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Optimization and Application of Cryogenic/Thermal Insulation Design for a Liquid-propellant Rocket Engine

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Abstract

In the development of Liquid-propellant Rocket Engine (LRE), the engine produces high temperature and cryogenic heat flux simultaneously over each engine components. Hot/cryogenic thermal insulation is essential to the coexistence between engine components, which is each insulated and designed with simultaneous heat transfer and thermal radiation, while the chill-down of the liquid oxygen and kerosene fuel combustion. By applying high temperature thermal insulation, it maintains the steady state performance of the engine and protects the other components above heat shield from heat plume at engine clustering. The designated cryogenic insulation keeps liquid oxygen from the tank low temperature (-183℃) during pre-chilldown circulation and protects from icing problem.

To apply the suitable thermal insulation design, cryogenic insulation, assembling, the proper material for the performance will be considered through the heat simulation over the entire engine, cryogenic test, and each engine test. In material design, the engine thermal insulation requires weight reduction with both cryogenic and high temperature insulation. Various methods of weigh reduction consists of heat analyzed insulation application regions of thermal insulation, choosing insulation materials by considering cryogenic isolation, and installing types of cryogenic and heat insulation. Insulation thickness and application provides important factor between the space of engine components and the attachments from vibration of engine start. Finally, thermal insulation for heat protection and flame prevention performs heat barrier of Main Fuel Valve (MFV) attached engine combustor to protect other engine components and heat resistance from heat plume below heat shield while engine clustering.

1. Introduction

In KSLV-II development (Korea Space Launch Vehicle, Korea's first rocket made by Korea's own efforts), the liquid-propellant rocket engines produces hot and cryogenic temperatures from different individual components at the same time while operating from the engine start to the end. Hot/cryogenic thermal insulation is essential to the coexistence between engine components, each insulated with simultaneous heat transfer and thermal radiation, while the chill-down of the liquid oxygen and kerosene fuel combustion. By applying Cryogenic/thermal insulation, it protects and maintains the steady state performance and the efficiency of the engine. To apply the suitable cryogenic/thermal insulation, it is required that the engine heat analysis and evaluation confirmed, the insulation design to the surface of each components and assembling determined after the proper material for the performance is considered through the engine test.

Two different Cryogenic/High temperature thermal insulations are applied simultaneously for the engine performance and the protection for each components. Cryogenic insulation for liquid oxygen passage lines and valves and the oxygen pump in Turbopump in LRE (Liquid-propellant Rocket Engine) maintains thermal resistance function and heat protection from high temperature components. High temperature thermal insulation protects the other engine components from the component that produces high temperature (Turbopump manifold). Thermal insulation for the heat protection and the flame prevention preform each the heat barrier of Turbopump to protect other engine components and the heat resistance from extreme heat flume on MFV (Main Fuel Valve to the combustor) components below heat shield while engine clustering.

Cryogenic insulation for liquid oxygen passage lines in LRE requires not only thermal maintenance function but also heat protection

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from high temperature components and flame prevention from oxygen leakage. Various methods for heat protection and flame prevention consists of selecting cryogenic insulation materials, and installing types for cryogenic insulation. Cryogenic insulation material can be chosen with considering light weight and providing heat transfer.

In development of liquid-propellant rocket engine, the engine gimbaling requires various types of bellows movements, and cryogenic insulation is applied with movement-based design and material on each axial and circular bellows. Cryogenic insulation of the bellows for high pressure passage line and recirculation line are necessary to maintain cryogenic temperature for engine efficiency and protect from heat transfer and radiation of high temperature components during the engine gimbaling.

The engine cryogenic/thermal insulation requires weight reduction for both cryogenic and high temperature components. Various methods of weight reduction consists of well-selecting application regions of thermal insulation, choosing insulation materials, and installing types of cryogenic and heat insulation. The application region for thermal insulation is selected considering cryogenic isolation and heat shield. Insulation material can be chosen with light weight with providing heat transfer with weight reduction.

To designate and optimize the cryogenic/thermal insulation to liquid-propellant rocket engine, the regions to apply the insulation in engine components are selected, and the regions are analyzed and evaluated through numerical simulation and cryogenic and heat performance experiments. The insulation materials and designs are determined by the analysis, and the application of cryogenic/thermal insulation is provided by each engine components with each installation technique considering weight reduction.

