ILC Cooling System

VE and Design Status at KEK

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ILC GDE Meeting

17 November 2008, UIC (Chicago)

From Dubna to this meeting

Dubna

1. Preliminary evaluation of ΔT = 20 deg.C
2. Pick up of alternative HVAC scheme

This meeting

1. Evaluation of ΔT 10, 20, 30 deg.C
2. Evaluation of three different alternatives for HVAC

Previous preliminary evaluations (at Dubna)

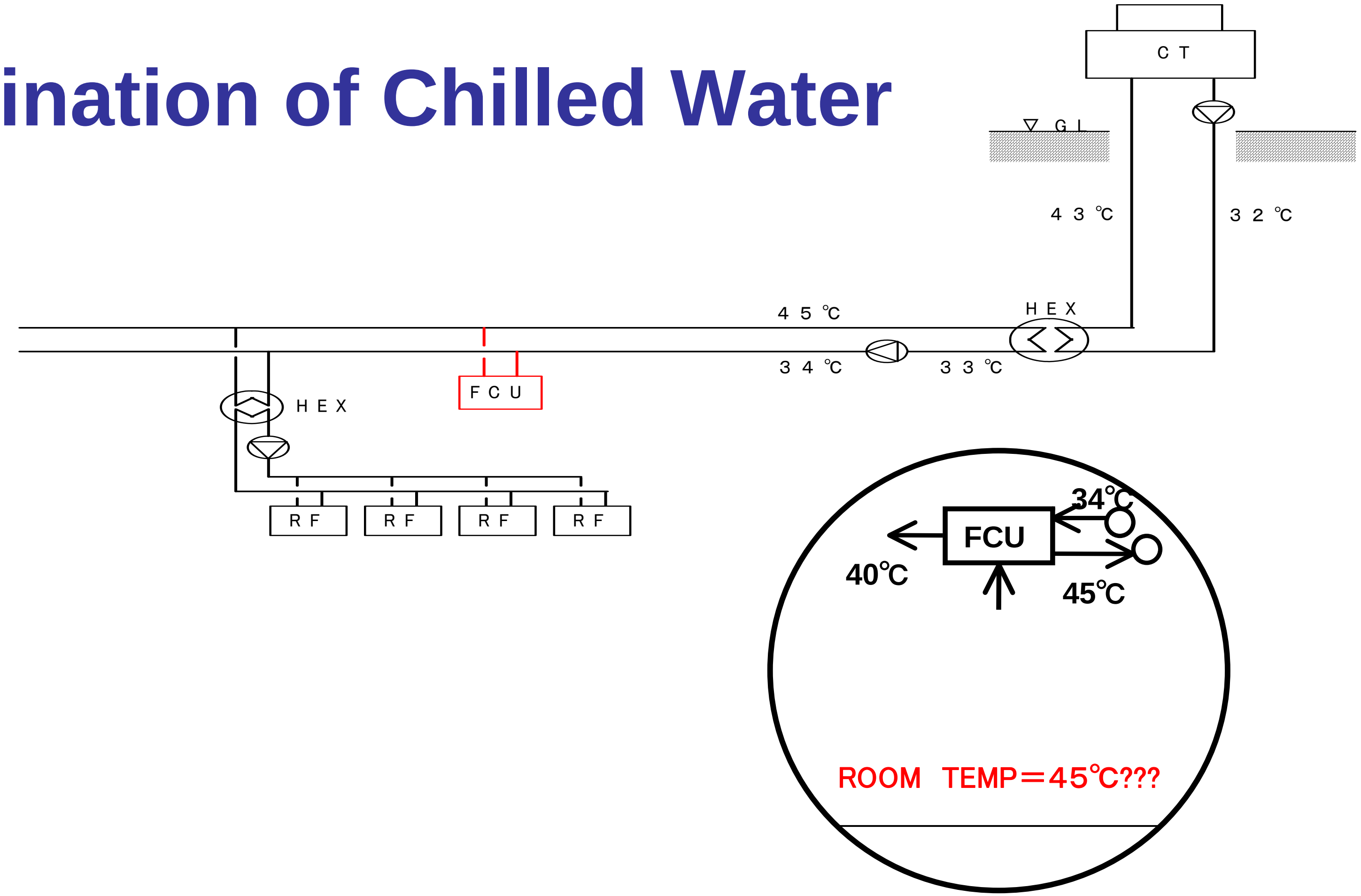
COST COMPARISON OF ΔT 11℃ & 20℃ @ #7

(Provisional Direct Cost) K¥

			Work Items	ΔT 11℃	ΔT 20℃
1752			Primary Stations		
	17521		Cooling Tower and Pump Station		
		175211	Cooling towers for process water		
		175213	Tower pump for process water		
		175216	Controls		
	17522		Primary Stations and Piping		
		175221 175222	Tower piping for processed water		
1753			Secondary stations		
	17531		LCW Stations and Distribution		
		175311	LCW pump/skid system		
	17535		Process Water Distribution		
		175351	Heat exchangers		
		175352	Distribution pump		
		175353 175354	Piping		
		175355	Piping connections etc.		
Total of Relevant Items					
					92.90%

