EUROPA CLIPPER

EEE Parts and Materials Program For Jupiter Missions

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Jet Propulsion Laboratory, California Institute of Technology

Radiation Effects in Components and Systems

Bremen, Germany

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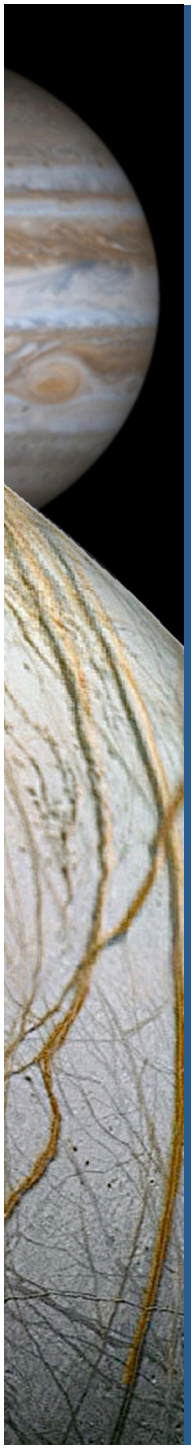

Overview

- Planned Mission Overview
- Radiation Environment Summary
- System Hardening Approach
- Electronic Parts Approach
- EEE Parts Radiation Testing Results
- Materials Approach
- Selected Materials Radiation Performance
- Summary

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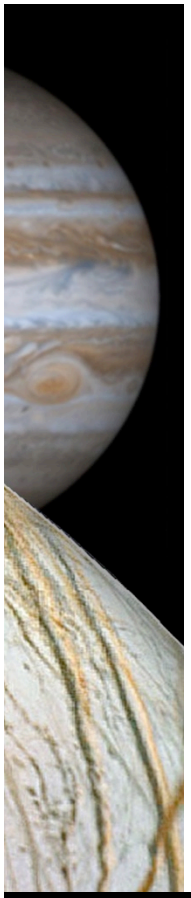
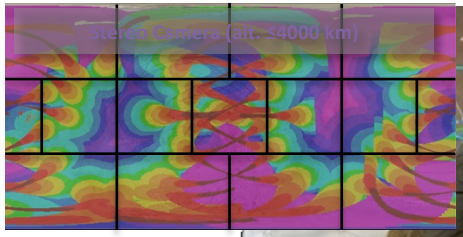
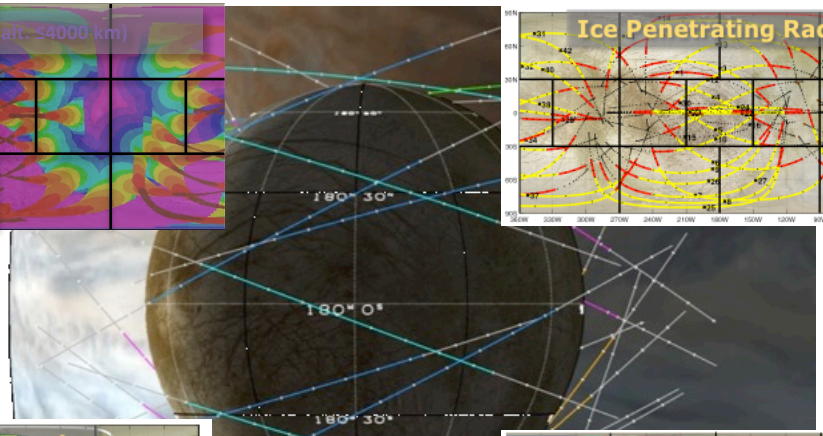
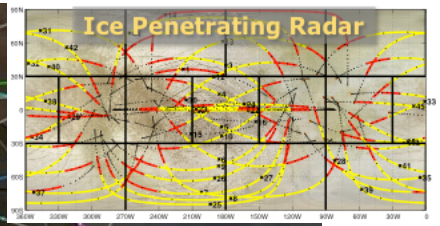
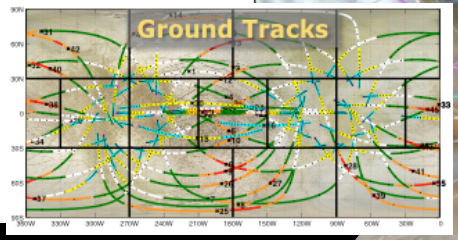
Innovative Mission Concept

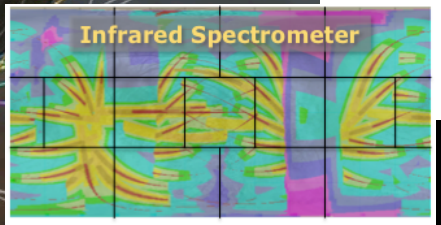


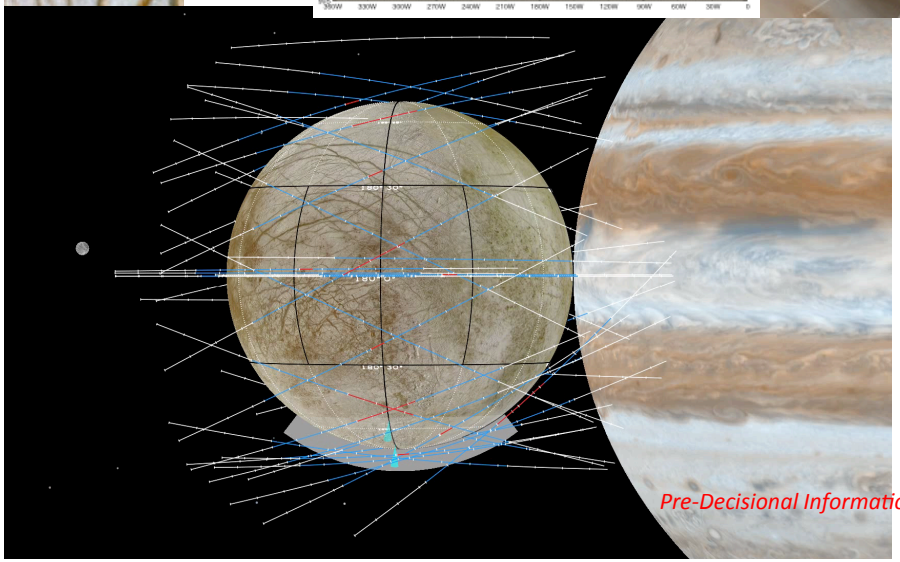


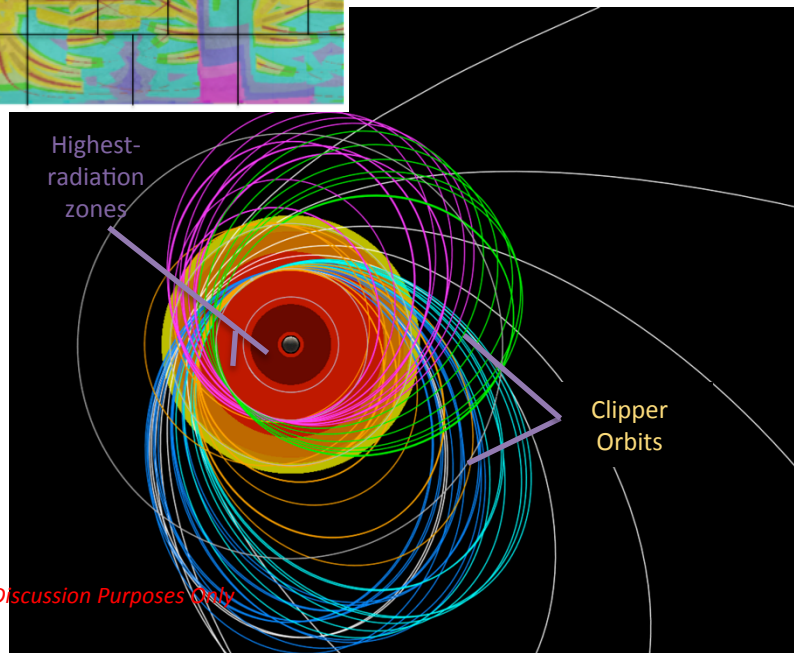












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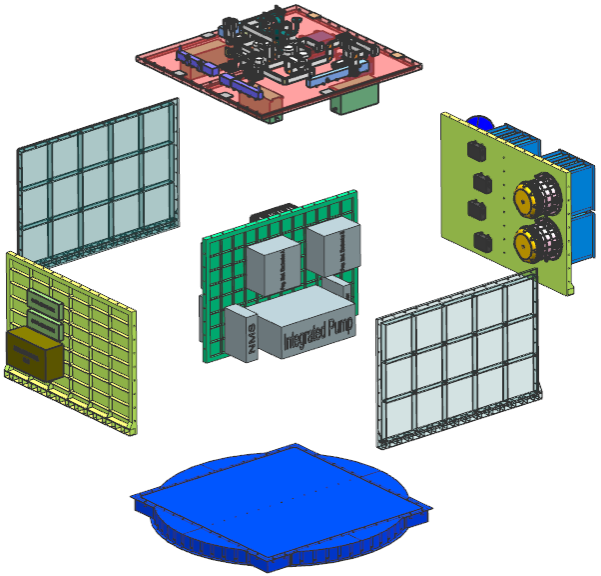
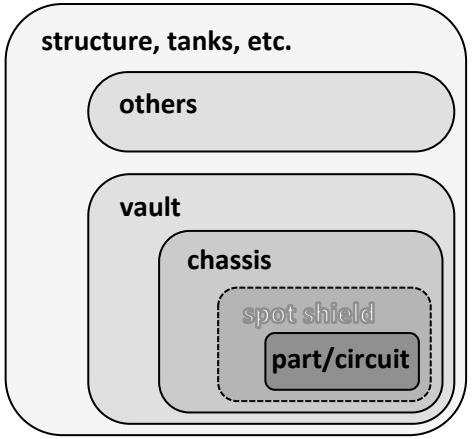
Radiation Management

- Bound mission total dose at 3 Mrad@100 mil Al
- Radiation Design Factor of 2
- Goal: 300 krad electronic parts
- Significant early characterization efforts
- Use of Preferred parts & materials database
- Utilization of radiation vault (shielding)
  - 150 krad environment inside of vault
  - Benefits of packing and self shielding
  - IESD protection
- When needed additional shielding at box level
  - Heritage subsystems
  - Some in the 100 Krad range
- Local shielding as needed
  - Some sensors
  - Few soft critical devices
- Circuit Design Mitigation





