Development of Porous-Metal-Restrictor Based Xenon Flow Control Modules

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15 – 20, 2019

IEPC-2019-400

Hang Guanrong[1], Li Lin[2], Jia Qingqing[3] and Yu Shuilin[4]
Shanghai Institute of Space Propulsion, Shanghai 201112, China
Shanghai Engineering Research Center of Space Engine, Shanghai 201112, China

Abstract: Two generations of miniaturized xenon flow control modules based on mini porous metal restrictors for electric propulsion systems, have been developed by Shanghai Institute of Space Propulsion. Xenon flow can be adjusted in a wide range by changing the input pressure and the temperature of the porous metal restrictors. The first generation xenon flow control module, with redundant branches and a weight of about 900 g, was developed for HET-40, a 660 W Hall thruster, and it was in-orbit flight qualified. The second generation xenon flow control module, with 3-D printed parts to reduce the weight and to improve the assembly efficiency, was developed for HET-700, a 10 kW Hall thruster. The nominal output xenon flows of both modules can be changed by replacing the porous metal restrictors, without changing the shape and the assembly process.

Nomenclature

SISP	=	Shanghai Institute of Space Propulsion
XFCM	=	xenon flow control module
XFCM-1	=	first generation XFCM
XFCM-2	=	second generation XFCM
XFC	=	xenon flow controller

I. Introduction

Xenon flow control module (XFCM) is used to control the micro xenon flows of electric propulsion system. Flow restrictors are usually used to limit the xenon flows as the key components of the XFCMs. There are several kinds of flow restrictors, such as capillary tube,[1] orifice,[2] porous metal restrictor,[3] etched or milled microchannel,[4] etc.

For porous metal restrictor, the advantages are tiny volume, compact structure, easy processing, easy flow control by heating, strong resistance to residues, and strong tolerance of high temperature and pressure.

Two generations of miniaturized XFCMs based on mini porous metal restrictors, have been developed by Shanghai Institute of Space Propulsion (SISP) in the recent years. Xenon flow can be adjusted in a wide range by changing the input pressure and the temperature of the restrictors. The first generation XFCM, XFCM-1, is developed for HET-40,

[1] Engineer, Department of Electric Propulsion, hanggr@163.com.
[2] Engineer, Department of Electric Propulsion, 1540625081@qq.com
[3] Engineer, Research and Development Center, qqjia0804@163.com.
[4] Engineer, Department of Electric Propulsion, 13501956174@163.com.

a 660 W Hall thruster, and it is flight qualified.[5] The second generation XFCM, XFCM-2, with 3-D printed parts to reduce the weight and to improve the assembly efficiency, is developed for HET-700, a 10 kW Hall thruster.
This paper summaries the research on flow control capability and qualification of the porous metal restrictors, the development and flight qualification of the XFCM-1, and the development and test of the XFCM-2.

II. Research on Flow control capability and qualification of the porous metal restrictors

The porous metal restrictor consists of the outer stainless steel tube and the inner porous metal core. By changing the density and the pore size of the porous metal core, different flow rates can be realized, as a result, to satisfy different Hall thrusters.
Flow control capability and qualification of the porous metal restrictors were studied to satisfy the requirements for the Hall thruster.

A. Flow control characteristics study

Aiming the flow control requirements of Hall thrusters with power ranging from 500 W to 10 kW, the flow control characteristics of mini porous metal restrictors were studied.
Figure 1 shows a mini porous metal restrictor, of which is about Φ8 mm in diameter and 10 mm in length, and a Xenon Flow Controller (XFC) prototype, which contains a restrictor for anode and a restrictor for cathode.

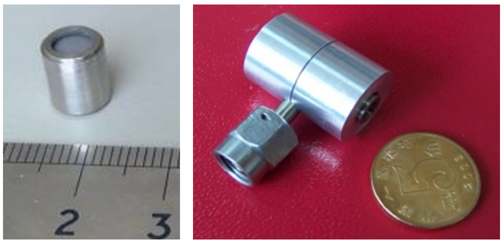

Figure 1. Mini porous metal restrictor and an XFC prototype.

