Unexpected Anomaly of GHF On-board

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- GHF （Gradient Heating Furnace)
- ANOMALY
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  - Direct Cause
  - Trouble shootings
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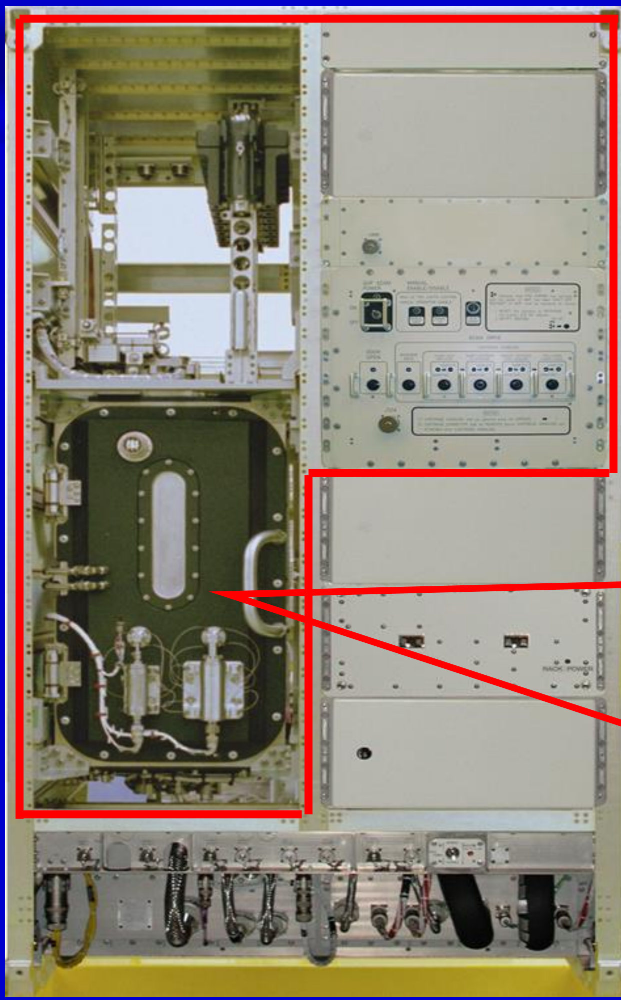
- BACK GROUND FACTORS
- LESSONS LEARNED
- CONCLUSION

GHF (Gradient Heating Furnace)