Systems Approach: Mission design, Shielding, Parts Selection, Mitigation

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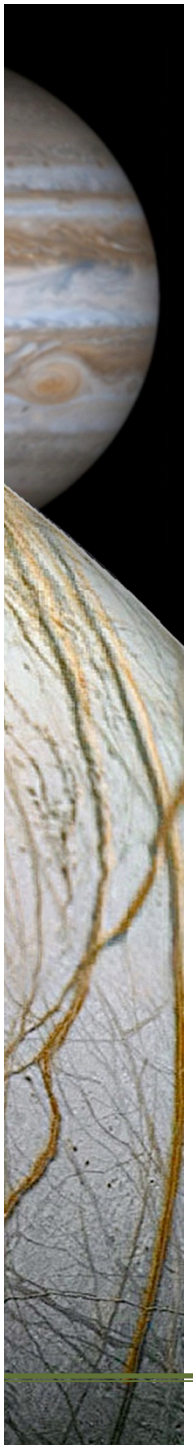
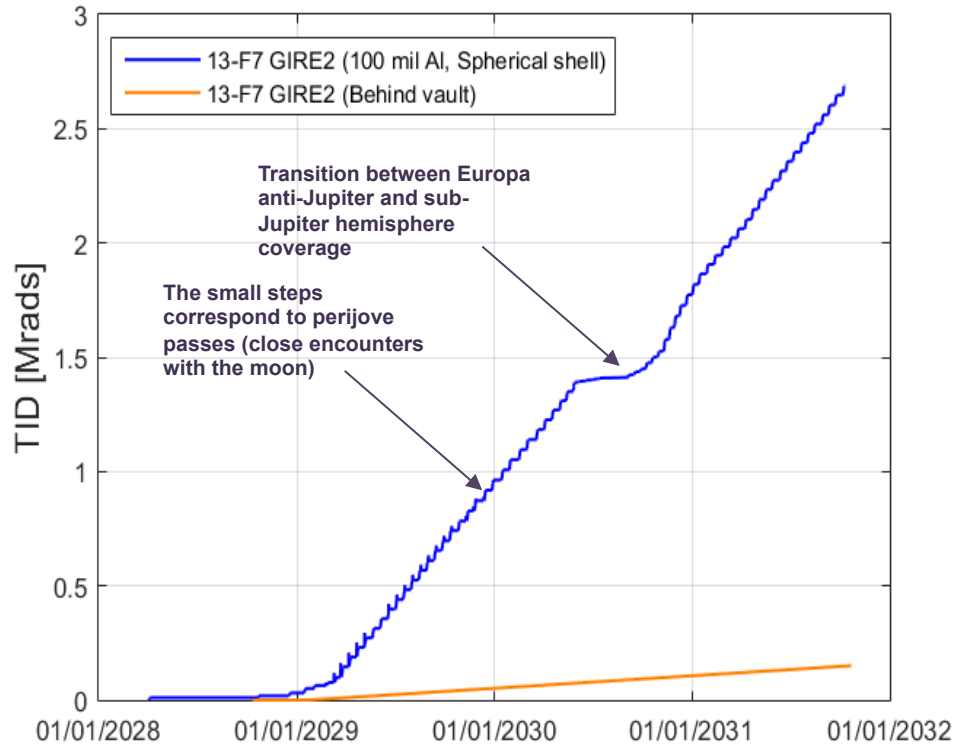


Europa Mission Radiation Environment – TID

- The **total ionizing dose (TID)** is a measure of the energy deposited by energetic electrons and protons in materials
- TID depends on the outside environment, shielding material, and target material
- The moon encounters are the times with the highest dose rate
- The spacecraft holds a heavily shielded box called “vault” (~400 mil thick Al) that contains most sensitive electronics
- The dose inside the “vault” is reduced to 150 krad compared to the 3 Mrad mission dose cap (behind 100 mil of Al)



Radiation sensitive components shall be shielded to ensure TID exposure of no greater than 50% of their demonstrated tolerance

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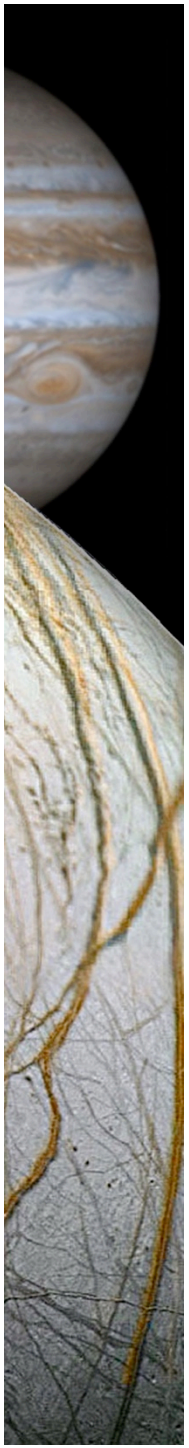
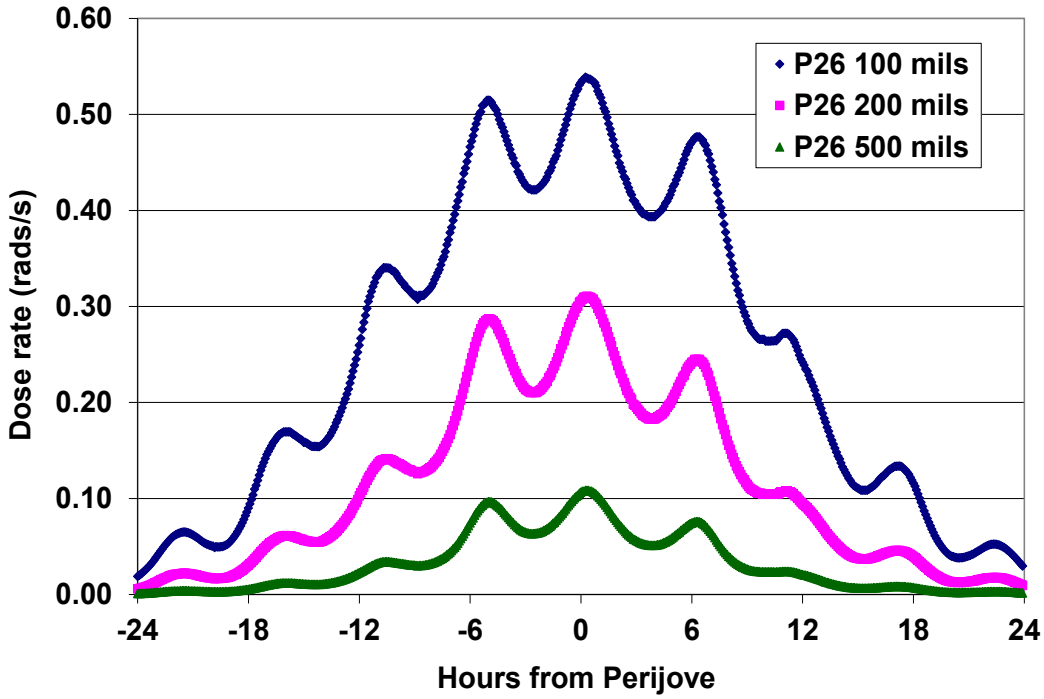
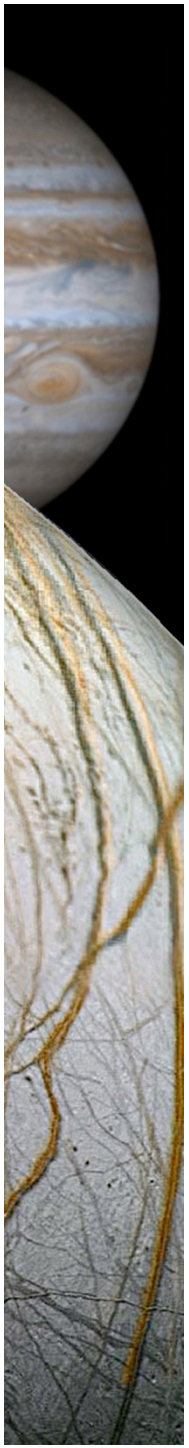


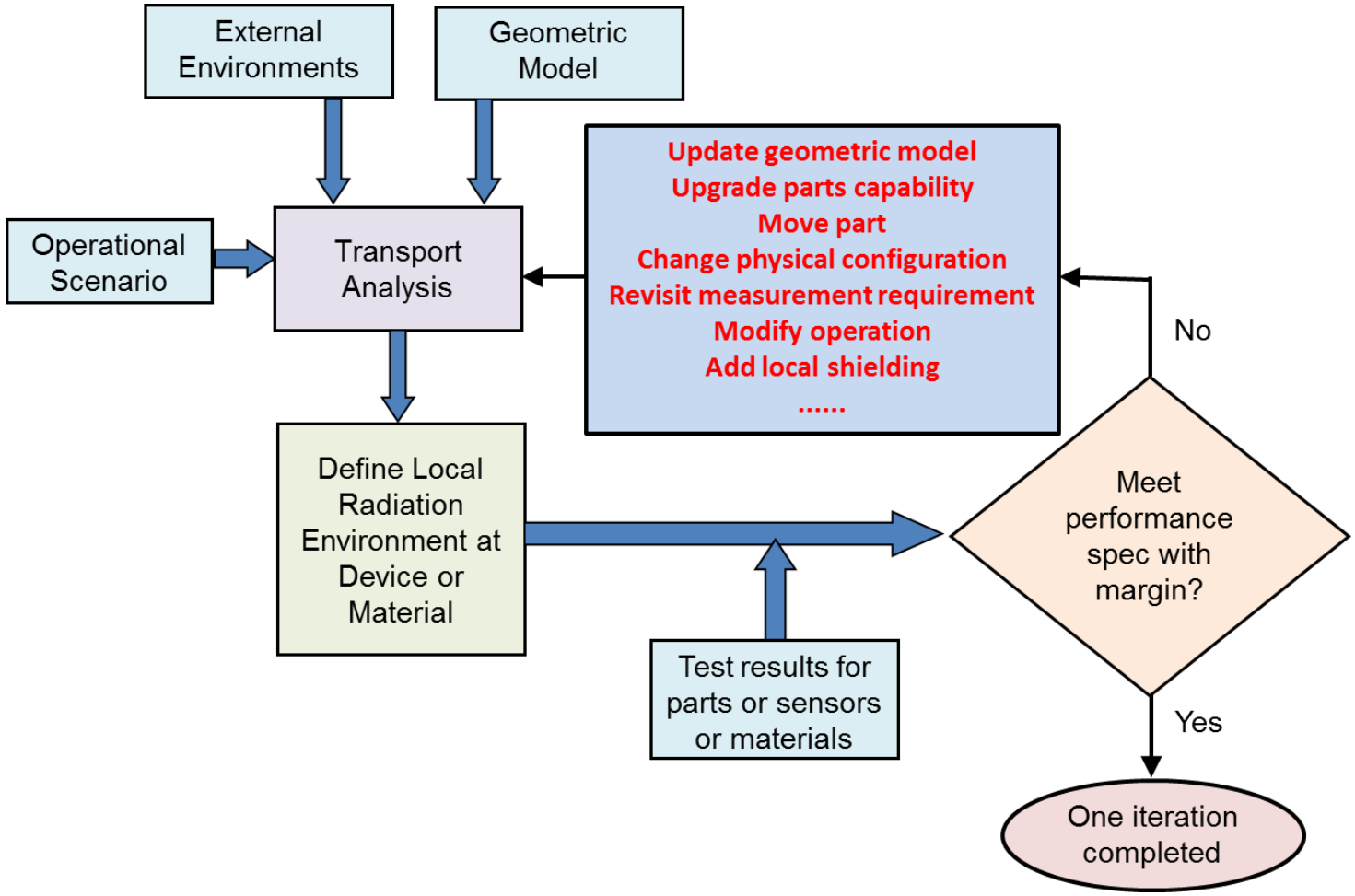
Dose Rates for a single Europa Flyby for various Al-Spherical shell shielding thicknesses. All flybys have similar dose profile



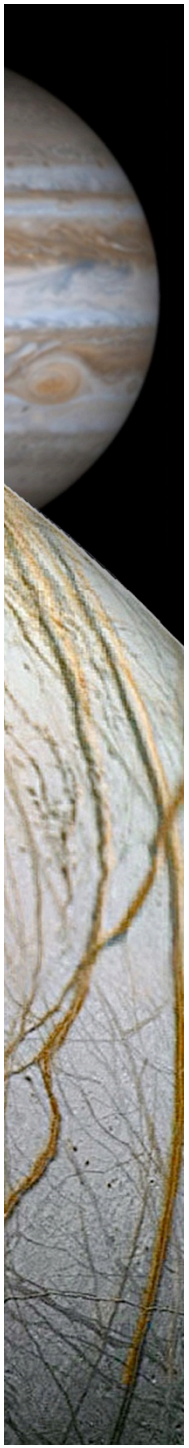
The mission would see ~50 flybys with variable dose rate profile
The dose rate profile is really dependent on shielding



General Radiation Hardening Process Flow for Spacecraft



Radiation Hardening of Spacecraft for High Radiation Environments is an Iterative Process



EEE Parts

Implementation Strategy

Europa's mission requirements necessitate the implementation of a comprehensive EEE parts program to reduce risk.

