Transient Analyses of sCO_2 Cooled KAIST-Micro Modular Reactor with GAMMA+ code

Nuclear & Quantum Engineering, KAIST

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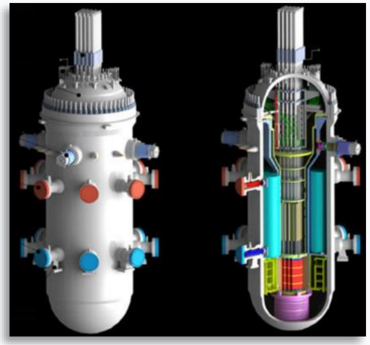
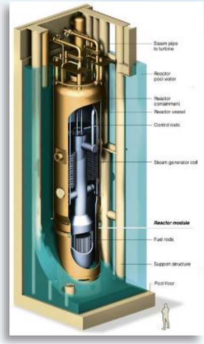
OUTLINE

Introduction

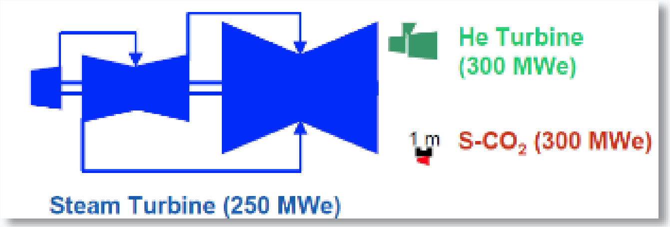
- Advantages of Small Modular Reactor
  - Flexible power generation.
  - Better economic affordability.
  - Options for remote regions without electricity grid infrastructures.
- Motivation of sCO_2 cooled SMR
  - High cycle efficiency in moderate temperature ranges (400°C~700°C).
  - Compact component size→Simple layout.
  - CO_2 is a cheap coolant, and abundant.

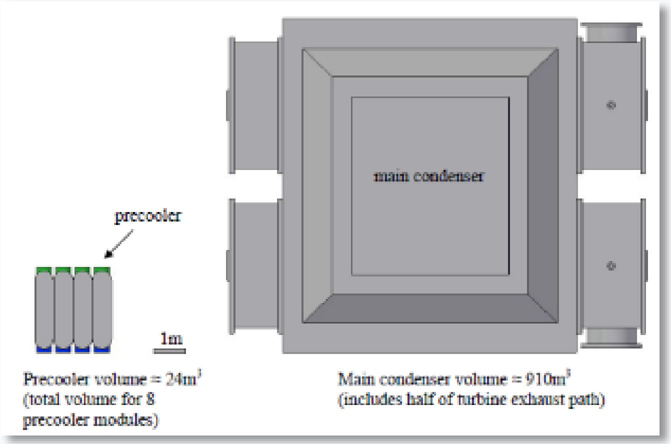


<SMART reactor (PWR 100MWe), KAERI>

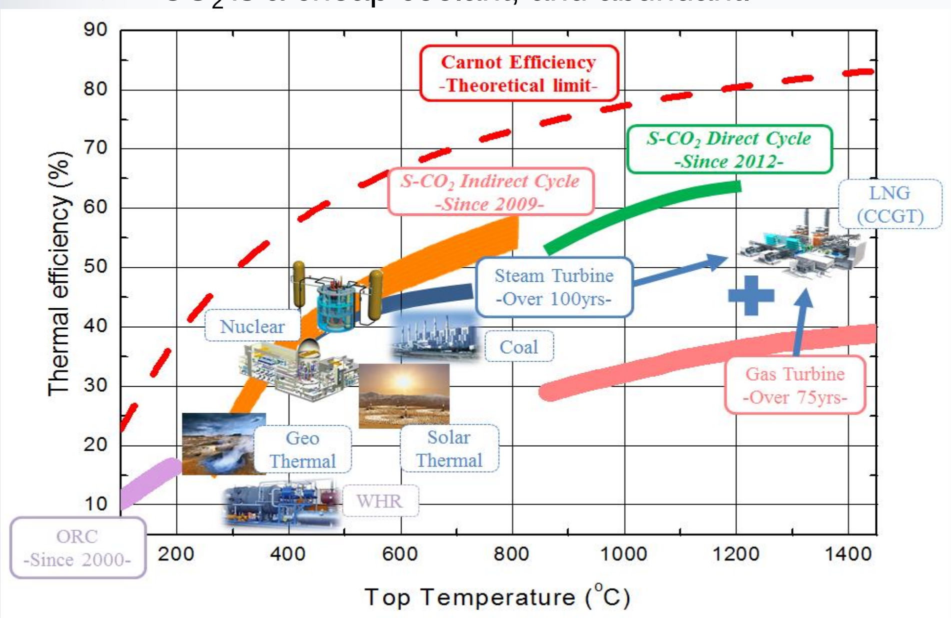


<NuScale (PWR 50MWe), NuScale Power>





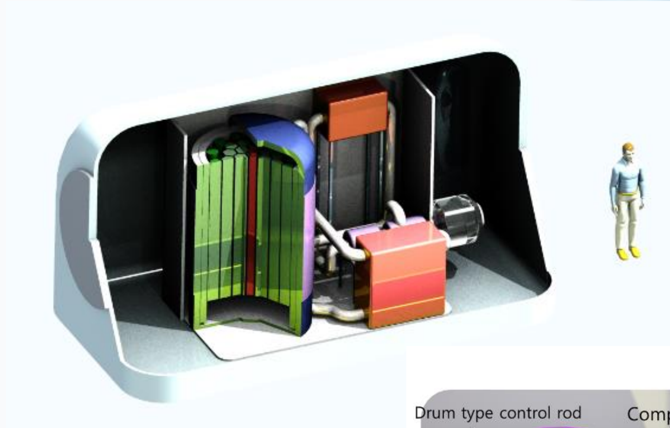
<Steven A. Wright, Supercritical technologies S-CO_2 overview>

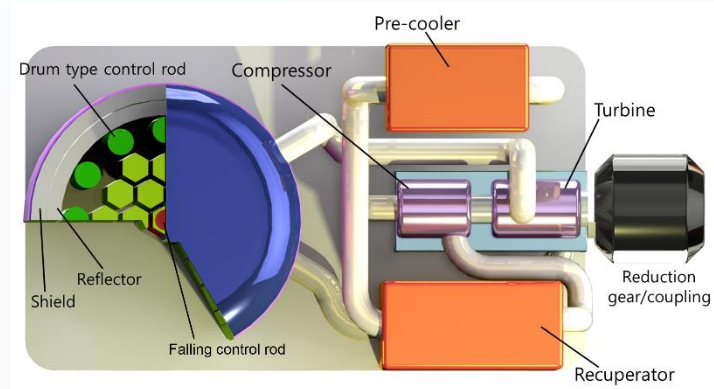


<Thermal efficiency of various cycles for range of temperature>

Introduction

- KAIST Micro Modular Reactor (MMR)
  - One module containing reactor core, power conversion system (PCS).
  - Economic benefit by shop-fabricated construction.
  - Transportable modular reactor.
  - Supplying energy to the remote regions.