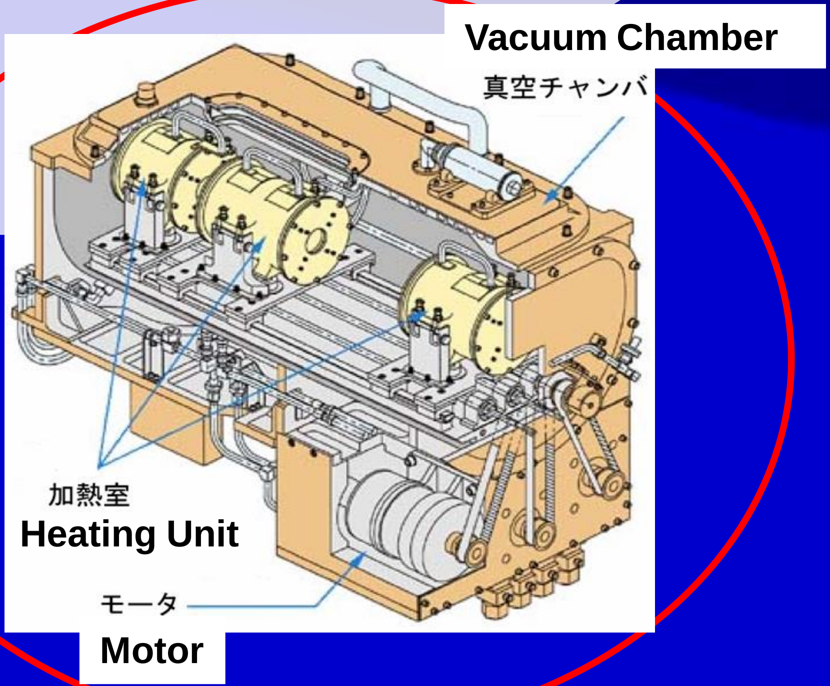
ISS Payload

GHF



GHF is a vacuum furnace that contains three heating units. Their positions and temperatures can be independently controlled, and various temperature profiles can be realized. This facility will be mainly used for high quality crystal growth experiments using unidirectional solidification. It can operates up to 1,600 degreeC. 150K/cm at 1,450 degreeC.

GHF has an automatic sample exchange system that can be accommodate up to 15 samples to reduce crew operation.



ANOMALY(1/5)

Phenomena

The following anomalies happened during on-board commissioning in April 2011. Over-current protection means reacted normally in both cases.

●Over power

GHF Control Equipment (GHF-CE) detected over-power condition of #2 heater unit of Center Heating Unit (limit:900W) and shut down GHF. Heater temperature was 800 degree C.

