System Modeling of the HTTR with RELAP5-3D

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International RELAP5 Users Group Seminar
Idaho Falls, ID
May 4, 2018

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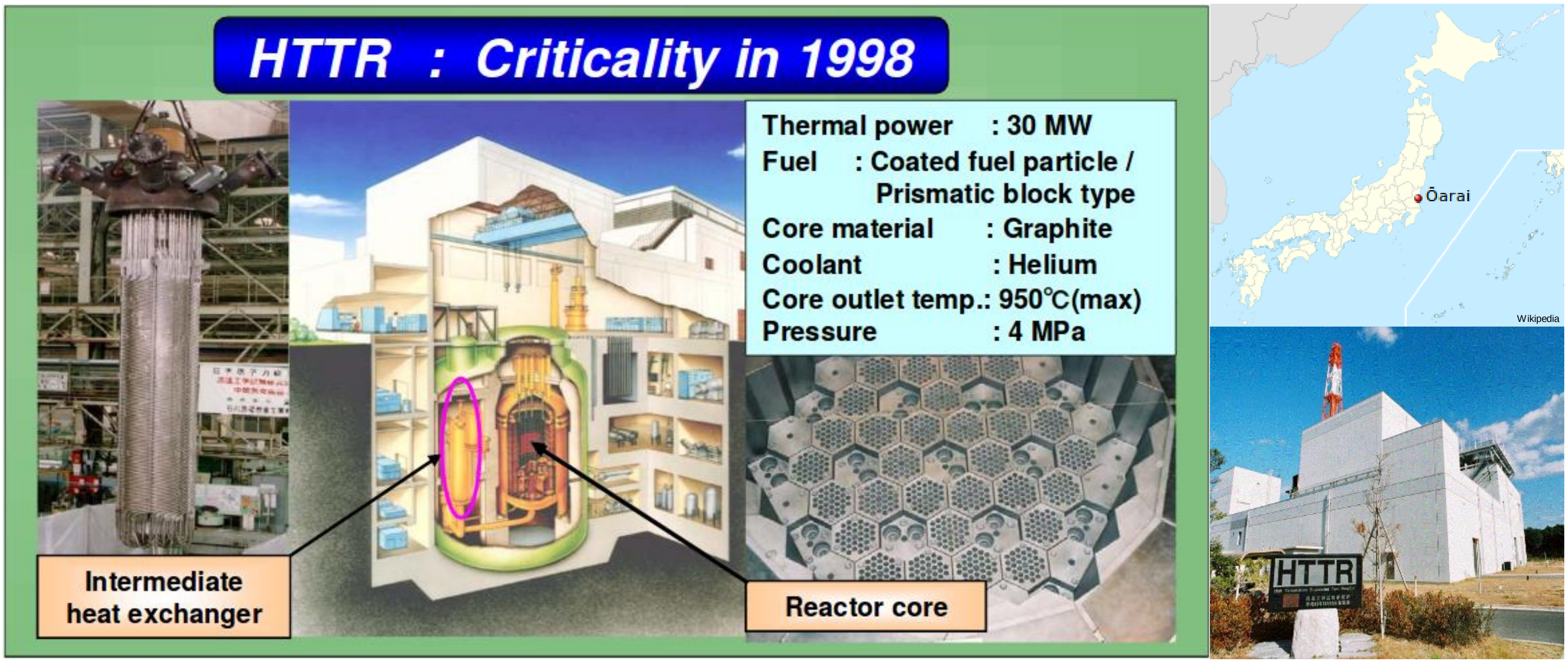
Overview

- The High Temperature Test Reactor (HTTR)
- Expansion plans- HTTR/GT-H_2 (Gas Turbine-Hydrogen)
- RELAP5-3D model of HTTR-GT/H_2 secondary system
  - Turbomachinery
    - Compressors
    - Turbines
  - Heat exchangers
    - Secondary IHX
    - 2nd IHX
    - Recuperator
    - Precooler
    - Cooler A
    - Cooler B
  - Statepoint comparisons

The High Temperature Test Reactor (HTTR)