- EEE parts that are hi-reliability and radiation hardened will be implemented in the design process whenever available
- A Preferred Parts Selection List (PPSL) has been developed for Europa. EEE parts on this list meet and/or exceed radiation and reliability requirements
- Where available, existing radiation hardened/tolerant devices will be used.
- The development of radiation hardened devices and processes will be avoided.
- Non-RH parts shall be characterized for all required environments and applications
- Where an RH part is not available, parts with known rad tolerant process will be used
- Trade studies will be required if non rad hard parts are selected when radiation hardened/tolerant parts are available
- JPL Parts Engineering will be working closely with manufacturers of radiation hardened electronic components to meet Europa mission goals (technical, schedule and cost objectives)

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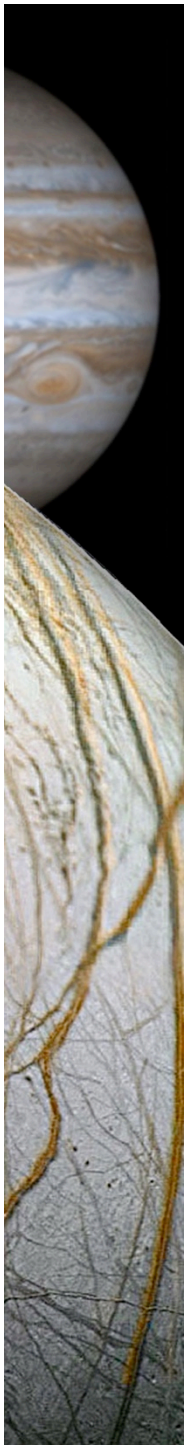
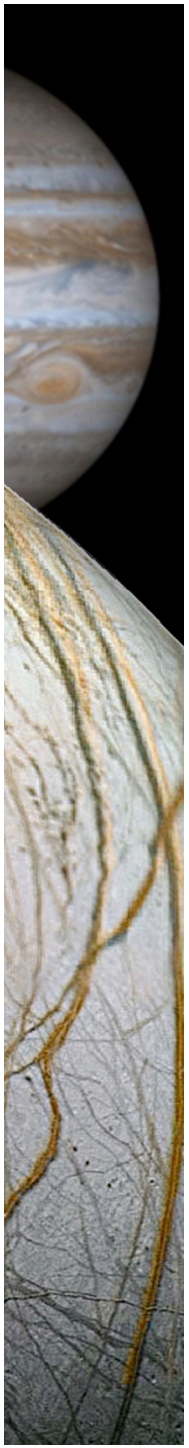


EEE Parts Plan Requirements

Radiation Requirements – Refer to JPL DocID D-80297

Radiation Effect	Radiation Level
TID, ELDRS	Refer to Environmental Requirements Document (ERD) for shielded environment. Parametric acceptance @ 90% confidence w/ 99% probability of success at part level or greater post irradiation specification limits
Displacement Damage	Refer to ERD for shielded environment. Parametric acceptance @ 90% confidence w/ 99% probability of success at part level or greater post irradiation specification limits
SEL	Linear Energy Transfer (LET)th >75 MeV-cm²/mg
SEGR/SEB	LETth >37 MeV-cm²/mg @ fully-off voltages or by application analysis
SEU	LETth >75 MeV-cm²/mg or $<10^{-10}$ per bit per day or by application analysis
SEFI	LETth >75 MeV-cm²/mg or $<10^{-3}$ events/yr or by application analysis
SET	LETth >75 MeV-cm²/mg or by application analysis

Application Analysis determined by Single Event Effects Analysis (SEEA)



Part's Selection

Total Ionizing Dose (TID) & Displacement Damage (DD)

- All parts must be shown to meet application requirements after irradiation to two times the radiation level as determined in the ERD
- Radiation data should demonstrate that a probability of survivability is at least 99% with 90% confidence level (99/90)
  - Recommended test sample size is 5 (per wafer lot) for each test condition
  - Minimum requirement is three (per wafer lot)
  - Minimum for characterization or investigation is case-by-case
- Effects of displacement damage and dose are considered additive
  - Slow BJTs, Photonics, and low-doped devices may require lot test
  - Testing for DDD and TID will be done on the same lot
- Radiation Lot Acceptance (RLAT) will be done with JPL Reliability Engineering concurrence on acceptance criteria
- Test readiness reviews (TRR) will be held prior to radiation testing
- Parts with application specific behavior will be considered in the Worst-Case Analysis
- Use annealing for CMOS - Dose rate recommend down to 100 mrad(Si)/s

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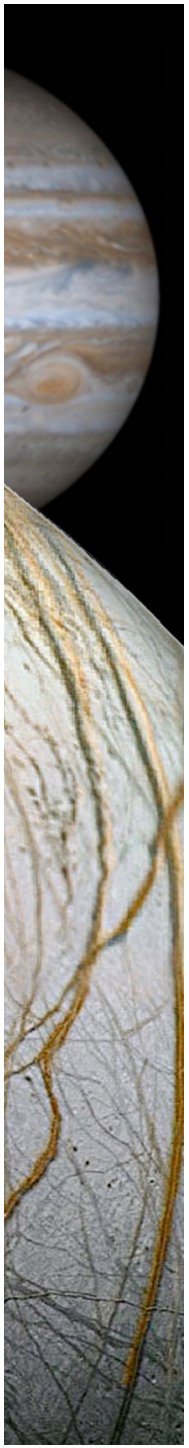

Radiation Requirements

ELDRS & Displacement Damage (DD)

- Enhanced Low Dose Rate Sensitvity (ELDRS)
  - Recommended characterization procedure includes high and low dose rate
  - Both biased and unbiased condition should be tested if worst case is unknown
  - MIL-STD-883, Method 1019 Condition B, C, or D as needed
  - Multiple lots or variable dose rates may be used
  - High dose rate (HDR) will always be tested
  - Current ELDRS recommendation is 45 mrad(Si)/s
- Displacement Damage
  - Total current displacement damage environment is 2.5E11 (1MeV eq. Neutrons, 1X)
  - Displacement damage is due mostly to electrons
  - Parts for test will be determined case by case
  - Electrons are predominate damage source
  - Testing is case-by-case
  - Electron-proton equivalency confirmed to this level for representative devices

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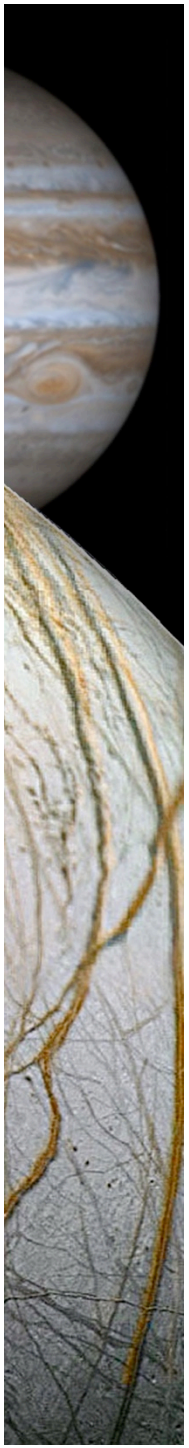


Preferred Parts Selection List (PPSL)

A Preferred Parts Selection List (PPSL) has been developed for the Europa Project. The EEE parts that are listed -

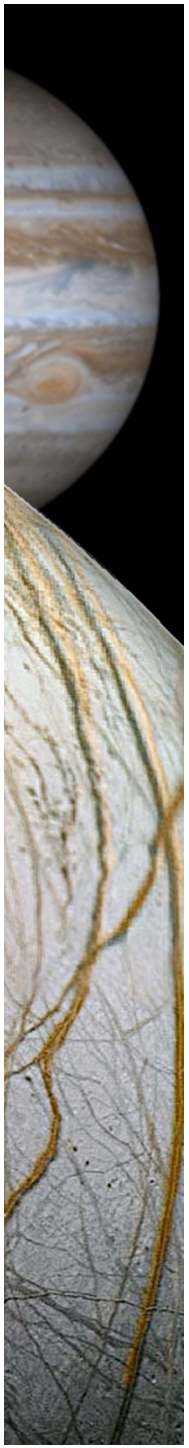
- Meet or exceed 300 krad TID
- Have demonstrated by test or analysis to meet the device application requirements for radiation effects
- Meet the quality/reliability requirements of the Europa Parts Plan

All parts under consideration start as candidates. The parts are reviewed to PPR technical requirements.

- Parts that fully meet requirements are approved will not require any added value testing and will be added to the PPSL provided that they are used within the data sheet limits.
- Parts that have been tested and proven to meet the mission requirements may be approved, but they may not be included in the PPSL. These parts will be assessed at the assembly level for the intended application.

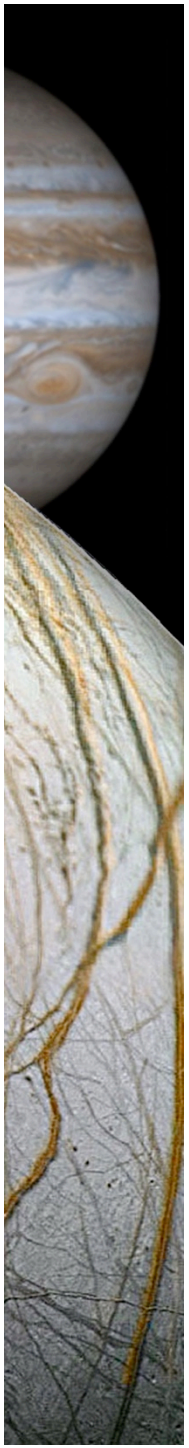
Worst-case data sheets (WCDS) will be available for all EEE parts.

There are presently over 375 active EEE parts on the PPSL. There are more than 375 active EEE parts on the Preferred Parts Candidate List.



