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Liquid Rocket Engine Development of the Upper-Stage for the Korea Space Launch Vehicle-II

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Abstract
The Korea space launch vehicle-II (KSLV-II), also known as NURI, is a three-stage launch vehicle developed by the Korea Aerospace Research Institute (KARI). The KSLV-II can lunch a 1.5- ton-class practical satellite into the Sun Synchronous Orbit (SSO) 600–800 km above the Earth. KSLV-II consists of three stages. All three stages of the KSLV-II are powered by fuel-rich gas generator cycle engines that use liquid oxygen (LOX) and kerosene (Jet-A1) as the propellant combination. Additionally, the KSLV-II upper-stage engine was designed with a simple structure to improve the system's reliability. Therefore, the engines do not control thrust and mixing ratios, implying that the developed engines operate in the form of a fixed thrust and mixing ratio that maintains a fixed control valve opening during actual flight after finally correcting the performance dispersion of the engines through ground tests.
The KSLV-II began development in March 2010. The goal of the KSLV-II program is to apply and use domestic technologies in all processes, such as design, production, and testing. The KSLV-II program comprises three phases. On November 28, 2018, the KSLV-II successfully launched a test launch vehicle (TLV). The KSLV-II first launched on October 21, 2021, but failed to place a dummy satellite into a targeted orbit. Thus far, the upper-stage engines have completed 96 hot-firing tests with a cumulative combustion time of more than 18,143 s. The second launch of the KSLV-II with several satellites is scheduled for June 15, 2022.
This study describes the development history and process of the upper-stage engine system/components and test area, as well as the hot-firing test results of the upper-stage engine that can generate a 7-tonf-class vacuum thrust.

1. Introduction

The Korea launch vehicle-II (KSLV-II), also known as NURI, is a three-stage launch vehicle that can directly move a 1.5-ton-class practical satellite into a solar-synchronous orbit (SSO) 600–800 km above the Earth. The goal of the KSLV-II program is to apply and use domestic technologies in all processes, such as design, production, and testing. The KSLV-II program consists of three phases. In the first phase (Mach 2010–July 2015), the main goals of the KSLV-II program were to create propulsion systems test facilities and perform a combustion test of a 7-tonf-class liquid rocket engine. The main goals of the KSLV-II program in the second phase (August 2015–March 2019) were to develop a 75-tonf-class liquid engine and launch a test launch vehicle (TLV) in 2018. The TLV is a single-stage launch vehicle composed of a 75-tonf liquid engine designed to verify the flight performance of a 75-tonf-class liquid engine. Finally, the goals of the KSLV-II program in the third phase (April 2019–October 2022) were to conduct the first stage comprehensive combustion test applying clustering technology tying four 75-tonf-class engines into one complete KSLV-II development and perform test flights twice [1].
The first flight test of the KSLV-II was launched on October 21, 2021, but failed to place a dummy satellite into the targeted orbit. The KSLV-II failed at the last minute because of the pressure drop in the upper-stage oxidizer tank. The second launch of the KSLV-II with several satellites is scheduled for June 15, 2022. Unlike the first flight in October 2021, which carried a dummy satellite, the second KSLV-II flight goes into space carrying several actual satellites. There are six satellites, including one performance verification satellite manufactured by AP satellite, four micro-satellites, and one dummy satellite for maintaining balance.

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1.1 KSLV-II

The KSLV-II is a three stages launch vehicle. The KSLV-II does not use a transition orbit and instead places a payload as a satellite into the orbit, so the reignition function is not required by the mission. The configurations and specifications of the Korea Space Launch Vehicle-I (KSLV-I, also known as NARO), the TLV, and the KSLV-II developed by the Korea Aerospace Research Institute KARI) are shown in Figure 1. The KARI, a leading institute for technology related to space launch vehicles and satellites in the Republic of Korea, has been continuously researching and developing technology related to space launch vehicles since 1989. The KSLV-I launched in 2013 and was Korea's first space launch vehicle. KSLV-I, jointly developed through international cooperation with Russia, consists of two stages. The first stage was developed by Russia's Khrunichev Space Center, and the second stage was developed by KARI. The TLV, launched in 2018, is a single-stage launch vehicle composed of a 75-tonf-class liquid engine designed to verify flight performance. KSLV-II comprises three stages. The KSLV-II engines use 75-tonf-class liquid engines and a 7-tonf-class liquid engine with an open-type fuel-rich gas generator cycle. The first stage comprises four 75-tonf-class engines clustered, the second stage uses a 75-tonf-class engine, and the third-stage uses a 7-tonf-class engine.