Flow control experiments to the XFC prototypes were conducted by adjusting the temperature and inlet pressure of the restrictors, to study the flow control characteristics of the porous metal restrictors.
Figure 2 shows the temperature dependency of xenon flow rates of anode restrictor and cathode restrictor at 0.2 MPa inlet pressure, 0.1 MPa outlet pressure, and 20 ℃ environment temperature. The restrictor was heated by armored heating wire wrapped outside the restrictor and the temperature was collected by a thermocouple. As the temperature of restrictors increased from 20 ℃ to 230 ℃, the anode flow rate decreased from 2.41 mg/s to 1.24 mg/s, and cathode flow rate decreased from 0.25 mg/s to 0.13 mg/s. The flow ratio of anode to cathode varied between 9.68 and 9.86, and the overall tendency was to decrease as the flow rate decreases. It is acceptable for the stable operation of the thruster. The flow adjust ratio was 0.485 for anode restrictor and 0.48 for cathode restrictor from 20 ℃ to 230 ℃.

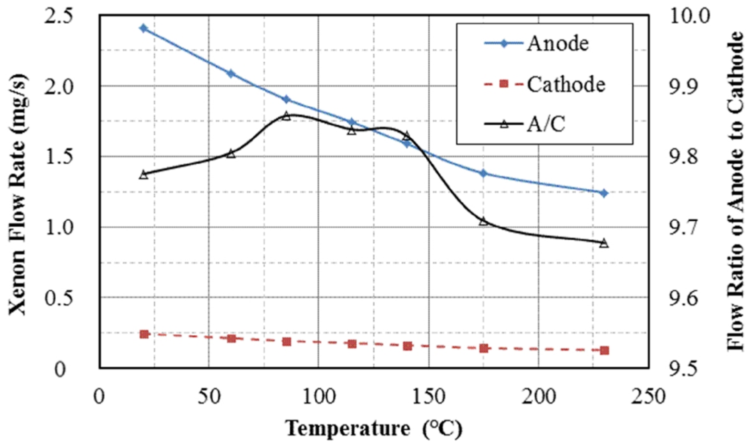

Figure 2. Xenon flow rates for anode and cathode, and the flow ratio of anode to cathode versus temperature of porous metal restrictors at 0.2 MPa inlet pressure and 0.1 MPa inlet pressure. A/C stands for the flow ratio of anode to cathode.

Figure 3 shows the inlet pressure dependency of xenon flow rates of anode restrictor and cathode restrictor at 0.1 MPa outlet pressure and 20 ℃ environment temperature. When the inlet pressure increased from 0.18 MPa to 0.24 MPa, the anode flow rate increased from 2.27 mg/s to 3.04 mg/s with a flow adjust ratio of 33.9%, and the cathode flow rate increased from 0.23 mg/s to 0.31 mg/s with a flow adjust ratio of 34.8%. The flow ratio of anode to cathode increased with the inlet pressure, from 9.70 to 9.95.
From the above studies, it is clear that:
(1) The throttling capability of the mini porous metal restrictor can be realized;
(2) The throttling capability can be adjusted by both temperature and inlet pressure, and it increases with the increase of the inlet pressure and decreases with the increase of the restrictor temperature;

(3) The maximum throttle range can be higher than 2.5:1 by adjusting both temperature and inlet pressure;
(4) Within the temperature and inlet pressure range studied, the flow ratio of anode and cathode increased slowly with the increase of inlet pressure, and generally increased slowly with the decrease of the restrictor temperature. The flow ratio is between 9.68 and 9.95, which is suitable for the normal operation of the corresponding thrusters.