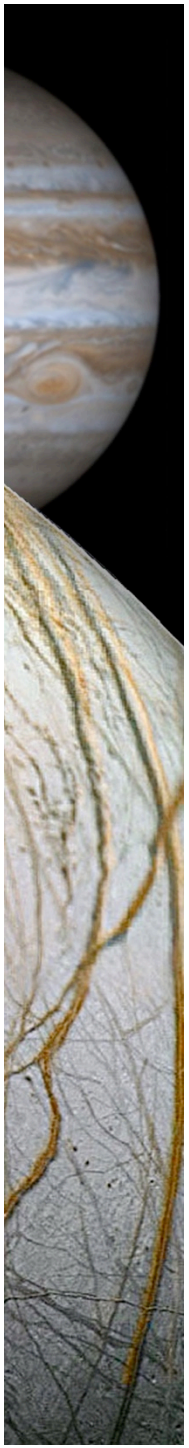
Europa Radiation Effects Evaluations

- Volatile Memory
- Non-Volatile Memory
- Power Subsystem devices
- Other Avionics devices
- Optocouplers
- ELDRS Testing
- Field Programmable Gate Arrays
- Materials



Volatile Memory - Significant Findings

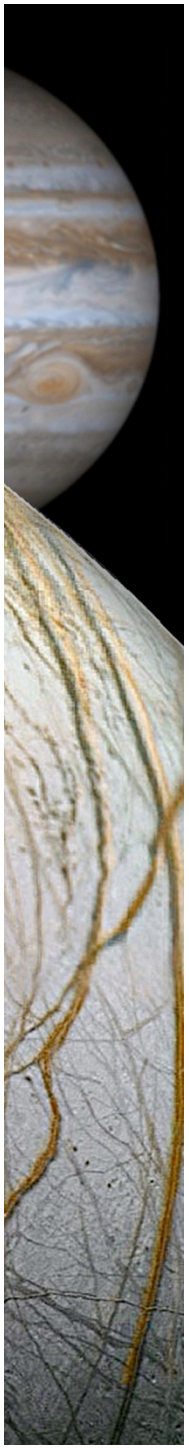
- SDRAM
  - Performance of all known devices is limited to 100 Krad or less
  - Vendor “100 Krad guaranteed” devices likely do not meet vendor spec when tested in worst case condition (refresh on)
  - Tests continuing to bound performance
- DDR2
  - Existing data sufficient to validate capability to 200 to 300 Krad but will require RLAT
- DDR3
  - Test results support TID capability to 200 to 300 krad
- All devices are prone to SEFI/SEU events and require mitigation, though none latch



Volatile Memory Radiation Test Status

Part#	Supplier	Size (GB)	Width	TID (krad)	Comments
DDR3					
MT41J128M8JP	Micron	1	x8	>200	Functional >300 krad with stuck bits
K4B1G0446G	Samsung	1	x4	>250	Functional >300 krad with stuck bits
DDR2					
IMXS108D2DEBG	Intelligent Memory	TBD	x8	TBD	
IS43DR81280	3DPlus-ISSI	1	x8	>200	Testing to > 300 krad Planned
SDRAM					
IS42S86400B	ISSI	0.5	x8	80	100 with stuck bits, refresh ”on” is worst case
EDS5104ABTA	3DPlus-ISSI	0.5	x4	50	Used on Juno
UT8SDMQ64M48	Aeroflex	3	x48	100	Actual performance in refresh mode may be less

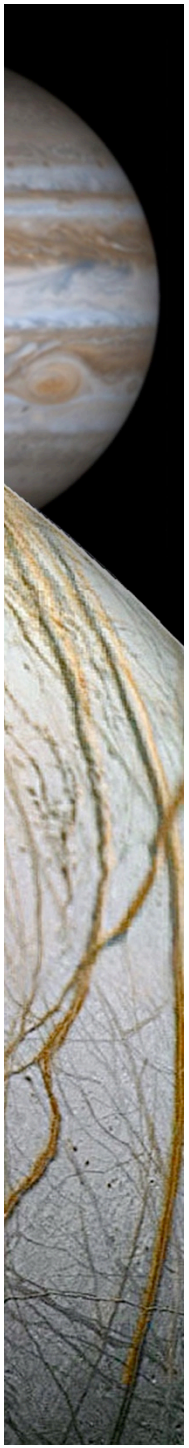
SDRAM limited to < 100 krad – DDR2/3 ~ 300 krad



Non-Volatile Memory

- Spacecraft requires 1 Gb memory storage
  - Driven by science data requirements
- Need to hold data until opportunity to transmit
- No radiation hardened devices large enough
- Commercial devices were evaluated
- A single device was found suitable (with mitigation) for the mission
  - Samsung 8Gb SLC Version M NAND flash

This device would still require Erase/Rewrite every 25 Krad to meet mission requirements



Non-Volatile Memory Radiation Test Status

Device	TID/DD (krad)	Comments
Micron 4Gb	<100	Not recommended for Europa 3/8 DUT non-functional after 100krad
Micron 32Gb	55	Not recommended for Europa 3/5 DUTs fail to erase
Micron 32Gb eNAND	10	Not recommended for Europa Non functional at 50 krad
Samsung 8Gb Rev A	>200	1% BER at 40krad Erase still possible after 600krad Not an ECM candidate due to SEE
Samsung 8Gb Rev M	>200	5E-5 BER @ 50krad, 10% BER at 200krad, write-able. Test to 300 krad with Erase/Rewrite in 25 krad steps Primary NVM for ECM
Samsung 8Gb Rev D	>200	
Samsung 8Gb Rev E	<100	Not recommended for Europa Unrecoverable page errors at 100krad
Samsung V-NAND 128 Gb	~ 20 krad (~200 krads array)	Control circuitry – limiting factor

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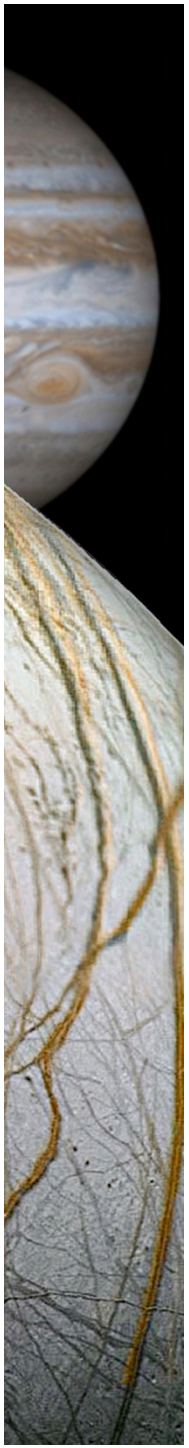

Optocoupler Displacement Damage Tests

Device	Equivalent Neutron (1 MeV) Fluence	Comments
Isolink OLH249	<5E11	CTR<20%, Not ECM Candidate
Isocom IS49	>2E12	CTR ~60% Candidate for Europa
Isocom CSM141A	>2E12	CTR ~70% Candidate for Europa
Isolink OLS049	<5E11	CTR<20%, Not ECM Candidate
Avago HCPL-5700	>2E12	CTR ~80% Candidate for Europa
Micropac 66179	<2E12	CTR<40%
Micropac 66296	<2E12	CTR~60%
Micropac 66294	>2E12	CTR ~75% Candidate for Europa

Several acceptable to Europa Displacement Damage Levels

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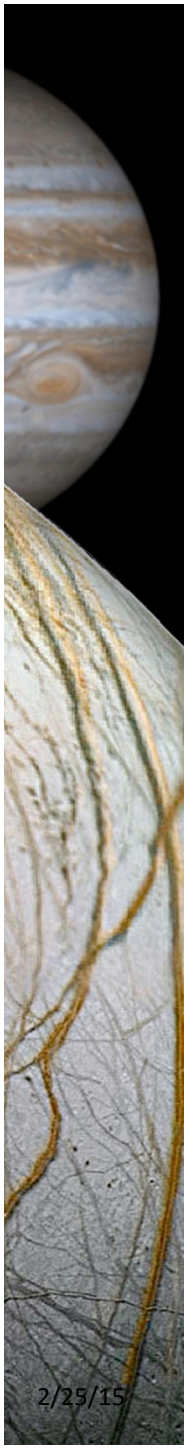

Power System Radiation Test

Part#	Supplier	Function	TID (krad)	Comments
MSK5063RH	**MSK**	Buck Regulator: Rad Hard High Voltage Synchronous Switching Regulator (w/FET)	300	@ 0.100 rad(Si)/s
MSK5055RH	**MSK**	Buck Regulator: Rad-Hard Regulator Controller, Switching, High Voltage, Synchronous	300	@ 0.100 rad(Si)/s
MSK196RH	**MSK**	Rad Hard Current Sense Amplifier	In work	Alternate parts being reviewed
MSK6000RH	**MSK**	Current limiting switch: Dual Rad Hard High Side Driver with Current Sense	300	@ 0.100 rad(Si)/s
MSK5800RH	**MSK**	Linear Regulator w/ adjustable output	In planning	Alternate parts being reviewed
DAC121S101 QM	**Texas Instr.**	12-bit Digital-to-Analog Converter	In Work	Will be tested at low rate to take advantage of annealing
LTC2977	**LTC**	PMBus Controller	Non functional at 20 krad(Si)	

- Power distribution is required throughout the SC
- Vast Majority of commerical devices fail at low dose levels
- Selected RH power devices can meet 300 krad

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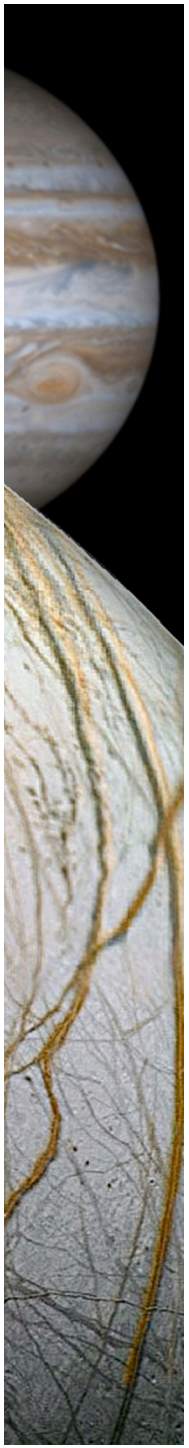
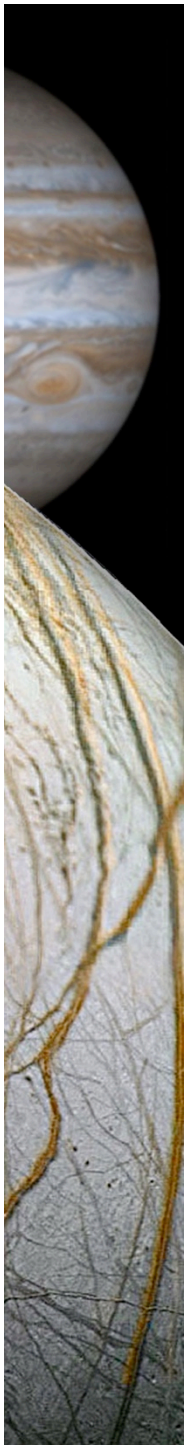


Avionics Device Testing

Part	Manufacturer	TID (Krad)	Comments
Isolator IL611	NVE	300	Likely Immune
Isolator IL715T	NVE	300	Likely Immune
SRAM UT8ER512K32	Aeroflex	300	Tested at 0.1 R/s
SRAM UT8R4M39	Aeroflex	300	Tested at 0.1 R/s
Spacewire	Aeroflex	>450	Tested at 0.1 R/s

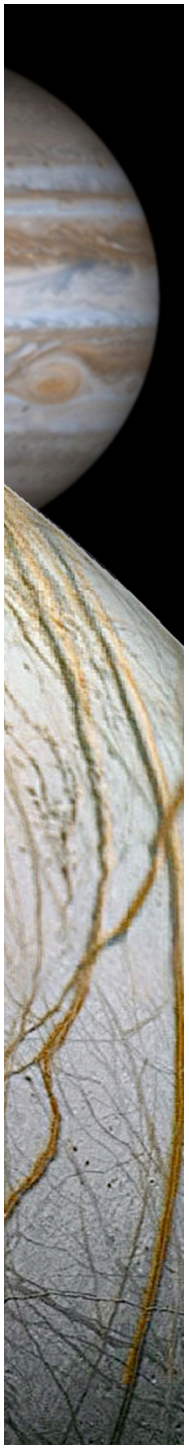
SRAMS/Spacewire were 100 Krad Vendor rated - Functionalto 300 Krad when tested at 0.1 R/s