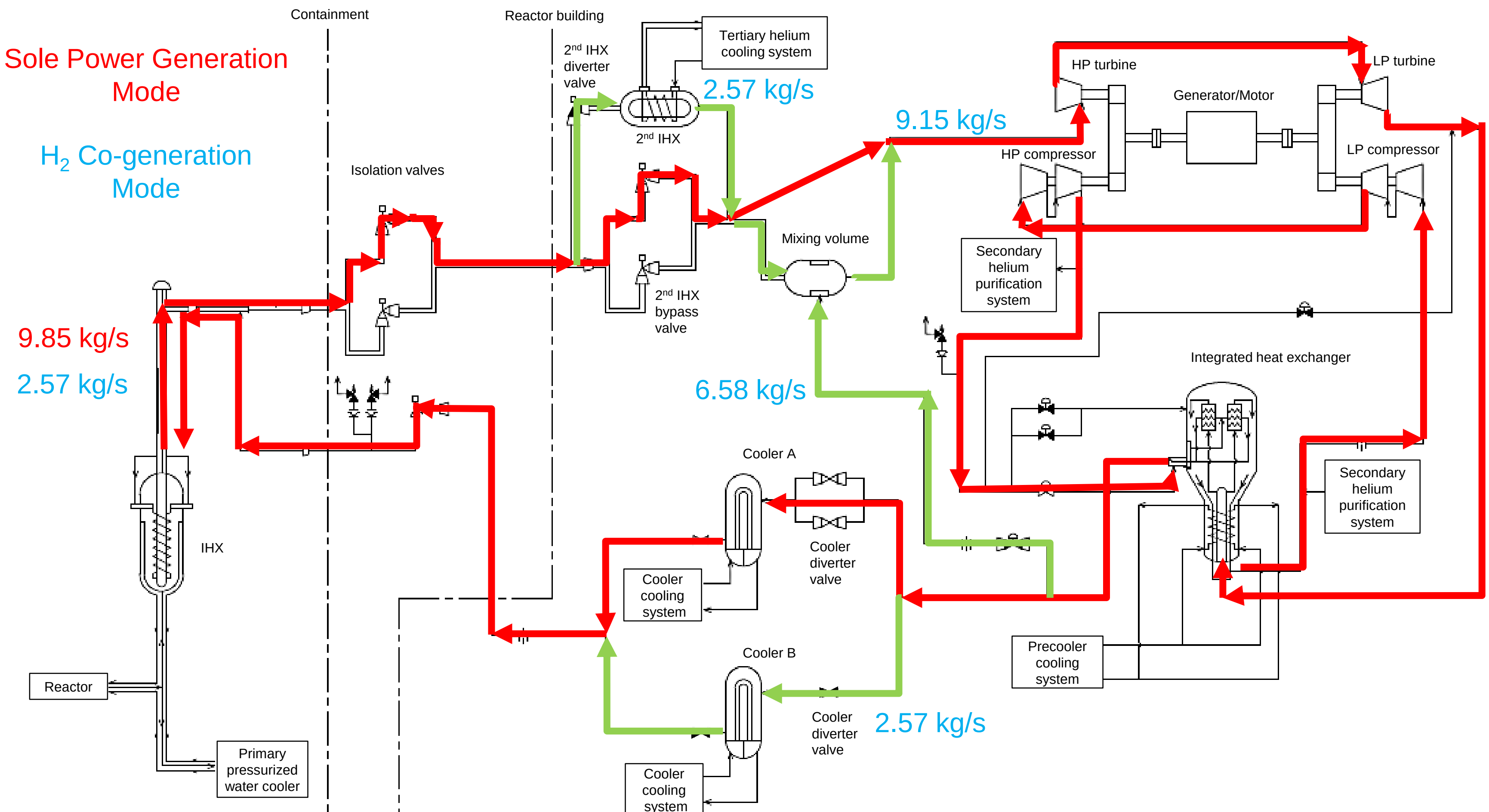


https://httr.jaea.go.jp/eng/G/HTTR_Pamphlet-ENG20100514.pdf

- Japan Atomic Energy Agency (JAEA) will use HTTR to demonstrate both:
  - Power extraction via Brayton cycle with closed-cycle gas turbine
  - Hydrogen generation via the iodine-sulfur process
  - Designed upgrade: *HTTR-GT/H_2*