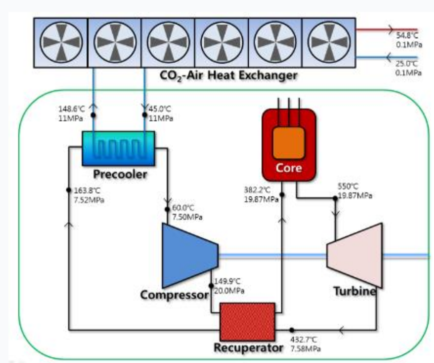




<Reactor core and power conversion system in a single containment >

- Conceptual design of MMR
  - Simple recuperated cycle for transportability.
  - Printed Circuit Heat Exchanger.
  - Centrifugal turbo-machinery.
  - Air cooling system to be independent for region.

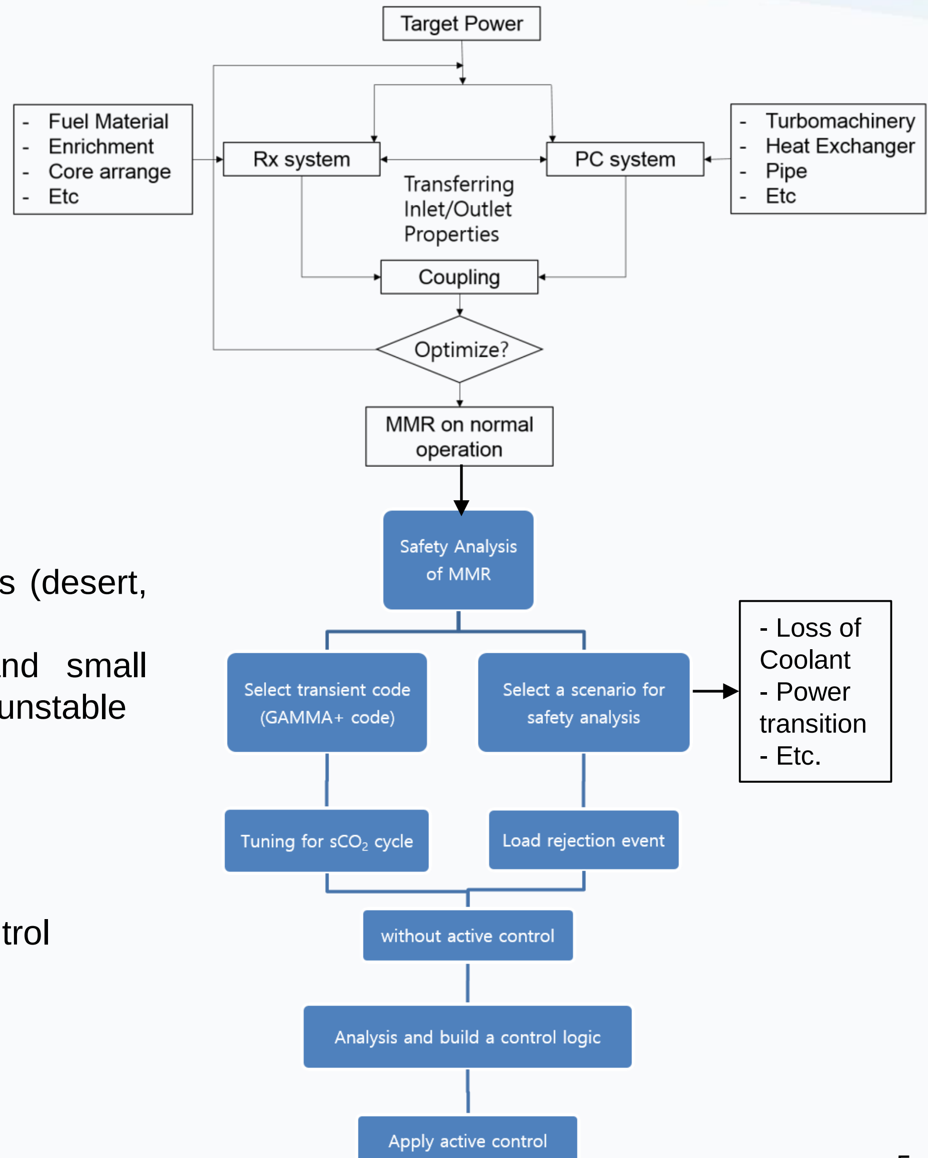
<Ground transport>



<Simple recuperated system by air cooling>

Introduction

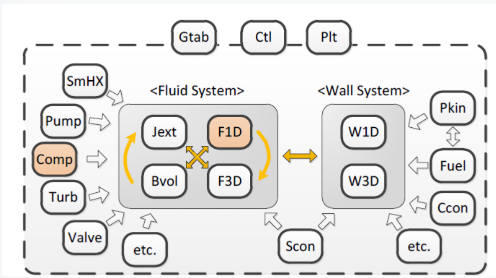
- Selection of transient code
  - GAMMA+ code is developed for HTGR
    - Inexact CO_2 properties near the critical point.
    - Turbo-machineries for ideal gas (ex. He,N_2..).
- Selection of scenario for safety analysis
  - Implementation of various nuclear power plant event
    - Loss of Coolant Accident
    - Power transition event
    - Load rejection event
  - Why load rejection?
    - MMR would be constructed on remote regions (desert, polar region).
    - These regions have tough environment and small population →Grid could be easily damaged or unstable
- Analysis of load rejection event.
  - Analyze result of the event without any control
  - Build target parameters to control the cycle
  - Apply active control and check the result with the control



Modification of GAMMA+ code

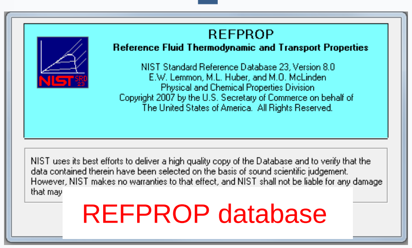
◆ CO_2 Properties Modeling in GAMMA+ code

- Original GAMMA+ code is developed for HTGR analyses.
  - Not incorporate the exact CO_2 properties especially near the critical point (T_c=304.1282 K, P_c=7.3773 MPa).



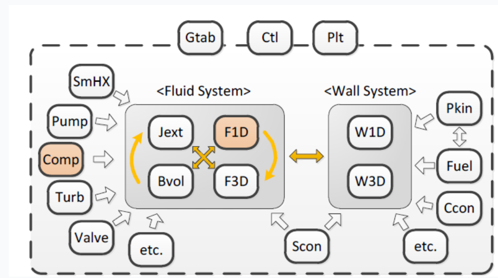
Original GAMMA+ code

+



REFPROP database

<Old solution: Connection REFPROP>



Original GAMMA+ code

EOS of CO_2 calculator

Thermal Properties

Critical region: Tabular properties calculator

Not Critical region: Transport properties calculator

Transport properties

<Current solution: Solving EOS of CO_2>

- The way how to calculate thermal properties by EOS.
  - Thermal properties can be obtained by differentiating EOS with respect to density and temperature

- The way how to calculate transport properties.
  - Unless state of CO_2 is near critical region (240°C<T<450°C, 25kg/m³<ρ<1000kg/m³), transport properties are simply composed of constant coefficient and temperature of the state.
  - It's too complicated to calculate transport properties of CO_2 near the critical region because calculation process includes root finding and inverse matrix →Alternative: Tabular properties proposed by N. A. Carstens.