2. Regions of Cryogenic/Thermal Temperature in LRE

In a liquid-propellant rocket engine, each component (combustor, turbopump, valves, pipes and lines) produces simoutaniously different temperature distribution. Especially, the components in cryogenic and high temperature are considered as insulation support to protection and prevention for the engine performance and efficiency.

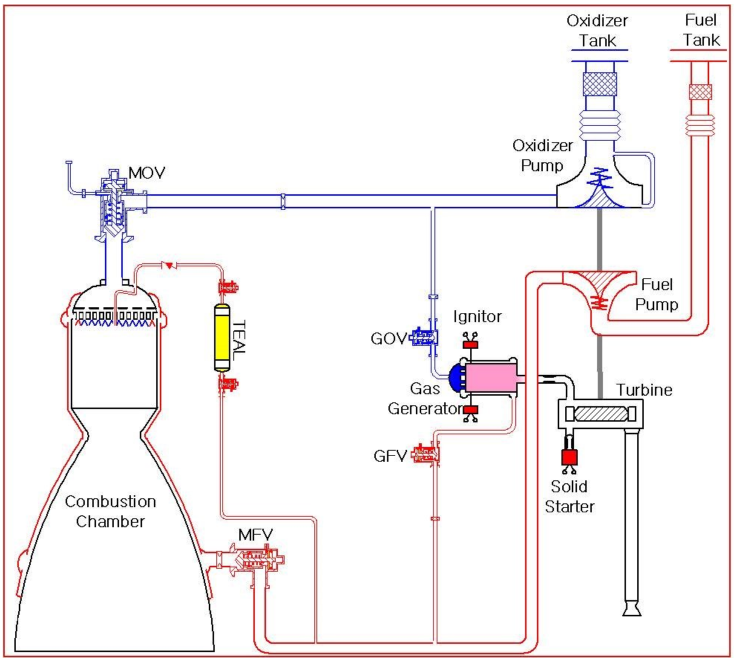
For cryogenic insulation, the engine liquid oxygen passage line is considered and selected. Figure 1 represents typical Scheme of GG Cycle Engine that shows the liquid oxygen and fuel passage. The liquid oxygen from the rocket liquid oxygen tank come to the engine by the pump. First it enters the oxygen pump in Turbopump and high pressured liquid oxygen goes HPOP (High Pressured Oxygen Pipe) with two bellows. The passage is separated to GG (Gas Generator) oxygen line through the control valve and MOV (Main Oxygen Valve) to the combustor. The considered cryogenic insulation regions are shown in figure 2(a)

- The oxygen pump in Turbopump
- HPOP (High Pressured Oxygen Pipeline)
- GG (Gas Generator) oxygen line
- MOV (Main Oxygen Valve)

The liquid oxygen passage line is necessary to keep thermal maintenance function and also heat protection from high temperature components and its heat radiation. For the cryogenic insulation, the components have various and complicated shape with limited surface to install the insulation. Therefore, the cryogenic insulation is required to consider the insulation materials with heat prevention and application methods.