HTTR-GT/H_2

- HTTR-GT/H_2 secondary system schematic



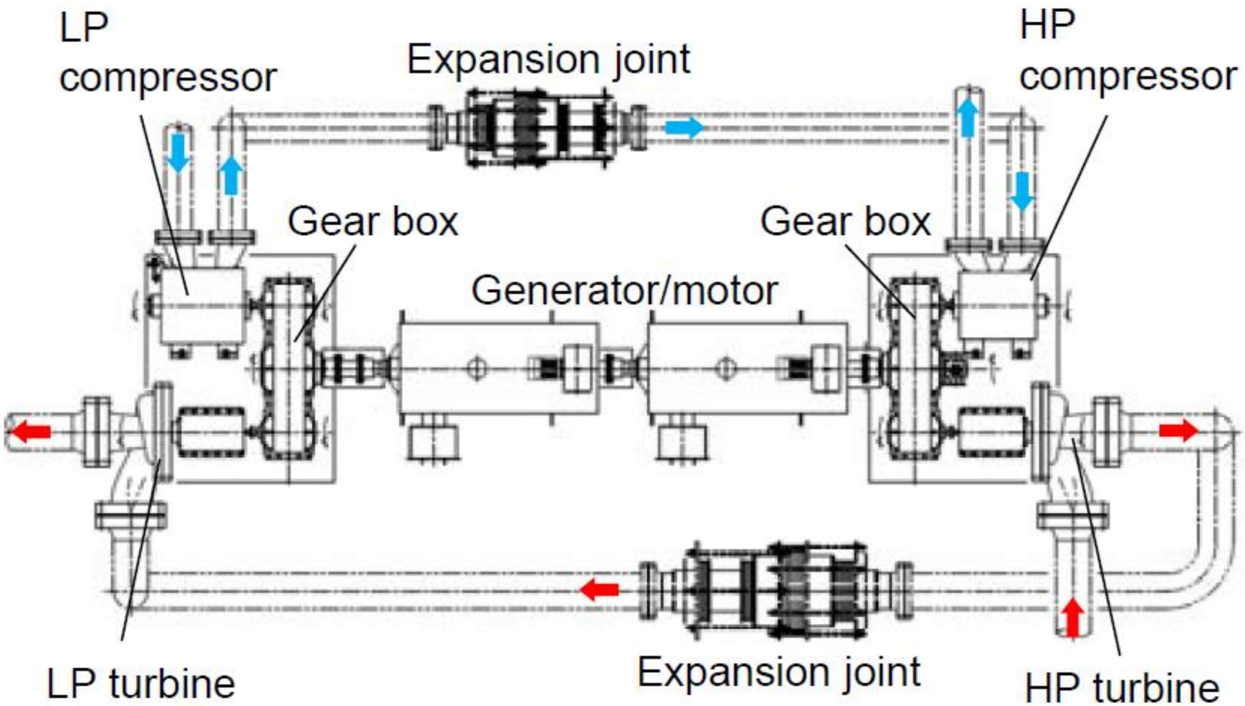
JAEA-Data/Code 2016-007

Component model development approach

- The RELAP5-3D model of the HTTR-GT/H_2 secondary is essentially a series of component models connected by pipes
- Each component model has been developed individually
- The component models are connected to time-dependent volumes upstream and downstream, with properties there fixed based on statepoint data provided by JAEA
- Each component model is adjusted (if/when applicable) to give the correct temperature change and flow rate across the component
- The component models are then assembled into a larger system model and connected by pipes
- Trip valves are used to switch between sole power generation and H_2 co-generation modes
  - Some components are only used in one mode or the other, and flow rates though all components change depending on the mode

Turbomachinery

- Two single-stage, radial turbines
- Two two-stage, centrifugal compressors
- Low pressure (LP) and High pressure (HP) turbines and compressors connected to common shaft, generator



JAEA-Data/Code 2017-011

Compressors

- Available compressor data gives *pressure coefficient* (μ) and *efficiency* (η) as a function of *flow coefficient* (ϕ)
- RELAP5-3D needs *pressure ratio* (π_C) and *efficiency* (η) as a function of relative *corrected flow* $\left(\dot{m}\sqrt{T}/P\right)$ and relative *corrected speed* $\left(N/\sqrt{T}\right)$

$$\phi = \frac{Q}{\pi(D/2)^2U} \qquad U = \pi ND$$

- Use ideal gas law to write:

$$\phi = \frac{\frac{\dot{m}\sqrt{T}}{P}}{\frac{N}{\sqrt{T}}}\frac{4R_s}{\pi^2D^3}$$

- Rearrange…

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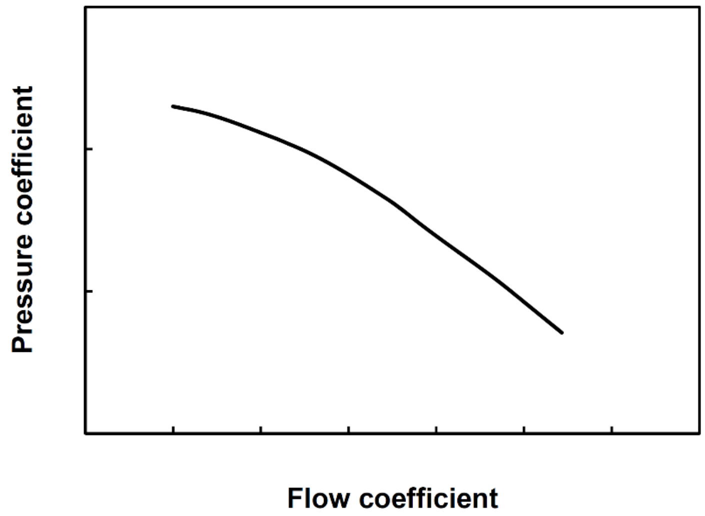

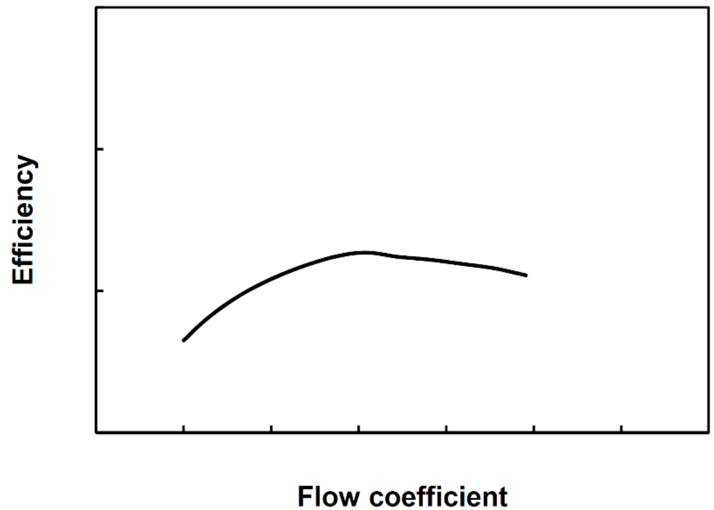

Compressors (2)

- Procedure for building compressor maps for RELAP5-3D:
  - For a given relative corrected speed,
    - For a range of flow coefficients,
      - Get pressure coefficient and efficiency using data at right
      - Get relative corrected flow rate and pressure ratio using the equations below:

$$\frac{\frac{\dot{m}\sqrt{T}}{P}}{\left(\frac{\dot{m}\sqrt{T}}{P}\right)_{rated}} = \frac{\pi^2 \phi D^3 \left(\frac{N}{\sqrt{T}}\right)_{rated}}{4R_s \left(\frac{\dot{m}\sqrt{T}}{P}\right)_{rated}} \frac{\frac{N}{\sqrt{T}}}{\left(\frac{N}{\sqrt{T}}\right)_{rated}}$$

$$\pi_C = \left(\frac{\mu \pi^2 D^2}{Z R_s} \left(\frac{N}{\sqrt{T}}\right)^2_{rated} \left(\frac{\frac{N}{\sqrt{T}}}{\left(\frac{N}{\sqrt{T}}\right)_{rated}} \right)^2 \frac{\kappa - 1}{\kappa} + 1 \right)^{\frac{\kappa}{\kappa-1}}$$

