a TRL of 5.

- Finalization of the material development for ETI
- Study of manufacturing parameters and freezing of them
- Manufacturing of samples for characterization & qualification tests
- Manufacturing of building blocks and scaled tank demonstrator

- Comprehensive characterization testing of performance parameters
- Qualification of ETI on building block / scaled tank level
- Investigation of NDI methods for both lab and field scale application and verification on samples with artificial typical defects
- Investigation of next steps to gain TRL6
- Study of an industrialization concept for ETI

The logic for these development activities is shown in Figure 5 on next page for IWTI. The entire development is subdivided in phases which will be performed staggered and in parallel.

Detailed performance targets for the ETI concerning functional, mechanical and thermal aspects are given in [1] and summarized also in [4]. The bulk of mechanical and thermal properties are generated by the foam material itself and are considered as already achieved in previous development phases [4]. Functional performances are related to the ETI concept, e.g. barrier function against water absorption by an e.g. surface coating. Functional performance demonstration is a major subject of the described development of the coming phase.

An important part of the next phase developments for both types of insulations would be the further investigation of manufacturing parameters, accomplishment of manufacturing trials and finally the freezing of the manufacturing parameters. The spray-on foaming process is illustrated in Figure 4 below.

Figure 4 . Foam spray-on process (illustrated here for a small simulation tank)