Figure 1: Configurations and specifications of the Korea Space Launch Vehicles developed by the KARI

1.2 Upper-stage engine

The upper-stage engine of the KSLV-II that has a 7-tonf-class vacuum thrust, is an open typed fuel-rich gas generator cycle with a turbopump that uses kerosene/Liquid Oxygen (LOX) as propellants. The configuration and specification of the upper-stage engine are shown in Figure 2 and Table 1.

A pyro-starter provides the initial start-up of the upper-stage engine, and after driving, more than 90% of thrust is generated in 2.2 s. The upper-stage engine uses fuel-rich combustion gas as the driving power of the turbopump. The spent driving gas is released into the atmosphere. The upper-stage engine controls the propellant flow by installing

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high-pressure piping, orifices, and valves between the thrust chamber, gas generator, and turbopump. Additionally, the upper-stage engine does not perform active thrust and mixing ratio control during the flight process, implying that the developed engines operate in the form of a fixed thrust and mixing ratio that maintains a fixed control valve opening during actual flight after the performance dispersion of the engines is finally corrected through ground tests [2].

Figure 2: Upper-stage engine configuration

Table 1: Specification of the upper-stage engine [2, 3]

Vacuum thrust	kN	69.0
Vacuum specific impulse	s	326
Mixture (O/F) ratio	-	2.24
Chamber pressure	MPa	7.0
LOX mass flow rate	kg/s	14.81
Fuel (Jet-A1) mass flow rate	kg/s	6.61
Nozzle expansion	-	94.5
Burn time	s	530
LOX temperature	K	93
Fuel (Jet-A1) temperature	K	278
Gas generator temperature	K	900
Height	m	1.88
Diameter	m	0.88
Dry weight	kg	187

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2. Main engine components

This section presents a thrust chamber, gas generator, and turbopump configurations designed for the upper-stage engine components and specifications. Additionally, the component test areas performed during the component development are shown in Table 5.

2.1 Thrust chamber

The thrust chamber comprises a mixing head with 91 coaxial swirl injectors, a regenerative combustion chamber, and a supersonic nozzle. The injector head face of the upper-stage engine is shown in Figure 4. The mixing head comprises a fuel manifold, an oxidizer manifold, injectors, and igniters. The combustion chamber and nozzle part of the thrust chamber enclose and block the open surface of the inner liner, as well as the inner liner where regenerative cooling manufactured the cooling flow path in a square cross-section, which has an outer jacket double-wall structure that structurally supports the inner liner. The configuration and specifications of the thrust chamber are shown in Figure 3 and Table 2 [4].

Figure 3: Thrust chamber assembly

Table 2: Thrust chamber design requirements and specification [5]

Vacuum thrust	kN	68.27
Vacuum specific impulse	s	339
Mixture (O/F) ratio	-	2.45
Chamber pressure	MPa	7.0
Propellant mass flow rate	kg/s	20.56
Characteristic velocity (C*)	s	1736
Nozzle expansion ratio	-	94.5
Throat diameter	mm	80.68
Nozzle exit diameter	mm	810
Height	mm	1563
Dry Weight	kg	66.20

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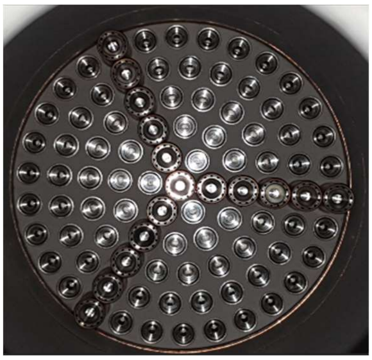