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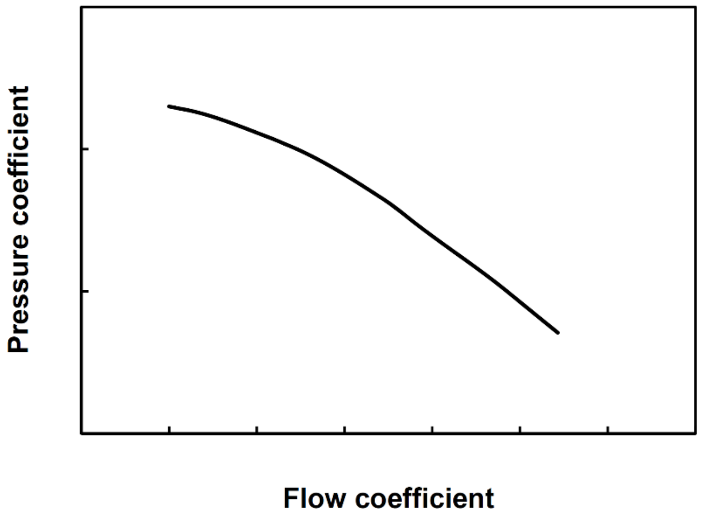

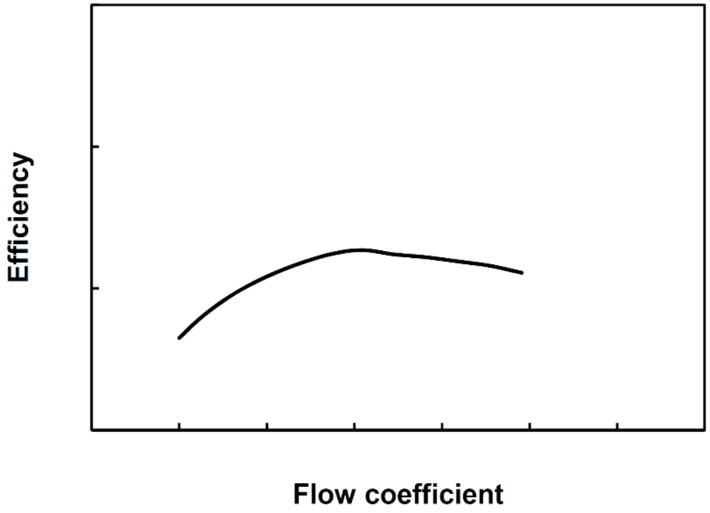

Turbines

- "Type 3" model (function of speed and power) used for both low and high pressure turbine efficiencies:
- $\eta = \eta_{rated} * f(\omega, W)$*mult
- JAEA design data used to customize "mult":
- $\dot{m}\frac{\sqrt{T}}{P} = f(\phi)$ inverted to get:
  - $\phi = f\left(\dot{m}\frac{\sqrt{T}}{P}\right)$ for each turbine
- mult= $f\left(f\left(\dot{m}\frac{\sqrt{T}}{P}\right)\right)$, form of function determined from efficiency data
- Form loss coefficient set to give correct pressure ratio

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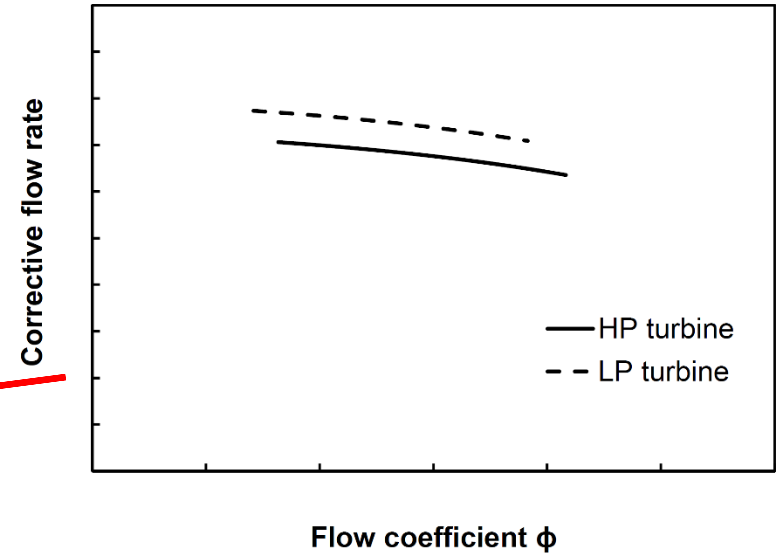
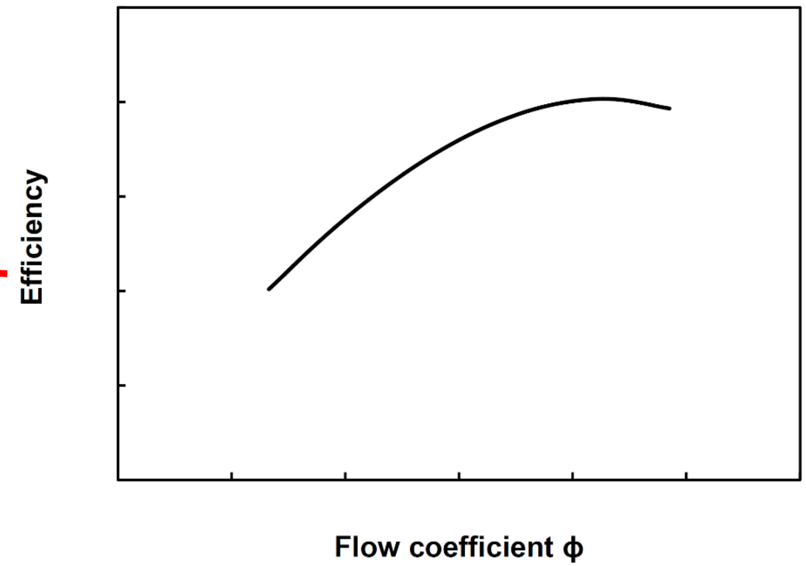