FPGA Radiation Test Status

Device	Manufacturer	TID/DD (krad)	Comments
Virtex V4QV	Xilinx	>300	
Virtex V5	Xilinx	>500	
Virtex V5QV	Xilinx	>1000	Candidate for Europa
Virtex 7-series	Xilinx	Not Tested	Not recommended for Europa
RTAX 250/1000/ 2000/4000	Microsemi	200/300	Candidate for Europa Static current increases, rise/file time degrades at 300 Krad
Aeroflex UT6325	Cobham/ Aeroflex	300	Candidate for Europa Following packages are qualified: 208 CQFP, 288 CQPF, 484 CLGA and 484 CCGA
Microsemi RTG4	Microsemi	150	Device will be rated to 100 krad

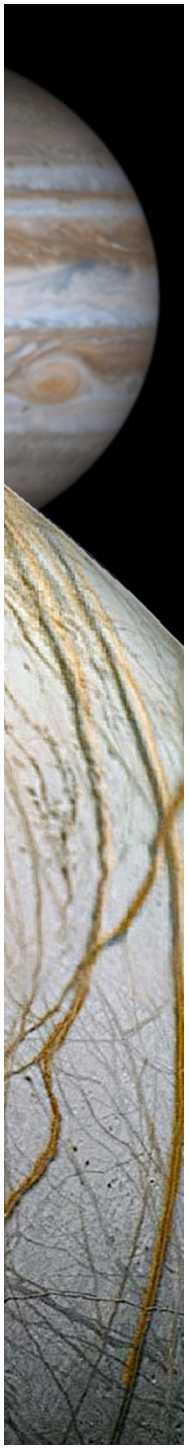
V5QV, RTAX, UT6325 found acceptable to 300 krad
However – Commercial devices exceed 300 Krad as well



ELDRS Test Method – Parts Tested

Parts	Description	Test type @300krad	Manuf.	Functional fail	Fail specs	comments	Recommended for Europa
LM124	Operational Amplifier	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	TI	No	Yes	LM124 do not fail functionally @300krad Need to work on spec limits No dose rate effects and no non-linearities	Yes
LM2941	Linear Regulator	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	TI	No	Yes	RM2941 do not fail functionally @300 krad Need to work on spec limits Degradation trends show a slight dose rate effect	Yes
LM136	2.5 Voltage reference	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	TI	No	Yes	LM136 do not fail functionally @300 krad Dynamic Z out of spec <125 krad LDR Degradation show a dose rate effect	Yes
LM139	Comparator	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	TI	No	Yes	LM139 do not fail functionally @300krad Ib, Vos goes out of spec < 150krad No dose rate effects and no non-linearities	Yes
REF05	5V voltage reference	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	AD	No	Yes	REF-05 do not fail functionally @300 krad Vref, Vload and Vline, Isource, Isink, Ishort-circuit go out of spec <125 krad LDR Dose rate effects and circuit effects	Maybe
PM139	Comparator	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	AD	No	Yes	PM139 do not fail functionally @300krad Ib, Isink goes out of spec < 200krad No dose rate effects and no non-linearities	Yes
RH117	Linear regulator	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	LT	Yes	Yes	RH117 Fails functionally @125 kRad(Si) (LDR) VRline, Vrload, Vout, Dropout, IADJ and Vref go out of spec < 125 krad (LDR) Severe dose rate effects	No
RH1014	Operational amplifier	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	LT	No	Yes	RH1014 do not fail functionally @300 krad Voffset and Ib go out of spec < 70 krad No dose rate effects and no non-linearities in degradation trends	Yes
RH1009	2.5V Reference	10 mRad/s 80 mRad/s 25 Rad/s Flight-like	LT	No	Yes	RH1009 do not fail functionally @300 krad Vref, Load Reg and Dynamic impedance goes out of specs below 150 krad (LDR) Dose rate effects	Yes

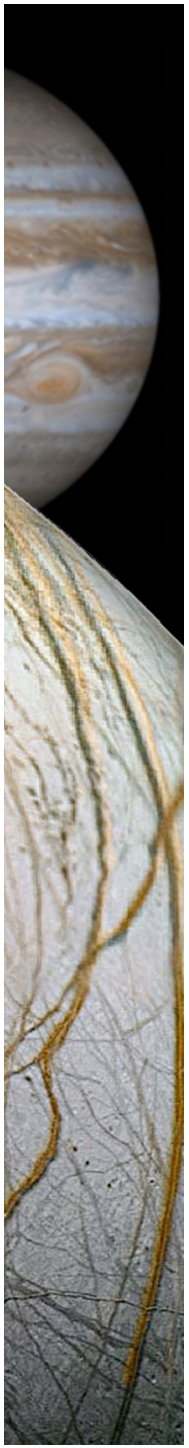
Accelerated ELDRS test developed – Test Duration ~100 days



Materials Approach

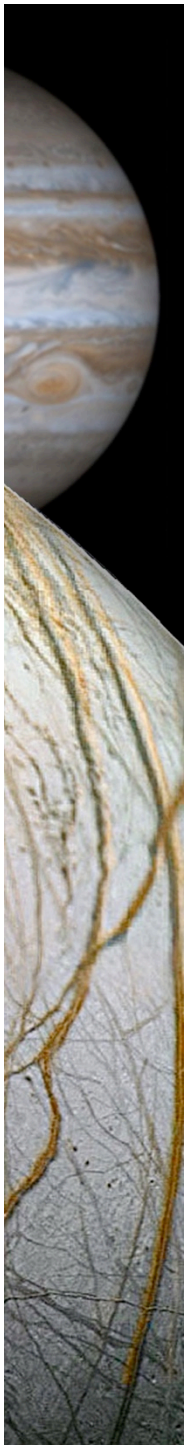
- Total Ionizing Dose for materials external to the vehicle or with little shielding may see doses greater than 1.0E10 rad(Si) (100 MGray)
- Issues include
  - Degradation of mechanical properties
  - Degradation of dielectric strength
  - Space charging effects and discharge
- Significant materials testing is being conducted
- Project use of Approved Materials List
  - Includes radiation capability

Dose to surface materials ~ 100 MGray



Materials Approach

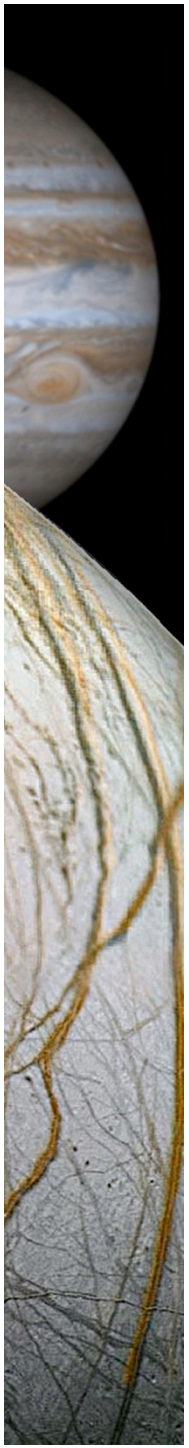
- Example of on-going Materials testing
  - Common Adhesives
  - Electrical Connectors
  - Wire/cable
  - Circuit card material
  - Thermal Control Coatings
  - Multi-layer Insulation
  - Glasses / Optics
  - Composite materials
  - Lubricants



Materials - Elastomers

Elastomers		
Material	**Radiation Dosage Limit (rad) in Air**	**Radiation Dosage Limit (rad) in Vacuum**
Viton	1.0×10^5	1.0×10^6
Buna N, Nitrile	1.0×10^6	1.0×10^7
Neoprene	1.0×10^6	1.0×10^7
Butyl	1.0×10^5	1.0×10^6
Silicone	1.0×10^7	1.0×10^8
Kalrez 1045, Chemraz	1.0×10^6	10×10^6
EPDM	1×10^7	1×10^8
EPR	1×10^7	1×10^8

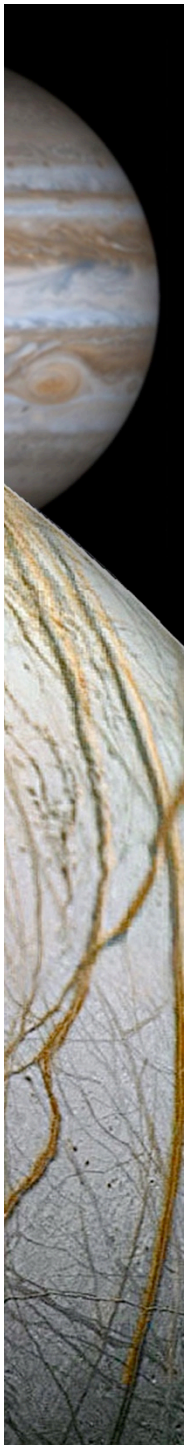
Based on Europa Clipper Approved Material List



Materials - Plastics

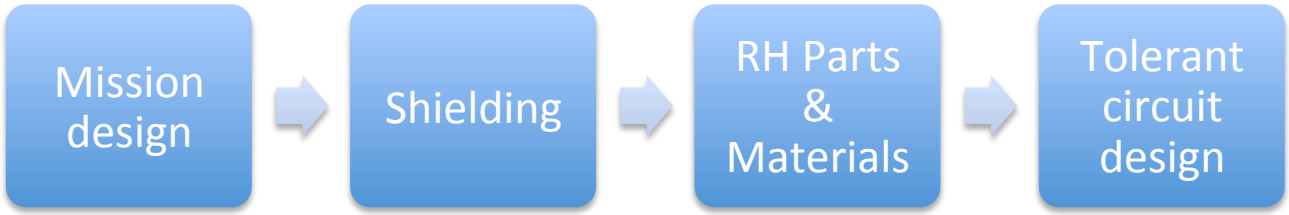
Plastics		
Material	**Radiation Dosage Limit (rad) in Air**	**Radiation Dosage Limit (rad) in Vacuum**
PTFE	1.5×10^4	5×10^5
FEP Teflon	2.4×10^5	1×10^6
PFA Teflon	5.0×10^6	10×10^6
MFA Teflon	1.5×10^4	5×10^5
Zymaxx (PFA + graphite fibers)	5.0×10^6	20×10^6
Glass Filled PTFE	1.5×10^4	5×10^5
Steel Filled PTFE	1.5×10^4	5×10^5
Carbon Filled PTFE	1.5×10^4	5×10^5
PEEK 450G	>1000 Mrad	>1000 Mrad
Kynar	1.0×10^8	1.0×10^9
PCTFE (Kel-F 81)	1.0×10^6	10×10^6
Torlon	1.0×10^9	$> 10^9$
Vespel	1.0×10^9	5×10^{10}

Based on Europa Clipper Approved Material List



Summary

- Radiation challenge for Europa is significant, 3 Mrad @ 100 mil eq. Al (30 kGray @ 0.25 cm)
- System level approach to surviving radiation
  - Mission design limits total dose to 3 Mrad @ 100mil Al eq.
  - Shielding vault for a majority of electronic systems
  - Subsystem and local shield as required
  - Characterization of parts and materials
  - Use of approved parts and materials lists
  - Selection of parts and materials for radiation tolerance