Figure 4: Injector head of the thrust chamber

2.2 Gas generator

A gas generator, the main component of the gas generator cycle engine, is a combustion device that generates a working fluid that drives a turbopump. The gas generator in the upper-stage engine is shown in Figure 5. The gas generator is divided into a head and a combustion chamber. The oxidizer flows into the manifold through the inlet located at the center of the head. Furthermore, it is injected into the combustion chamber through an injector. In the case of fuel, it was designed to flow into the fuel ring located in the combustion chamber, then pass through a cooling channel to cool the combustion chamber, then into the fuel manifold, and finally injected into the combustion chamber through injectors. Seven injectors were arranged concentrically in the gas generator, one in the center and six in one row. In the case of the gas generator in the upper-stage engine, combustion occurs under fuel-rich conditions where the flow rate of the fuel is greater than that of the oxidizer [6]. The gas generator's specifications for the upper-stage engine are presented in Table 3 [7].

Figure 5: Gas generator

Table 3: Gas generator Specification [7]

Chamber pressure	MPa	6.01
Mass flow rate	kg/s	0.822
Mixture (O/F) ratio	-	0.313
Dry weight	kg	1.7

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2.3 Turbopump

The turbopump development for the upper-stage engine was based on the experience gained from designing, manufacturing, and testing the previously developed 30- and 75-ton turbopumps for the liquid rocket engine of the KARI [8]. The turbopump of the upper-stage engine is a single-axis connection type that supplies high-pressure propellant to the combustion chamber and is composed of a single-stage centrifugal pump, a single-stage centrifugal pump, and a single-stage supersonic impulse turbine. The turbopump's turbine uses fuel-rich gas generated by the gas generator. The turbopump assembly for the upper-stage engine is shown in Figure 6. The turbopump specification of the upper-stage engine is presented in Table 4.

Figure 6: Turbopump assembly

Table 4: Turbopump specification [9]

	Unit	Oxidizer pump	Fuel pump	Turbine
Nominal inlet temperature	K	93	278	900
Nominal inlet pressure	MPa	0.39	0.23	6.01
Mass flow rate	kg/s	14.81	6.61	0.822
Density	kg/m^3	1,128	804.3	-
Nominal outlet pressure	MPa	8.53	11.40	0.22
Rotational speed	rpm		27,000	

2.4 Component test area

The upper-stage engine's components must be tested in broader areas than the system test areas because the operation of the upper-stage engine's components must be guaranteed even in unexpected operation errors or abnormal conditions during engine testing. The component test areas performed during the component development are presented in Table 5.

Table 5: Components test areas of the upper-stage engine

Upper-stage engine				
Thrust chamber		Combustion pressure	MPa	6.8–8.1
		Mixture ratio	-	2.17–2.76
Gas generator		Combustion pressure	MPa	5.0–7.2
		Mixture ratio	-	0.29–0.35
Turbopump	Fuel pump	Mass flow rate	kg/s	5.5–8.2
		Discharge pressure	MPa	9.8–14.5
	Oxidizer pump	Mass flow rate	kg/s	12.5–17.6
		Discharge pressure	MPa	7.7–10.7
	Turbine	Rotational speed	rpm	24800–29300

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3. Upper-stage engine test facility

To efficiently use engine combustion pressure in high-altitude rocket engines, nozzles with a significant expansion ratio are required. When a high expansion ratio nozzle is tested underground backpressure conditions, the flow is separated from the inside of the expansion nozzle to induce vibration. The heat load is concentrated in the local area of the nozzle, which may destroy the nozzle. Therefore, during ground tests, a sufficiently low nozzle backpressure environment should be simulated for the performance evaluation of the upper-stage engine.

Figure 7: Upper-stage engine test facility [2, 10]

The engine high-altitude simulation combustion test facility is used to implement various high-altitude environmental conditions encountered during ground flight tests. It is similar to the high-altitude environment, where the upper-stage engine is operated as much as possible while considering its realistic cost, period, and technical limitations.
An upper-stage engine operating at high altitudes has a large expansion ratio optimized for high-altitude and low-pressure environments. Verifying the operability and reliability of a space launch vehicle in a flight and on a ground environment is a critical part of the upper-stage engine development when developing a liquid rocket engine that operates at high altitudes. The test facility for a 7-tonf-class liquid rocket engine of the KSLV-II upper-stage built considering overseas cases and the domestic development capabilities are shown in Figure 7. The test facility is composed of ground and high-altitude cells. The ground cell tests the combustion of an engine with a short nozzle. The high-altitude cell performs a combustion test on an engine with a full nozzle [2, 10].