Turbine model performance

- Efficiency and pressure ratio match design parameters well in sole power generation mode
- Turbine power is somewhat higher

	HP Turbine			LP Turbine		
	Design	RELAP SPG mode	RELAP H_2 mode	Design	RELAP SPG mode	RELAP H_2 mode
Efficiency	~90%	90.3%	84.8%	~90%	90.4%	86.4%
Power (kW)	~1710	1891	1853	~1778	1954	2224
Pressure Ratio	1.13	1.13	1.15	1.15	1.15	1.19

- In H_2 mode, form loss has been changed to give correct flow rate for specified pressure drop!
  - Need a way to model variable loss for the turbines…
    - RELAP5-3D allows for f(Re), but probably $f(\dot{m},T,P)$ is needed

Heat Exchangers

- HTTR includes many different types of heat exchangers, but most are based on tube bundles in cross-flow
- Initial RELAP5 models did not match design data well using built in correlations, which are based on an average of parallel and cross flow
- We have therefore implemented the “Delaware method” and associated correlations to model heat transfer and friction
  - Heat transfer implementation makes use of “-2xxxx” boundary condition type for heat structures, which sets the heat flux based on a control variable
    - Control variables can then be used to calculate the heat transfer coefficient based on flow conditions
  - Friction factor correlations can not be implemented *exactly*, but can be closely approximated at high Re using the alternate turbulent wall friction model (e.g. card CCC2601 in a pipe component)

The Delaware Method

- Heat transfer- Colburn j-factor:

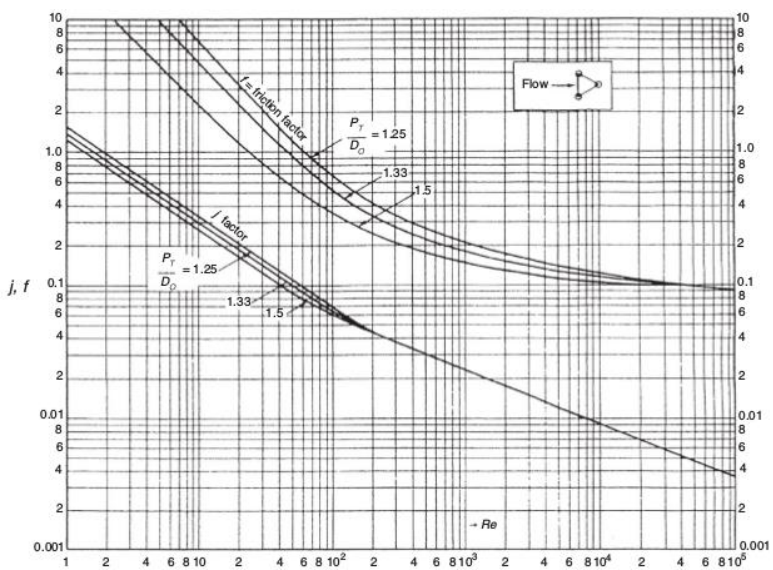
$$j = \frac{hPr^{2/3}S_m}{C_p\phi\dot{m}} = a_1\left(\frac{1.33}{P_T/D_0}\right)^a (Re)^{a_2}$$

$$a = \frac{a_3}{1 + 0.14\,(Re)^{a_4}}$$

- Fanning friction factor:

$$f = b_1\left(\frac{1.33}{P_T/D_0}\right)^b (Re)^{b_2}$$

$$b = \frac{b_3}{1 + 0.14\,(Re)^{b_4}}$$

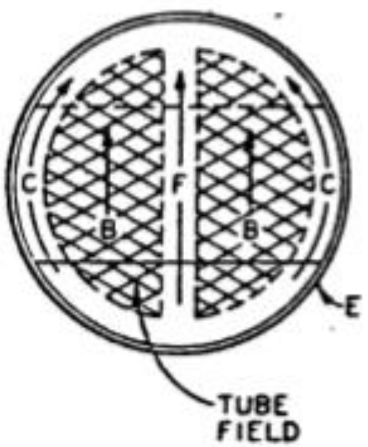


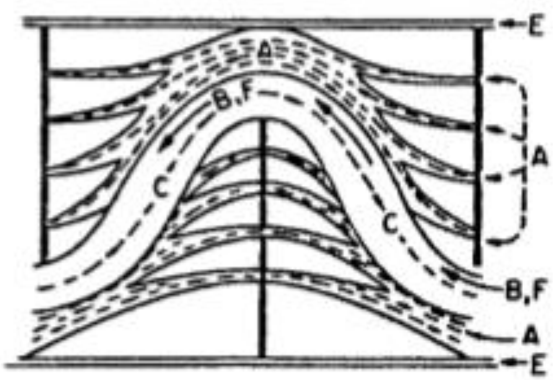
Taborek J., in: Heat Exchanger Design Handbook, v. 3, 1988.