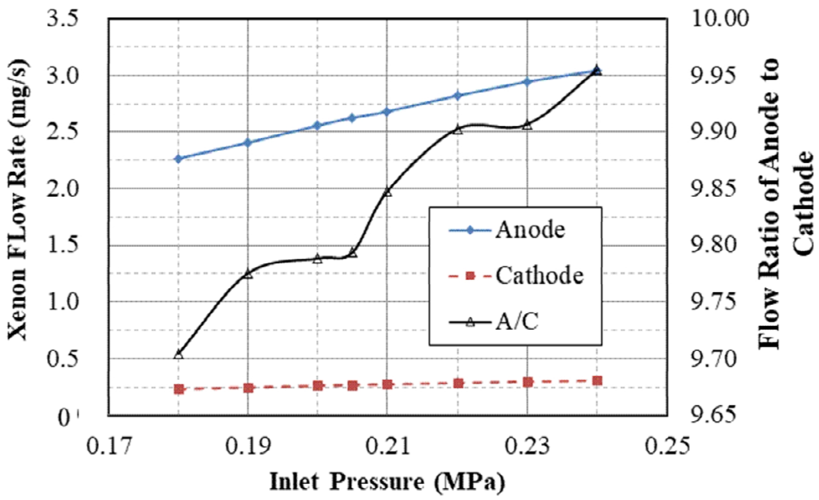

Figure 3 Xenon flow rates for anode and cathode, and the flow ratio of anode to cathode versus inlet pressure of porous metal restrictors with 0.1 MPa outlet pressure, and 20 ℃ environment temperature.

B. Qualification of the porous material restrictor

As there was no precedent for the application of porous material restrictor in domestic in-space electric propulsion system, it was necessary to qualify the porous material restrictor. First, close-loop working capability of the XFC with a Hall thruster was studied. And then, a sinusoidal vibration test, a random vibration test and a shock test were carried out. At last, a life time test with an ignition cycle test was carried out.

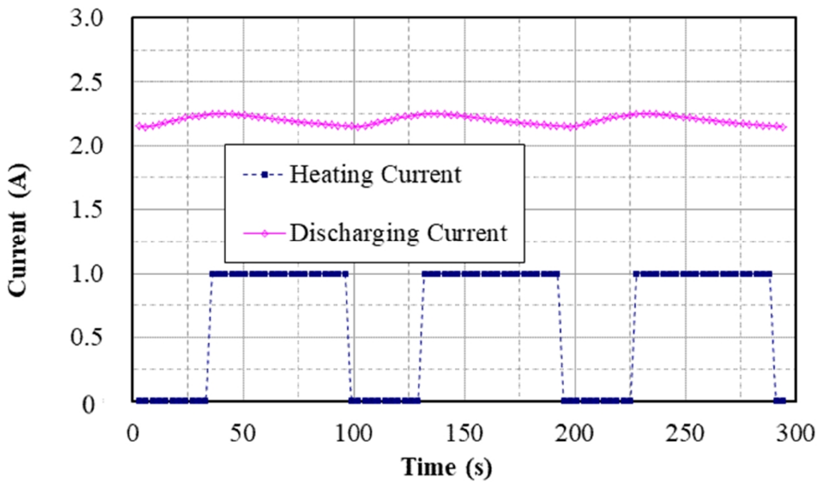

Figure 4. Heating current of porous metal restrictor and discharging current of the HET-40 Hall thruster during the close-loop working test.

Aiming the flow control capability of the HET-40 Hall thruster, for which the xenon flow rates are 2.39 mg/s and 0.262 mg/s, an XFC prototype close-loop working test with the HET-40 thruster was carried out. The heating current of XFC was provided by a 1 A constant current source. During the test, when the inlet pressure varied between 0.19 MPa and 0.26 MPa, the discharge current of the HET-40 thruster was controlled between 2.15 A to 2.25 A by turning the 1 A heating current on and off. The discharging current was always near the rated value of 2.2 A, and it met the work requirements. Figure 4 illustrates the heating current of the XFC prototype and the discharging current during the close-loop working test.

Table 1. Sinusoidal vibration test requirements.

Frequency Range (Hz)	Vibration Amplitude
10~20	10 mm
20~100	1000 g
Sweep Rate	2 oct/min

According to the requirements of the satellite mechanical environment test, mechanical environment tests including sinusoidal vibration, random vibration and shock test were carried out. Table 1 to Table 3 show the qualification requirements of sinusoidal vibration, random vibration, and shock test. After the tests, the performance of the XFC and the restrictors were normal.

To qualify the reliability of the porous metal restrictor, a life time test of 1120 h with an ignition cycle test of 3360 cycles was carried out to a porous metal restrictor for cathode. The nominal xenon flow rate was 0.251 mg/s when the inlet pressure was 0.17 MPa and the outlet was connected to the vacuum. During the tests, the flow rate varies between 0.250 mg/s to 0.253 mg/s. It indicated that no significant changes were found in the flow rate of the restrictor.

The reliability of the porous metal restrictors and the design method of XFC were proved. The results set a stage for subsequent applications.