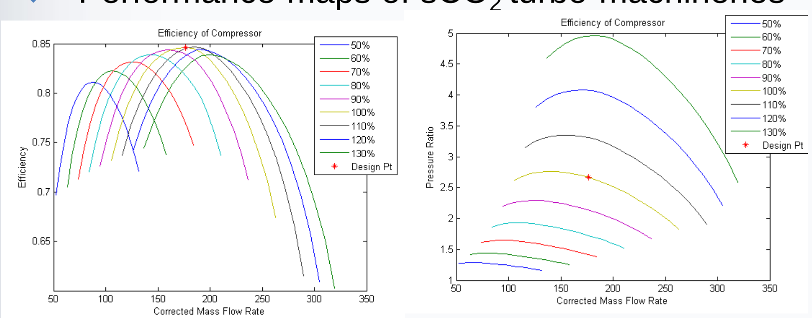
Modification of GAMMA+ code

Turbo-machinery Modeling by performance map.

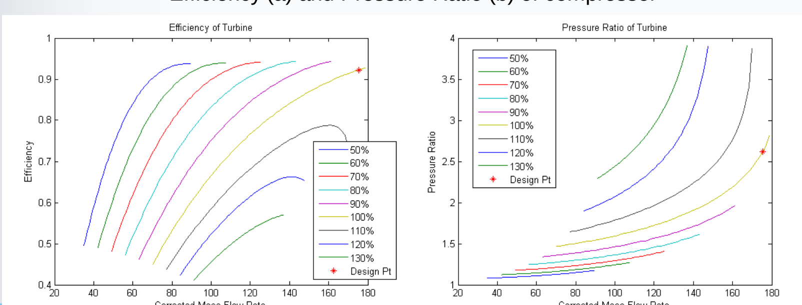
- Turbo-machinery modeling based on real gas
  - Due to abrupt change of properties of CO_2 near the critical region, real gas effect should be considered when sCO_2 turbo-machineries are modeled.
  - Heat rise of compressor and release of turbine could be calculated by enthalpy difference.

$$q_{comp} = (h_{outlet} - h_{inlet})\dot{m} = \left(\frac{h_{ideal} - h_{inlet}}{\eta_{comp}}\right)\dot{m} \qquad q_{turb} = (h_{outlet} - h_{inlet})\dot{m} = \eta_{turb}(h_{outlet} - h_{ideal})\dot{m}$$

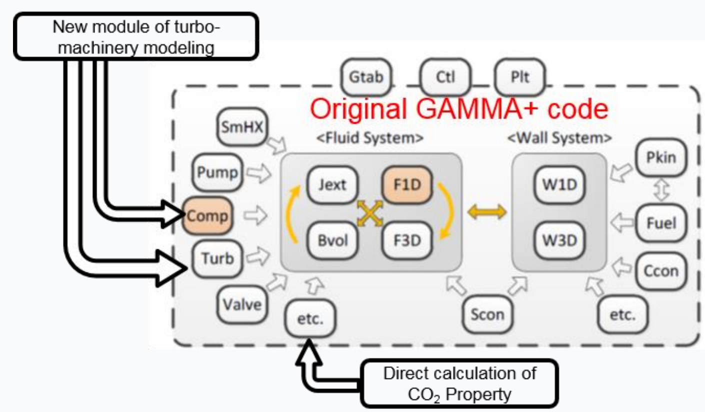
  - To obtain h_{ideal} and $\eta_{comp\&turb}$, a user has to utilize pre-generated performance maps, drawn with respect to the corrected mass flow rate and RPM.
- Performance maps of sCO_2 turbo-machineries



Efficiency (a) and Pressure Ratio (b) of compressor



Efficiency (a) and Pressure Ratio (b) of turbine



<schematic diagram of modified GAMMA+ code>

Code Results

◆ Nodalization and modeling of MMR in GAMMA+ code.

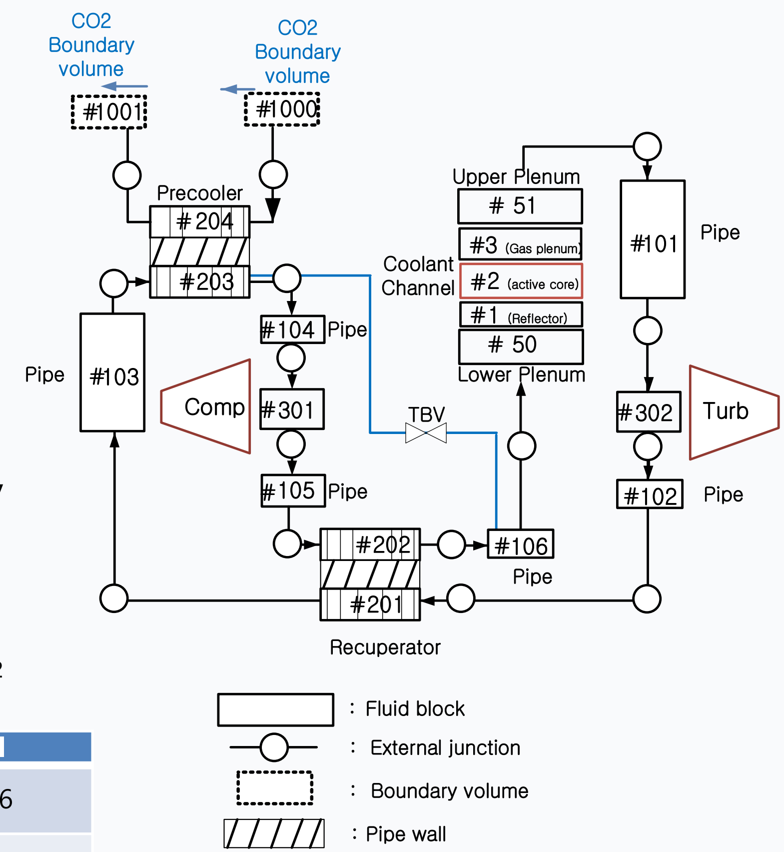
- Simplified configuration of MMR
  - Heat of the MMR can be rejected to ambient air via cooling fan but precooler of MMR is not directly connected with air → CO_2 loop is inter-connecting the precooler and air to maintain the purity of MMR primary cycle when even the precooler channel breaks.
  - However, cooling loop of MMR in GAMMA+ code is not fully modeled but simplified by prescribing the inlet CO_2 of the cooling loop.

- Difference between Design parameters and code results

Reactor Power	0.00633 %	Mass flow rate	0.0239 %
Compressor inlet Pressure	1.044 %	Turbomachinery RPM	0.0 %
Compressor Inlet Temperature	0.067 %	Turbine Power	1.78 %
Turbine inlet Pressure	0.0654 %	Compressor Power	1.835%
Turbine inlet Temperature	0.0055 %	Generator Power	2.2 %

- Moments of inertia modeling
  - Moments of inertia of MMR turbomachineries are not fully modeled yet.
  - Assume the inertia is proportional with reactor power ratio.
    - $I_{MMR}/Q_{MMR} = I_{refer}/Q_{refer}$
    - Reference reactor is defined as2400 MWth S-CO_2 cooled fast reactor developed by Pope.