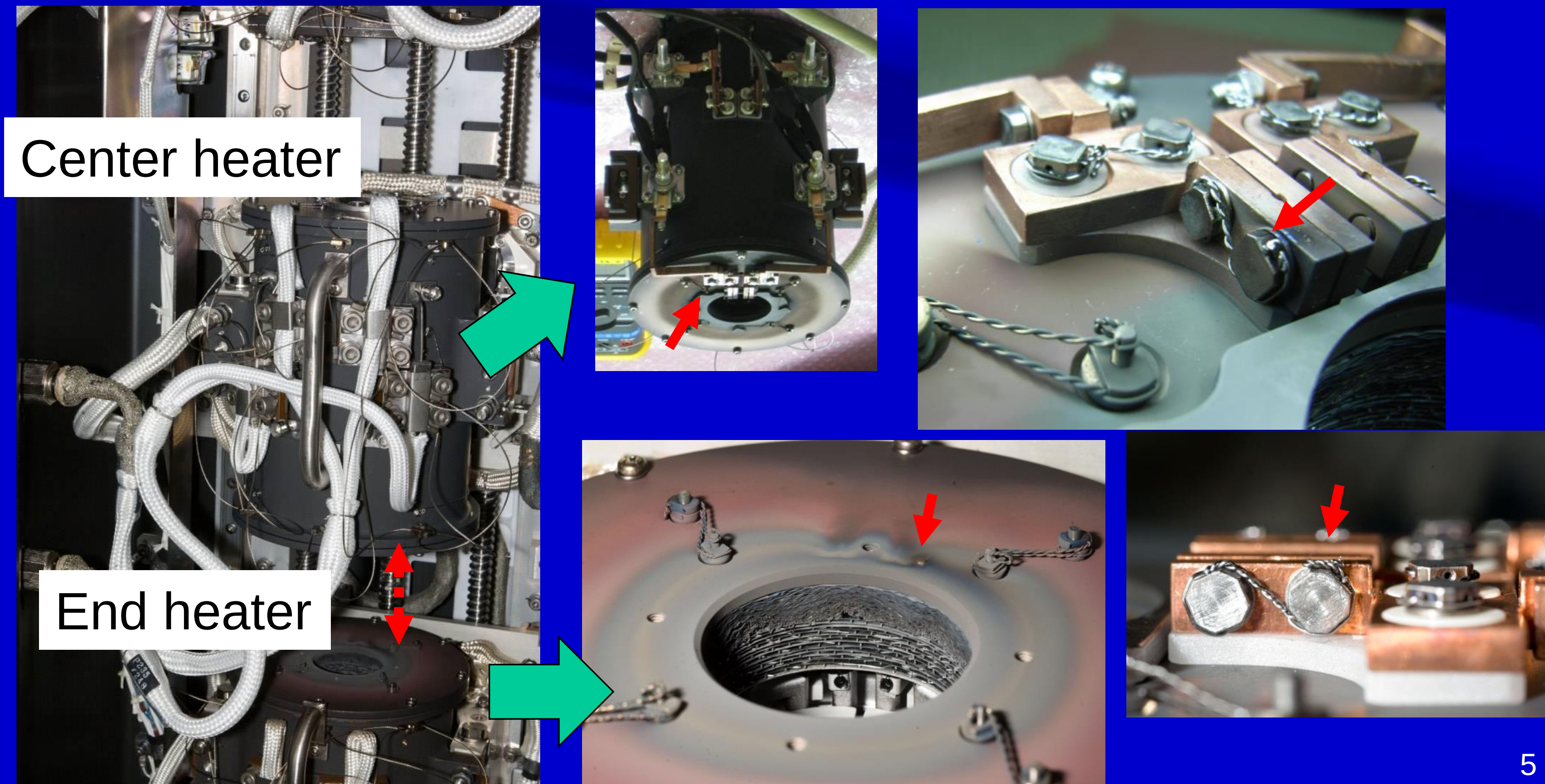
●Over current

GHF-CE detects over-current condition of #2 heater of Center Heating Unit and initiated warning. Heater temperature was 1265 degree C.

ANOMALY(2/5)

Direct Cause

Electrical short between two heaters via lock-wire. Lock-wire on center heater changed shape somehow, and contacted on the surface of End heater due to thermal expansion of heater chassis and lock-wire when both heaters were close.



ANOMALY(3/5)

Trouble Shootings

●Inspection on-board

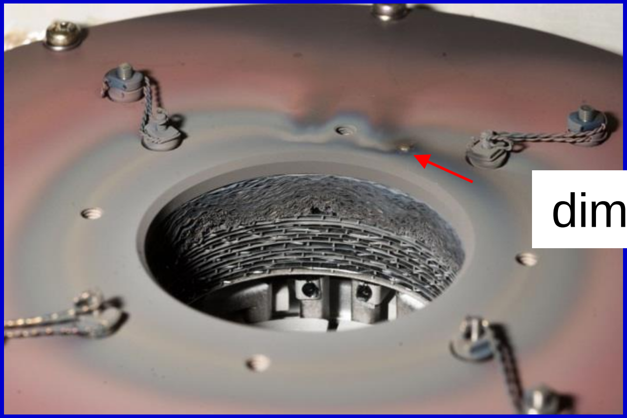
1. Insulation resistance : Center heater 0.16 MOhm, other heaters 5.67MOhm
2. Contamination on bus bar of Center Heater
3. Resistance between dimple and chassis of End heater : 0.3 ohm

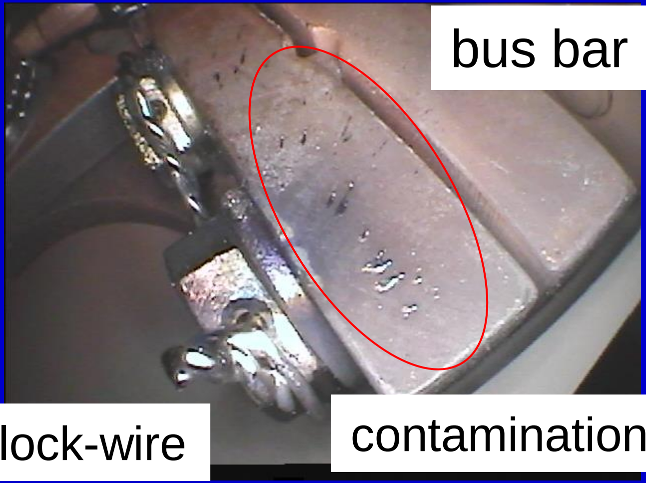
●Center heater return to ground and inspection

1. XPS (X-ray Photoelectron Spectroscopy) inspection
   Contamination on bus bar : Ta, Ti
   (lock-wire : Ta, flange of heating unit : Ti)