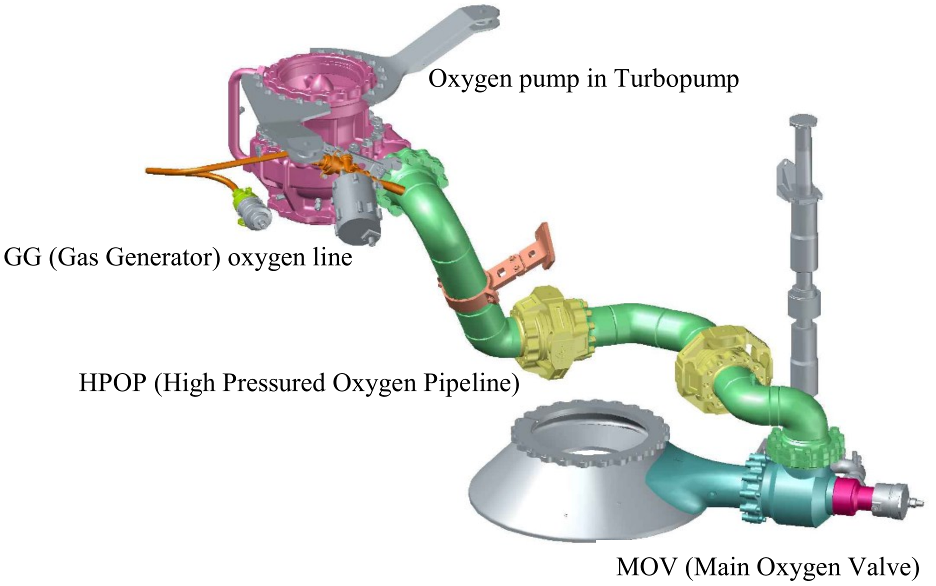
High temperature thermal insulation is strongly demanded in two different reasons. One is needed for heat prevention in order to protect the other components. High temperature from GG (gas generator) start passes Turbopump manifold that easily goes up to 900 ℃. Its high temperature affects the other components with heat radiation and cryogenic components which disturbs to maintain cryogenic temperature. The other is to protect the component below heat shield from the extreme high temperature combustion flame while the engine clustering. The considered high temperature thermal insulation regions are shown in figure 2(b)

- Turbopump manifold from GG
- MFV below heat shield

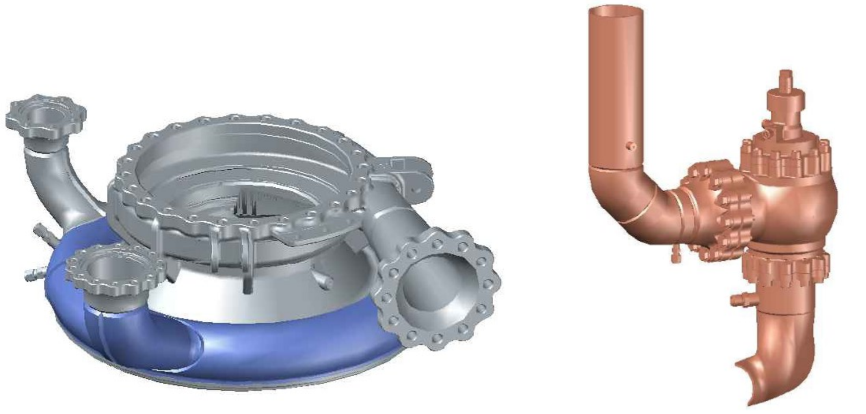


- Bi-propellant Gas-Generator(GG) Cycle
- Turbopump(TP) Fed Type
- Pyrotechnic Starter(PS) for Turbine
- Single Axis TP
- Triethylaluminum(TEAL) for Combustion Chamber(CC) Ignition
- Main Oxidizer Valve(MOV)
- Main Fuel Valve(MFV)
- GG Oxidizer Valve(GOV)
- GG Fuel Valve(GFV)
- Liquid oxygen and Kerosene

Figure 1: Typical Scheme of GG Cycle LRE



(a)



Turbopump manifold from GG

MFV below heat shield

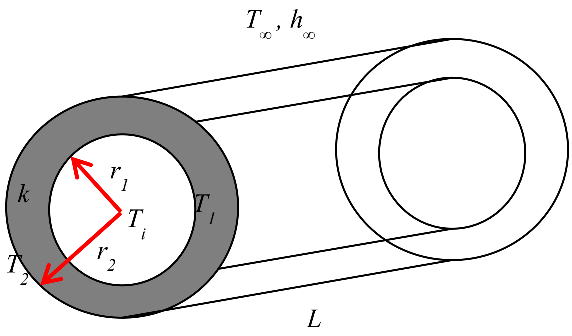
(b)

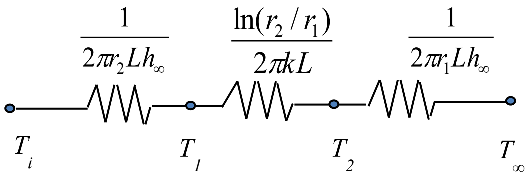
Figure 2: Regions of Cryogenic(a) and Thermal(b) Insulation in LRE