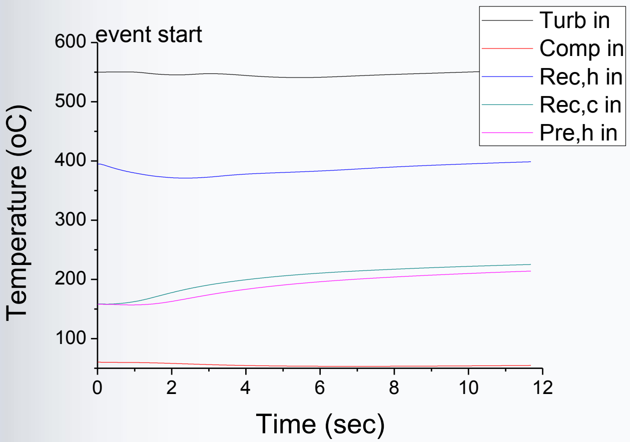
NPP	Generator	Turbine	Compressor	Total
MMR (36.2MWth)	15.075	12.814	4.607	32.496
Pope (2400MWth)	1000	850	305.6	2454.7



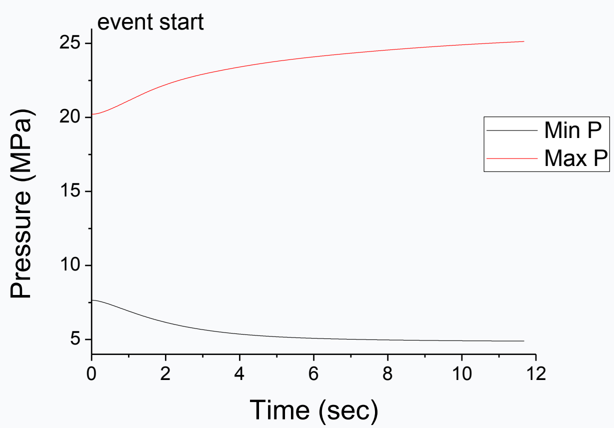
Code Results

◆ Load rejection event without active control.

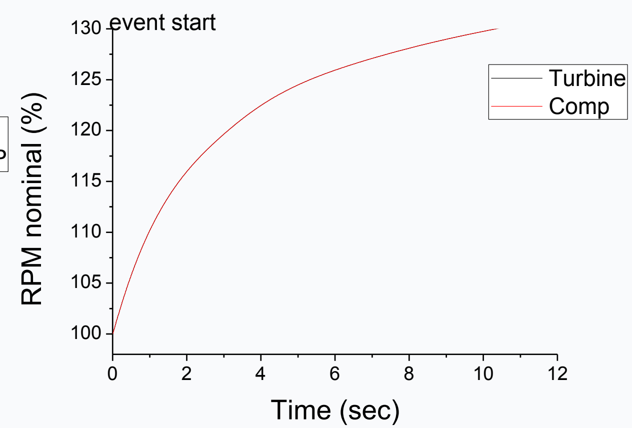
- Code results of load rejection event without control action
- Load is rejected at 0.0 second.



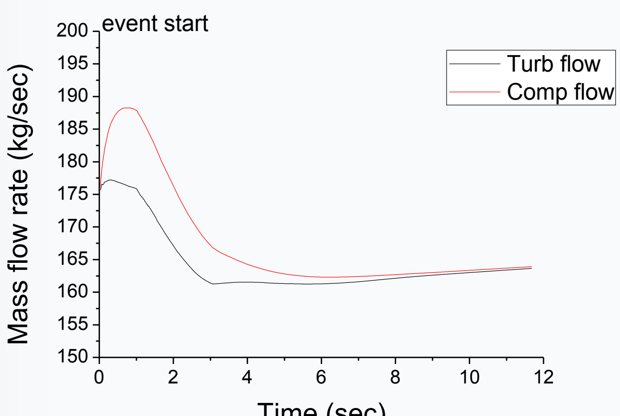
<Temperature of MMR components on the event w/o control>



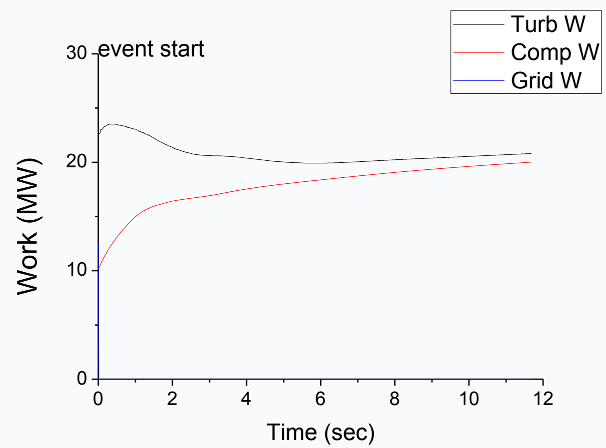
<Minimum and Maximum pressure on the event w/o control >



<RPM of turbo-machinery on the event w/o control >



<Mass flow rates on the event w/o control >

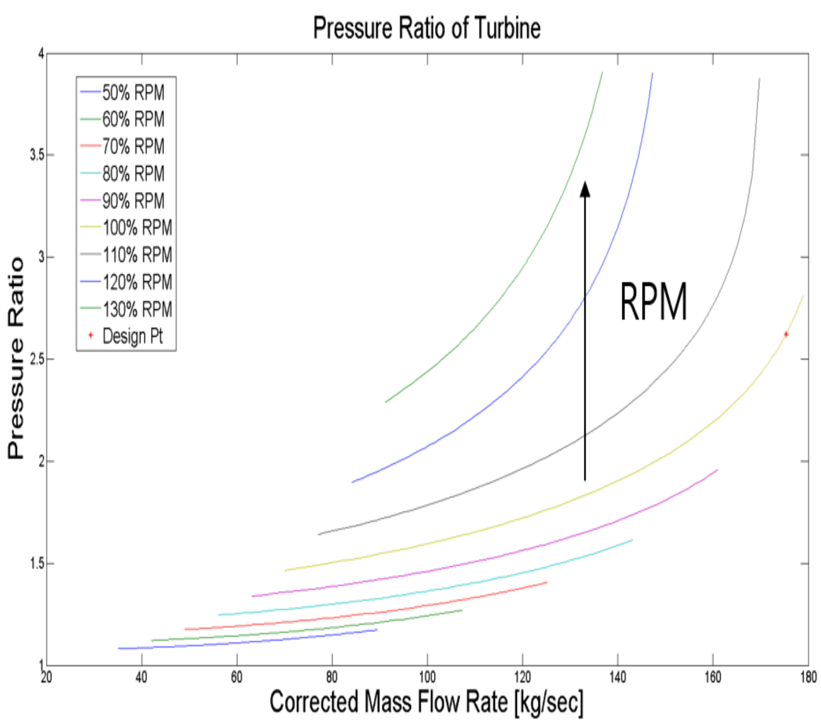


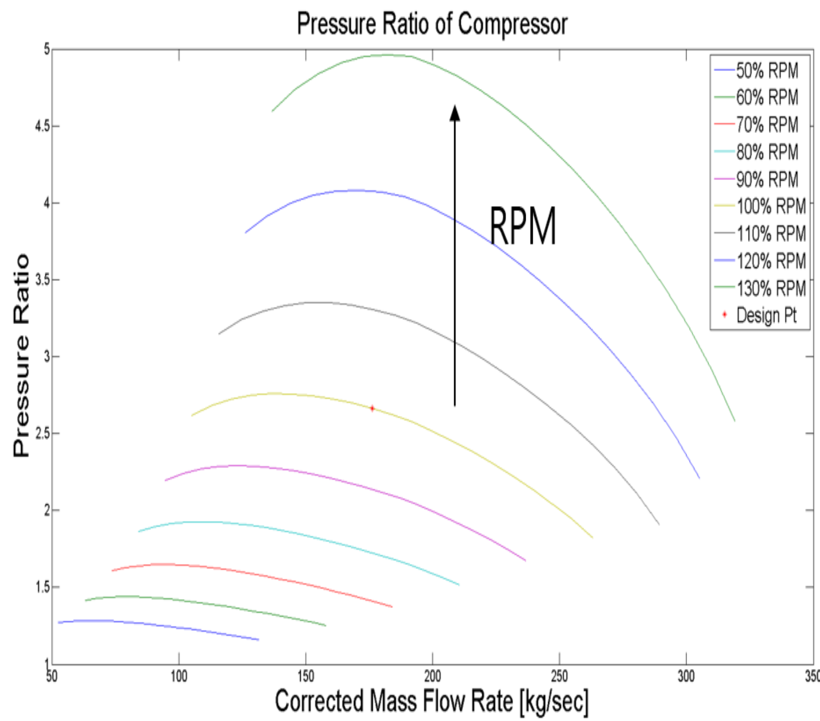
<Work of turbo-machinery on the event w/o control >

Code Results

◆ Load rejection event without active control.

