Development of Xenon Ion Engine Subsystem for ETS-VIII

Eiji Nishida, Toshiyuki Ozaki, Yukikazu Kasai, Yoshifumi Gotoh
325 Kamimachiya, Kamakura, Kanagawa, Japan 247-8520
Mitsubishi Electric Corporation (MELCO)
E-mail : Eiji.Nishida@kama.melco.co.jp

Masafumi Ikeda, Ken-ichi Kajiwara
National Space Development Agency of Japan (NASDA)

Abstract

Following the successful development and on-orbit operation on ETS-III (2 mN class, mercury propellant) and ETS-VI and COMETS (20 mN class, xenon propellant), Mitsubishi Electric Corporation has started a program for the further improvement of 20 mN class xenon ion engine subsystem (IES).

ETS-VIII IES is designed on the basis of the IES for ETS-VI and COMETS, and its improvement design aims at:

(1) longer life capability that can cover NSSK of 2 to 3 ton class, over 10-year-life GEO satellite.
(2) simpler subsystem construction and better satellite integrity
(3) easier operation

ETS-VIII IES is in the engineering model phase under contract with NASDA, while ETS-VIII is scheduled to be launched in 2002.

1. Introduction

MELCO is now approaching the step to improve the 20 mN class IES for the NASDA's flight program of Engineering Test Satellite-VIII (ETS-VIII).

Basically, design of the improved IES and its components for ETS-VIII is based on the design heritage and development achievement of ETS-VI[1-2] & COMETS, including totally over 70, 000 hours life test on ground.

IES design was reconsidered after the completion of ETS-VI program.

This follow-on reconsideration work includes not only the subsystem / components redesign effort but also include system requirement reconsideration i.e. operation, components layout etc. of IES on standard geosynchronous communication satellite.

This reconsideration work is reflected to the preliminary design work for ETS-VIII system and subsystem.

ETS-VIII is a geosynchronous satellite with basic requirements as follows:

(1) 3 ton of BOL mass
(2) 10 years life
(3) Ion Engine for NSSK and bipropellant thrusters for orbit insertion, attitude control and EWSK.
(4) large antennas for mobile telecommunication are deployed at the east and west side of satellite.

During the preliminary design work on the basis of the above basic satellite requirements, design modification points of IES were coordinated with the satellite system engineering and clarified.

ETS-VIII program is now in the process of EM manufacturing and testing.

This paper describes the design of improved 20-mN Xenon Ion Engine Subsystem and its components in comparison with the ETS-VI IES.

Ongoing test plan of Engineering model (EM) IES is also presented, which includes environmental & performance testing of each components and interface verification testing of total IES.

2. IES subsystem description

2.1 Design modification from ETS-VI

Based on the ETS-VI IES's heritage, design reconsideration of satellite system and ion engine subsystem was conducted.

Table 2-1 (a) and (b) summarize the main design modification points and main performance parameters of ETS-VIII in comparison with ETS-VI IES.

The IES subsystem refinement works aims at the following points:

(1) parts design of thruster is refined for longer thruster life.
(2) better satellite system integrity and minimum interference on the other subsystem
(3) propellant storage and feed system components were re-selected in consideration of the state-of-work technology for commercial satellites.
(4) electrical components design was refined in consideration of ongoing technology improvements of parts.
(5) easy operation with operation commands storage in orbit based on no fine performance adjustment