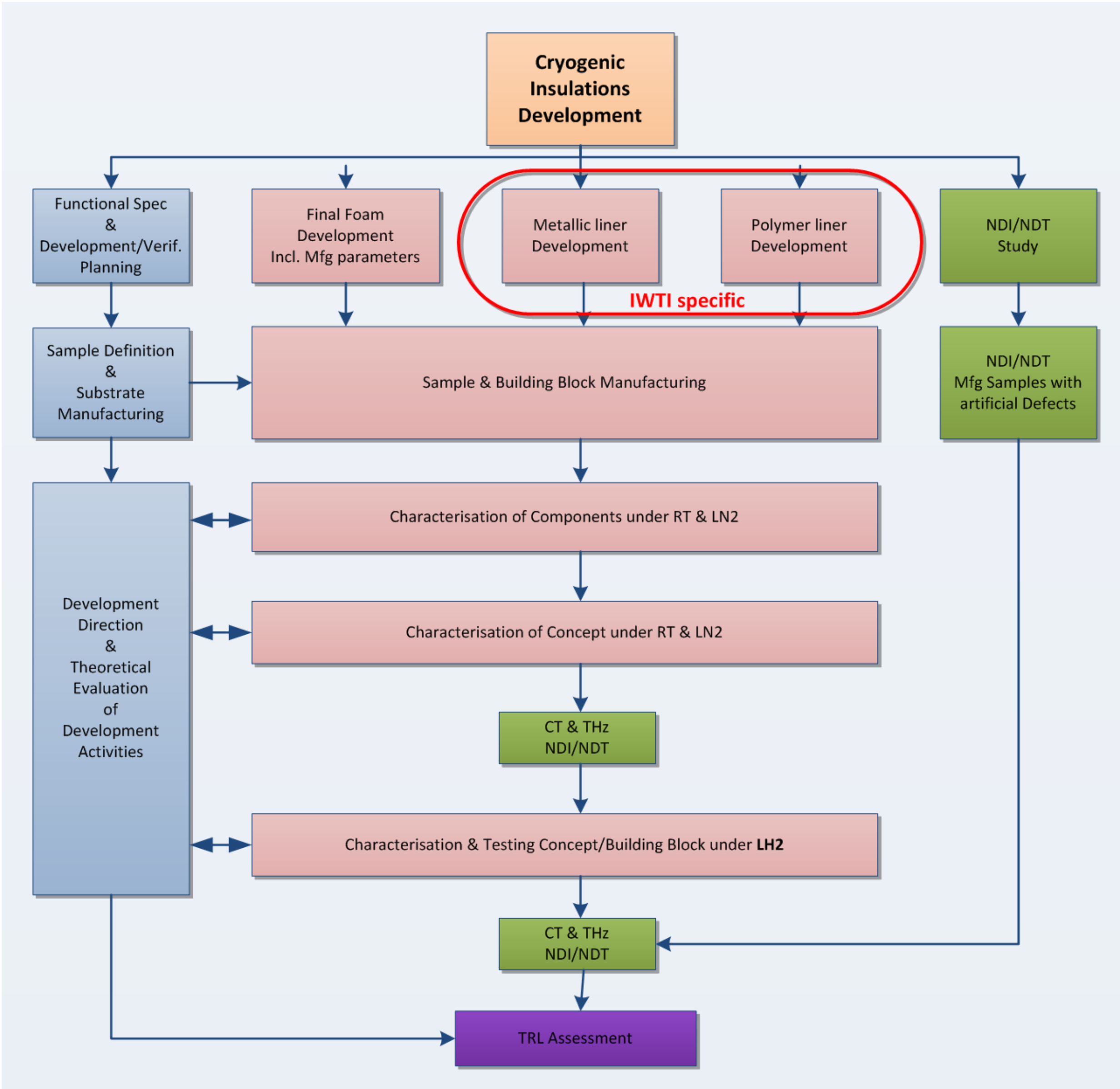

Figure 5. Next Phase Development Logic

IV. Verification Test Approach

There are the following categories of testing:

1. Characterisation tests of IWTI/ETI PU-foam material under RT and LN2 conditions
2. Characterisation tests of IWTI metallic/polymeric liner under RT and LN2 conditions
3. Characterisation tests of IWTI/ETI concepts under RT and LN2 conditions
4. Characterisation tests of IWTI concepts under LH2 conditions
5. NDI tests on specimen with artifial defects (in foam/liner/fixation) and those used for category 4 tests.

Categories 1. to 3. as defined above are inherent part of the components and concepts developments. Here basic physical, thermal and mechanical properties and performance under RT/LN2 conditions will be determined.

Category 4 tests are the most important ones to verify the concept mechanical and thermal performance in the anticipated (LH2) environment).

Within category 5. different NDI methods (pre-selected in foregoing development phases) will be investigated by means of samples with artificial defects and and those subjected to Cat 4. testing (before and after tests).

Cat. 4 & 5 tests for IWTI will be performed only on breadboard sample level. For ETI same tests on breadboard sample level and in addition tests on building block level will be executed due to the one step higher TRL (5 instead of 4).

A test matrix for Cat. 4 tests (as the most important ones as explained above) is given in Table 3 below. Here it is shown that some of the tests are similar and other are different respecting the different environments of the inner and the externmal insulations. E.g. ETI is subjected to plasma windtunnel testing in order to investigate the behavior under aero-thermal loads where for IWTI this is not done. IWTI is subjected to LH2/He barrier testing which is not necessary in case of ETI et cetera.

Most of the tests will be done in a facility providing the required LH2 equipment and conditions. Besides a shaker is used for vibration testing as well as a plasma windtunnel for aerothermal testing.

TEST	IWTI	ETI
Thermal conductivity measurements	X	X
Temperature shock/cycle (sample level)	X	-
LH2/He Permeation/purg. gas compatibility	X	-
Particle emission	deleted for TRL4 only	-
Temperature shock/cycle (building block level)	deleted for TRL4 only	X
Cryopumping (dia 1m, l=1m tank demonstrator)	-	X
Vibration Test	-	X
Plasmawindtunnel -Test (aero-dynamic heat loads)	-	X

Table 3. Test Matrix for Cat. 4 Concept Verification Tests

The flow plans for Cat . 4 tests are illustrated as an example for IWTI for breadboard samples, for ETI on building block level as well as for samples with artificial defects in Figure 6 below.

Typical test set-up's used in the foregoing phases for material characterization are illustrated in Figure 7 below.