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EUROPA CLIPPER
NASA
Thanks
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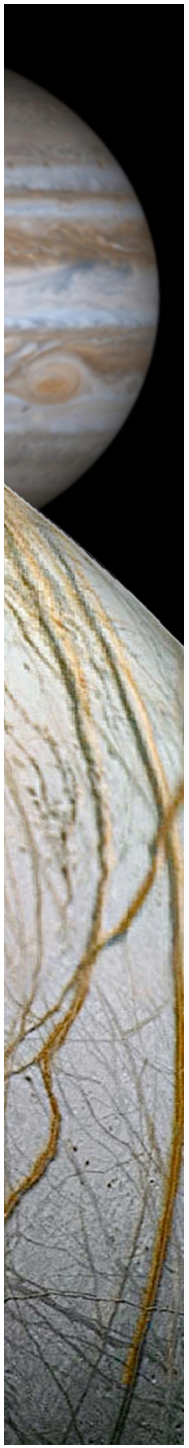
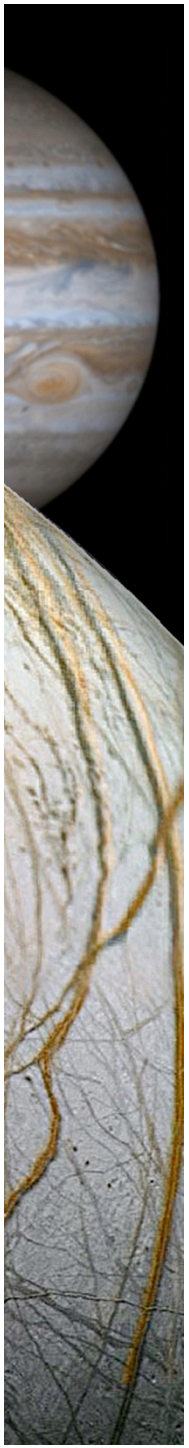
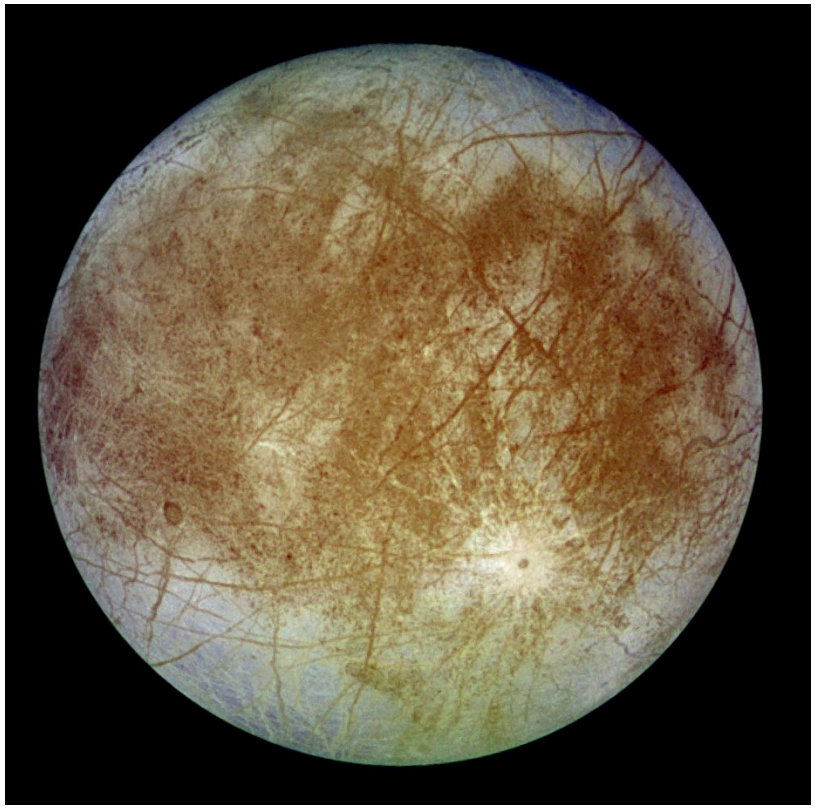


Backup

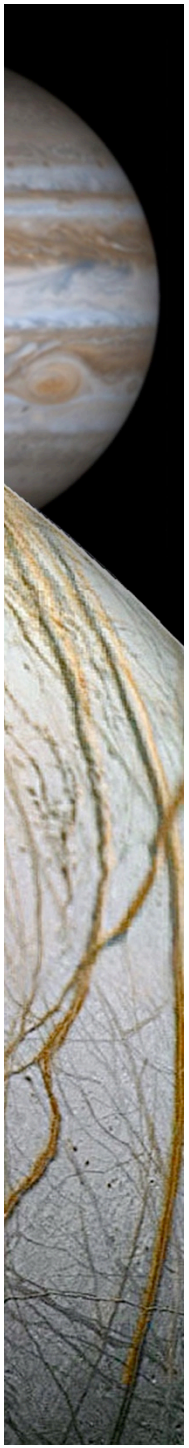


Europa: Key to Icy World Habitability



- **A world of rock, ice, and water the size of Earth's moon**

The Motivation



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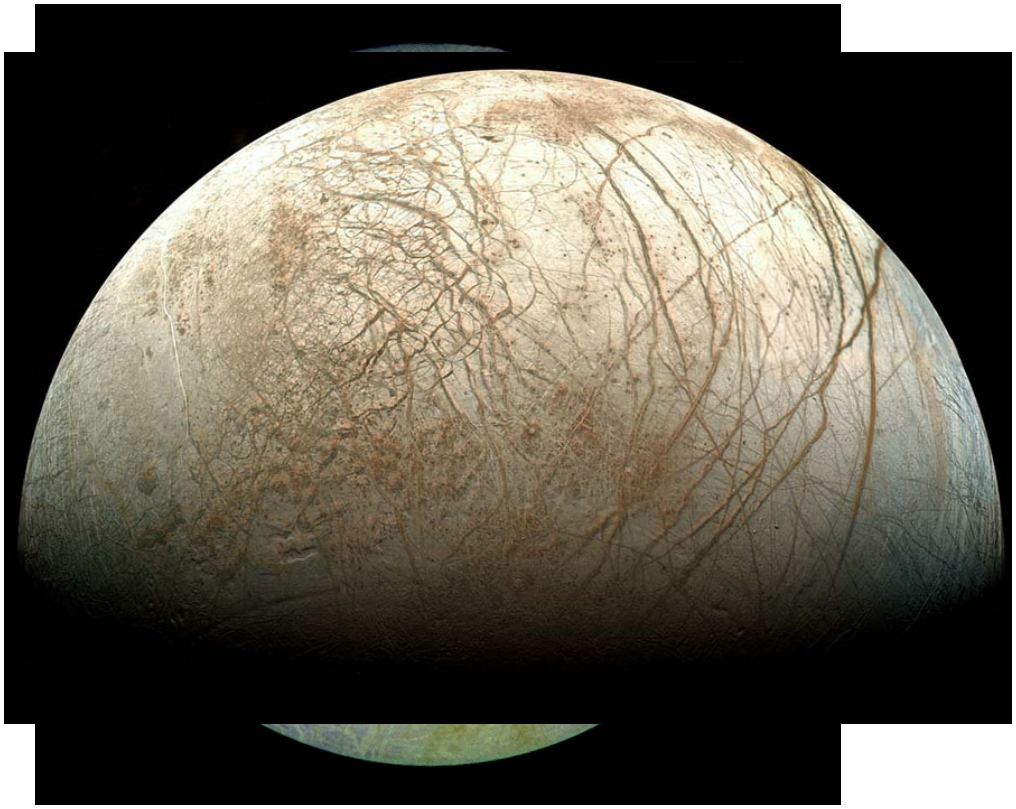
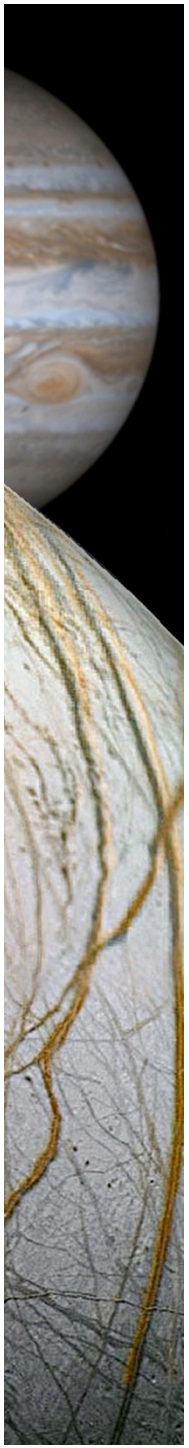
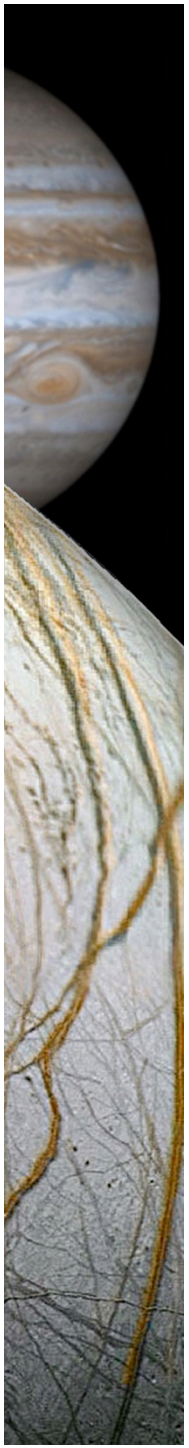


- **A world of rock, ice, and water the size of Earth's moon**
- **One of the youngest surfaces in the solar system**



Europa: Key to Icy World Habitability

- A world of rock, ice, and water the size of Earth's moon
- One of the youngest surfaces in the solar system
- Plentiful cryovolcanism