Table 2-1 (a) Main design modification of ETS-VIII & ETS-VI IES

		ETS-VIII IES	ETS-VI IES	objectives for modification
1.system requirements				
1-1	thruster location	north and south edge of anti-earth panel	center of satellite east and west panel	to avoid interference with the large antennas on east & west
1-2	operation	one north thruster at ascending node and one south thruster at descending node	simultaneous operation of two thrusters at ascending node	for lower peak power consumption for simpler control sequence of IES
1-3	thrust vector aiming point	each thruster aims at center of satellite mass	synthetic thrust vector aims at the center of satellite mass	system operation reconsidered based on the above item 1-1&1-2
1-4	tight thrust adjustment	not needed	needed for synthetic thrust vector alignment	to eliminate the fine operating parameter adjustment for PMU and PPU on the basis of above item 1-2
1-5	on-orbit thrust vector adjustment	needed (by mechanical gimbaling)	not needed	to cope with the requirements of the above item 1-2 & 1-3
1-6	commands storage	IES stores operation parameters and system computer stores firing timing parameters	no	for easy operation
2.subsystem construction				
2-1	PPU	2 (include redundant PPU)	4 (include redundant PPU)	component requirements reconsidered based on the above item 1-2
2-2	propellant management unit and valve driver	1 integrated set for all	2 individual sets for east & west TRSs and valves	for better integrity as satellite propulsion system
3.component design				
3-1	TRS	total impulse > 1.2 MN-s	total impulse > 0.67 MN-s	for larger and longer life satellite requirements
3-2	PPU	one PPU for two TRSs with thruster selection relays	one PPU for each TRS	for simpler IES construction on the basis of the above item 1-2
3-3	Pressure regulation	by mechanical regulator	by active feedback control of valves at upstream of subtank	for simpler IES construction and for easier operation on the basis of the above item 1-4
3-4	propellant flow rate control	by passive orifices	by mass flow controller with active feedback control	
3-5	operating parameter adjustment	coarse adjustment only	fine adjustment needed for tight thrust adjustment	

Table 2-1(b) main performance parameter of ETS-VIII & ETS-VI IES

		ETS-VIII IES	ETS-VI IES	components needed to be modified
1	thruster	Kafuman type Ion Thruster		N/A
2	propellant	Xenon, 180kg max.	Xenon, 41kg max.	xenon tank
3	operation	one thruster operation at ascending and descending node	simultaneous two thruster operation at ascending node	xenon tank and xenon feed system, power processing unit, ion engine controller, mass flow controller, thruster
4	thrust	>20 mN average from BOL to EOL with coarse operational parameter adjustment	23.3mN±1% with fine operation parameter adjustment	
5	specific impulse	> 2200 sec average from BOL to EOL with coarse operational parameter adjustment	>2906 sec with fine operation parameter adjustment	
6	total impulse	> 1.2 MN-s	> 0.67 MN-s	thruster
7	MEOP	15 MPa	10MPa	xenon tank & xenon feed system

2.2 IES subsystem construction

Figure 2-1 shows the schematic diagram of ETS-VIII and ETS-VI IES.

From the viewpoint of function and integration grouping, IES consists of the following 5 units and components.

(1) North and south ion thruster units (ITUs)
(2) One Propellant Management Unit (PMU)
(3) Two Ion Engine Controllers (IECs) including redundancy
(4) One Internally redundant Ion Engine Driver (IED)
(5) Two Power Processing Units (PPUs) including redundancy

Sub-components construction of ITU and PMU and the function of each units / components are shown below.

2.2.1 Ion Thruster Unit (ITU)

One ITU consists of redundant pair of thrusters (TRSs) and flow control modules (FCMs), one internal redundant ion thruster gimbal (ITG).

These sub-components are integrated on one satellite interface panel with CFRP brackets.

TRS generates thrust with electrical power supplied by PPU and xenon propellant fed by each FCM.

ITG tilts the thrust vector to compensate the satellite center of mass migration etc. within the accuracy of ± 0.1 degree. Satellite mass property analysis requires the ITG's gimbaling stroke as ± 5 degrees maximum from the initial point in azimuth and elevation directions.

FCM controls the mass flow rate for TRS's propellant feed paths by mechanical orifice under conditions of both PMU's precise pressure regulation and precise temperature control.

FCM supplies propellant of fixed flow rate through orifices to each TRS's feed paths, while ETS-VI Mass Flow Controller (MFC) had electrical feedback control for variable flow rate setting.

This modification was selected on the basis of loose thrust adjustment requirements allowed by change of thruster location, and makes the FCM design be simple and reliable.

FCM also have bypass feed line for thruster's neutralizer. This bypass feed path is activated by opening its miniature latching valve (ILV(FCM)) to increase propellant flow rate for neutralizer during the thruster ignition.

2.2.2 Propellant Management Unit (PMU)

PMU consists of two xenon tanks(TKXs), pararell redundant pair of normally closed pyrotechnic valves (IPVNCs), one pressure regulation module (PRM), high / low pressure transducers (IPTH/L), two high pressure fill & drain valves (IFDVHs) and one low pressure fill & drain valve (IFDVL).