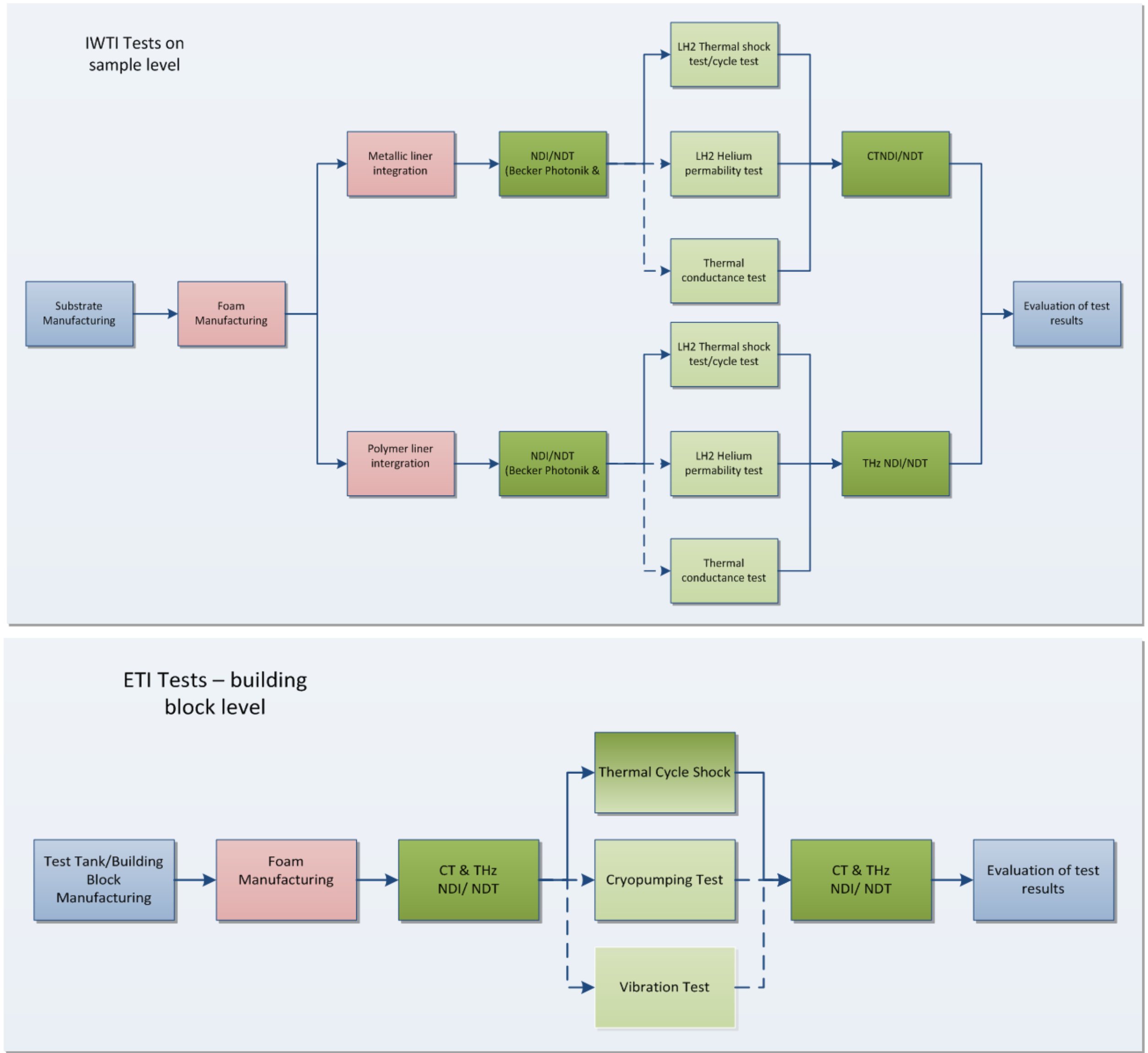

Figure 6. Flow plans for Cat . 5. and 6. Tests shown as example for IWTI for breadboard samples, for ETI on building block level

