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Results of Hot-fire Testing of 30kN LOX/Methane Full-expander Cycle Engine

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Abstract

Methane/Liquid oxygen (LOX) rocket engines are promising candidates for propulsion systems of various future space transportation systems such as reusable launch vehicles, orbital transfer vehicles and space exploration vehicles due to the larger density compared with liquid hydrogen, the higher specific impulse (Isp) compared with kerosene and the good storability. Japan Aerospace Exploration Agency (JAXA) started the research and development of methane/LOX propulsion system in early 2000's. Since 2013, JAXA has been studying a 30kN class high-performance methane/LOX rocket engine system, which adopts the full-expander cycle to achieve the high Isp. Technical feasibilities of components such as combustion efficiency and combustion stability of the injector, cooling performance of the combustion chamber and turbopump system performance which can achieve the target Isp of 370 s are demonstrated through the series of component tests, and component characteristics are obtained to evaluate the system level feasibility. Engine system integration tests are conducted to demonstrate engine system level performances and feasibilities of the methane/LOX full-expander cycle engine. Ignition and cut off sequences for the full-expander cycle are established. Stable operations of the engine system are achieved, and system level engine performance is evaluated. Therefore, technical feasibilities of 30kN class high-performance methane/LOX rocket engine are demonstrated through the engine system integration tests.

1. Introduction

Methane/Liquid oxygen (LOX) rocket engines are promising candidates for propulsion systems of various future space transportation systems such as reusable launch vehicles, orbital transfer vehicles and space exploration vehicles due to the larger density compared with liquid hydrogen, the higher specific impulse (Isp) compared with kerosene and the good storability. Various methane/LOX rocket engines have been developed mainly for reusable launch vehicles such as ULA Vulcan, SpaceX Starship, Blue origin New Glenn and RocketLab Neutron. PROMETHEUS, which is a methane/LOX rocket engine designed for low-cost, flexibility and reusability is also under research and development in Europe [1]. LUMEN (Liquid Upper Stage Demonstrator Engine) which is a modular LOX/LNG bread-board engine, is also under research and development in DLR. Various component-level experiments and analysis on methane rocket engines have been conducted.

Japan Aerospace Exploration Agency (JAXA) started the research and development of methane/LOX propulsion system in early 2000's. JAXA focused on ablative cooling engine during the early phase of methane propulsion research activities. Since 2013, JAXA has been conducting studies on regeneratively-cooled methane/LOX engines [2]. Various system studies were conducted with different target thrust and engine cycle, and a 30kN class methane/LOX rocket engine with the full-expander cycle was selected for a technical demonstrator for achieving the high-performance.

A series of component tests of the technical demonstrator such as injector tests, regeneratively cooled combustion chamber tests and a single-shaft turbopump tests were conducted from 2017 through 2019[3-5]. Technical feasibilities of components such as combustion efficiency and combustion stability of the injector, cooling performance of the combustion chamber and turbopump system performance which can achieve the target Isp of 370 s were demonstrated through the series of component tests, and component characteristics were obtained to evaluate the system level feasibility.

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System level test campaigns has been conducted from 2021 through 2023 to demonstrate system level feasibilities of the full-expander cycle engine. System level feasibilities such as ignition transient sequence and stable operations with closed cycle configuration of the full-expander methane/LOX engine were demonstrated through the test campaigns. This paper reports the overview of the system level test campaign results.

2. Engine Description

2.1 Overview of engine system

Figure 1 shows the external view of the 30 kN technical demonstrator engine. Specifications of the engine is shown in Table 1. The target thrust is set to 30 kN, which is a typical required thrust for in-space propulsion such as landers and Orbital Transfer Vehicle. Full expander cycle, which is the most simple closed cycle, is selected for the engine cycle of the technical demonstrator since one of the major purposes of the project is demonstrating technical feasibilities of achieving high Isp for methane/LOX engine. A single-shaft turbopump is selected for the simplicity and mass reduction of the engine. Electrical actuated valves are adopted to increase the thrust controllability due to the throttling requirements.