TKX is mounted on the satellite separation ring with CFRP support structures and other PMU components are integrated in the lower deck near the anti-earth panel with the components of chemical propulsion subsystem.

Two TKXs store up to 180 kg of xenon propellant.

Redundant pair of IPVNCs isolates the stored propellant during launch.

After actuating the IPVNC to be opened, the TKXs feed the propellant to PRM.

PRM filtrates the xenon propellant gas by high pressure filter (IFLTH), mechanically regulates the propellant feed pressure by a series redundant regulator (IREG) very precisely for precise mass flow rate control at FCM.

IREG regulates the propellant feed pressure only by pneumatic feedback and no electrical feedback control is not used, while the ETS-VI PMU regulate the pressure by electrical feedback control of Thruster Control Unit (TCU) with valves and subtank.

This mechanical feedback regulator is selected for its simple & reliable mechanism, development heritages and its precise regulation performance.

Combination of ILVs at a PRM outlet and each FCM's inlet selects one TRS/FCM branch from four. This combination of PRM and FCM ILVs is designed to have valve's series redundancy in every four branch with minimum numbers of 6 valves.

Two IFDVHs are for the xenon propellant loading and PMS purging inlet. One IFDVL is a test port.

High and low pressure transducer generate health check telemetries of tank pressure and IREG's regulation pressure, respectively.

2.2.3 IEC, IED, PPU

IES has three kind of electrical components, i.e. two IECs, one IED and two PPUs.

These electrical components are mounted in the satellite bus module with some other electrical components of other subsystems.

IEC controls all the operational sequence of all IES components and it also governs most of IES's telemetry & command interface with the satellite system.

Internally redundant Ion Engine Driver (IED) generates electrical drive pulse to all of the latching valves in PMS and ITG's stepping motors in accordance with the IEC's command.

IED receives each latching valve's open/close telemetry and ITGs' potentiometers telemetries and sends back those telemetry to IEC.

Power Processor Unit (PPU) supplies electrical power for both north and south thrusters. A group of relays is installed in PPU to switch the output between north and south thrusters.

In order to achieve the high reliability of signal processing, telemetry and command transmission lines between IEC and IED / PPU are fully cross-strapped architecture.