7% cost saving expected by increasing ΔT = from 11 to 20 deg.C

Elimination of Chilled Water



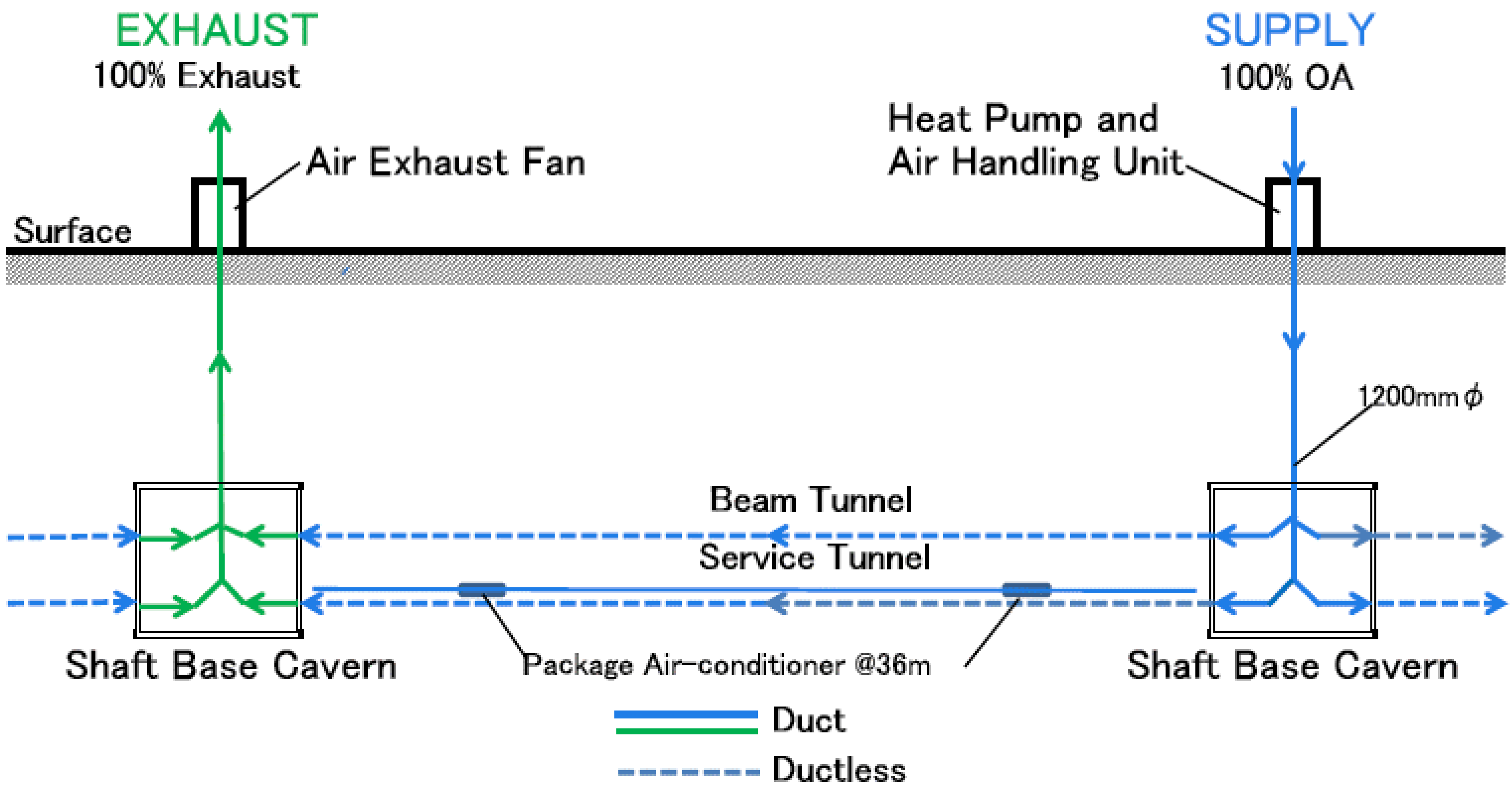
Service tunnel

Without chilled water to FCU, temperature of the service tunnel might rise to 45℃

Alternative HVAC scheme for tunnels

- supply & exhaust @ every other shafts

- package air-conditionaer at every 36 m

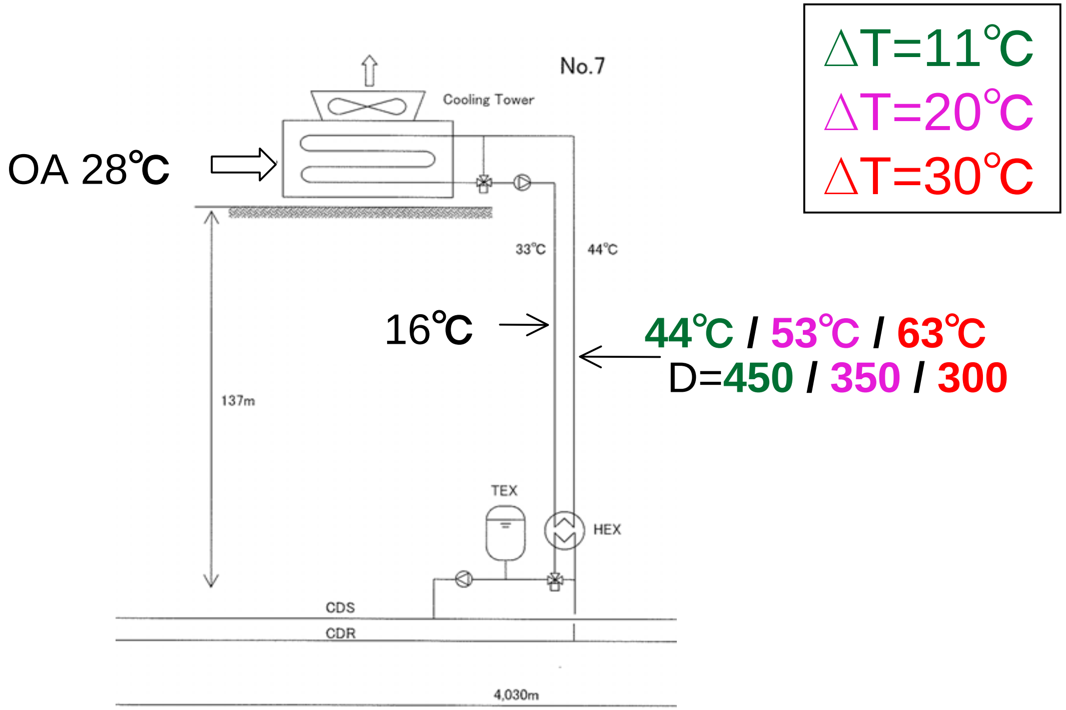


Studies after Dubna

- **Process Cooling Water System**
  - **- Elimination of chilled water**
  - **- Increase of *ΔTs* from 11℃ to 20℃ & 30℃**
- **HVAC System**
  - **- Tunnel temperature without Chiller**
  - **- Alternative air-conditioning system**