●Thermal stress relief test of lock-wire

●Reproductive test on over current protection : Maximum 53.9A

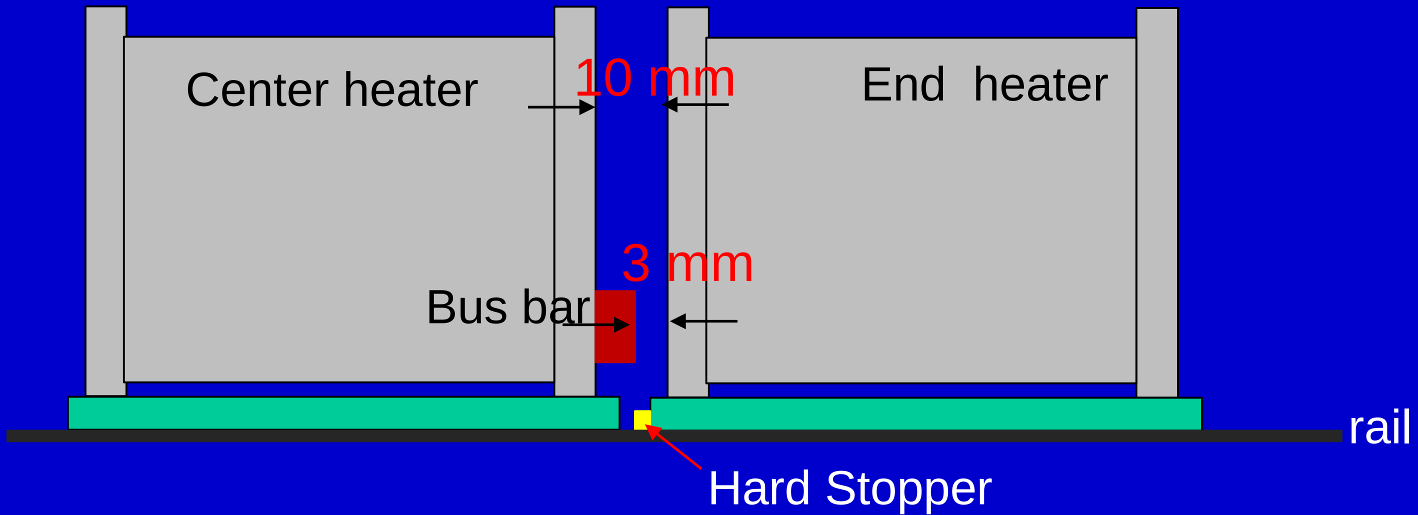




ANOMALY(4/5)

Failure analysis

- **Clearance on drawings**
  - 10 mm between Center heater and End heater
  - 3 mm between top of bus bar and End heater
- **Manufacturing and control error is 1 mm**
- **Thermal expansion of each heater**
  - 0.44 mm (at 800 degree C) to 0.719 mm (at 1265 degree C)
- **Minimum clearance between bus bar and End heater**
  - 1.56 mm (at 800 degree C)
- **Lock-wire can extend 1.75 mm.** It is credible for lock-wire to reach End heater.



ANOMALY(5/5)

Failure scenario

- Failure scenario analysis using material physical specification like melting temperature, resistance, density and specific heat.
- If maximum current (53.9 A) flows in lock-wire (Ta) and End hearer flange (Ti), they rapidly reaches melting temperature.
- At room temperature, lock-wire did not contact with End Heater, but increasing temperature causes thermal expansion of each unit, and finally lock-wire contacted with End Heater.
- At first anomaly, only Ti flange melted because GHF shut down before Ta lock-wire reached melting temperature. JAXA assumes lock-wire changed configuration a bit and clearance between lock-wire and End Heater expanded a bit.
- At second anomaly, Ti flange and Ta lock-wire reached melting temperature because large amount of current flew before lock-wire was isolated from End Heater. JAXA assumes Ti flange reached boiling temperature, so Ti particle flew and attached to bus bar.