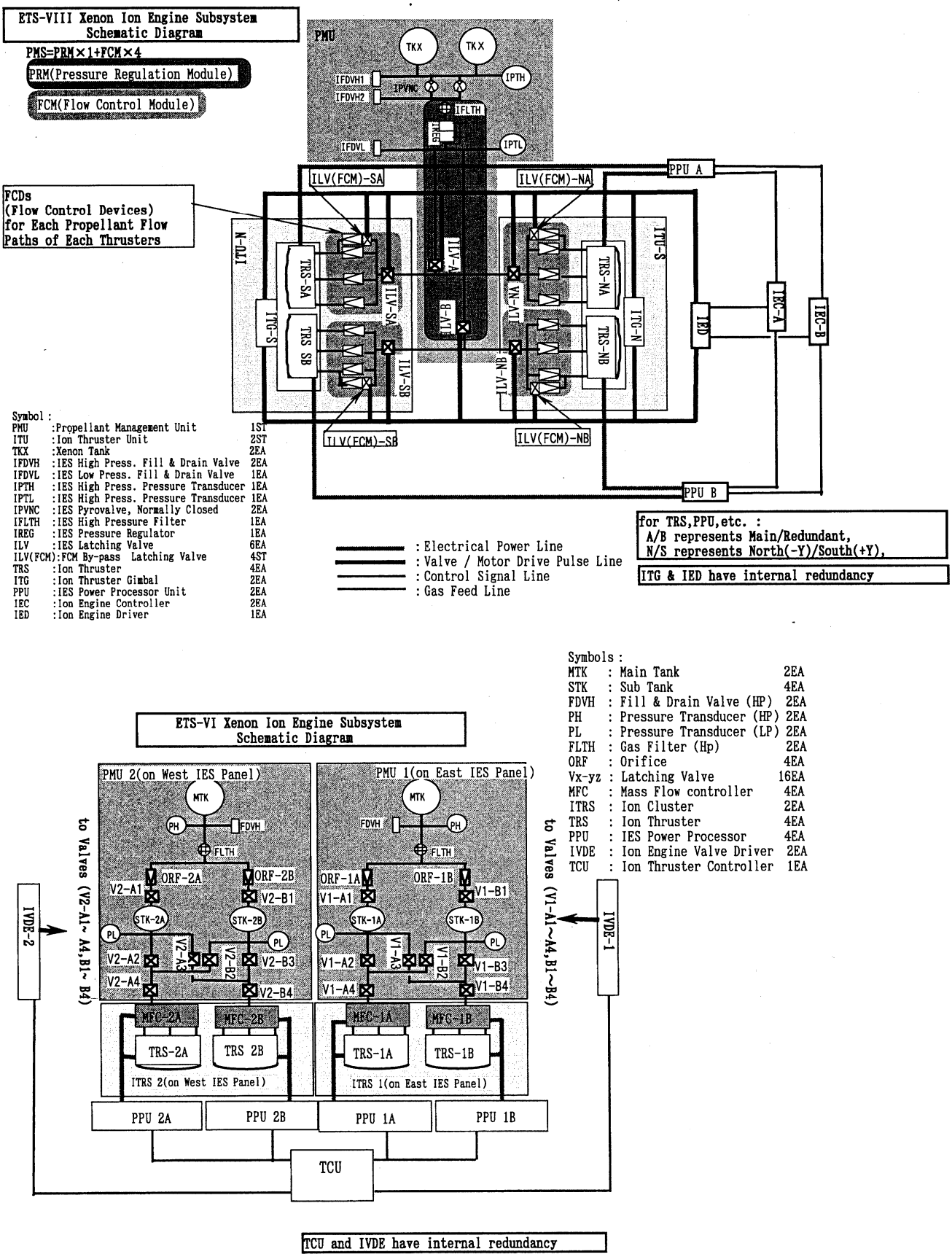

Figure 2-1 ETS-VIII and ETS-VI IES Subsystem block diagram

3. IES Components description

Each IES components and sub-components were re-designed in accordance with the above system and subsystem requirements.
Their design was summarized as follows.

3.1 Thruster (TRS)

Figure 3-1 and table 3-1 shows the photograph of improved thruster for ETS-VIII and the main design parameters, respectively.

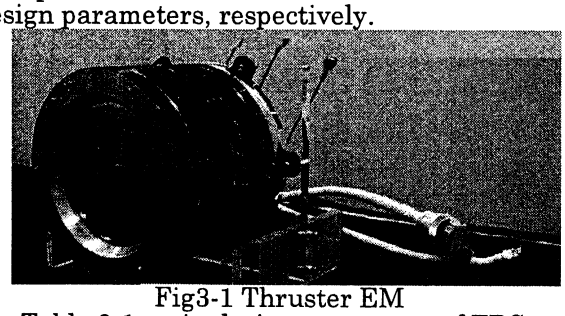

Fig3-1 Thruster EM

Table 3-1 main design parameter of TRS

parameter	value
Type	Kaufman-type
Propellant	Xenon
Average thrust	>20mN
Average Isp	>2200 sec
Mass	<2.8kg
Life	>1.2M N-s
Required power	<650W@BOL

This thruster has basically the same design with the one for ETS-VI and COMETS, of the same kaufman-type discharge chamber, same beam extraction diameter, etc.
However, design of each part is refined in the follow-on refinement program under contract with NASDA and MELCO's in-house funding.
This thruster is designed to have a capability of generating over twice greater total impulse than the ETS-VI thruster

Detailed design refinement is reported in the other paper[3].

3.2 Ion Thruster Gimbal (ITG)

ITG's main design parameter is outlined in the table 3.2-1.

Table 3.2-1 main design parameter of ITG

parameter	value
Type	Two axis tilting gimbal
Accuracy	< 0.1 degree
Stroke	> ±5 degree
Life	>1E4 cycles

ITG is designed to have:
(1) two linear actuators and one center pivot for two axis tilting
(2) a pair of pyrotechnic launch-lock mechanisms.
(3) enough stiffness to support two thrusters and their brackets

One ITG has two linear actuators with high-precision stepper motors. Operation of each linear actuator is monitored by rotary potentiometer.

The precise linear actuators tilt with the accuracy of < 0.1 degree within ± 5 degree range in azimuth and elevation direction.