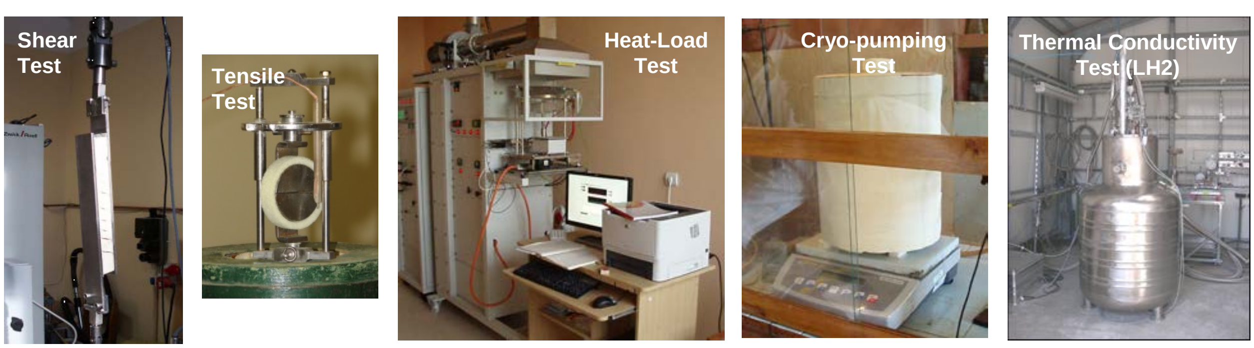

Figure 7. Typical Test Set-up's used in previous phases for foam characterization

In order to detect defects within the cryogenic insulations NDI/NDT methods have to be developed for use in laboratory environment during the development and for field application later if the insulations will be applied on upper stages of the future launch vehicle.

In the last development phases methods have been preselected for lab scale application as well as for field applications. For lab scale samples computer tomography (CT) method has been found most appropriate. This gives an excellent and simple to interpret view on defects like delaminations or voids. A simple-to-apply method for making field measurements was sought, and the Terra-Hertz (THz) method appears to be attractive relative to US methods. This method is using an imaging process assuming that defects can be detected based on the behaviour of the outer surface. Evaluation of defects is only possible by having reference samples.

Typical defects are illustrated in table 4 below. In principle those defects can occur in the PU-foam itself or in the LH2 barrier (liner). In Figure 9 on the next page typical results are illustrated for both NDI methods.

Type of Defect (exemplary given for foam)	Defect Description
Delamination from the substrate	• Separation between foam and substrate resulting in a layer of broken cells remaining on the primed aluminium surface • Due to: thick spray passes; a substrate temperature that is too cold; surface contamination
Formation of elongated cells	• Presence of cells with excessive expansion • Due to: Thick foam applications where blowing agent escapes during foam rise
Porosity	• Concentrations of elongated cells. • Due to: high spray temperature/excessive 'heat of reaction'
Crack s	• Break in foam exhibiting no material loss. • Due to: Stress build up/physical inducement. Large difference in coefficients of thermal contraction between foam and substrate - greater thermal contraction of foam causes it to crack / split
Voids	• Absence of foam. • Due to: Air pockets close to substrate when applying foam; conditions where air becomes trapped during foam application process; moisture present causing chemicals in foam to react forming carbon dioxide which is an excess volatile

Table 4. Possible Defects in PU-foam or corresponding Liners

The study of these methods will be continued in the envisaged development phase on samples with artificial, representative defects as well as on specimens subjected to Cat. 4 tests (before and after testing). A detailed evaluation of the methods will be done at the end of the development in order to finally select the field method.

In Figure 8 below a typical flow plan for samples with artificial defects is illustrated.