4. Upper-stage engine development

In the case of upper-stage engine development, 10 to 11 models, including development and qualification models, are typically put into development [11]. The KSLV-II upper-stage engine development manufactured and tested twelve upper-stage engines considering overseas cases and domestic liquid rocket engine development experience. The schematic of the upper-stage engine is shown in Figure 8. Twelve engines were manufactured, but after assembling and testing, the engines were reassembled several times to address issues discovered during the testing process. Seven engines were put into the development test among the manufactured engines, and two were used for the qualification test. All engines (two engines for the flight and one for the flight reserve models) completed the acceptance tests [2]. Among these engines, one flight model engine was assembled into the KSLV-II, and the first flight test was performed on October 21, 2021, but failed to place the dummy satellite into a targeted orbit. It flew to a target altitude of 700 km but failed to place the dummy satellite into an orbit as its third-stage engine burned out 46 s earlier than expected. Additionally, because of increased buoyancy during the flight, the helium tank fell off its anchoring device inside the oxidizer tank. The detached tank then caused cracks in the oxidizer tank and damage to the tank pipes as it flew around unfastened, causing leakage of helium and oxidizer. The lack of an oxidizer flowing into the third-stage engine eventually caused the engine to shut down prematurely.

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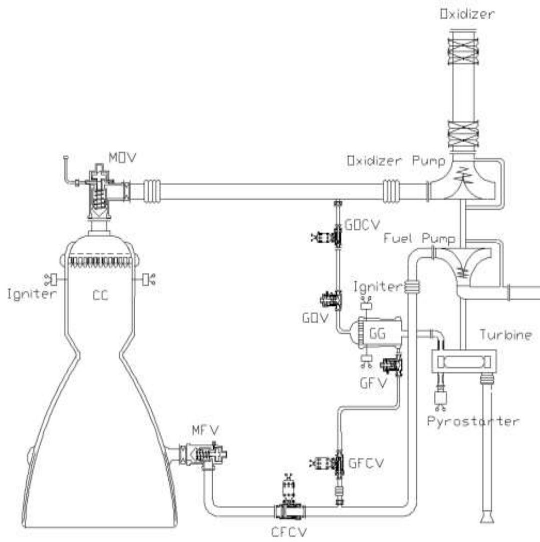

Figure 8: Schematic of the upper-stage engine [2]

4. 1 Powerpack test

From April to July 2015, a power pack test was conducted at the NARO space center as an intermediate stage of upper-stage engine development. Powerpack tests were performed 7 times. Two preliminary tests and a pyro-starter test were performed, and four tests were conducted that ignited the pyro-starter and gas generator. The powerpack schematic and powerpack test stand are shown in Figures 9 and 10, respectively. The power pack tests were performed on the entire supply system, including the gas generator, turbopump, control valves, shut-off valves, and orifices. The thrust chamber was excluded from the engine's main components. The thrust chamber was simulated by installing an orifice on the outlet side of the turbopump. The primary purposes of these tests were to reduce the risk of the initial engine development test and to obtain preliminary data for the engine test. The powerpack test results were used to determine the start-up and ignition sequences of the upper-stage engine system [12, 13].

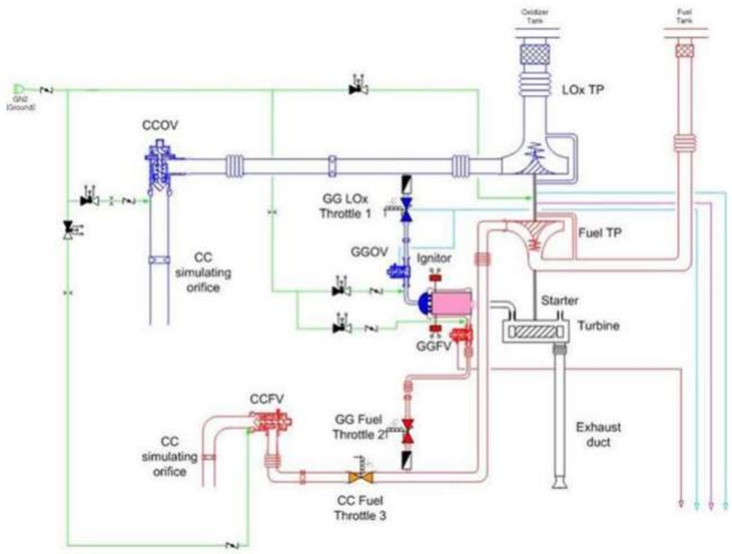

Figure 9: Powerpack schematic [12]