3.3 Xenon Storage Tank (TKX)

Fig 3.3-1 shows the view of the TKX and table 3.3-1 outlines the main design parameter of TKX.

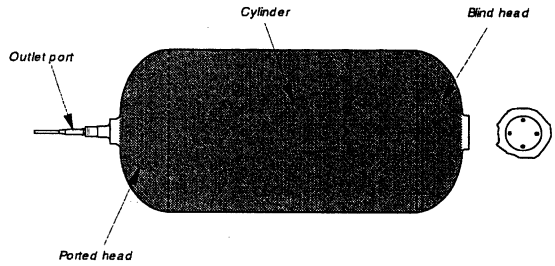

Fig 3.3-1 Xenon Tank for ETS-VIII IES

Table 3.3-1 main design parameter of TKX

parameter	value
type	composite overwraped, polarmount
material	T-1000(Fiber) Ti-6Al-4V(Liner)
capacity	> 0.050 m^3
MEOP	15MPa
proof / burst	>1.25 / 1.5 x MEOP
LBB feature	Yes
propellant storage capability	maximum 89 kg Xenon
mass	< 7kg

This tank was designed on the basis of the tank manufacturer's heritaged design and the state-of-art technologies of composite overwrapped pressure vessel (COPV) for commercial satellites.
This tank has about 90-kg xenon storage capacity with the MEOP of 15 MPa.
TKX is designed to have Leak Before Burst (LBB) feature per MIL-STD-1522A.
The qualification testing has successfully completed including LBB demonstration and burst test.
Detailed description about the development of TKX is reported in the other paper[4].

3.4 Normally Closed, Pyrotechnic Valve (IPVNC)

Table 3.4-1 outlines the main design parameters of IPVNC.

Table 3.4-1 main design parameter of IPVNC

parameter	value
type	Normally Closed
initiator	Redundant NSIs
material	Titanium Alloy (Body & Interface pipe)
MEOP	15MPa
no blow-by gas feature	Yes (sealed by metal-to-metal shrink fitting)
mass	< 136grams (Initiator included)

IES requires no blow-by gas and low particle contamination generation features for high propellant purity requirements from thruster.
This requirements can be achieved by the

accurate process control of metal to metal shrink fittings in the pyrovalve body.

Blow-by gas sampling and particle contamination count were successfully conducted during the lot acceptance testing. And all of the performance was successfully qualified.

3.5 Propellant Management sub-unit (PMS)

ETS-VIII IES's propellant management sub-unit was designed to have modular construction with heritage components for easy integration in satellite and for low-risk development.

PMS has two modules, i.e. Pressure Regulation Module (PRM) and Flow Control Module (FCM).

These two modules are designed under the heritage for chemical and electrical propulsion subsystem.

Since the PMS requires no active electrical feedback control for both pressure regulation and flow rate control, which the ETS-VI design did, cross-strapped connection of electrical control and gas feed line for high reliability is not needed.

The main features of each modules of PMS are summarized in the following sections. Further detailed description about PMS is shown in the other paper[5].

3.5.1 Pressure Regulation Module (PRM)

Figure 3.5-1 shows a schematic view of the PRM and table 3.5-1 outlines the main design parameter of PRM.

PRM is designed to be a compact module of heritage components, which provides easy satellite system integration.

The series redundant regulator is selected for its high accuracy for accurate flow rate control at FCM. The regulator is equipped with the qualified active flow limitter to minimize slam start effects.
The inlet and outlet interface tube of PRM is made of titanium alloy.

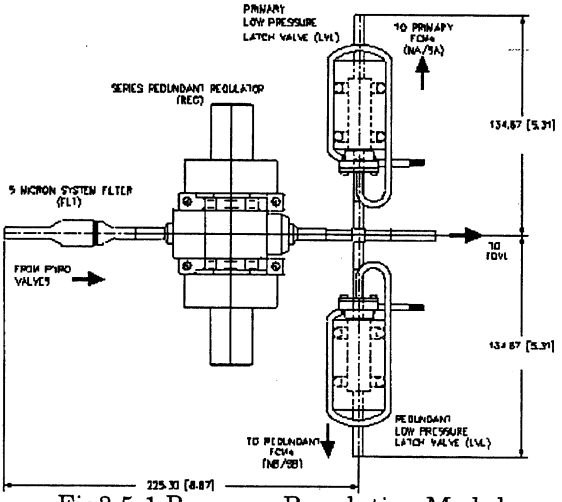

Fig3.5-1 Pressure Regulation Module

Table 3.5-1 main design parameter of PRM

parameter	value
filter	5 μm abs, stacked etched disk filter
regulator	series redundant regulator
latch valve	two torquemotor LV
MEOP	>15MPa (inlet) > 0.5MPa (outlet)
regulation Pressre	0.276 $\pm$0.0025MPa (Nominal)
mass	< 1.9 kg