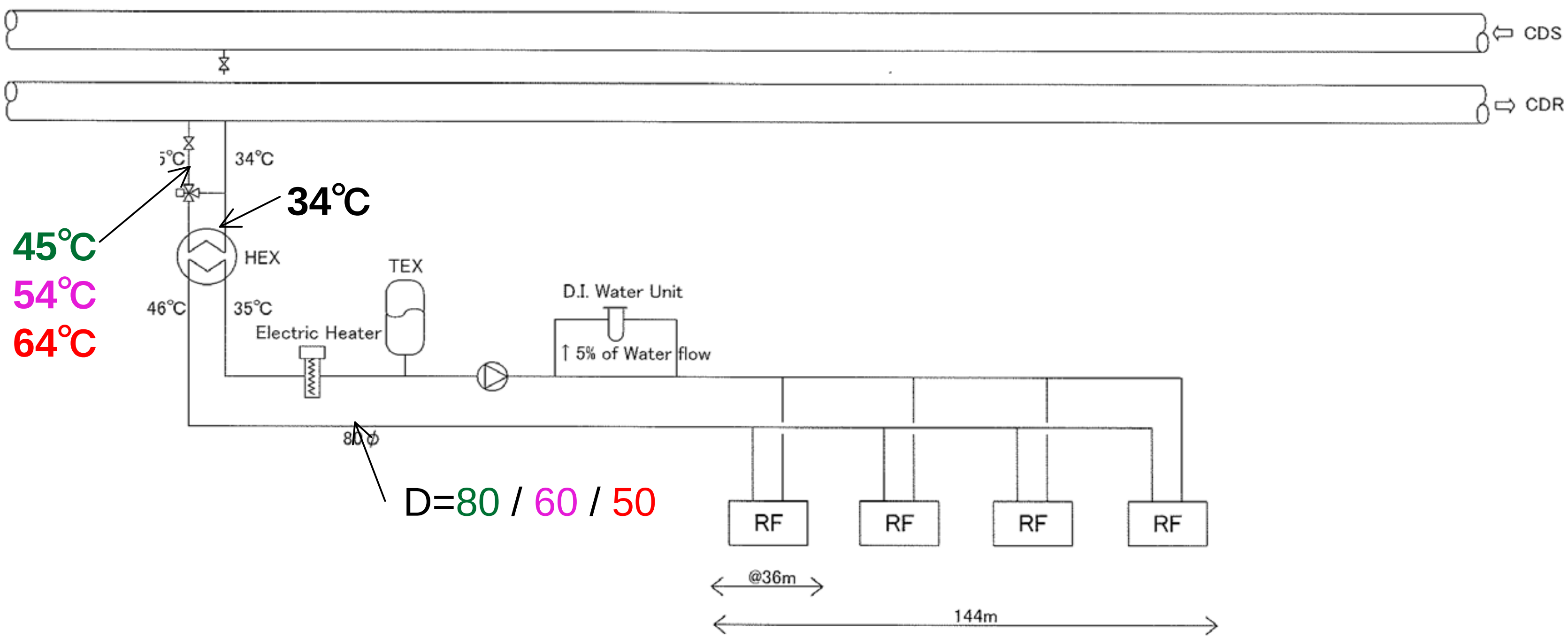
Process Cooling Water System

Primary Station



- **Elimination of chilled water and increase of ΔT**

Secondary Station



Cost Estimation done by Consul.

装置冷却水コスト30℃.xls

コード			工事名	内容・仕様	数量	単位	定価(千円)	掛率	単価(千円)	金額(千円)	計(千円)
1752			一次冷却水設備								
	17521		冷却塔およびポンプ								
		175211	冷却塔	密閉式空冷冷却塔 冷却熱量15,000kW、63/33℃、外気28℃DB	1	台					
		175213	冷却塔ポンプ・付属品	冷却水ポンプ 3,600L/min×30m、防振装置	2	台					
		175216	制御装置	冷却塔廻り制御	1	式					
	17522		一次設備・配管								
		175222	冷却塔配管(地上)	鋼管300φ(屋外仕様)	50	m					
		175224	冷却塔配管(シャフト)	鋼管300φ(屋内一般仕様)	274	m					
			配管支持架台他	@3mピッチ	54	個					
1753			二次冷却水設備								
	17531		脱塩水装置及び配管								
		175311	脱塩水スキッド	プレート型熱交換器 交換熱量450kW	26	台					
				冷却水ポンプ 220L/min×30m、SUS製、防振装置	26	台					
				純水装置	26	台					
				電気ヒータ	26	台					
				膨張タンク	26	台					
				ステンレス鋼管50φ(屋内一般仕様)	4030	m					
				ステンレス鋼管40φ(屋内一般仕様)	4030	m					
				バルブ スウェジロック 30φ	208	個					
				自動制御	26	式					
	17534		圧縮空気								
		175341	圧縮空気	空冷オイルフリーコンプレッサ165L/min、ドライヤ内臓、空気槽、フィルタ	26	台					
				ステンレス鋼管20φ(屋内一般仕様)	4030	m					
				バルブ スウェジロック 13φ	104	個					
	17535		冷却水配水								
		175351	熱交換器(地下空洞)	プレート型熱交換器 交換熱量5000kW	3	台					
		175352	配水ポンプ	冷却水ポンプ 3,600L/min×60m、防振装置	2	台					

(continued)

Done based on makers' current estimations and summed according to WBS items in RDR.