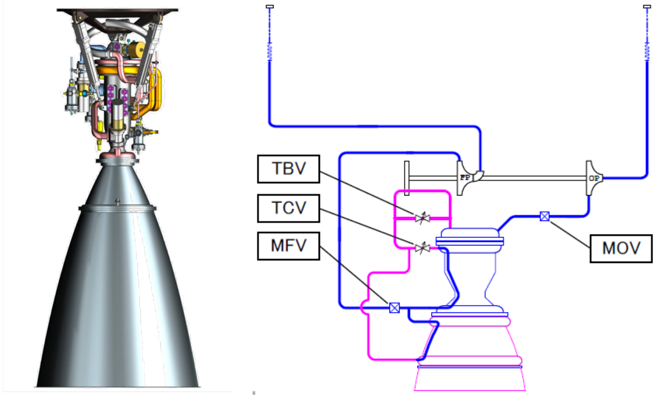

Figure 1: External view of the engine (left) and simplified schematic (right)

Table 1. Reference Engine Specification [5]

Item	Specification	Unit
Thrust (Vacuum)	30	kN
Isp	370	s
Engine Cycle	Full Expander Cycle	-
Propellant	LOX/Methane	-
Pc	4.7	MPa
MR	3.3	-
Throttling	50 to 100	% (Continuous)
Valve system	Electrical	-

2.2 Combustion device

Shear coaxial type element is selected for the propellant injector of the main combustion chamber. The element geometries are determined based on the results of single element injector test [6]. The injector assembly is designed to have 36 co-axial LOX/GCH4 elements as shown in Fig. 2. A porous plate manufactured by additive manufacturing is installed as a faceplate to enhance transpiration cooling and avoid damage to the injector. No combustion stability enhancer such as acoustic resonators, baffles etc. are equipped.

The multi-injector performance such as combustion efficiency, combustion stability and heat flux profiles are investigated with water cooled calorimetric chamber before the engine system test campaigns. The details of the results of multi-element injector tests are shown in Ref[4].

Combustion chamber and nozzle configurations are shown in Figure 3. The main combustion system for vacuum operation consists of a regeneratively cooled combustion chamber assembled with the injector followed by a

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regeneratively cooled nozzle and radiatively cooled nozzle extension to achieve higher Isp. The LCH4 which is discharged by fuel pump is supplied to the regeneratively cooled combustion chamber and nozzle as a coolant to cool the chamber and nozzle wall. The coolant itself absorb the thermal energy from the combustion gas, and supplied to a turbine to drive both pumps. The engine system can operate at sea level without the regeneratively cooled nozzle and nozzle extensions in addition to the vacuum configuration.