3. Analysis and Evaluation through Numerical Simulation of LRE

3.1 Heat Analysis

In a liquid-propellant rocket engine, cryogenic/thermal insulation is designed to protect and prevent the engine components. Cryogenic insulation is mainly required to protect from the heat and maintain the temperature, -183℃(90K) to avoid the vaporization. The simple numerical simulation is performed using governing equation as following





$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_v=\rho c_p\frac{\partial T}{\partial t}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)=0 \tag{1}$$

$$q_r=-kA\frac{dT}{dr}=-k(2\pi rL)\frac{dT}{dr}=\frac{2\pi Lk(T_1-T_2)}{\ln(r_2/r_1)} \tag{2}$$

$$T_i \approx T_1$$

$$R_{tot}=\frac{\ln(r_2/r_1)}{2\pi Lk}+\frac{1}{2\pi r_2 Lh_\infty}$$

$$q_r=\frac{(T_\infty-T_i)}{R_{tot}}=\frac{(T_\infty-T_1)}{R_{tot}}=\frac{(T_\infty-T_1)}{\left[\frac{\ln(r_2/r_1)}{2\pi Lk}+\frac{1}{2\pi Lr_2h_\infty}\right]} \tag{3}$$

$$\frac{2\pi Lk(T_1-T_2)}{\ln(r_2/r_1)}=(T_\infty-T_1)/\left[\frac{\ln(r_2/r_1)}{2\pi Lk}+\frac{1}{2\pi Lr_2h_\infty}\right] \tag{4}$$

1-D governing equation on heat transfer is simulated for insulation analysis. In equation (1), no heat generation and steady state are cancelled out terms. From (1), equation (2) is integrated and q_r is generated from combination of (2) and (4) with the assumption $T_i \approx T_1$. This simple 1-D analysis is applied to each component and decides the material and thickness of cryogenic/thermal insulations.

3.2 Material Selection

As the numerical analysis determines insulation thickness and temperature distribution, the several candidate cryogenic insulations are tested through liquid nitrogen experiment comparing with the numerical analysis (figure 3). The liquid nitrogen is substituted due to the reason relatively safe and easy-handling comparing to the liquid oxygen. The most ideal cryogenic insulation material is Aerogel (cryogel z) to protect from heat flux and maintain liquid state temperature for oxygen by the numerical analysis. However, Aerogel (cryogel z) contains nano-sized particles which is not suitable for LRE and has no flexibility to apply on the surface of the engine components.

In the international rocket engine industry, many other cryogenic insulations are used and applied to protect and maintain the cryogenic temperature. For heat radiation form the exhaust plume, nickel-foil/refrasil blanket was insulated and mostly, the polyurethane foam was applied to liquid oxygen pipeline after all engine assembly was completed in table 1. The polyurethane foam has disadvantages that are no reusable, dust occurrence, hard managing insulation thickness.

Table 1: Cryogenic Insulation types in LRE

LRE	Cryogenic Insulations
VULCAIN	LOX/LH2 pipeline: polyurethane foam + AL Tape
LE-7A	LOX/LH2 pipeline, TP: polyurethane foam + AL Tape
HM-7B	LOX/LH2 pipeline: polyurethane foam + AL Tape
J2-X	LOX/LH2 pipeline: polyurethane foam + AL Tape
MERLIN	LOX pipeline: polyurethane foam + AL Tape
KSR-III	polyurethane