Cost Comparison by ⊿T

K$ @USD1=JPY120

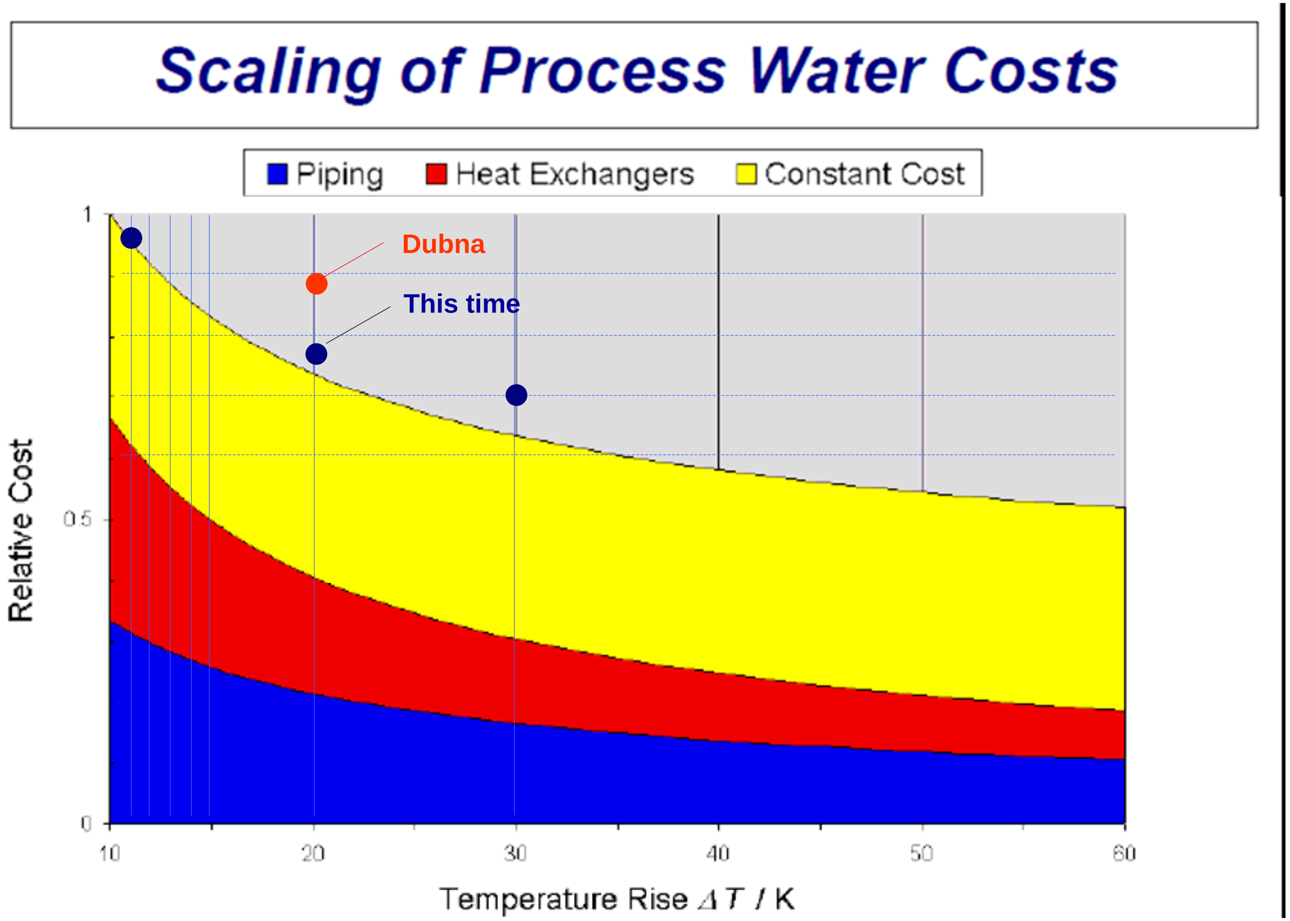
(Conversion rate used in RDR)

Cost for shaft #7

(w/o. Chilled water system)

			⊿T=11℃	⊿T=20℃	⊿T=30℃
1752		Primary Stations			
	17521	Cooling tower & pump			
	17522	Tower piping			
1753		Secondary Stations			
	17531	LCW Stations & distributions			
	17534	Compressed air			
	17535	Process water distribution			
		Total			
			100	**81**	**73**

VE Results on ΔT



Air-conditioning system for tunnel

$$K_L = \frac{q}{l(t_w - t_0)}$$ l : length of pipe, t_w : temperature of water in the pipe

t_0 : temperature of outside of the pipe

$$\frac{l(t_w - t_0)}{q} = \frac{1}{2\pi}\left\{\frac{1}{\alpha_w d_0} + \frac{\log_e(d_1/d_0)}{\lambda_1} + \frac{\log_e(d_2/d_1)}{\lambda_1}\right\} \quad l = 1m$$

$$q = \frac{21{,}4\,kw \times 1000}{36\ m} \approx 600\ w/m$$

$\alpha_w = 6\ w/m^2 K$ $\quad \alpha_w$:

$d_o = 2.5m$ $\quad d_0$: inside radius of the pipe

$d_1 = 3m$ $\quad d_1$: outside radius of the pipe

$d_2 = 10\ m$ $\quad d_2$: radius of insulated pipe

$t_0 = 10\ °C$

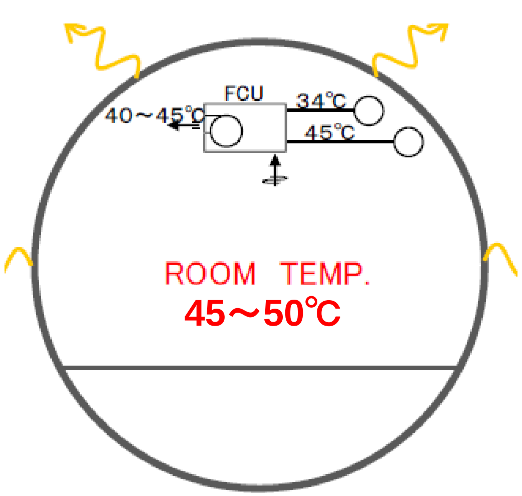
$$\frac{t_w - 10}{600} = \frac{1}{2\pi}\left\{\frac{1}{6 \times 2.5} + \frac{\log_e 3.0/2.5}{1.4} + \frac{\log_e 10/3.0}{3.1}\right\}$$

$$t_w = \frac{600}{2 \times 3.14}\left\{\frac{1}{6 \times 2.5} + \frac{0.18}{1.4} + \frac{1.2}{3.1}\right\} + 10 = 65.6°C$$

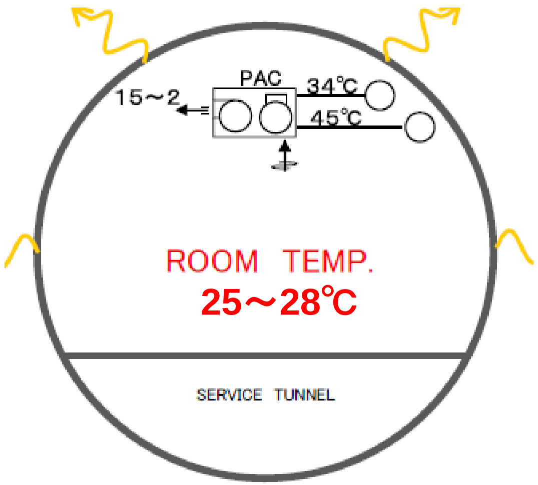
Without air-conditioning, temperature in the Service Tunnel will become *65.6 ℃.*

Measures to improve tunnel ambience

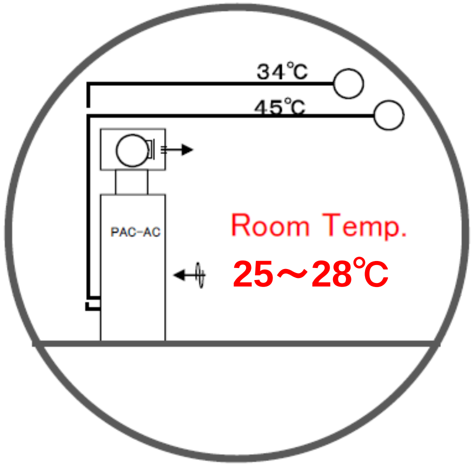
Fan coil unit with cooling water



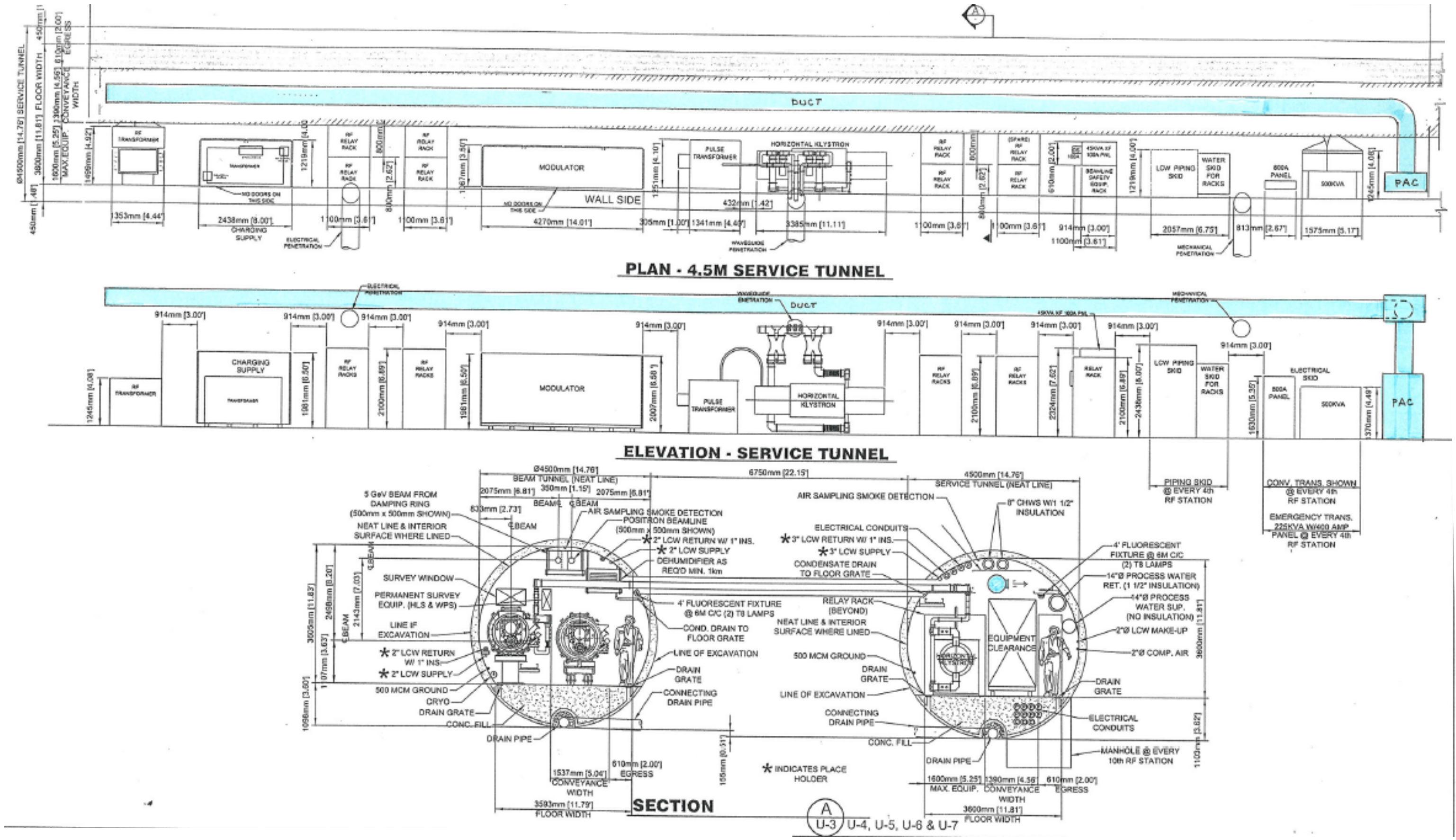
Suspended air-conditioner with compressor