- Analysis of load rejection event w/o active control
  - Slight decreasing of temperature is due to over-expansion → lastly, temperature is again increased.
    Generated heat is not converted to useful work.
  - The minimum pressure is declined but the maximum pressure is increased
    the pressure ratio of turbine and compressor is abruptly increased along with increasing of RPM





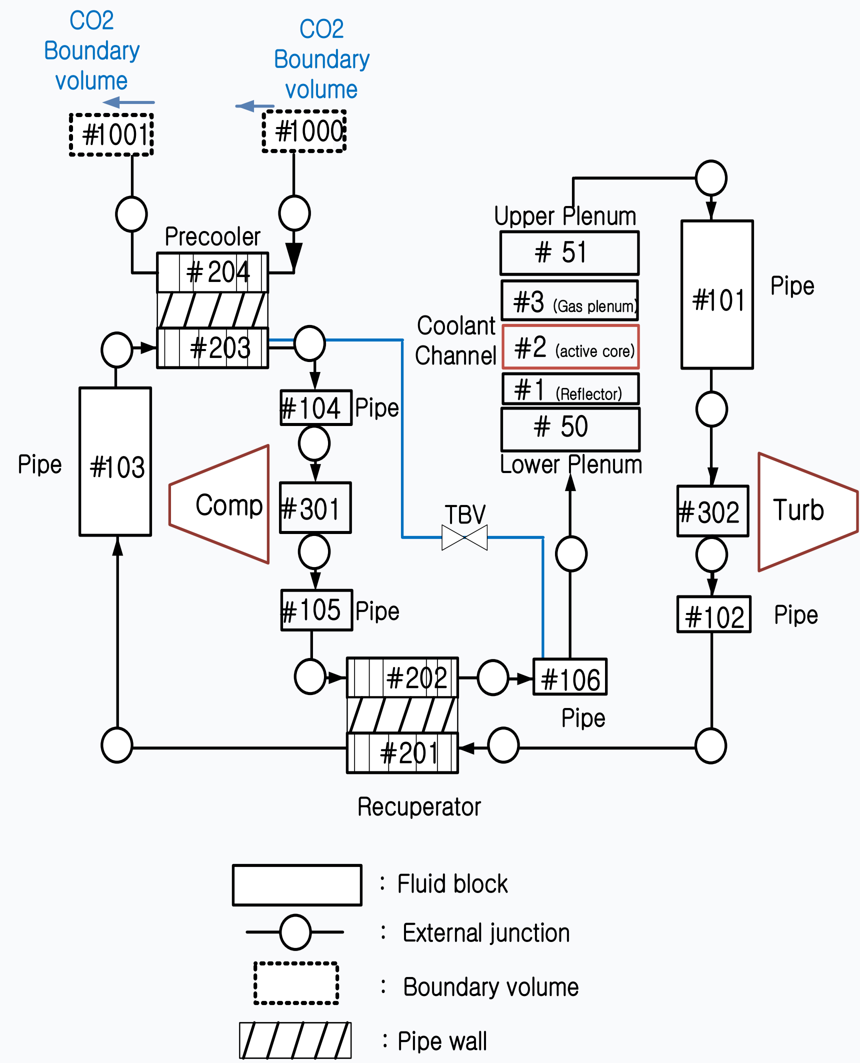
  - Rotational speed of turbine is seriously increased because load rejection could act as loss of fluid resistance so that mass flow rate is also increased

Code Results

◆ Load rejection event without active control.

- Control logic of MMR: Reducing the rotational speed of turbine
  1. Reducing rotational speed of turbine → Bypass mass flow rate at turbine inlet.
  2. Since generated heat from the core isn't converted to the useful work → Reduce the core power.
  - Assumption: MMR is equipped with energy storage system that can operate at least valve systems
  - air cooling fan is remaining their integrity during accident.

- Bypass valve location
  - Core inlet bypass line from the core inlet pipe to the precooler.
    1. Can maximize the bypass efficiency because core inlet fluid has quite high density.
    2. Can minimize the thermal shock of precooler because core inlet fluid has quite low temperature.



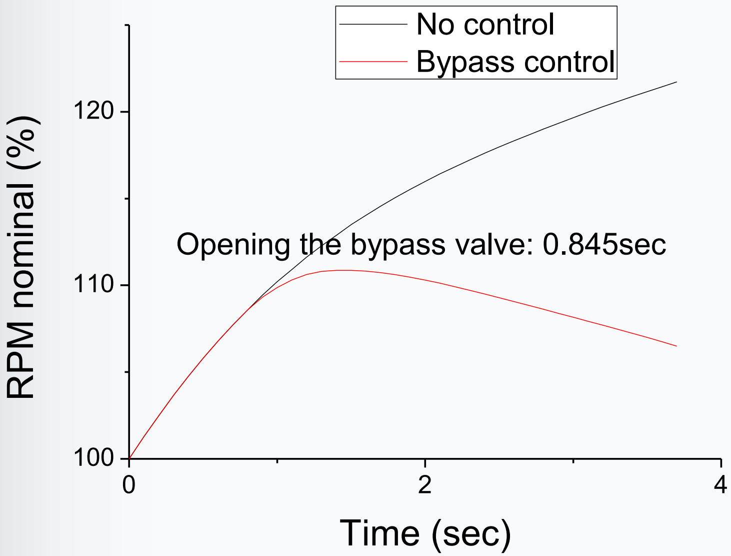
Code Results

◆ Time step control action.