3.5.2 Flow Control Module (FCM)

Figure 3.5-2 and table 3.5-2 show the schematic view and main design parameters of FCM, respectively.

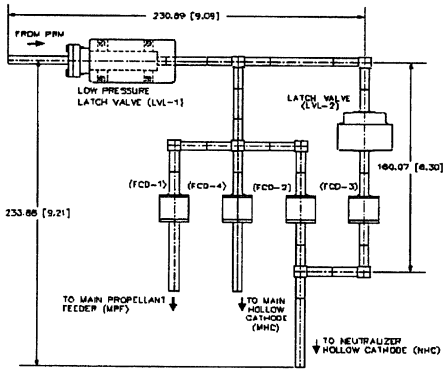

Fig3.5-2 Flow Control Module

Table 3.5-2 main design parameter of FCM

parameter	value
flow control device	stacked etched disks
latching valve	one torquemotor LV & one miniature LV
MEOP	> 0.5MPa
flow rate accuracy	< 5% (MHC,MPF) <10% (NHC)
mass	< 0.7 kg

FCM consists of one torquemotor latching valve for selecting one FCM / TRS branch, four mechanical flow constrictor orifices and one miniature latch valve for bypass line selection.
The flow constrictor, which is called flow control device (FCD), consists of stacked etched discs, which is manufactured by identical process of system filters. The flow path dimension is precisely controlled by the heritaged process control of chemical etching for filters, and thus FCM provides the precise flow rate control for thruster.

This precise control capability without electrical feed back system causes no long-term degradation and eliminates the thrusters' performance shift caused by the flow rate change.

3.6 Ion Engine Controller (IEC)

Table 3.6-1 shows the main design parameter of the IEC.

IEC is featured to have high-performance space use 64 bit MPU, which is newly developed by NASDA. This processor is developed for the standard MPU of the next generation satellite and is commonly used for the ETS-VIII

satellite controller.

IEC can store a set of IES operational parameter setting for more than two weeks operation.
Satellite controller stores commands relating to the orbital parameter and absolute timing.
With the combination of the above stored commands, IES has an ability to be operated automatically for more than 10 days

IEC's MPU and interface circuits are designed to have maximum commonality with the other ETS-VIII computers.

IEC's onboard software is also designed on the basis of MELCO's software design scheme. The control sequence of the IEC is based on the one in ETS-VI heritage and is updated for the IES configuration refinement.

The IEC circuit board is also designed to have maximum commonality with the one in the other components in ETS-VIII with commonly developed "slice module" design.
This mechanical design of the slice module is developed and verified in the design verification testing in the ETS-VIII program.

Table 3.6-1 main design parameter of IEC

parameter	value
processor	NASDA 64 bit MPU
fault detection	Yes
digital interface	EIA RS422 interface
mass	8.5 kg (Nominal)
power dissipation	<13.5W

3.7 Ion Engine Driver (IED)

Table 3.7-1 outlines the main design parameters of IED.

IED drives totally 10 latching valves in the PMS and totally 4 stepper motors in the ITG.

Table 3.7-1 main design parameter of IED

parameter	value
Redundancy	Internally Redundant
digital interface	EIA RS422 interface
mass	9.8 kg (Nominal)
power dissipation	12.5W(Nominal @ standby)

IED receives the open / close telemetry from the above valves and potentiometer telemetry from ITG and sends back those telemetry to IEC.
IED is an internally redundant component, which is similar design concept to the ETS-VI's IVDE (ion engine drive electronics).
IED is also designed on the basis of MELCO's heritaged standard design of valve drive electronics for chemical propulsion systems and antenna pointing electronics.
IED also has "slice module" design and each slice circuitry is designed to have maximum commonality among the IED's sliced boards and the driver of chemical propulsion of ETS-VIII.