Table 2. Random vibration test requirements.

Frequency Range (Hz)	PSD Level
10~95	+6 dB/oct
95~130	1 g^2/Hz
130~200	-13 dB/oct
200~600	0.16 g^2/Hz
600~2000	-15 dB/oct
Overall GRMS	13.6 GRMS
Loading Time	2 min
Loading Directions	3 axes

Table 3 Shock response spectrum requirements (Q=10)

Frequency Range (Hz)	Qualification Test
100~600	6 dB/oct
600~4000	1000 g
Loading Directions	3 axes

III. 1st generation porous-metal-restrictor based XFCM

The 1st generation porous-metal-restrictor based XFCM (XFCM-1) was developed for the 1st Hall electric propulsion space qualification mission. As the power limit of the satellite, a 660 W HET-40 Hall thruster was chosen as the in-orbit qualification thruster. The HET-40 Hall electric propulsion system consisted of an HET-40 Hall thruster, a propellant storage and feeding unit, an 800 W power processing unit and a filter unit.

According to the design idea based on modularization and miniaturization, a compact XFCM, belonging to the propellant storage and feeding unit, was designed for the HET-40 electric propulsion system.

Figure 5 and Figure 6 are the schematic and the flight model of XFCM-1.

XFCM-1 consists of two identical branches. From upstream to downstream, each branch consists a filter at the entrance, an inlet solenoid valve, an XFC, an anode solenoid valve, and a cathode solenoid valve. The branch A is the primary branch (including filter A, solenoid valves SVA, SVaA, SVcA, anode restrictor RaA with a heater, cathode restrictor RcA), and the branch B is the backup branch (including filter B, solenoid valves SVB, SVaB, SVcB, anode restrictor RaB with a heater, cathode restrictor RcB). The restrictor with a heater is commonly named as the thermal valve.

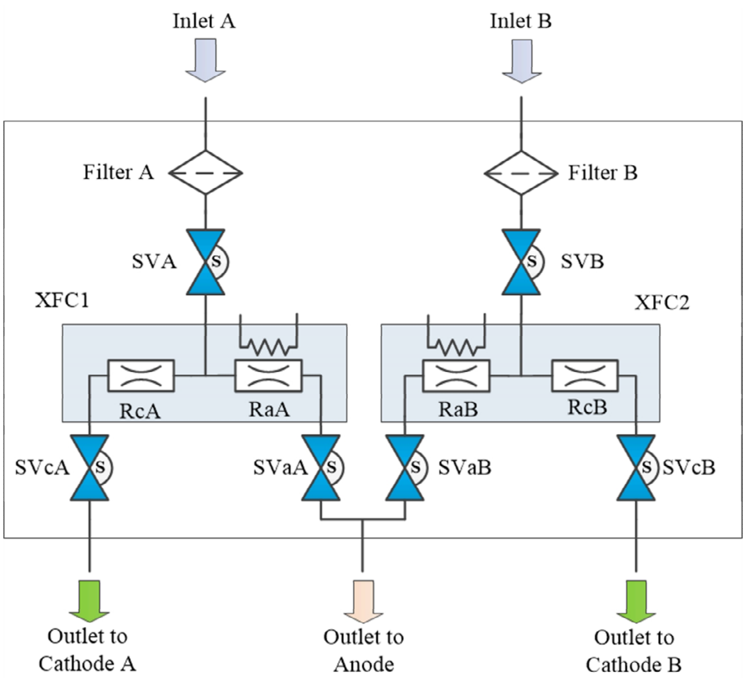

Figure 5. Schematic of XFCM-1.

XFCM-1 has two inlets, one anode outlet and two cathode outlets. Two anode outlets of the two branches merge into one anode outlet of XFCM-1.

Figure 6. XFCM-1 flight model.

The XFC integrates a porous metal restrictor for anode and another porous metal restrictor for cathode, and it has one inlet and two outlets, which connect to the anode and the cathode of the HET-40 thruster, respectively. There is a heater surrounding

the anode restrictor, which is used to adjust the propellant flow by heating. In order to monitor the temperature of the XFC, a thermistor sensor is installed on the outside surface of the XFC.
Table 4 shows the design values and experimental value of the XFCM-1 flight model.
The XFCM-1 was launched at 11:25 on October 14, 2012 with the HET-40 Hall electric propulsion system on a technical test satellite.
On the morning of November 5, it was determined by telemetry data that the XFCM-1 was in normal condition. On the same day, the exhaust of the propellant storage and feeding unit was carried out. The main branch of the XFCM-1 worked twice, each time 2 hours. When the pressure of the low pressure buffer tank was lower than the expected value of 0.04 MPa, the exhaust task was successfully completed.