Figure 3: Cryogenic Insulation experiment setup using Liquid Nitrogen

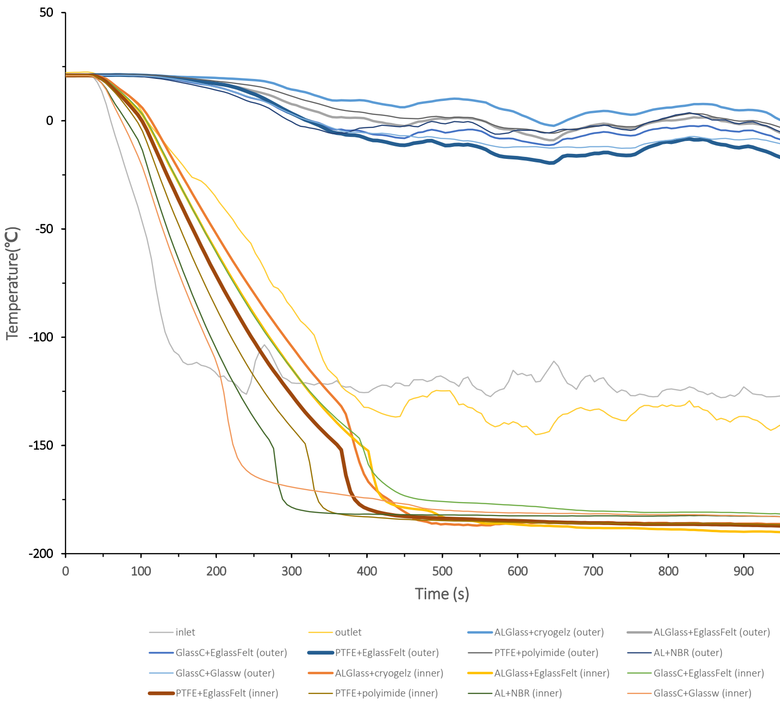


Figure 4: Cryogenic Insulation Test using liquid nitrogen

The several cryogenic insulations that have similar properties with Aerogel (cryogel z) are tested in liquid nitrogen test (fiqure 4). The inner and outer temperatures of each cryogenic insulation with time are recorded and compared. The materials in the liquid nitrogen test are glass felt, NBR, glass wool, and cryogel z with cover material PTFE, ALcoating glass, glass coating. The cryogenic insulation, glass felt type with ALcoating glass cover is selected best close to Aerogel (cryogel z). ALcoating glass cover helps remaining the cryogenic temperature and solving icing problem, and also protects the radiation from the heat up to 400 ℃ (glass material)

LRE (Liquid-propellant Rocket Engine) are commonly clustered into more than 3-4 engines in order to create combined thrust in 1st stage (figure 5). When LRE clustering, the engine exhaust plume by several engine exhaust flame is created and large amount of heat and radiation affects the engine itself specially in the middle of engine clustering. Heat shield is to exist for this problem but each MFV of KSLV-II LRE is exposed to the exhaust plume below the heat shield although the fuel in MFV keep running and flowing into the combustor.

In high temperature thermal insulation, the insulation thickness and temperature distribution from the numerical analysis considering Turbopump manifold temperature by actual engine test determines the material and installation method. Figure 6 shows the comparison between silica type thermal insulation and required insulation specification. Silica type and alumina silica type (up to 1600 ℃) are selected each for turbopump manifold and MFV protection from exhaust plume while clustering.