3.8 Power Processor Unit (PPU)

Figure 3.8-1 shows the block diagram of PPU and Table 3.8-1 outlines the main design parameters of PPU.

Table 3.8-1 main design parameter of PPU

parameter	value
mass	11.6 kg (Nominal)
power dissipation	<106W@BOL
Efficiency	> 83%

PPU is designed to have relays and their driver electronics in order to have the function of thruster selection between north and south thrusters.
This additional function reduces the quantity of PPU in one set of IES, thus results in the reduction of mass and cost of total IES.
The design verification testing of relays has conducted and successfully completed.

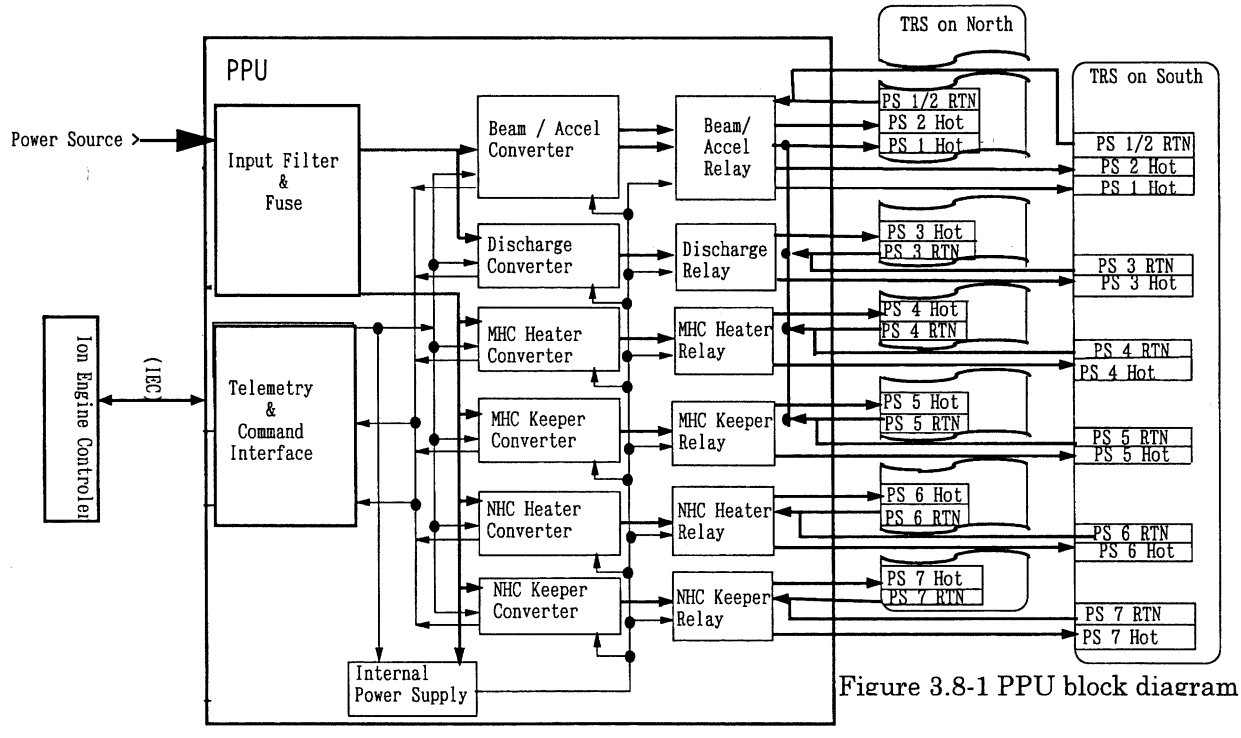

Figure 3.8-1 PPU block diagram

4. Development Testing of IES

Figure 4-1 shows the basic EM verification flow of ETS-VIII IES.

After the completion of each component's testing, interface among the IES components and subsystem EMC characteristics are to be verified by the IES subsystem testing.

Mechanical environmental test and thermal balance test are conducted at the level of ITU.

Electrical components (IECs, IED, PPUs) are subjected to the System Engineering Model (SEM) testing for system-level electrical signal, power and EMC interface verification.

TKX-STM, IPVNC LAT model and thermal dummy of IES components are subjected to the System Thermal Model (STM) testing.