- Values of a_1-a_4 and b_1-b_4 depend on Reynolds number and orientation of the tube bank (square, rotated square, or triangular)
- These are provided by tables in the RELAP5-3D implementation

Corrections in the Delaware method

- Heat transfer coefficients and friction factors are typically reduced by a factor of as low as 0.5 due to non-idealities (baffle leakage, bundle bypass, etc.
- The Delaware method applies geometry-based correction factors (based on TEMA type E heat shell-and-tube heat exchangers) to calculate this overall reduction factor
- In order to match state points, we have adjusted the correction factor (for both the heat transfer coefficient and friction factor) to achieve the correct heat transfer and pressure drop
- The correction factors applied are summarized for each component on the following slides





Bell, *J. Heat Transfer* **126** (2004) 877.

Precooler

- Helical coil with radial low-finned tubes
- Helium secondary loop on shell side
  - Pipe component with 12 segments
- Water coolant on tube side
  - Tubes are lumped as one pipe component with 12 segments
- Heat transfer rate: 4.784 MW
- Includes effect of radial fins:

$$q'' = h\left(\frac{A_t}{A_{RELAP}}\left[1 - \frac{A_f}{A_t}\left(1 - \eta_f\right)\right]\right)\Delta T$$

$$\eta_f = \frac{(2r_1/m)}{(r_{2c}^2 - r_1^2)} \frac{K_1(mr_1)I_1(mr_{2c}) - I_1(mr_1)K_1(mr_{2c})}{I_0(mr_1)K_1(mr_{2c}) + K_0(mr_1)I_1(mr_{2c})}$$

- Heat transfer correction factor: 0.87
- Friction correction factor: 3.025

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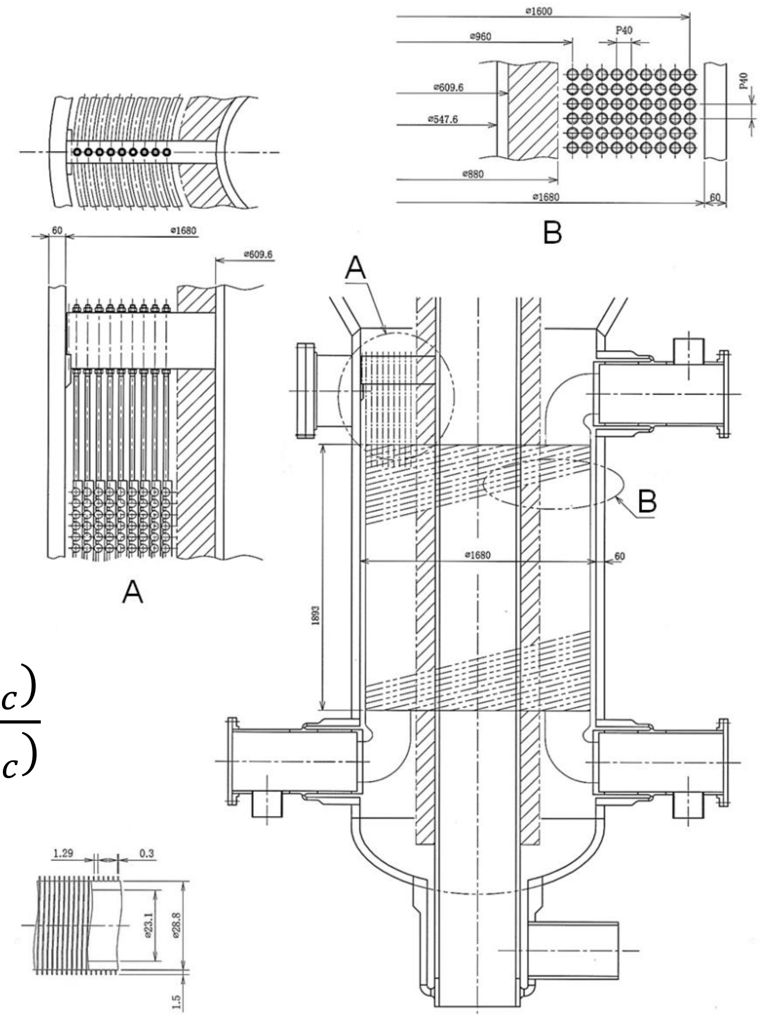
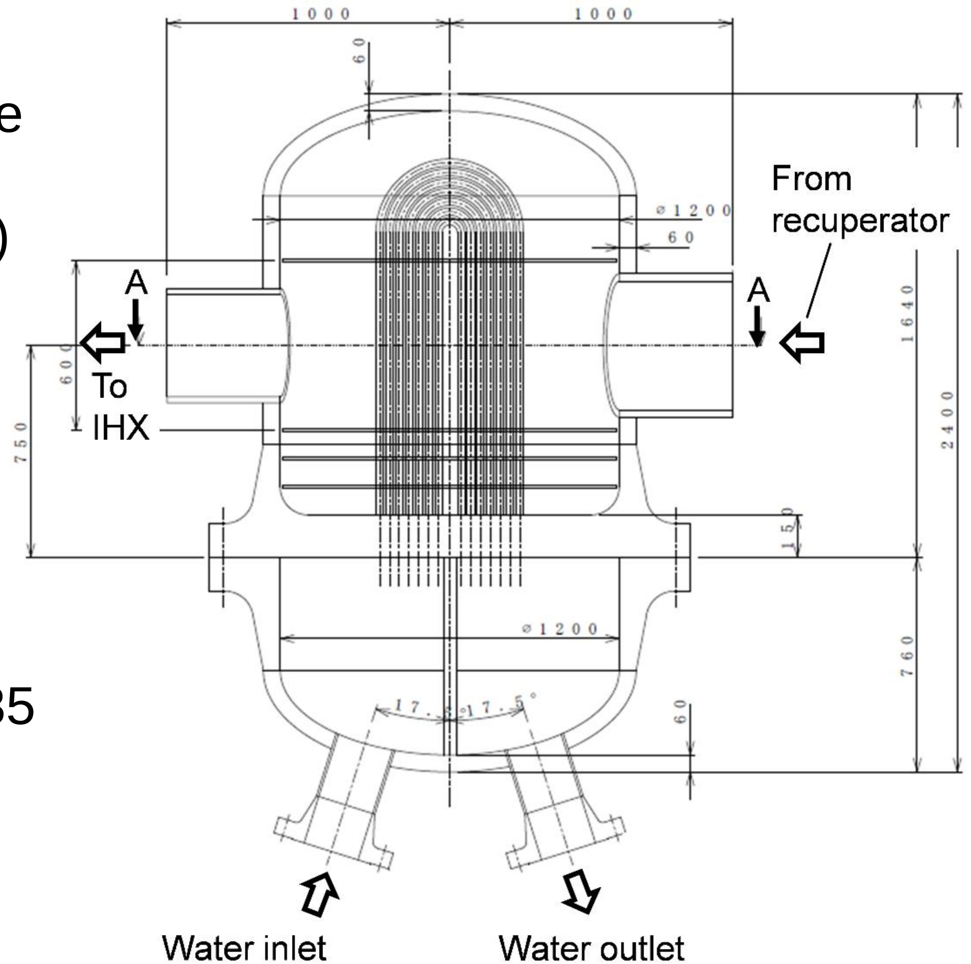