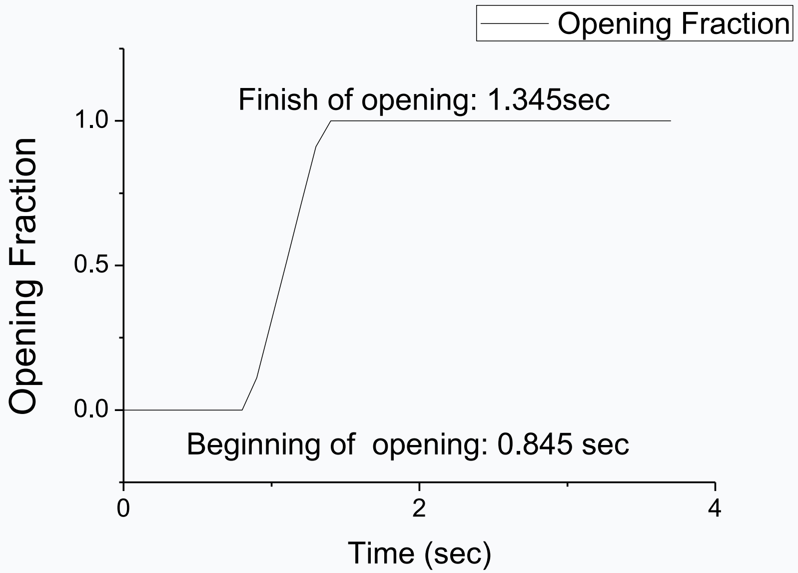
❖ Control action in load rejection event of MMR

Time (sec)	Event	Setpoint or Value
0.0	Load is rejected.	-
0.845	High shaft speed condition	110%
1.345	Opening of core inlet bypass	-
3.5	Shutdown of reactor	-

- Rotational speed of turbine is 110% nominal value at 0.845 sec and then core inlet bypass valve is opened having 1/0.5 sec opening rate.



<Setpoint of core inlet bypass valve opening>



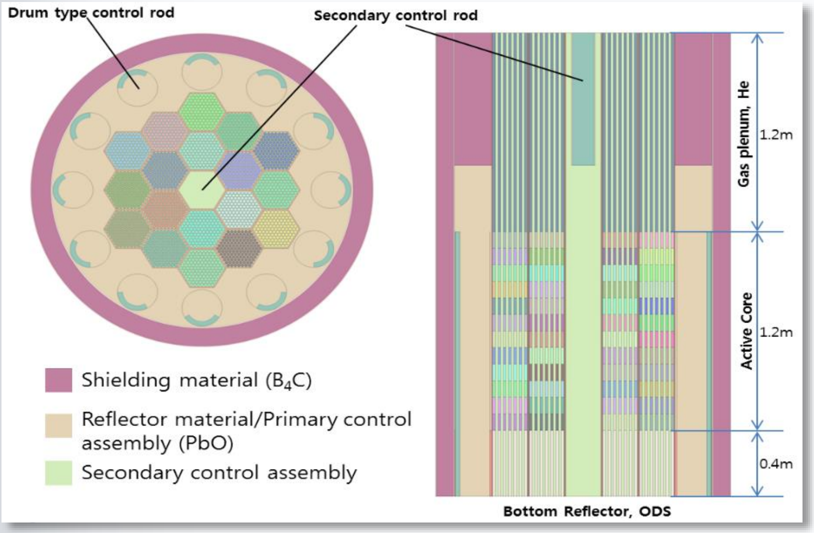
<Opening rate of core inlet bypass valve>

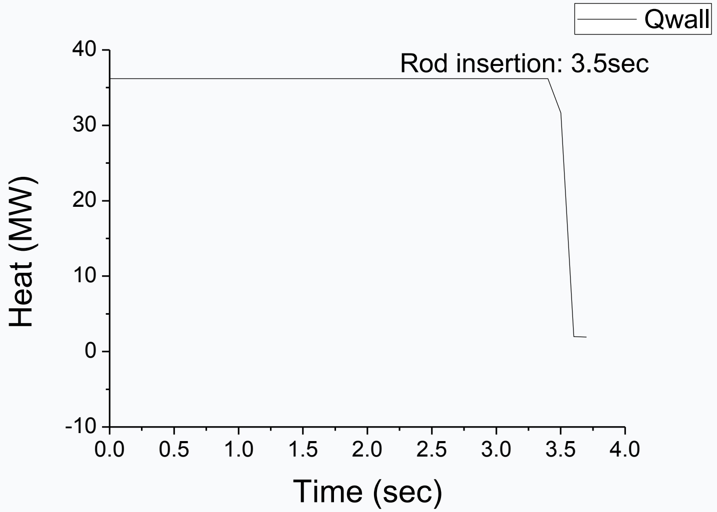
Code Results

◆ Time step control action.

❖ Safety limitation of control parameters

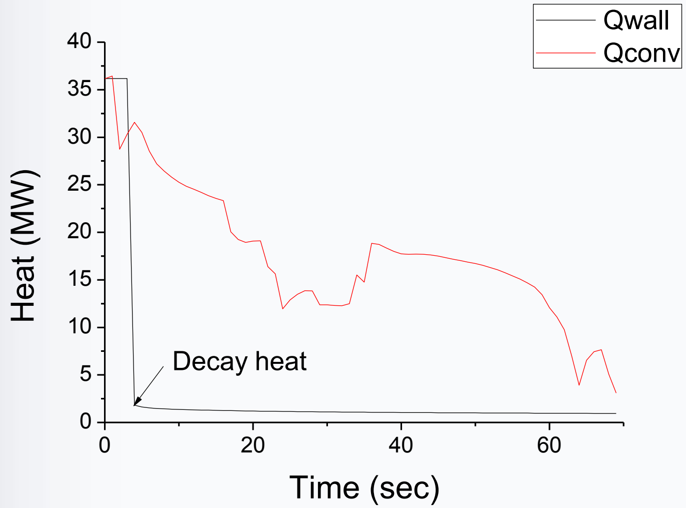
- In general, PWR has safety limit of turbine speed as 120% nominal value.
- Turbine speed of PWR is generally 1500 RPM and blade length is about 1.3m but MMR has very high rotational speed 20200 RPM and blade diameter is about 0.16m → Turbine tip speed of MMR is much faster than conventional PWR
- Considering conservative design MMR, setpoint of opening core inlet bypass is determined as 110% nominal value of rotational speed of turbine
- Opening rate of high pressure valve is proposed as 1/0.5sec in Preliminary Safety Analysis Report of PWR.
- After reactor trip signal is generated, actual time to scram a core is determined as 3.5 sec in PWR. MMR also has falling secondary control element in center of the core and additionally devises drum type control element in side of core as shown following figure so that this trip delay time of PWR could be again applied in MMR