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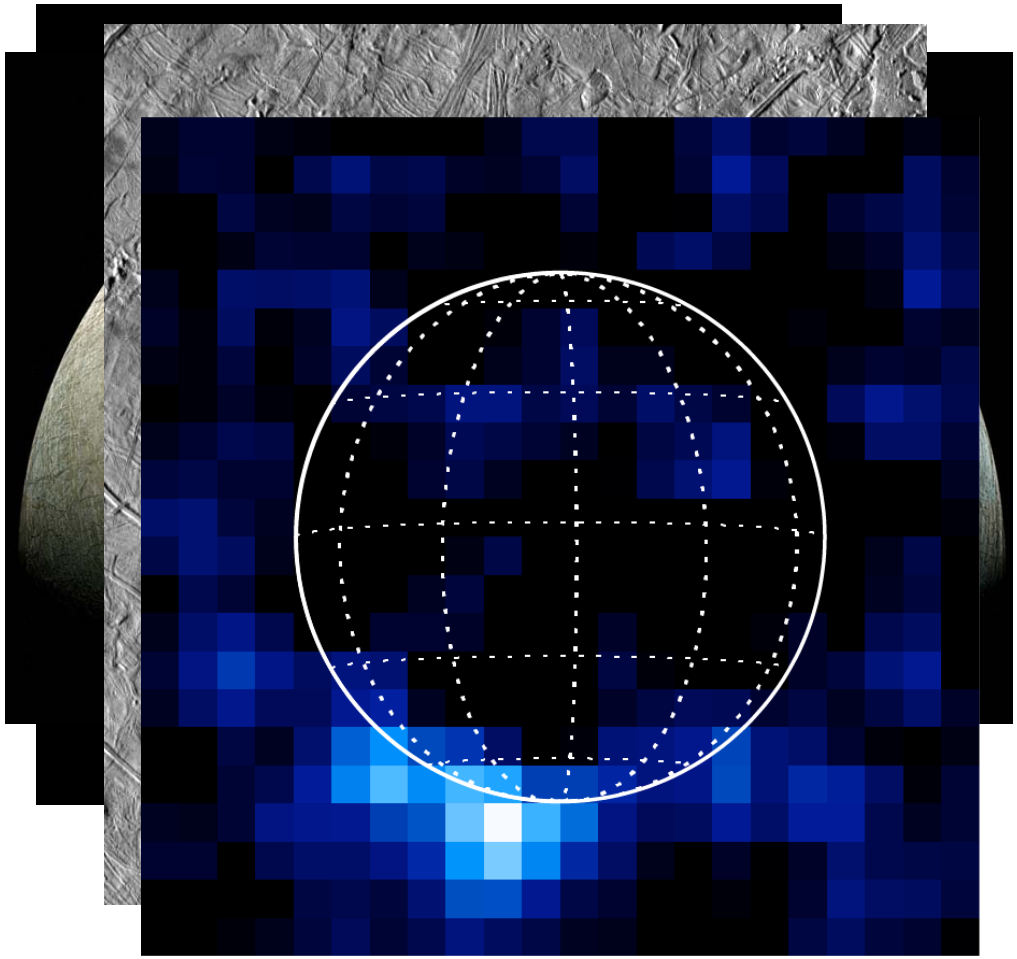
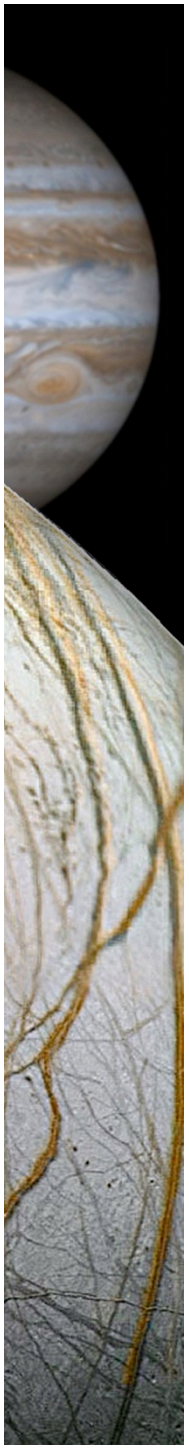


- A world of rock, ice, and water the size of Earth's moon
- One of the youngest surfaces in the solar system
- Plentiful cryovolcanism
- Possible geysers and plumes



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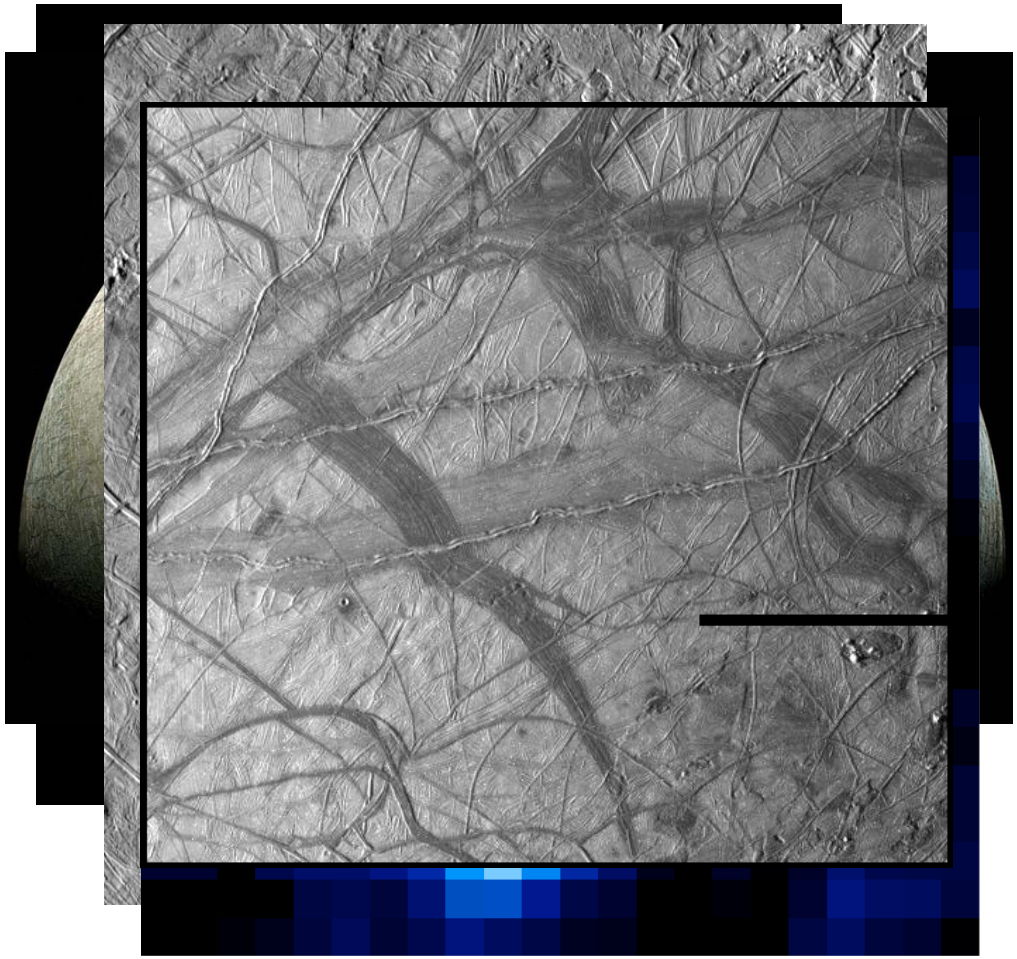

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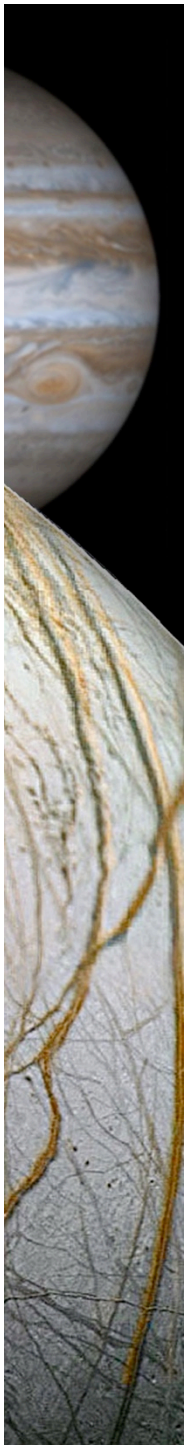
- Earth-like global tectonic activity



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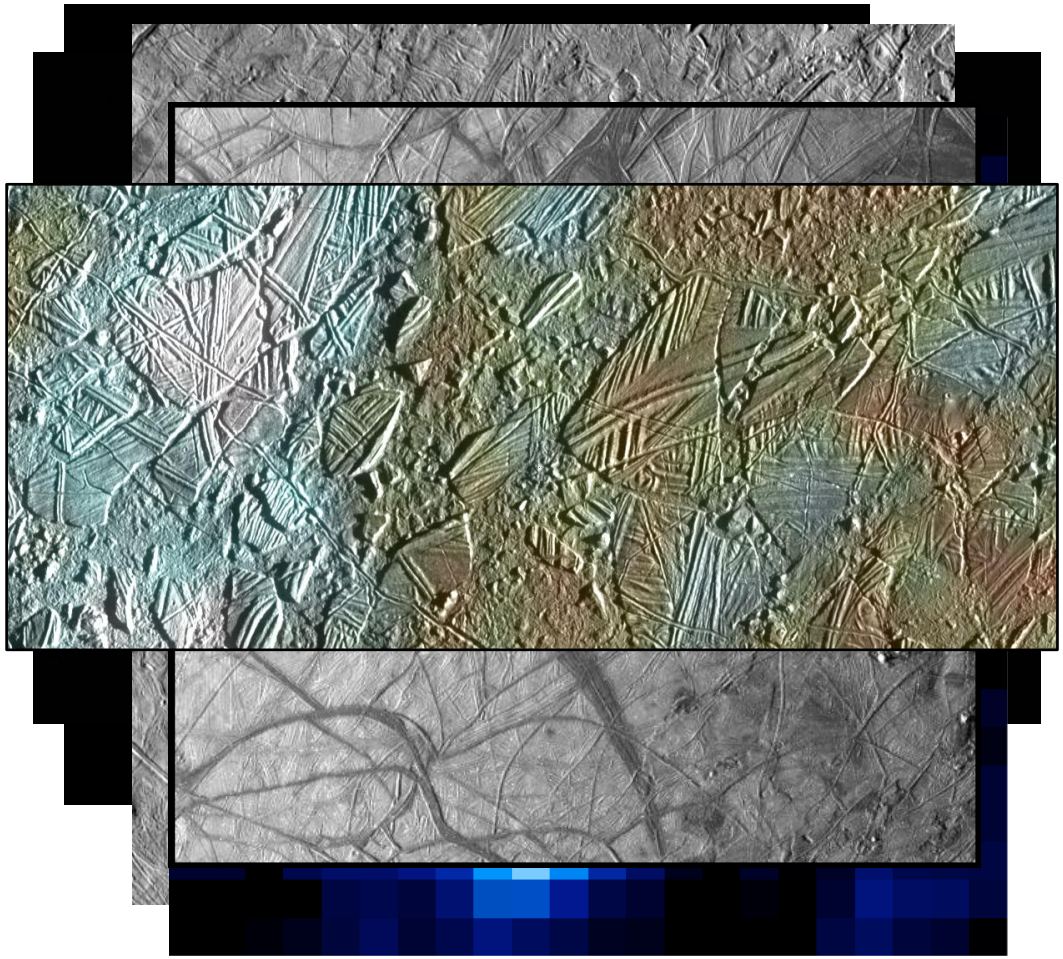

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- Widespread surface disruption

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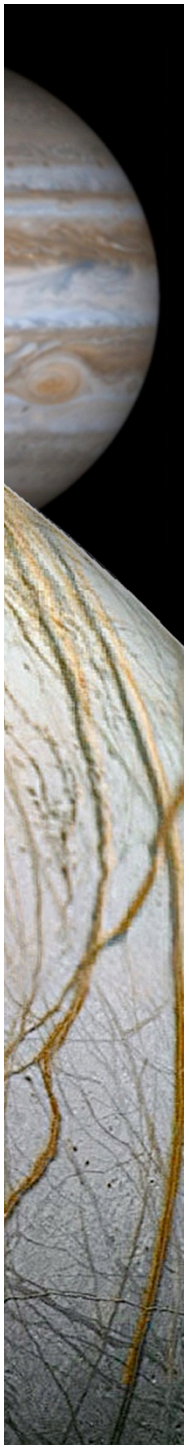