Cooler A

- Shell-and-tube, TEMA type X
- Helium secondary loop on shell side
  - Shell side (cross flow) divided into two regions (split in middle)
- Water coolant on tube side
  - Tubes lumped into one pipe component with 22 segments (12 in crossflow region, 6 per side)
- Heat transfer rate: 4.43 MW
- Heat transfer correction factor: 0.935
- Friction correction factor: 25.67



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Cooler B

- Shell-and-tube, TEMA type E
- Helium secondary loop on shell side
  - Shell side divided into:
    - 2 entrance/exit regions
    - 4 baffle window regions
    - 3 tube cross-flow regions
- Water coolant on tube side
  - Tubes lumped into pipe component with 28 segments
    - 2 up, 2 down between baffles
- Heat transfer rate: 4.19 MW
- Heat transfer correction factor: 1.39
- Friction correction factor: 7.02

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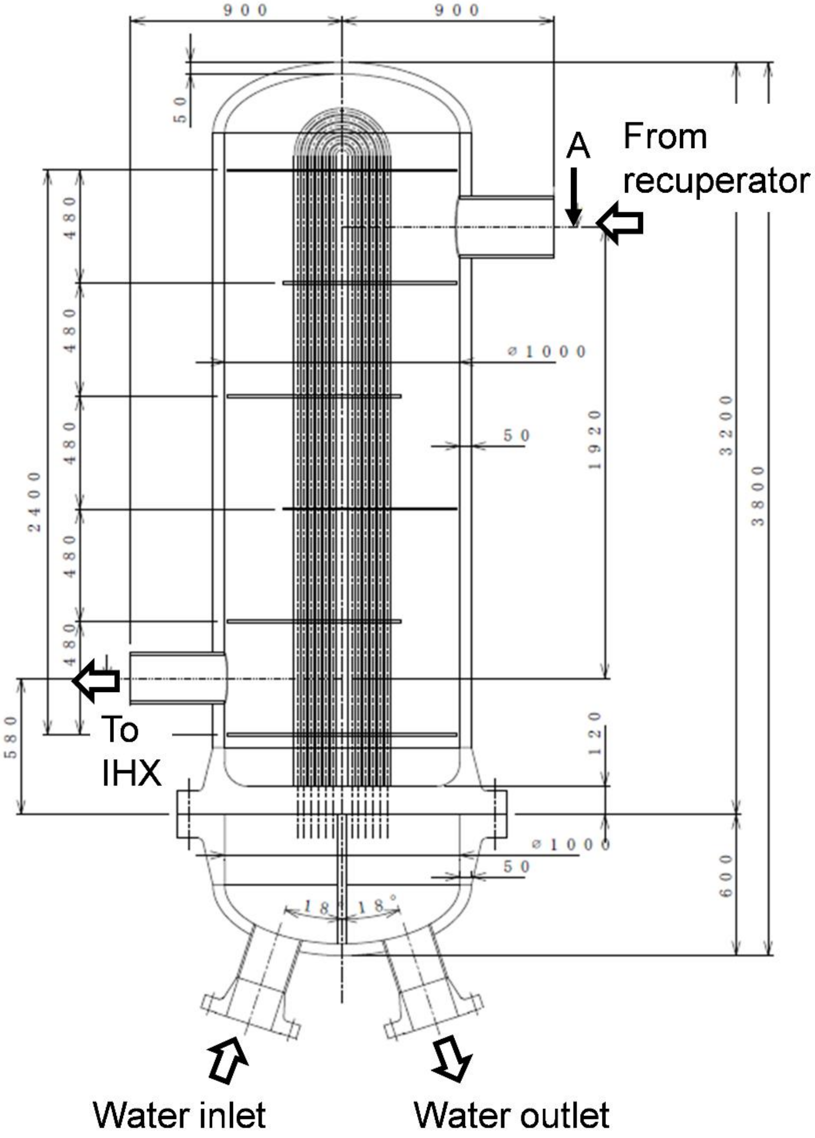

Statepoint comparison – sole power generation

- Flow rate of closed loop = 9.835 kg/s (design: 9.85 kg/s)
- Most points match well!