Package air-conditioner on the floor



Layout of Package Air-conditioner & Duct



Cost Comparison

Cost for shaft #7

K$@USD1=JPY120
(Conversion rate for RDR)

			Fan coil unit with cooling water	Air-conditioning unit suspended from top of the tunnel	Package air-conditioner on the floor
1732		HVAC Equipment	[illegible]	[illegible]	[illegible]
	17321	OA & Exhaust air processing	[illegible]	[illegible]	[illegible]
	17322	Air-conditioning for tunnel	[illegible]	[illegible]	[illegible]

Conclusion

(1) VE on ΔT of process cooling water was investigated with cost estimation by consultant.

(2) Higher ΔTs certainly reduce cost. The highest limit will be given by heat load operation spec. of RF equipment.

(3) Local package air-conditioner scheme seems effective in cost reduction.

APPENDIX

(0) Cost profile

(1) Heat loads

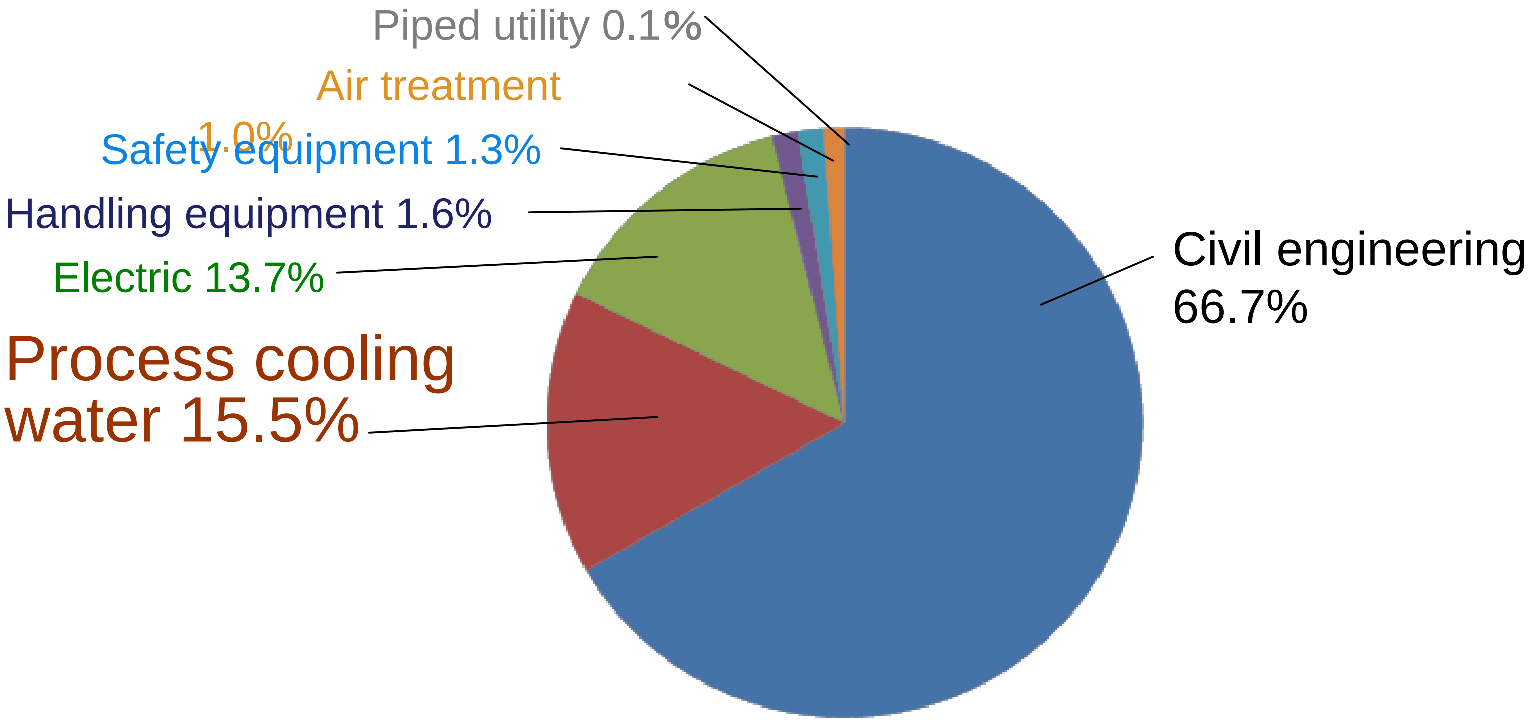
(2) Heat diffusion

(3) Suppress heat diffusion

(4) Surface and underground temperature

Priority of study on process cooling water

Proportion of process cooling water in total infrastructure (excl. survey)