Table 4. Design values and experimental data of the XFCM-1 flight model

Parameter		Design Value	Experimental Value	
			Primary Branch	Backup Branch
Inlet Pressure		0.20±0.01 MPa (Rated value 0.20 MPa can be adjusted appropriately with actual product conditions)	0.206 MPa	0.206 MPa
Flow Rate	Anode	2.39±0.239 mg/s	2.39 mg/s	2.39 mg/s
	Cathode	0.262±0.0262 mg/s	0.249 mg/s	0.263 mg/s
Proof Pressure		⩾0.75 MPa	0.75 MPa	
Total Internal Leakage (Sum of the Leakages of 3 Outlets) (0.2 MPa Helium Test) (Gauge Pressure)		≤8×10^{-6} Pa·m^3/s	After Assembly: 1.9×10^{-6} Pa·m^3/s	
			After Pressure Test: 3.2×10^{-8} Pa·m^3/s	
			After Flow Rate Test: 1.2×10^{-7} Pa·m^3/s	
Total Leakage (0.2 MPa Helium Test) (Gauge Pressure)		⩽1×10^{-6} Pa·m^3/s	After Assembly: 8.2×10^{-7} Pa·m^3/s	
			After Pressure Test: 8.5×10^{-7} Pa·m^3/s	
			After Flow Rate Test: 3.8×10^{-7} Pa·m^3/s	
Mass		⩽1.2 kg	0.897 kg	

The following are the in-orbit performance of the Hall electric propulsion system and the in-orbit performance of the flow adjustment module obtained by on-orbit calibration.
At 10:50 on November 7, the Hall electric propulsion system successfully ignited in orbit and completed the first ignition time of 180 s. Each parameter met the requirements. On November 9, calibrated Hall electric propulsion performance was calibrated by 4 accurate orbit measuring. The on-orbit calibration result was that the steady state input power of the system was 734 W, the thrust was 38.32 mN and the specific impulse was 1495 s. The calculated Hall thruster power was 621 W. The data showed that the Hall electric propulsion system operated normally.
During the 4 periods of orbit calibration, the average current of the Hall thruster was 2.07 A. According to the ground test data of the XFCM-1 flight model, it was found that the average flow rates of the anode and cathode were 2.37 mg/s and 0.247 mg/s, respectively, both within the design ranges.
After that, a number of ignition tests of the Hall electric propulsion system were carried out. By December 16, 2013, 200 scheduled ignition tests were carried out. By January 5, 2014, 12 more ignitions were carried out. The performance of Hall Electric Propulsion System was stable. All of these showed that the XFCM-1 worked normally and its performance was stable.

IV. 2nd generation porous-metal-restrictor based XFCM

Based on the XFCM-1, the 2nd generation xenon flow control module, named XFCM-2, was developed for HET-700, a 10 kW Hall thruster. The thruster operates at input powers of 10.5 kW while providing a specific impulse of over 2500 s, and a thrust over 500 mN at a discharge voltage of 500 V. The nominal flow rates of the anode and the cathode are 19.39 mg/s and 1.02 mg/s.

Figure 7 is the schematic of XFCM-2 and Figure 8 is the XFCM-2 principle prototype. Compared to XFCM-1, XFCM-2 is much simpler, lighter, smaller and more efficient to assembly. 3-D printed parts are employed to reduce the weight and to improve the assembly efficiency. It is more flexible for different applications. For example, 2 units of XFCM-2 can be used in parallel, one for primary branch and another for backup branch. By replacing porous metal restrictors of different throttling ability, different flow rates can be achieved, without changing the shape, the layout and the assembly process of XFCM-2.