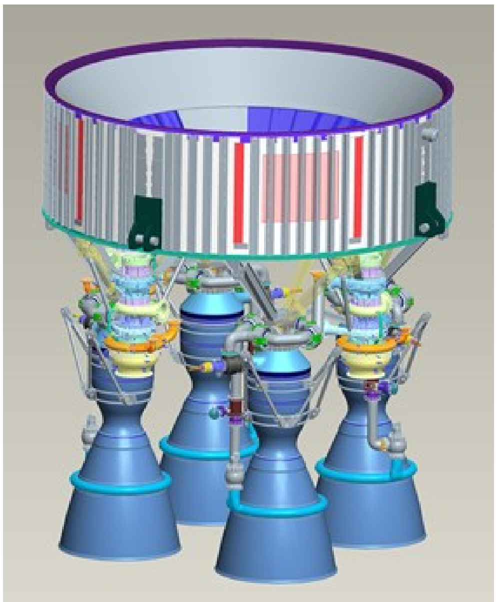


Figure 5: LRE clustering

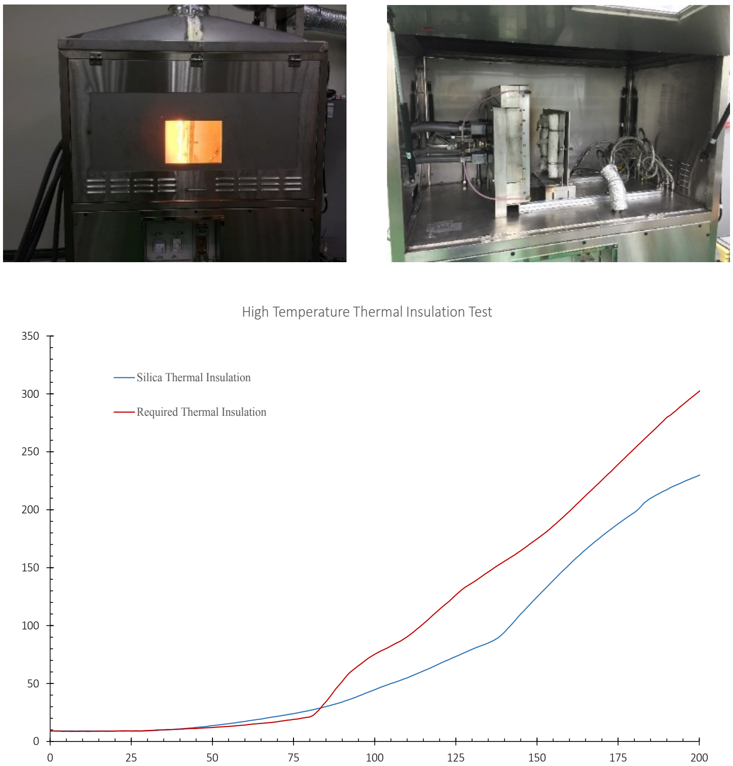


Figure 6: Comparison between Silica-type Thermal Insulation and Required Insulation Specification

4. Application and Installation

After the regions of insulation by temperature disutribution, thickness, and materials are confirmed, cryogenic insulations and thermal insulations are separately designed and fabricated. For cryogenic insulations, the cryogenic componets in LRE have difficult and complicated shape that each cryogenic insulation needs a mold (plastic and 3D printted) to design. Each cryogenic insulation is fabricatied in glass felt material with AL coating glass cloth inner and outer (PTFE string). HPOP (High Pressured Oxygen Pipeline) have two bellows to make movement in LRE so that the the insulation is required to have movement-based design and material on each axial and circular bellows. GG (Gas Generator) oxygen line is too thin and complicate to design in regular. The cryogenic insulations of both HPOP and GG oxygen line are designed and fablicated in PTFE inner and outer cover that has strong toughness heat resistant and water reppellant.

Figure 7 shows the process of insulation fablication for the designed configuration using 3D printing. In cryogenic insulation, the glass felt insulation itself protects and maintains cryogenic liquid-state oxygen temperature, and the inner and outer cover (AL coating glass cloth) helps preventing heat radiation and heat resistance up to 400. All strings for cryogenic insulations are used in PTFE and the velcro with high temperature resistance is applied to the insulation to fasten and connect each insulation pieces. PTFE insulation cover is provided to the fragile and complicated engine components as well as the bellows with movement (figure 8).

The installation of high temperature thermal insulation is shown in figure 9. Silica based wool and silica inner/outer cover protects heat to the other engine components and from the flame by exhaust plume while the engine clustering. To fasten and install onto the surface of the components, the band type with stainless steel D-ring connection is used for high temperature protection.

Figure 7: Process of Insulation Fabrication

5. Discussion

Currently, KSLV-II is in the middle of developmental stage of Liquid-propellant Rocket Engine (LRE), so that the crucial and decisive numbers and configurations are confidential and classified yet. When a LRE engine runs, it produces cryogenic and extremely high temperature heat flux over each engine components at the same time. Hot/cryogenic thermal insulation is essential to the coexistence among engine components and the protection the engine components from the exhaust flame while the engine clustering. In this study, the temperature distribution on components are analysed and the materials and thickness of hot/cryogenic insulation are selected. The optimization of insulations is required to make provision to hot/cryogenic temperature and the application of insulations is important to each component by materials, configurations, fasten and connection to increase the surface of insulated area.