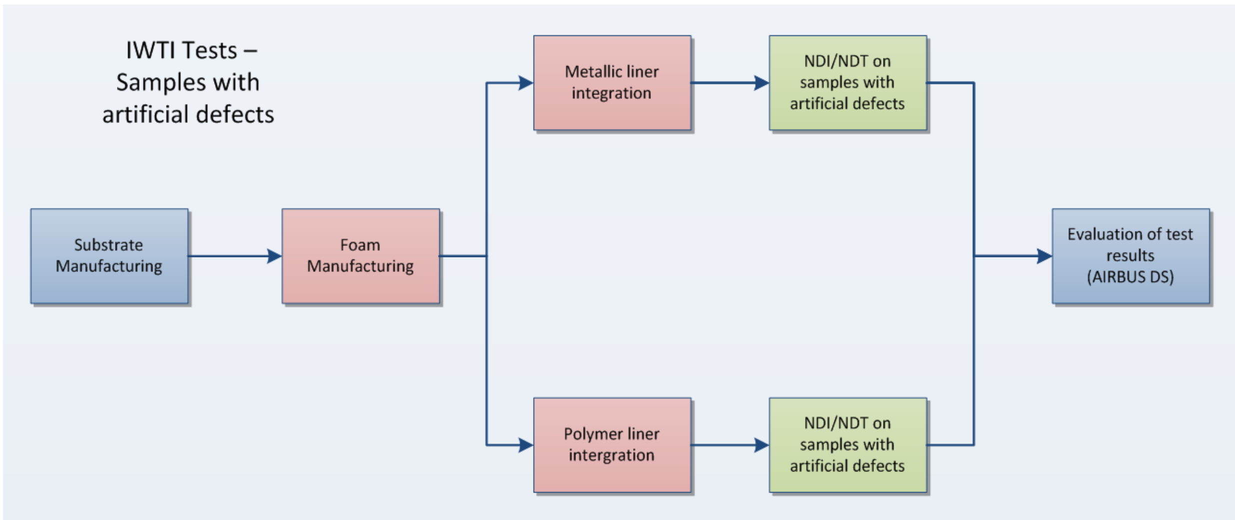

Figure 8. Flow plan for NDI Specimens with artificial Defects

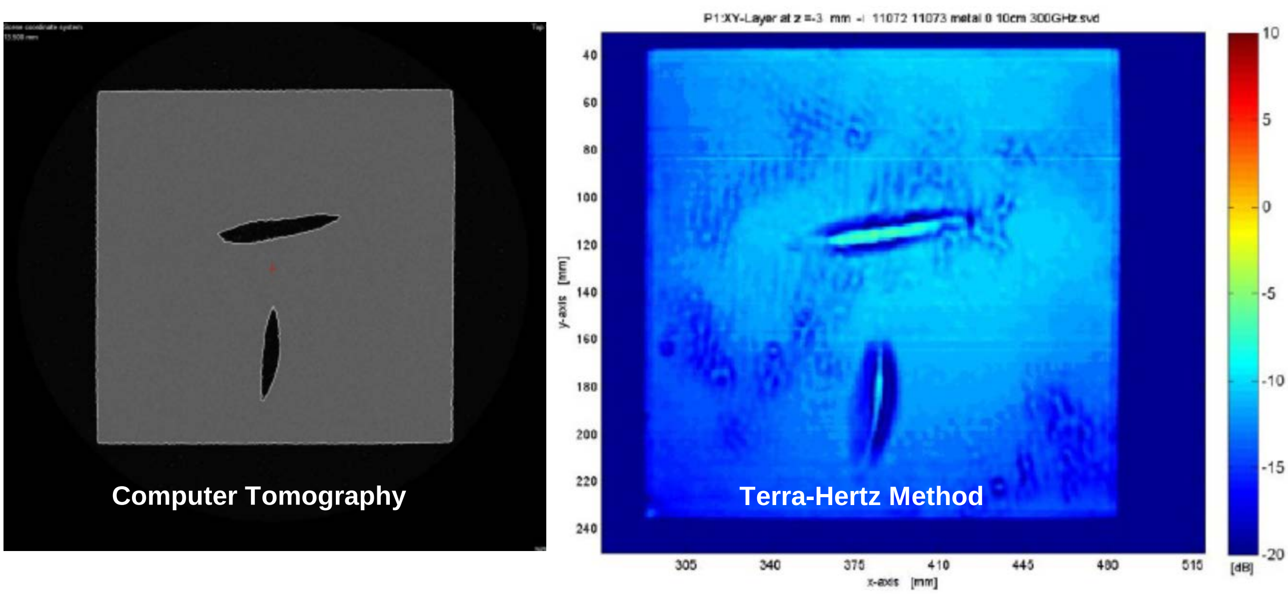

Figure 9. Typical NDI Results for lab (CT) and field (Terra-Hz) scale methods (type of defect: voids)

V. TRL Assessment and Maturity Development

A 1st loop assessment of the expected TRL is done for ETI (shown here as example) by answering TRL assessment questions given in the ESA TRL handbook [6].