IPVNC-EM and structural dummy of IES components are subjected to the System Structure Model (SSM) testing.

Life testing of thruster is already started for the verification of ETS-VIII's long life requirement.

By the total evaluation of the above testing, all the function and performance of IES subsystem is to be verified.

5. Conclusion

1. System & subsystem requirements for IES were reconsidered for the improved IES on the basis of ETS-VI IES's heritage design.
2. ETS-VIII IES was designed on the basis of the above improvement requirements.
3. EM phase test is planned including thruster life testing a

nd environmental testing is now undergoing.

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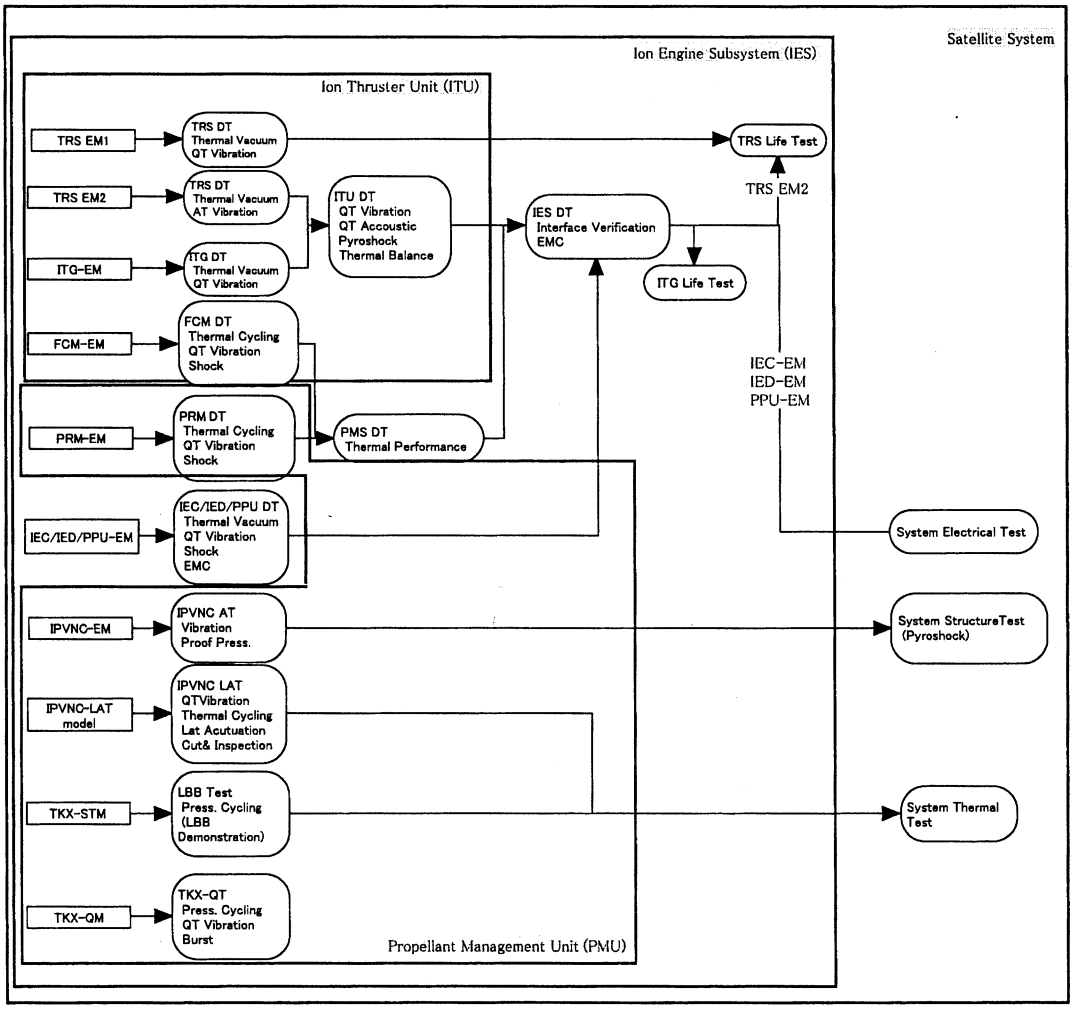

Figure4-1 Basic Development Test Flow