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Figure 10: Powerpack test stand [12]

4. 2 Engine tests

The general testing procedure for liquid rocket engine development is a Test-Fail-Fix-Test cycle. The procedure also included an upper-stage engine. The test type and performance test items for the upper-stage engine are presented in Table 6.

Table 6: Upper-stage test classification

	Engine performance test items
Development Test (DT)	Chill-down and start-up procedure Performance confirmation of operating mode SRT (Stability Rating Test) evaluation Operating area's confirmation of the inlet condition of the engine Gimballing and roll control test, heat-exchanger test
Qualification Test (QT)	Long duration operation test
Acceptance Test (AT)	confirmation and correction of the main performance

4. 3 Development Test and Qualification Test (DT/QT)

During the ground development tests, the upper-stage engines underwent many design changes and modifications. The hot-firing test scenes of the upper-stage engine with the short nozzle are shown in Figure 11. The history of significant design changes in the KSLV-II upper-stage engine is as follows [14];

- Oxidizer re-circulation line design change
- Spherical flange application Main Oxidizer Valve (MOV), Main Fuel Valve, Gas Generator Fuel Control Valve, Combustion chamber Fuel Control Valve, and high-pressure line
- Thrust chamber igniter change
- Pyro-starter mounting improvement
- Pyro-igniter connector change
- Vacuum valve change
- Turbine exhaust duct fixture design change
- Change in the number of turbine nozzle necks

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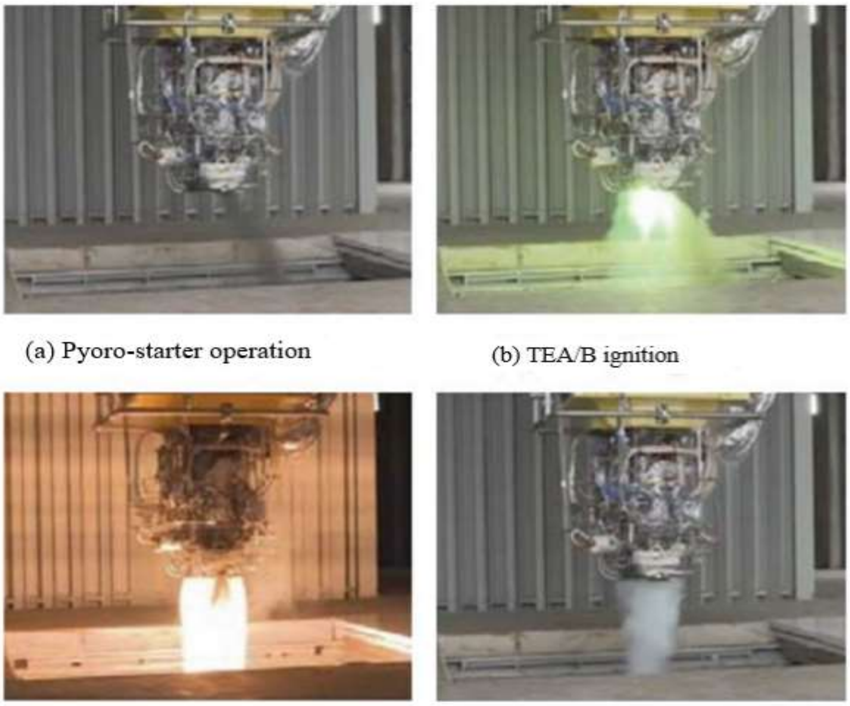
- Addition of a soot removal port
- Pressure regulator change



(a) Pyoro-starter operation

(b) TEA/B ignition

(c) Nominal combustion

(d) Furge operation after burning

Figure 11: Hot-firing test scenes of the upper-stage engine with the short nozzle [2, 10]

Figure 12 shows the upper-stage engine's hot-firing and ignition number results performed in the period of development test.