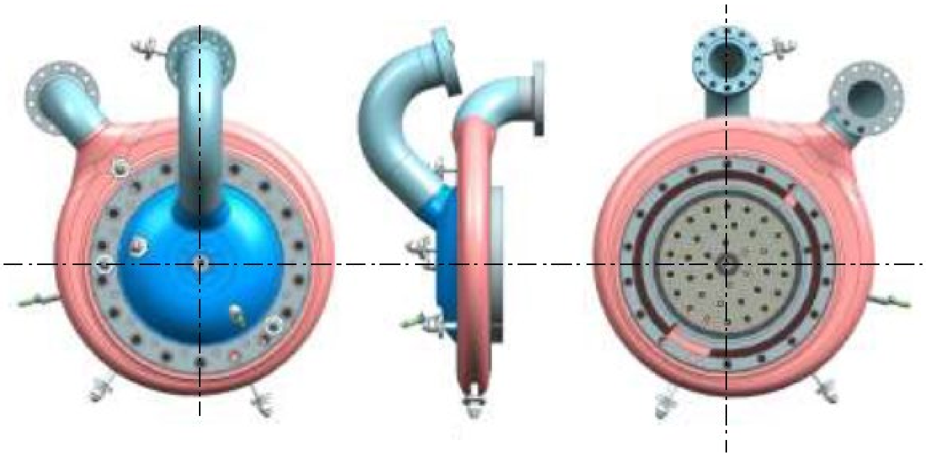

Figure 2: External view of the injector assembly

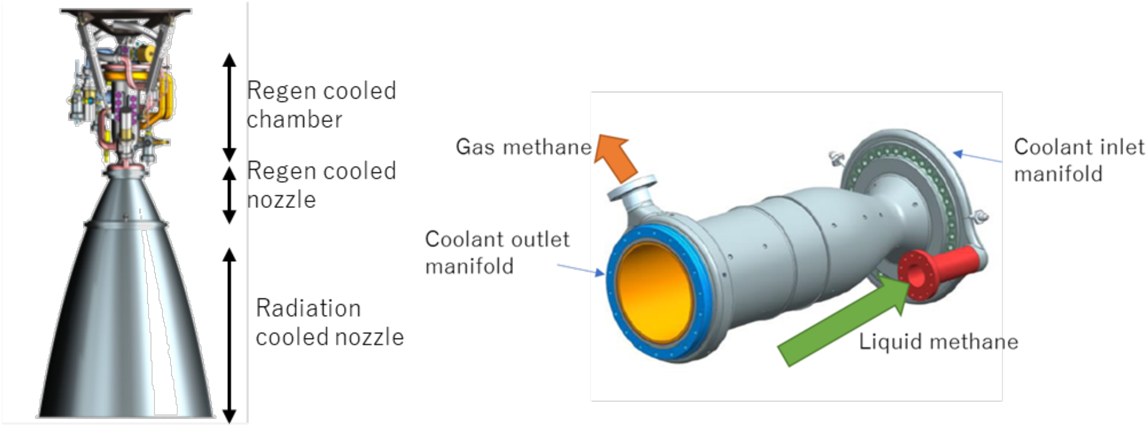

Figure 3: Combustion chamber and nozzles

2.3 Turbopump

A turbopump is designed to meet the requirement of engine system. Figure 4 shows external view of the turbopump with the following technical features.

- Single-shaft turbopump: The LOX pump and the methane pump are driven by the one turbine through single-shaft.(simplicity and mass reduction)
- Balance piston mechanism: Balance piston is adopted for axial thrust adjustment.
- Labyrinth seal: the labylinth seals are used to reduce the shaft length and manufacturing cost.
- Throttling capability: Designed to meet the approximately 50% throttling requrement.
- Rigid rotor design: The turbopump aims a rated rotational speed of 65,000 rpm and also 42,000 rpm as a throttling operation whereas a primary critical speed of about 70,000 rpm.
- Small and lightweight: The small and lightweight turbopump with a mass of approximately 16 kg and a total length of approximately 350 mm.
- Low manufacturing cost and short production time: most of the component is additively manufactured

The details of the design and component test results can be found in Ref [5] and [7].

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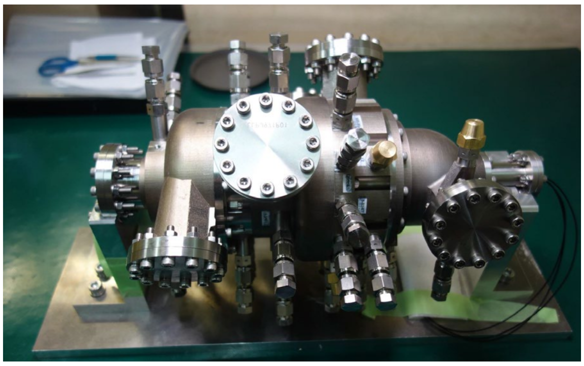


Figure 4: External view of the single-shaft turbopump

2.4 Valve

Electrically actuated valves are adopted as engine system main valves such as Main Fuel Valve (MFV), Main Oxidizer Valve (MOV), Thrust Control Valve (TCV), Turbine Bypass Valve (TBV) due to the throttling capabilities. Most of the design of MFV, MOV and TCV are common except for Cv values for development efficiency. TCV is specially designed since the Cv value of the TCV is smaller than Cv values of other valves. Major specifications and design features of the valves are shown in Table 2 and following, respectively. External view and notional structure of the main valves are shown in figure 5. The details of the design and component test results can be found in Ref [6] and [8].

- ➢ Poppet type valve, which can control mass flow rate easily, was selected.
- ➢ Bellows is adopted for sealing the fluid since to be non-leak.
- ➢ The actuator of the valve has unique system to generate high thrust, which consist from stepping motor, HarmonicDrive® speed reducer and 3D toggle.
- ➢ Stepping motor generates and transmits torque to HarmonicDrive®.
- ➢ 3D toggle transduces torque to axial thrust and move poppet stem.