Turbine pressure drop close to design point

Turbine temperature drop (and turbine power overestimated

Compressor performance as expected

						Pressure [MPa]		ΔP [K]		
						esign	RELAP	Design	RELAP	RELAP/Design
						.11	4.10274	-	-	-
Turbine inlet	841.35	832.91				4.059	4.0594			
Turbine outlet	776.65	758.09	-64.7	-74.82	115.6414%	3.152	3.12698	-0.907	-0.93242	102.8026%
Recuperator LP side inlet	776.65	758.09				3.151	3.12648			
Recuperator LP side outlet	391.65	390.86	-385	-367.23	95.3844%	3.143	3.11975	-0.008	-0.00673	84.1250%
Precooler inlet	391.65	390.86								
Precooler outlet	298.15	298	-93.5	-92.86	99.3155%	3.14	3.1157	-0.003	-0.00394	131.3333%
Compressor inlet	298.15	298				3.13	3.11522			
Compressor outlet	348.85	350.7	50.7	52.7	103.9448%	4.307	4.30221	1.177	1.18699	100.8488%
Recuperator HP side inlet	348.85	350.68				4.304	4.30104			
Recuperator HP side outlet	733.85	717.13	385	366.45	95.1818%	4.298	4.29466	-0.006	-0.00638	106.3333%
Cooler A inlet	733.85	717.08				-	4.29223			
Cooler A outlet	647.15	634.84	-86.7	-82.24	94.8558%	-	4.26319		-0.02904	
IHX secondary side inlet	647.15	634.93				4.26	4.25971			

Running in H_2 co-generation mode

- Running the same model in hydrogen co-generation mode did not work well! Primary reasons for this:
  - The main Intermediate Heat Exchanger model does not transfer enough heat at the lower flow rate (2.57 kg/s), and IHX outlet temperatures did not get close to the desired outlet temperature (900 ºC)
  - The pressure drop across the turbines does not change appropriately with flow conditions, because the form loss coefficient used to set this in SPG mode is fixed
  - Design pressures are not always precise enough to appropriately adjust friction models
  - In closed-loop mode, all of the above result in components seeing conditions far from the design points
- To assess performance of components in HCG mode, consider a model with time dependent volumes in place of the IHX to that these state points are correct…

H_2 co-generation mode: work in progress

- In the following slide:
  - Loop is connected to time-dependent volumes at both ends of IHX
  - Turbine form loss has been adjusted to match H_2 co-generation operating conditions
  - Recuperator and precooler friction has been modeled with the alternate turbulent wall friction model:
    - $f = A + B(Re)^{-C}$
    - B, C set to attempt to match pressure drop in both modes
      - (2 points, 2 unknowns)
  - Form losses and flow areas have been adjusted to get correct flow split between IHX/2nd IHX and turbomachinery

Statepoint comparison – H_2 co-generation

- Flow rate through 2nd IHX: 2.59 kg/s (2.57 kg/s design)
- Flow rate through turbomachinery: 9.25 (9.15 kg/s design)

Some adjustments to loss coefficient needed to achieve these!

Turbine power, ΔP overestimated

Location	Temperature [K]		ΔT [K]			Pressure [MPa]		ΔP [K]		
	Design	RELAP	D[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	RELAP/Design
IHX secondary side outlet	1173.15	1172.8	-	-	-	4.11	[illegible]	-	-	-
2nd IHX secondary side inlet	1160.55	1170.5				-	4.10309			
2nd IHX secondary side outlet	1108.15	1118.4	-52.4	-52.1	99.4275%	-	4.10098	-	-0.00211	-
Turbine inlet	841.35	839.36				4.077	4.07651			
Turbine outlet	779.45	755.04	-61.9	-84.32	136.2197%	3.283	2.99114	-0.794	-1.08537	136.6965%
Recuperator LP side inlet	779.45	755.04				3.282	2.99067			
Recuperator LP side outlet	389.65	369.16	-389.8	-385.88	98.9944%	3.275	2.98409	-0.007	-0.00658	94.0000%
Precooler inlet	389.65	369.16				3.267	2.984			
Precooler outlet	298.15	296.83	-91.5	-72.33	79.0492%	3.265	2.98038	-0.002	-0.00362	181.0000%
Compressor inlet	298.15	296.83				3.265	2.97994			
Compressor outlet	347.35	350.04	49.2	53.21	108.1504%	4.402	4.12563	1.137	1.14569	100.7643%
Recuperator HP side inlet	347.35	350.02				4.138	4.12455			
Recuperator HP side outlet	737.15	735.17	389.8	385.15	98.8071%	4.134	4.12007	-0.004	-0.00448	112.0000%
Cooler B inlet	737.15	735.2				-	4.11993			
Cooler B outlet	423.15	423.37	-314	-311.8[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
IHX secondary side inlet	423.15	425.5		[illegible]	[illegible]	4.125	4.11121	[illegible]	[illegible]	[illegible]

Compressor performance still good

Summary, conclusions, and future work

- A RELAP5-3D model of the HTTR-GT/H_2 secondary system has been developed
- Compressor models match design data well
- A mechanism to appropriately model turbine pressure ratio with changing flow conditions (T, P) is desired
- Heat transfer models based on the Delaware method and implemented via control variables generally gave good agreement with design data
- Friction models for heat exchangers are presently difficult to assess since design data are somewhat imprecisely known
- Detailed models of the IHX, 2^{nd} IHX, and recuperator still need to be developed (some design details still needed)
- Refined component models should give a better result for operation in hydrogen co-generation mode

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