XFCM-2 is mainly composed of 1 inlet, 3 solenoid valves (SVA, SVa and SVc), 2 thermal valves (TVa and TVc), and 2 outlets (one for the thruster anode and another for the thruster cathode). The thermal valve is mainly composed of a porous metal restrictor, a heater surrounded the restrictor, and a thermistor as the temperature sensor to monitor the temperature of the porous metal restrictor. The branch composed of TVa and SVa is for the thruster anode, and the branch composed of TVc and SVc is for the thruster cathode. The anode flow rate and the cathode flow rate can be adjusted independently.

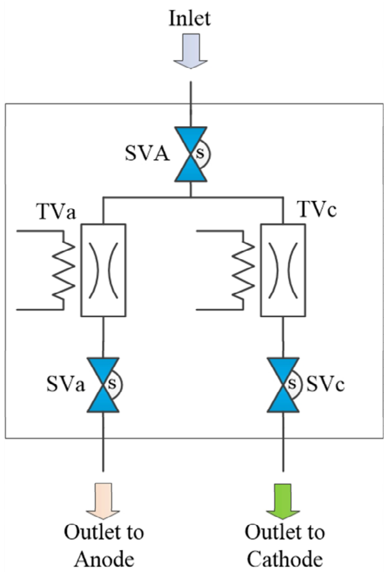

Figure 7. Schematic of XFCM-2.

Figure 8. XFCM-2 principle prototype.

The main specifications of the XFCM-2 for HET-700 thruster are as follows:

(1) Inlet pressure: 0.20±0.01 MPa (Rated value 0.20 MPa can be adjusted with actual product conditions, between 0.1 to 0.3 MPa);

(2) Nominal xenon flow rate of the anode outlet: 19.39±1.94 mg/s;

(3) Nominal xenon flow rate of the cathode outlet: 1.02±0.10 mg/s;

(4) Heating power: ≤3 W of each thermal valve;

(5) Mass: ≤320g;

The flow characteristics of XFCM-2 were studied. The flow rates of both anode and cathode branch were in the normal range. The flow rates of both branches were adjusted by controlling the inlet pressure and the heating power. Both the anode and cathode flow rates of XFC-2 can be decreased by more than 25% by heating the thermal valves, compared to the flow rates of restrictors when they are at 20 ℃. And the maximum temperature of the restrictors can be set to more than 80 ℃ by heating the thermal valve.

The XFCM-2 principle prototype was employed to provide the flow rate for the firing test of an HET-700 Hall thruster successfully. The inlet pressure of XFCM-2 prototype was adjusted between 0.11 MPa to 0.21 MPa, and the operating power of the HET-700 Hall thruster was between about 3 kW to 10.5 kW.

V. Conclusions

Based on the study of several types of flow restrictor, porous metal restrictor is chosen as the functional part of XFCMs developed by SISP.

In recent years, two generations of miniaturized XFCMs based on mini porous metal restrictors, XFCM-1 and XFCM-2, have been developed for HET-40 and HET-700 Hall thrusters by SISP. Because of the modular design idea of XFCM-2, different output flow rates can be achieved easily by replacing the porous metal restrictors of different throttling ability, without changing the shape and the layout.

Now, the design team of SISP is making efforts on improving the design of the XFCMs, to make them simpler, lighter, smaller and more reliable.

References

[1]Nouri-Borujerdi, A., Javidmand, P., "Critical Mass Flow Rate through Capillary Tubes", *ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels*, Montreal, Canada, 2010, FEDSM-ICNMM2010-30250

[2]Sarver-Verhey, T. R., Hamley, J. A., "Discharge Ignition Behavior of the Space Station Plasma Contactor", *30th Joint Propulsion Conference cosponsored by AIAA, ASME, SAE, and ASEE*, Indianapolis, USA, 1994, AIAA-1994-3311

[3]High Purity Porous Metal Flow Restrictors.URL: https://files.valinonline.com/userfiles/documents/pmfrspecs.pdf [cited 19 July 2019]

[4]Harmann, H.-P., Rothaus, S., Wanot, G., "μFCU - A Miniaturized Flow Control Unit for Xenon", *33rd International Electric Propulsion Conference*, Washington, D.C., USA, 2013, IEPC-2013-227

[5]Hang, G., Yu, S., "Development and in-orbit flight verification for flow control module of Hall electric propulsion system" (In Chinese), *Journal of Rocket Propulsion*, Vol. 42, No. 1, 2016, pp. 20-25, 32