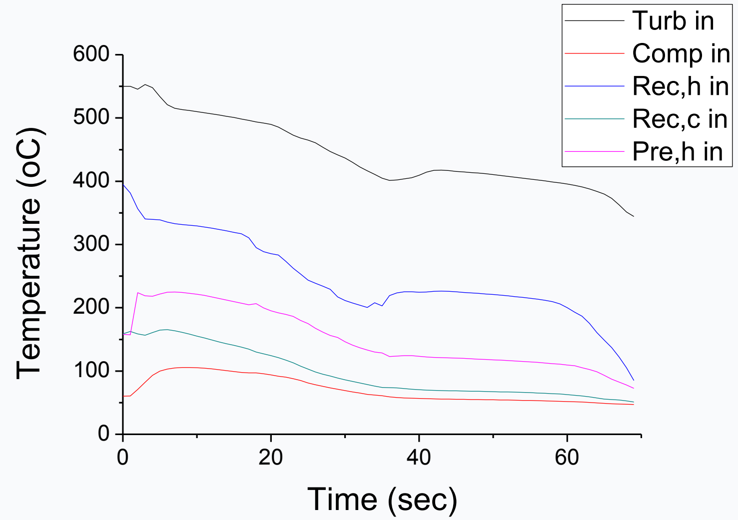


Code Results

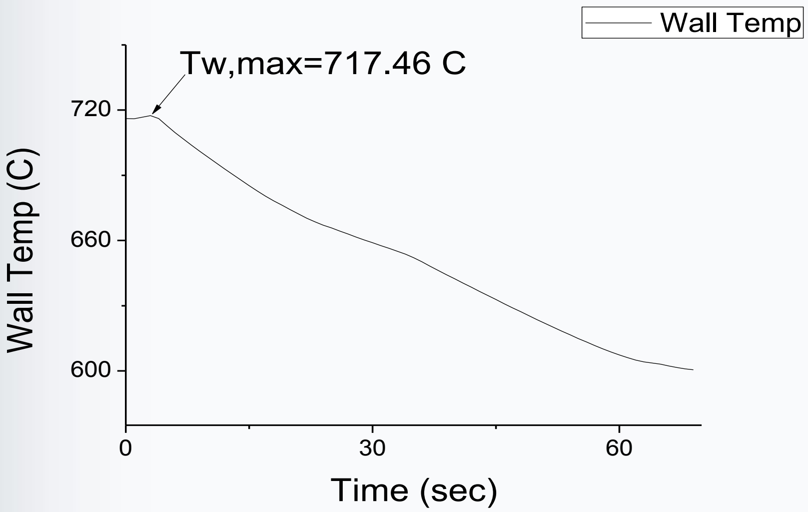
- Load rejection event with cycle control.



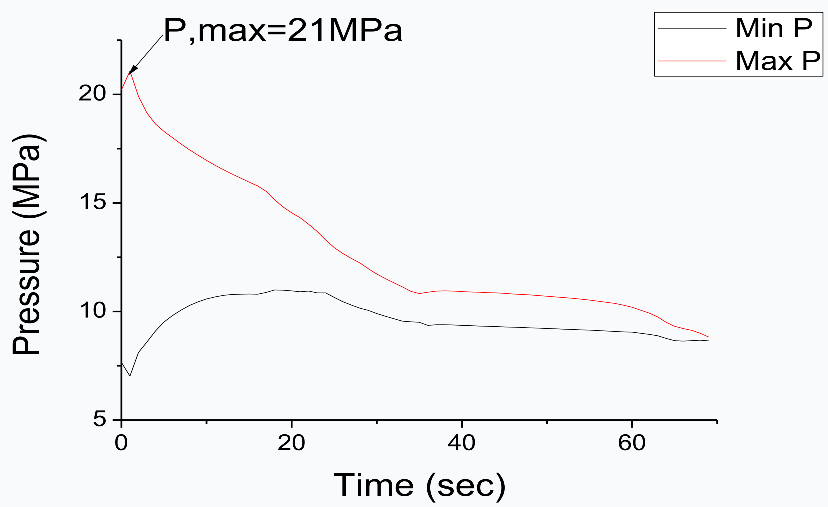
<Heat balance of reactor core on the event with control >



<Temperature of MMR component on the event with control>



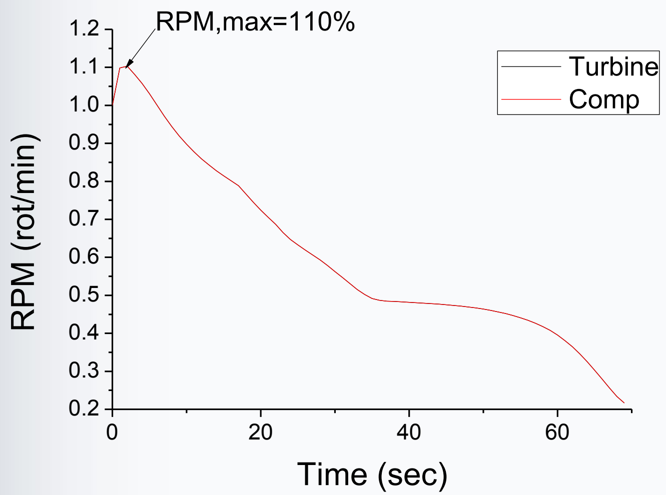
<Temperature of cladding on the event with control>



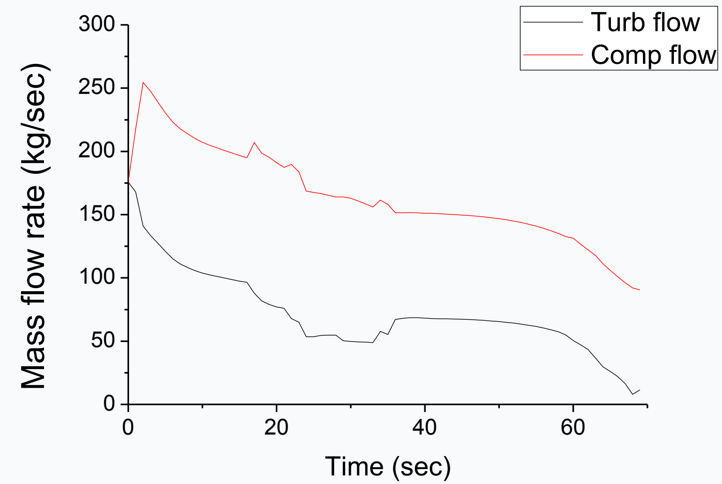
<Minimum and Maximum pressure on the event with control >

Code Results

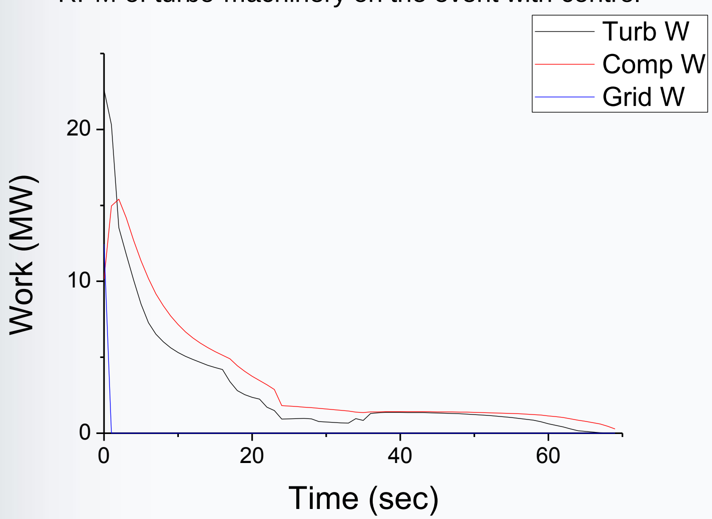
◆ Load rejection event with cycle control.