Focus on - Shaft #7 Area -

Geometry of Facility

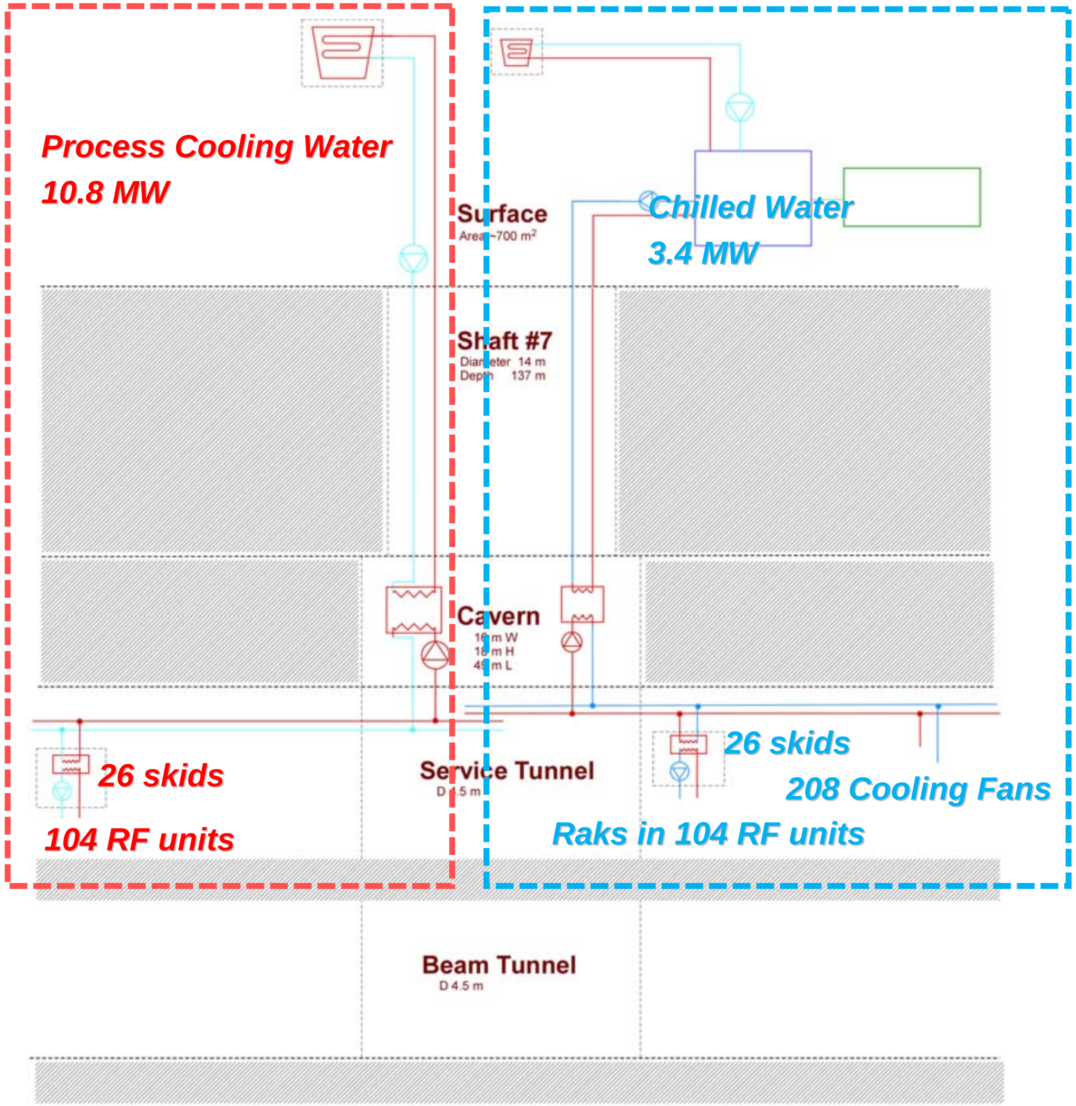
Cooling Tower building ~700 m2
Shaft 14 mϕ, 137 m (450 ft) depth
Cavern 16 m(W), 18 m(H), 49 m(L)
Tunnel 4.5 mϕ, ~4030 m (1550 + 2480)

RF Unit Heat Loads

To Low-Conductivity Water	104 kW
To Chilled Water	21.2 kW
Rack	11.5 kW
Service Tunnel Air	9.7 kW
To Beam Tunnel Air	5.9 kW

Shaft #7 Total Heat Loads

Number of RF units	104
Low-Conductivity Water	10.8 MW
Chilled Water	3.4 MW (Air2.2+Rack1.2)