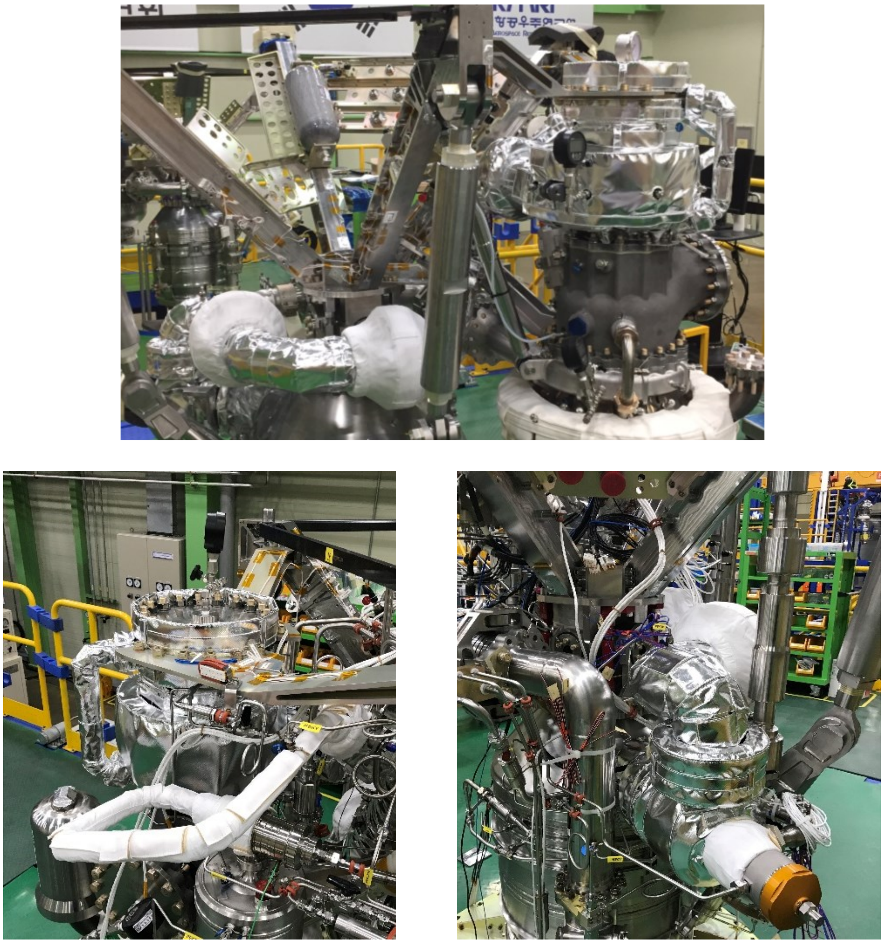


Figure 8: Cryogenic Insulations

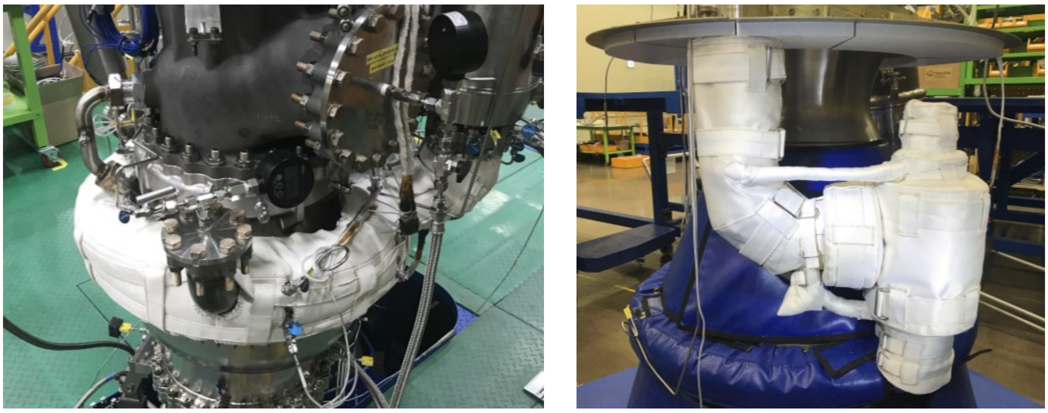


Figure 8: High Temperature Thermal Insulations