Table 2: Major specifications of the valves

Name	Operating Pressure [MPa]	**Cv**	Function
MOV	6.8	17.9	Flow control, ON/OFF
MFV	13	17.9	Flow control, ON/OFF
TCV	13	24	Flow control
TBV	13	2.5	Flow control

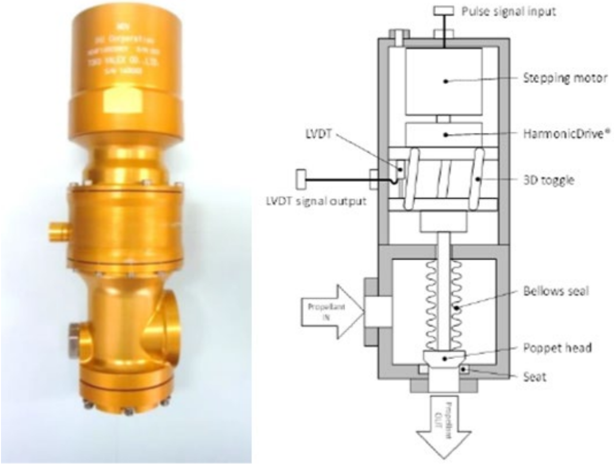


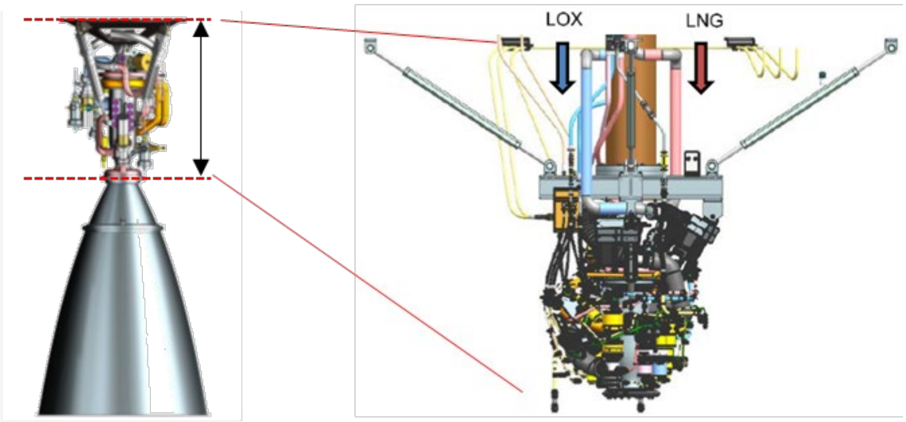
Figure 5 External view and notional structure of the main valves

DOI: 10.13009/EUCASS2023-536

3. Engine system test

3.1 Test configuration

Figure 6 shows the configuration of the engine system level demonstration tests. The regeneratively cooled nozzle and the nozzle extension are not equipped since the demonstration tests are conducted in the atmospheric conditions. Even though the nozzles are not equipped, engine system feasibility such as ignition transient sequence, system level operation stability, engine performance can be evaluated since the nozzles have few effects on system level behaviour. All the experiments are conducted AIOI test site owned by IHI AEROSPACE.



Vacuum configuration **Demonstration configuration**

Picture of hot fire testing (RDE017)

Figure 6: External view of the demonstration configuration and a picture of a typical hot fire testing.

3.2 Test results

Table 3 shows a test matrix of the engine system demonstration campaigns. Nine combustion tests were conducted with the demonstration configuration to demonstrate stable operations at various operating conditions. An operating point map is shown in Figure 7. Combustion pressures and engine mixture ratio vary from 2.1 to 4.4 MPa and 2.8 to 3.1, respectively.