- *TRA Q 5.1: Has the new concept, technology and/or approach been clearly described and modeled? What are the critical functions that would be performed by the conceptual approach, device, and/or software? What are the new capabilities that would result from this new concept?*
  - Technology is clearly described. Critical functions are thermal and mechanical performance and the resistance against aero-thermal heat loads. New capabilities are the better thermal performance and better mechanical behavior (increased cryogenic safety factor).
- *TRA Q 5.2: Has a prospective application been defined with sufficient fidelity that the necessary technological elements involved in the new capability have been fully identified? Are the interactions among those elements well understood? Have the functional, operational environment and performance metrics for this application been defined, and do prospective customers agree?*
  - Application is clearly envisaged and defined in detail in view of the various requirements. New capabilities are expected to be confirmed clearly at the end of this phase. Interactions between the elements are considered as well understood at the end of the study since of extensive testing planned. The functional, operational environment as well as the performance metrics will be clearly defined at the end of the TRL5 development and evaluated.
- *TRA Q 5.3: Have laboratory demonstrations been performed rigorously and successfully that included key elements being tested individually and/or in an integrated fashion? In such tests, were the results consistent with the characteristics (identified in Question 5.2) that the new technology must possess in order for a prospective future application to be technically and/or economically viable? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the laboratory demonstration(s) worked as desired?*
  - Key elements will be demonstrated by laboratory testing individually and on concept (system) level. It will be shown that results are consistent with characteristics required for the future application and at reasonable effort. Tests will be defined to be representative for the anticipated environment, loads and sequential order of loads. Metrics are chosen in such way to complain with the flight environment/requirements.
- *TRA Q 5.4: Is there a clearly identified path forward that would lead the experiment and/or demonstrations forward to the specific application described in Question 5.2? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?*
  - A clear path forward towards the launcher application has been defined. The needed capabilities will be detailed assessed at the end of the described development phase.
    The technical risk will be assessed after envisaged tests and the effort for continuation is expected to be clearly identified at the end.

The maturity of both ETI and IWTI will be developed further within the next phase according to the approach mentioned before. The key performance parameters the development is aiming for as well as the status and planning for achievement are depicted in Table 5 on the next page.

Key Performance Parameter	required	achieved / planned
Thermal performance (heat loss, shock, cycling)	maximum heat flux to cryogenic propellants shall be less than 0.2 W/m² h	already achieved and planned to be further verified in this phase by corresponding tests
Mechanical performance (tensile, compression, shear)	No formation of significant cracks under cryogenic conditions, temp. and pressure cycles	planned to be verified in this phase by corresponding tests
I/F tank wall - insulation (th. expansion, shear loads)	Shear stress to be compensated by foam for entire temperature range without separating from wall	planned to be verified in this phase by corresponding tests
Aero-thermal heating (ETI only) (ascent phase)	to withstand heat flux 10-60 kW/m²	planned to be verified in this phase by corresponding plasma wind tunnel tests
Cryo - pumping (ETI only) (launch pad)	Minimum water adsorption (< 10g/m² h)	planned to be verified in this phase by corresponding tests
Permeability (IWTI only) (start to re-ignition)	Minimum ingress of LH2 ($< 10^{-16}$ mol m / s m² Pa)	planned to be verified in this phase by corresponding tests
Mass (complete insulation)	< 2.2 kg/m²	already achieved and planned to be further verified in this phase by corresponding tests
Volume (complete insulation)	envelope for the volume around the LH2 / LOX tanks is limited to 60 mm thickness	already achieved and planned to be further verified in this phase by corresponding tests

Table 5. Key Performance Parameters

VI. Conclusion

This paper presents the status achieved so far in the current developments of IWTI and ETI.

The approach for the next phases of the development is described in some detail. Verification of mechanical as well as thermal parameters and performance will be done by extensive testing on breadboard and building block levels.

Emphasis is given on tests under realistic operational conditions. This means subjecting the insulation system fixed on a simulated tank wall (substrate) to liquid hydrogen conditions and those conditions resulting from the operating environment expected (e.g. aero-thermal & vibrational loads).

To be prepared for the application on a future launcher NDI methods are investigated for cryogenic insulations aiming at detecting defects which are thougt unacceptable. NDI methods are highlighted and the further proceeding is described.

A 1st loop TRL assessment for the end of the coming development phase has been accomplished. Results are described in some detail.

The current status of both cryogenic insulations is considered as a good and safe starting point for the future development phase envisaged to end in the application on a future launch vehicles.

Acknowledgments

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The envisaged development is proposed to be performed within the frame of the FLPP3 program directed by ESA.

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