BACK-GROUND FACTORS(1/2)

- **Lock-wire on exposed electrode (bus bar)**

  Lock-wire to prevent loosening of fasteners on bus bar
  - Other means than lock-wire cannot meet or be installed due to high temperature environment and small area to be installed.
- **Heater position control and hard stopper**
  - There are three means to avoid collision with adjacent heaters. One is software control, second is hardware control and third is hard stopper.
  - Clearance between adjacent heaters was set considering mechanical and control errors and thermal expansion.
  - Operators understood the above logic, but stopped consideration about any conductive objects which connects with two heaters because three measures to prevent collision are set.
- **Technology transfer**
  - GHF was designed and developed in 1990's. Most of original designers are gone, and it is very hard to find many design document and development records.
  - Original designer identified short failure caused by lock-wire, so left remarks on design drawings that lock-wire shall be under bus bar. Unless lock-wire is out of envelop of bus bar, short between two heaters does not take place.
  - Due to poor technology transfer, engineers later on may not be aware with important meaning of remarks on design drawings.

BACK-GROUND FACTORS(2/2)

- **Hazard analysis**
  - Because "hard stopper" can physically avoid contacts with adjacent heaters, short between them was considered incredible.
  - Not only designers, but also safety stopped consideration for short between two heaters.
  - Actually, safety data package remained now does not describe detail design of insulation and bonding/grounding scheme and clearance between two heaters.
- **Success experience**
  - The design to apply "lock-wire" and "bus bar" in heater has been taken since FMPT (First Material Processing Test, 1992) by STS-47, Space Shuttle "Endeavor" and no short had happened.
  - Success experience causes to stop further thinking to re-design because design change may introduce design error.
- **Function test**
  - Function test included to move heaters where software limiter is activated (3 mm), but it was not performed at extremely high temperature. It did not cover heater movement test where hard stopper contacts. The reason why they did not perform heater movement test at high temperature is because heater material might degrade by oxidization.
  - Safety should have been involved in test planning to consider worst case

LESSONS LEARNED

- **Special attention on exposed electrode**
  - Special attention shall be paid to exposed electrode in order not to generate electrical short.
  - Is is doubtful that safety understood minimum clearance is just few mm between adjacent heaters.
  - Not only designers, but also safety shall understand insulation methods for exposed electrode and review design on all short paths if they are properly protected from contact.
  - **Flight hardware inspection by safety**
  - Safety shall inspect flight article for exposed electrode because safety could find short path that is overlooked by designers and operators.
  - **Hard stopper design**
  - Designers often apply hard stopper when they want to constrain mechanical movement of objects.
  - They shall consider role of Hard stopper.
  - If Hard stopper acts as a kind of insulation between conductive articles, designers shall take into consideration of mechanical and control error, thermal distortion and manufacturing and operation failure for design of Hard stopper.
- **Electrical short control document**
- Designers shall leave design including background by written document on electrical short prevention. Safety data package is best for document.