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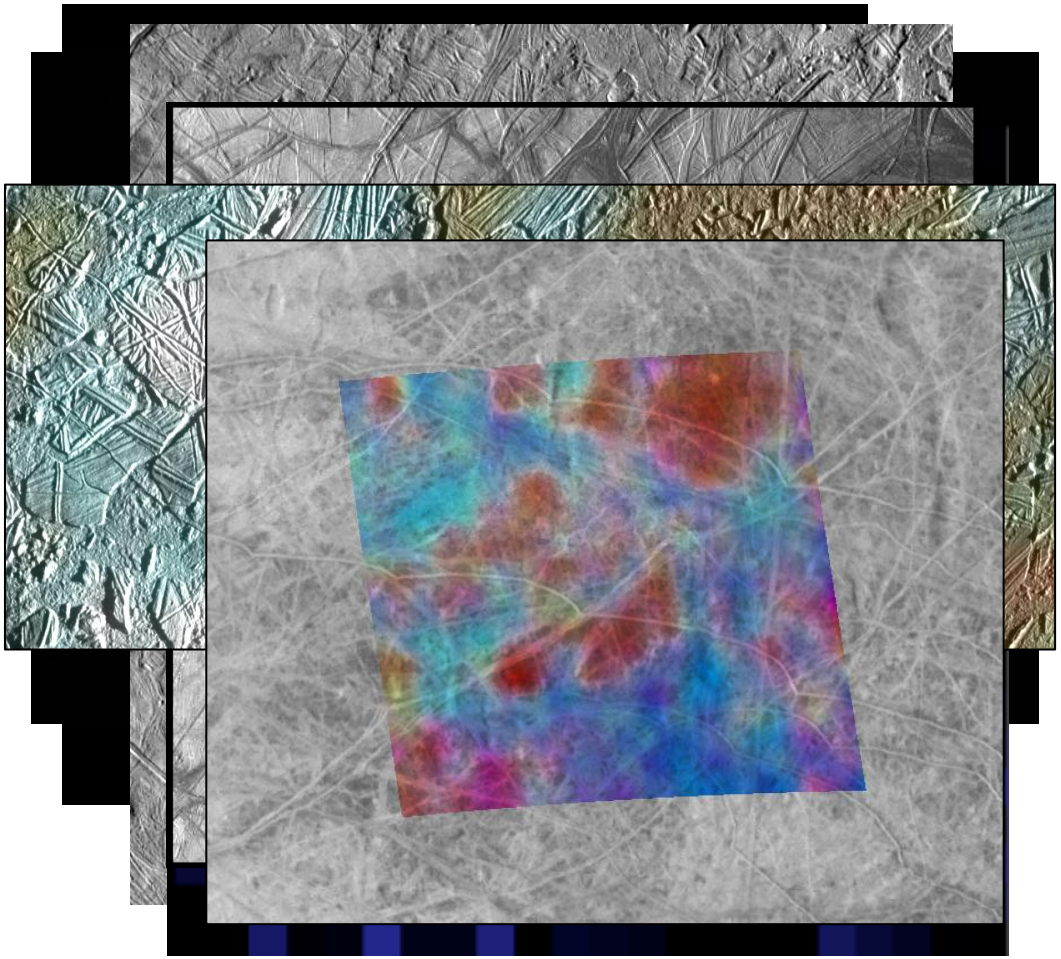

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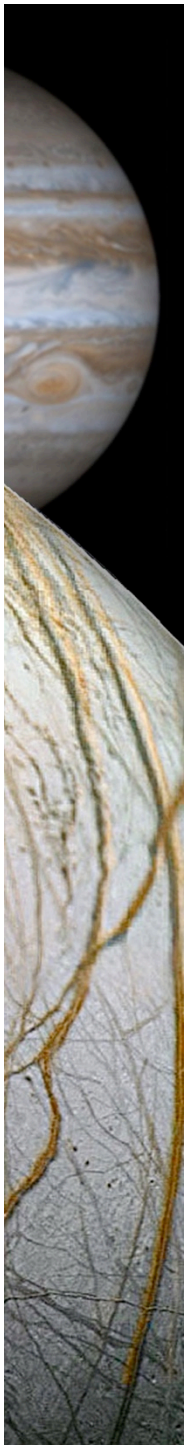

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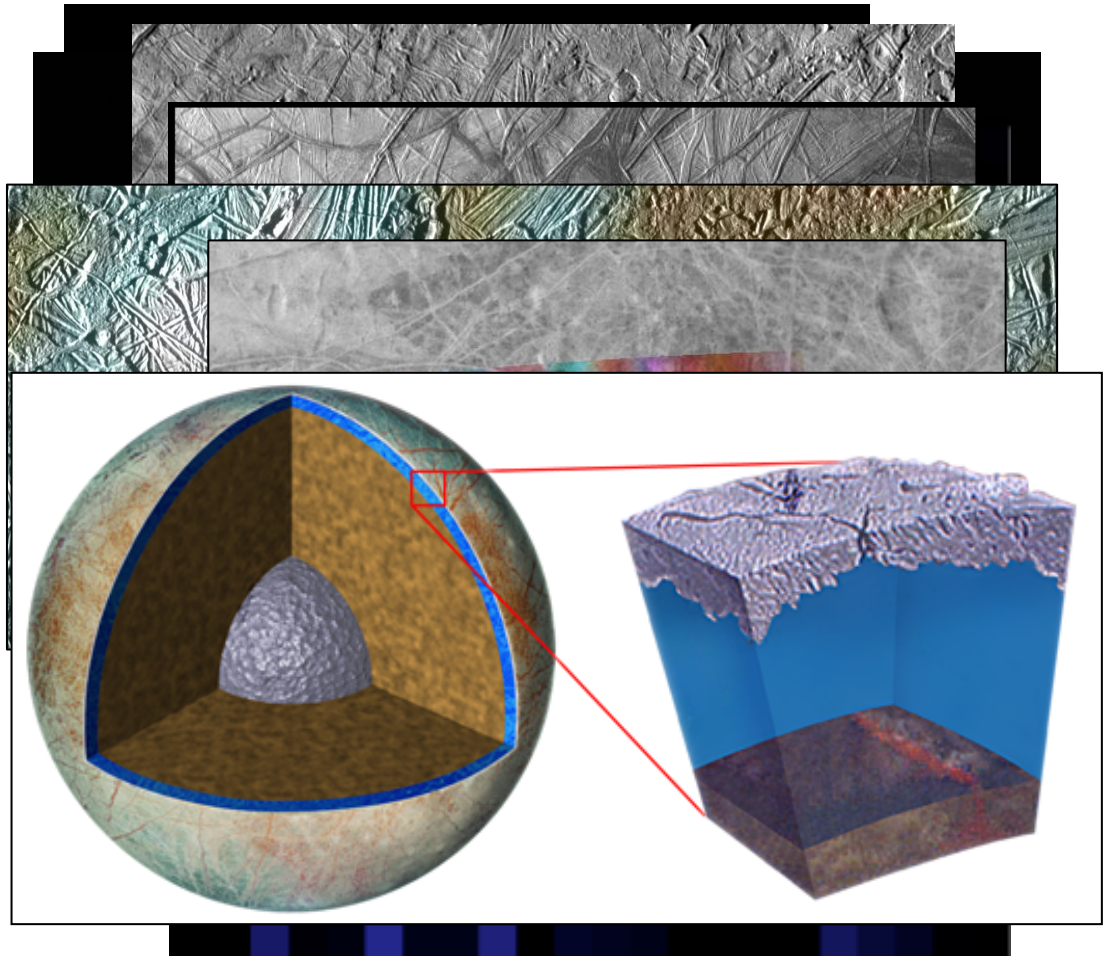

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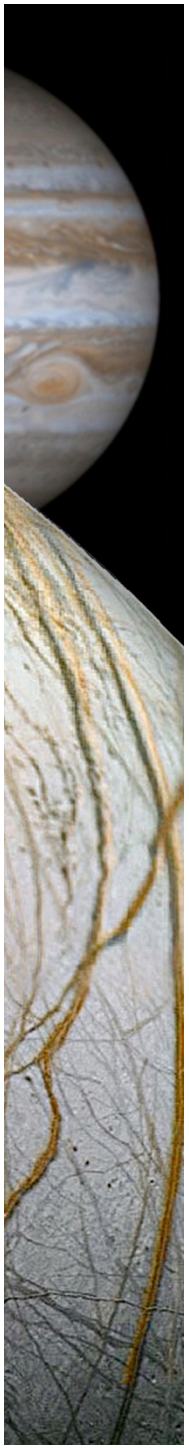
- Subsurface ocean: our Solar System's best chance for extant life beyond Earth?



Habitability: Ingredients for Life

Water:

- Probable saltwater ocean, implied by surface geology and magnetic field
- Possible lakes within the ice shell, produced by local melting

Chemistry:

- Ocean in direct contact with mantle rock, promoting chemical leaching
- Dark red surface materials contain salts, probably from the ocean

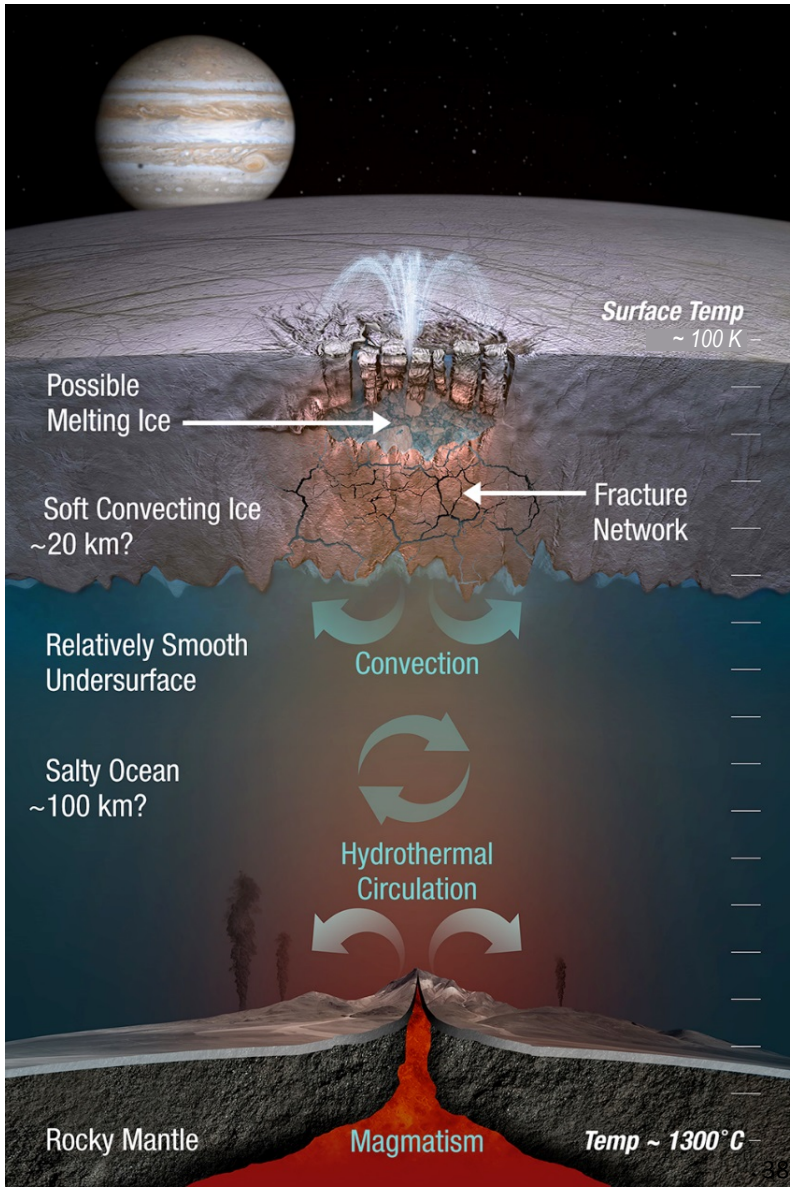
Energy:

- Chemical energy could sustain life
- Surface irradiation creates oxidants
- Mantle rock-water reactions could create reductants

Activity:

- Geological activity "stirs the pot"

Europa Flyby Mission would verify key* habitability *hypotheses



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