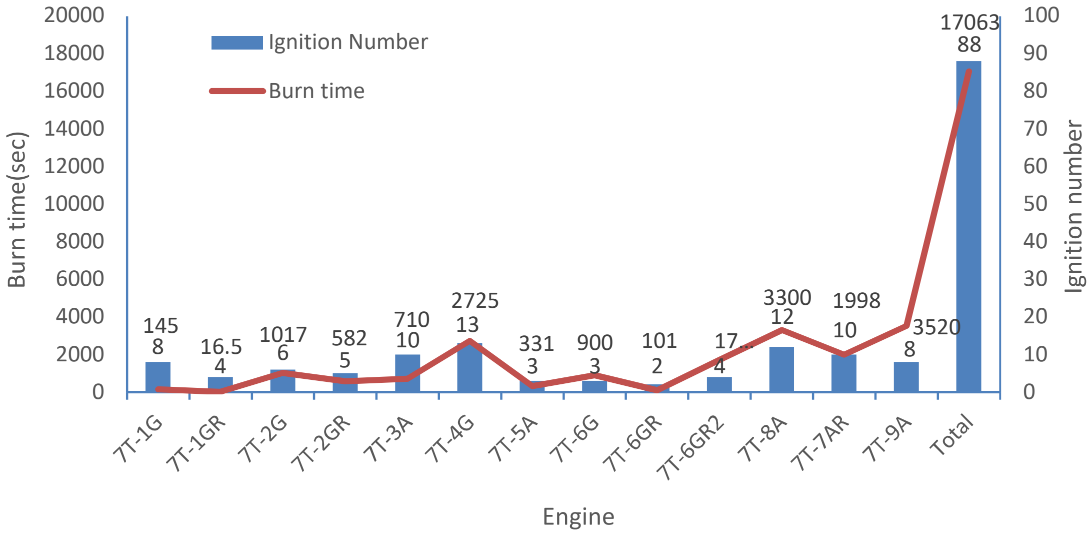


Figure 12: Hot-firing development test of the upper-stage engine

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4. 4 Acceptance Test (AT)

The acceptance test of the upper-sage engine is performed through the hot-firing test of the engine twice before delivery to assemble the engine into the launch vehicle. The acceptance test's combustion time is divided into two tests, the first test, 70 s, and the second test, 200 s. The engine start-up test in the acceptance test is performed without changing the opening degree of the control valve using the start-up sequence secured in the qualification test. The operability of the engine is confirmed during the first and second hot-firing tests of the acceptance test under the engine's nominal inlet condition. Feedback control corresponding to a combustion pressure of 71.5 bar, an engine mixing ratio of 2.24, and a gas generator mixing ratio of 0.30 are performed to correct engine performance. Furthermore, unlike in the first hot-firing test, the soot deposited on the turbine nozzle neck in the previous test is removed in the second hot-firing test by cleaning the turbine nozzle neck before the test [2].

4. 5 Engine test status

Figure 13 shows the results of the annual hot-firing test for the total accumulative combustion time (18,143 s) and the cumulative number of ignitions (96 times) of the upper-stage engines performed thus far. Additionally, the upper-stage engine repeated the combustion test for 530 s without changing the control valve to confirm the lifetime of the upper-stage engine. The required assembly time for the new upper-stage engine in the currently developed upper-stage engine was approximately 2.5 months. The accumulated combustion time of the reassembled engine is approximately 2,979 s, and the number of ignitions also reached 24. The reassembled engine completed more than 16% of the total accumulative combustion time [2]. The overall engine failure (96 numbers) of the upper-stage engine was 16 numbers (17%). The failure items and numbers of the upper-stage engines are presented in Table 7.