Table 3: Test matrix of engine system demonstration campaign

Test No.	Test Duration [s]	**Pc [MPa]**	MR
1	11	3.3	2.8
2	15	4.3	3.1
3	10	2.1	3.1
4	21	4.1	3.0
5	36	4.0	2.8
6	15	3.8	3.0
7	28	4.4	3.1
8	45	3.9	2.9
9	43	3.9	2.9

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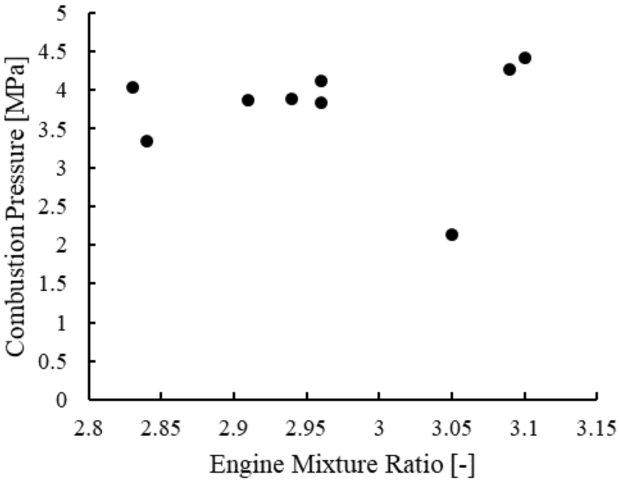

Figure 7: Engine operating conditions

Figure 8 shows histories of pressure and turbopump rotation speed during a typical engine operation condition. It should be noted that the combustion pressure in the Figure 6 shows the internal pressure of the torch igniter, therefore, the combustion pressure increases before the ignition of the main combustion pressure. After the ignition of the combustion chamber, combustion and turbopump discharge pressures increase with the increase in the turbine power, which is supplied by regenerative cooling chamber. Figure 9 shows the histories of the combustion pressure and fuel temperatures. The coolant outlet temperature, which is the temperature of the fuel at the outlet of the regenerative cooling channel, increases gradually at the ignition phase. The turbine power increases with the increase in turbine inlet gas temperature which is equivalent to coolant outlet temperature since the engine cycle of the engine is full-expander cycle where almost all the fuel is supplied to turbine. The pump speed increases due to the turbine power increase, which results in increase propellant flow rates. The increased propellant flow rates lead combustion pressure build up and thermal energy input to the regenerative combustion chamber. Due to the positive feedback mechanism, the engine system power increases rapidly several seconds after the ignition. Steady engine operations are achieved approximately 30 seconds after the ignition. For cutting off the engine operation, the turbine power is decreased by controlling the valves first, then propellant flows are shutoff by main valves. Neither combustion instability nor unstable operation observed all the engine operation phase. Nominal vacuum Isp is 368 s which is estimated with the combustion efficiency observed in the engine system tests and the assumed thrust coefficient in the vacuum configuration.

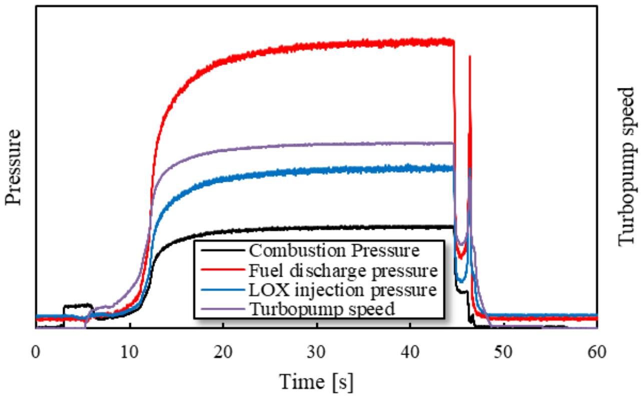

Figure 8: Typical combustor pressure and turbopump rotation speed histories during engine operation

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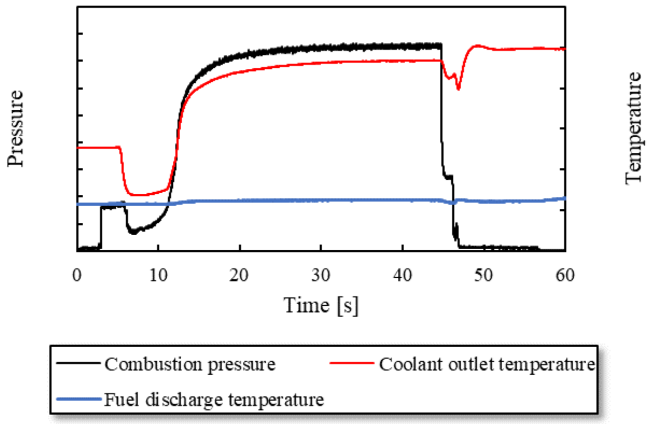