CONCLUSION

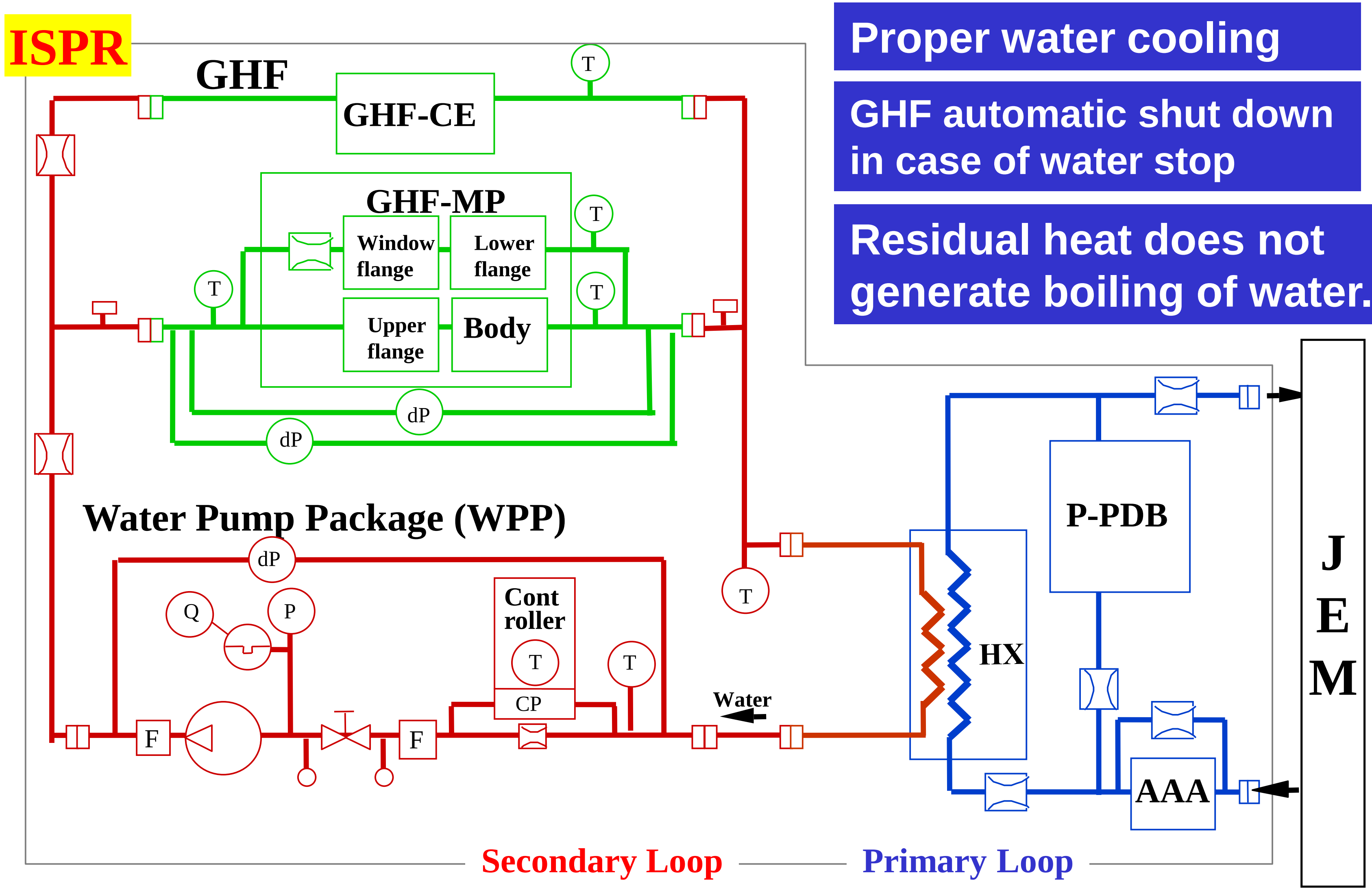
For the anomaly cited in this paper, JAXA could avoid it if more attentions were paid to heater design and operations by designer, operator and safety. So, it was not “Unexpected Anomaly”.

Safety shall seek “worst case” together with designers, assess hazard potential and severity, and set proper controls together with designers as unexpected anomaly related with safety does not happen.

Back-up Charts

GHF (Gradient Heating Furnace)