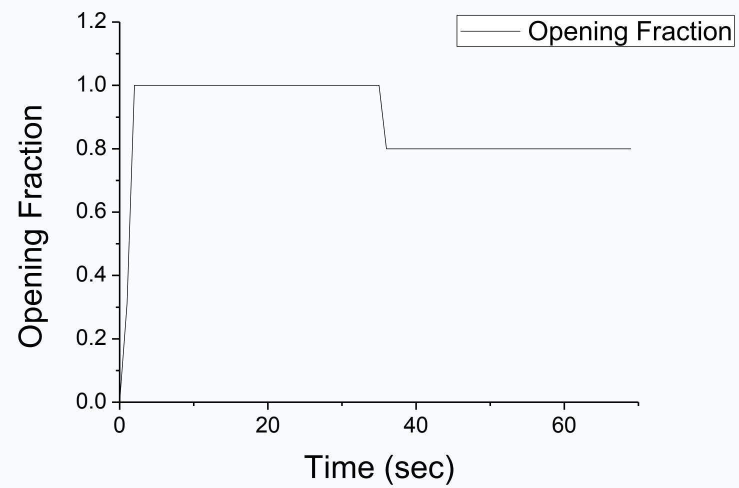
<RPM of turbo-machinery on the event with control >



<Mass flow rates on the event with control >



<Work of turbo-machinery on the event with control >



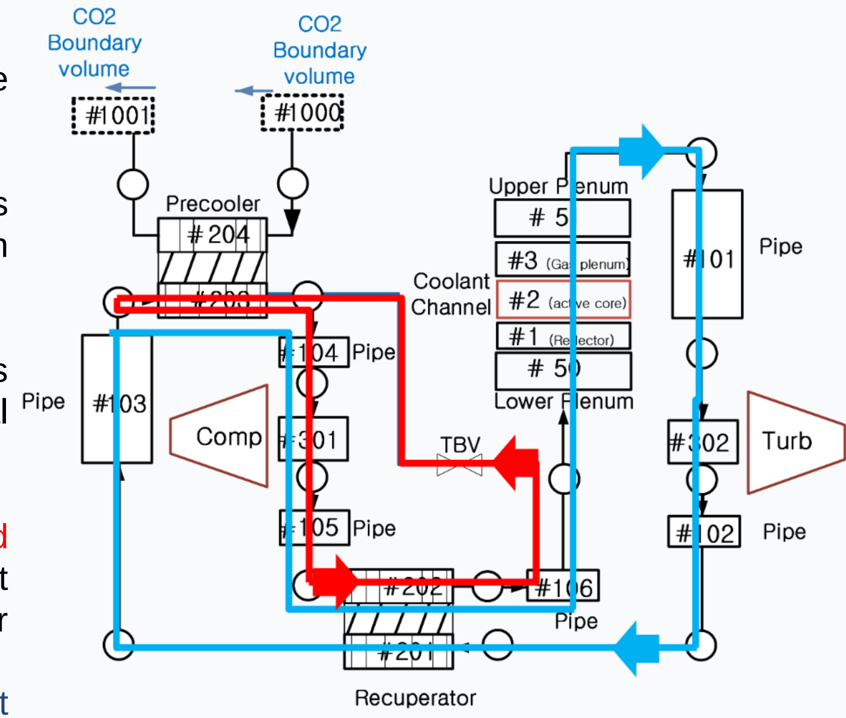
<opening fraction of TBV on the event with control >

Code Results

◆ Load rejection event analysis.

- Analysis of load rejection event with active control
  - After core inlet bypass is opened, mass flow rate would be divided into two stream lines.
  - From reactor core to No.103 pipe, the mass flow rate is lower than nominal value because a portion of fluid which would flow into reactor is bypassed to precooler.
  - On the other hand, the mass flow rate where stream lines are overlapped from 203 to 202 is higher than nominal value.
  - At the beginning of the event, temperatures of hot line fluid from core to No.103 pipe is lower than nominal value but temperatures of cold line fluid from precooler to recuperator is higher than nominal value.
    → Hot and cold side fluid are smeared by core inlet bypass!
  - Turbo-machinery work become zero or converged because rotational speed become almost zero by rotor dynamic equation at the end of the event.

$$I_{tot}\omega\frac{\partial\omega}{\partial t}=(W_{turb}-W_{comp})\varepsilon_{gen}-W_{grid}$$

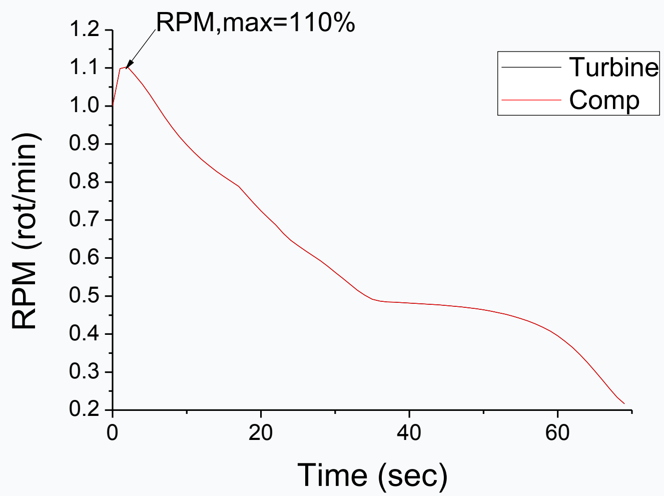


Code Results

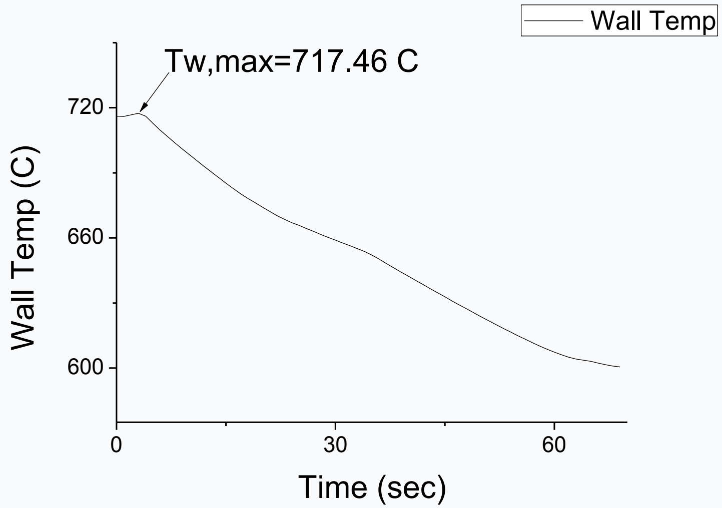
◆ Safety limits.

❖ Two safety limits of MMR

- Pressure boundary limit: Pressure boundary of the system shall not exceed 110% of nominal value from ASME code.
- Maximum pressure is 105% of nominal value during load rejection event with control action as shown in right figure.



- Wall cladding temperature limit: Wall cladding temperature should not exceed 800°C because previous conceptually developed S-CO_2 cooled fast reactor selects this temperature for cladding safety criteria by Pope.
- Maximum wall temperature is not exceeding 800°C during load rejection event with control action as show in right figure



Conclusions and Further Works

- MMR is designed to be operable and capable of supplying energy to the remote and isolated regions
  - Perfectly modularized.
  - Transported to a site via land or sea.
- Necessity of transient analysis of MMR.
  - The integrity of the system should be demonstrated for various selected design basis accidents.
  - Built control logics could be validated whether the logics are appropriate.
- Load rejection event modeling
  - The population in the remote region where MMR would be operated is small.
  - Grid connected to the MMR could become easily unstable due to small capacity or tough condition of the region.
- Transient code and results for sCO_2 power plant
  - GAMMA+ code firstly developed by KAERI was modified to analyze the sCO_2 cycle.
  - The steady state of the MMR is checked whether it is exactly modeled in GAMMA+ code or not.
  - According to transient result, load rejection event could damage to the turbine blade and let the system overheated
  - Consequently, core inlet bypass and reactor shutdown could lead to alleviate system on load rejection event with satisfying limitation of 110% over-pressurization and 800 ^oC wall cladding temperature

- Modified GAMMA+ code still requires implementation coupling with CO_2 properties and turbomachinery modeling.
- Further investigations on various accident scenarios are necessary to enhance the design and evaluate the safety of developed concept

THANK YOU