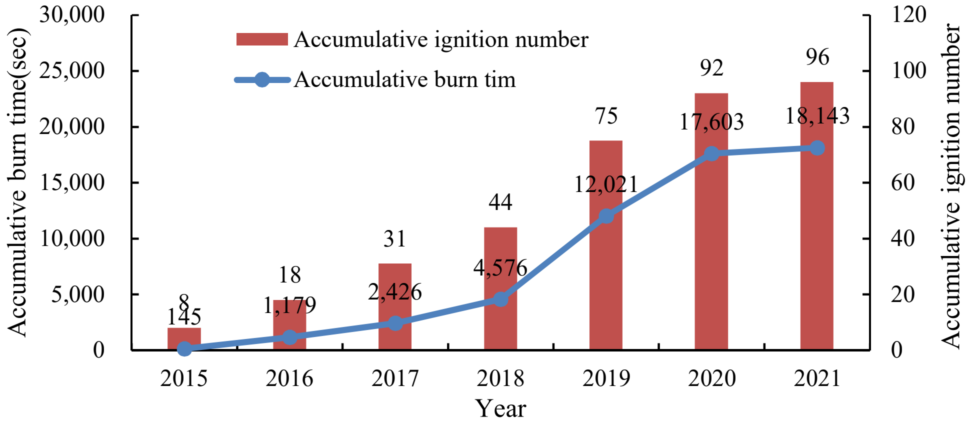

Figure 13: Combustion test status of the upper-stage engine [2]

Table 7: Upper-stage engine failures

Failure items	Failure test number
Poor connection of pressure induction pipe of the gas generator	1
Pressure regulator failure	1
thrust chamber start-up instability	1
thrust chamber start-up impact	2
pressure sensor failure of the thrust chamber	1
Turbine exhaust orifice misfit	1
Turbine exhaust fixing pin missing	2
gas generator combustion instability	6
GOV (Gas generator Oxidizer Valve) closing error	1
total engine failure	16

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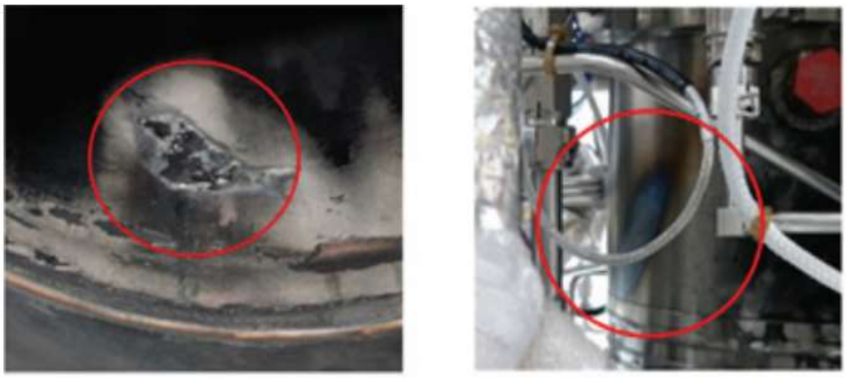

Figure 14: Damages to the inner wall(left) and outer wall(right) of the thrust chamber during the hot-firing test

Figure 14 shows the damage to the inner wall of the thrust chamber and the laceration of the outer wall due to the start-up impact that occurred during the hot-firing test of the upper-stage engine, which is damaged due to the failure of normal fuel flow through the regenerative cooling channel because the flow path is blocked because of the deformation of the primary and secondary film cooling units of the thrust chamber due to the start-up impact. The start-up sequence of the upper-stage engine consists of the opening and closing procedures of the pyro-starter, gas generator igniter, gas generator shut-off valves, and thrust chamber shut-off valves, which are used to prevent start-up impact. In terms of the changes in the starting sequence, the opening time of the MOV was delayed from 0.26 to 0.30 s after the pyro-starter ignition by 40 ms, eliminating the engine start-up impact [2].

5. Conclusion

Generally, numerous design changes and modifications (improvements) are made during the development process of liquid rocket engines, and many physical phenomena that are difficult to understand intuitively are also experienced. Therefore, various solutions have been implemented and tested to address the problems that occurred during the development of the liquid rocket engine for the KSLV-II upper-stage. The goal of the KSLV-II program is to apply and use domestic technologies in all processes, such as design, production, and testing. The TLV of the KSLV-II successfully launched on November 28, 2018. The KSLV-II first launched on October 21, 2021, but failed to place a dummy satellite into a targeted orbit. The second launch of the KSLV-II with several satellites is scheduled for June 15, 2022. Thus far, the upper-stage engines have completed 96 hot-firing tests with an accumulative burn time of more than 18,143 s. The design change and improvement case performed to deal with the engine's start-up impact that suffered difficulties during the development process are also introduced in this study.

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