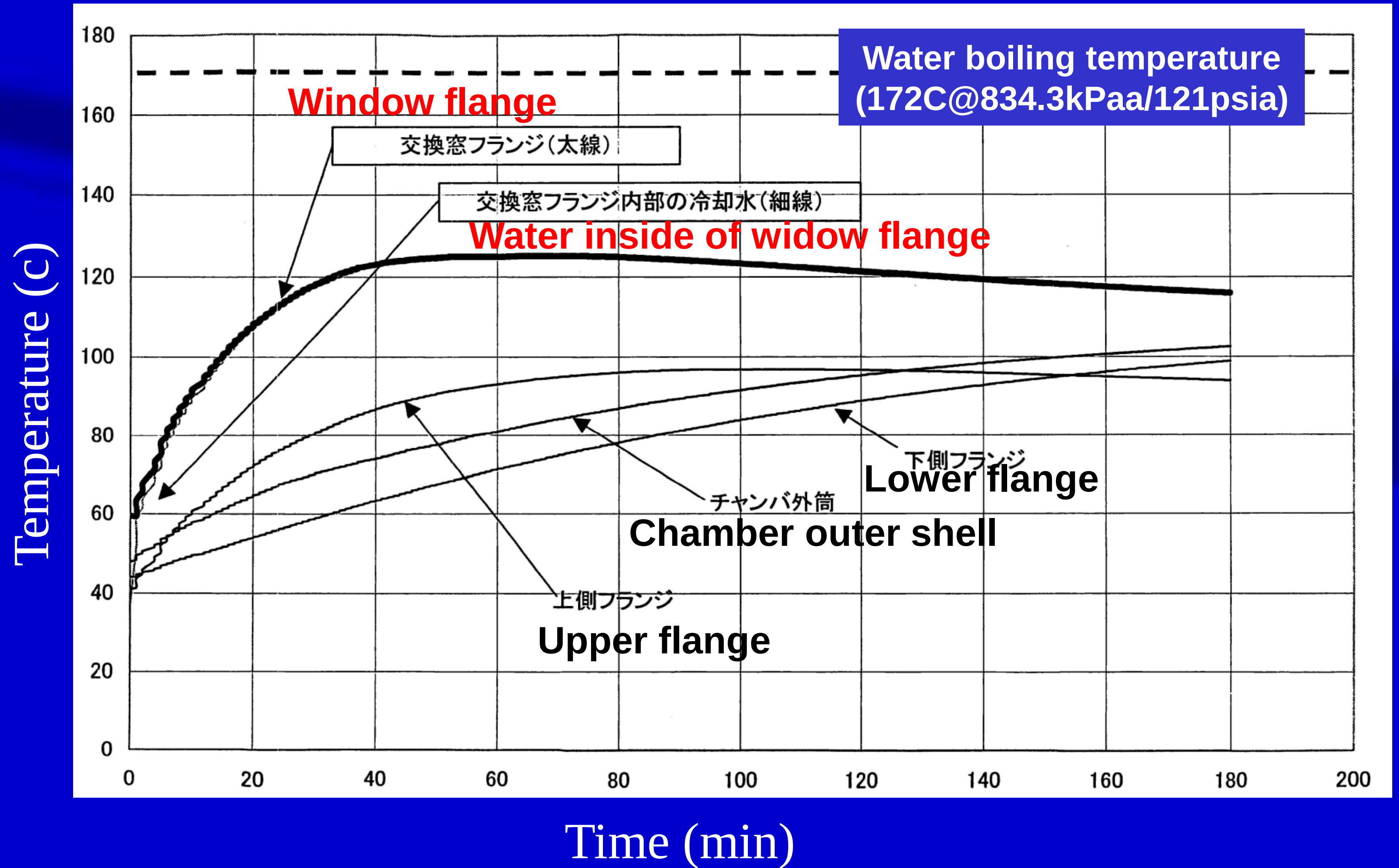
Major Hazard: Explosion of water cooling loop



- Proper water cooling
- GHF automatic shut down in case of water stop
- Residual heat does not generate boiling of water.

GHF (Gradient Heating Furnace)

Water temperature rise by residual heat



GHF (Gradient Heating Furnace)

Explosion of furnace

- Both waste gas and vacuum venting lines are used to keep vacuum in chamber.
- Valves of upstream to the chamber are closed by software and hardware logic during heating in order not to have influx of gas into chamber.
- Chamber is cooled by water and inner gas expansion due to thermal environment is restricted.