Figure 9: Typical combustor pressure and fuel temperature histories during engine operation

4. Conclusion and Future plan

Technical feasibilities of 30kN class high-performance methane/LOX rocket engine are demonstrated through the engine system integration tests. Not only the system level TRL but also TRL of the major components such as turbopump, combustion chamber, injector, main valves, igniter for the full expander cycle methane/LOX engine are increased.

As shown in figure 10, engine components and system level feasibility studies has been completed successfully. Flight demonstrations of methane/LOX propulsion system are now under planning. A suborbital flight with a rocket plane is one of the flight demonstration missions for methane/LOX propulsion system. Tokyo University of Science has been developing a winged experimental rocket vehicle (WIRES#15) and plans to launch it in 2025[9]. The Engineering model of methane engine which is used for the engine system integration test discussed in section 3 will be used for the WIRES#15 main propulsion system.

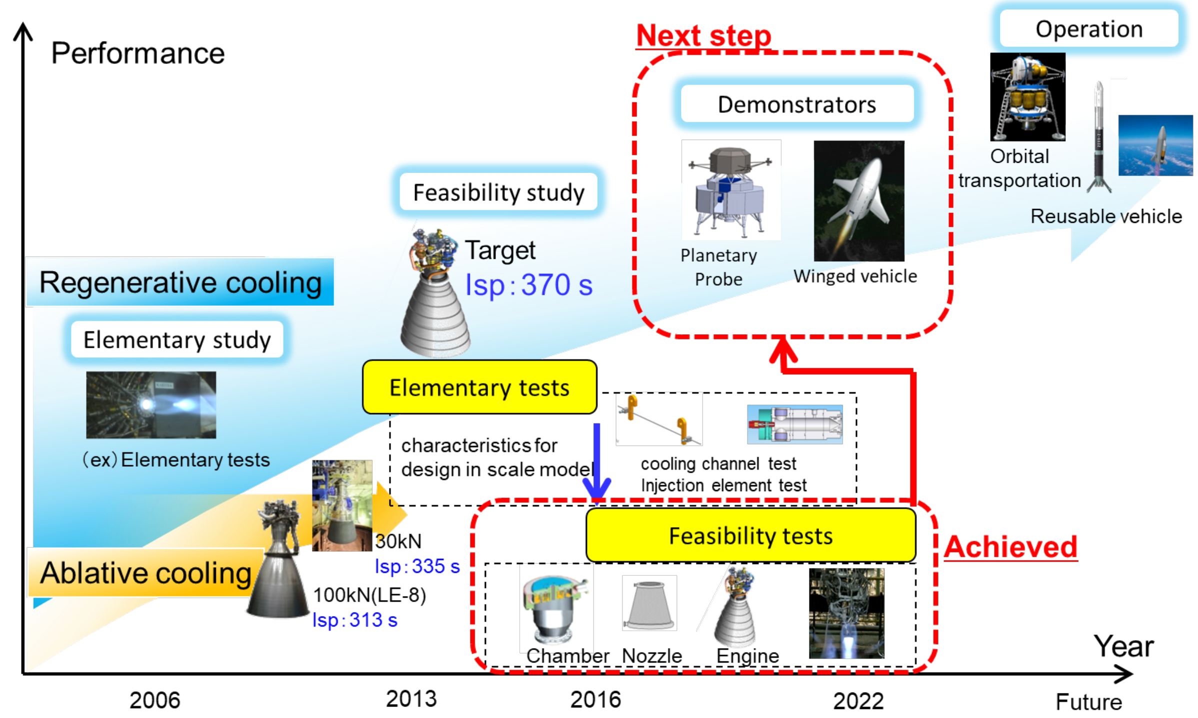

Figure 10: R&D roadmap of methane/LOX propulsion system

Acknowledgement

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