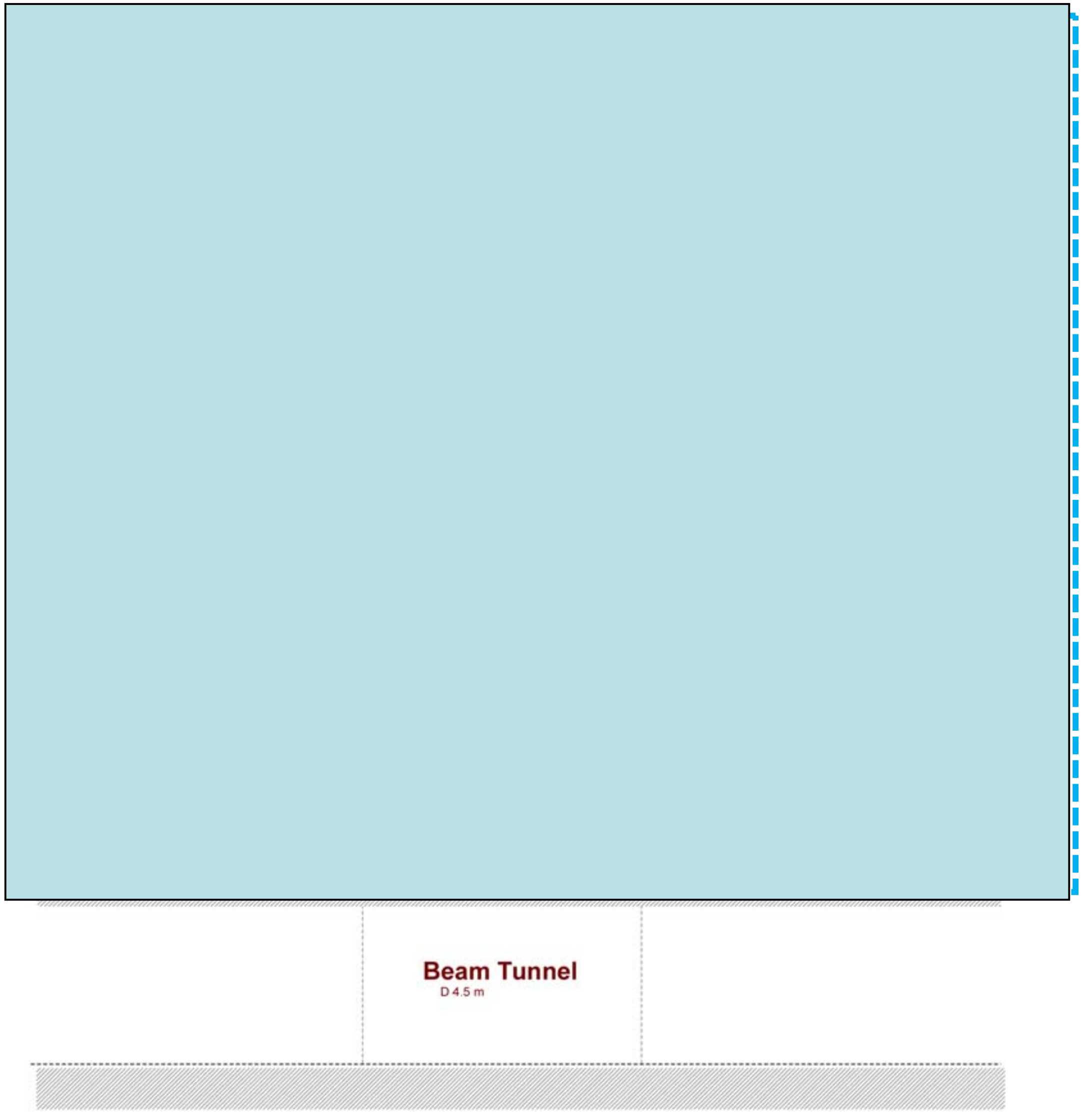
Cost Profile

ML cooling system cost is ~half of total area

Process Cooling Water piping cost is expensive,

including high percentage of LCW skids system (37%)

Low cost performance of Chilled water system



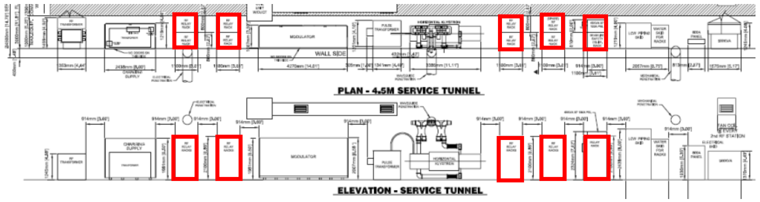
Dec 14 2007

WATER AND AIR HEAT LOAD (all LCW) and 9-8-9 ML

Top-5 heat loads to Air/ChW

MAIN LINAC - ELECTRON & POSITRON					To Low Conductivity Water	to Chilled Water	keith Jobe load to Air Nov 22 06	
Components	Quantity Per 36m	Location	Total Heat Load (KW)	Average Heat Load (KW)	Heat Load to Water (KW)	Heat Load to Water (KW)	Power fraction to Tunnel Air (0-1)	Power to Tunnel Air (KW)
Non-RF Components								
LCW Skid Pump 1 per 4 rf -Motor/Feeder Loss	0.25	Service Tunnel	0.60	0.60	0	0	1.00	0.60
I^2R Loss and Motor Loss (misc)	1	Service Tunnel	8.99	8.22	0	0	1.00	8.22
Fancoils (5 ton Chilled Water) 1.5 Hp	2	Service Tunnel	2.91	2.91	0	0		
Rack Water Skid	0.25	Service Tunnel	0.20	0.20	0	0	1.00	0.20
Lighting Heat Dissipation ~1.3W/sf		Service Tunnel	1.65	1.65	0	0	1.00	1.65
AC Pwr Transformer 34.5-.48 kV	0.25	Service Tunnel	2.00	2.00	1.50	0	0.25	0.50
Emerg. AC Pwr Transformer 34.5-.48 kV		Service Tunnel	1.00	1.00	0	0	1.00	1.00
RF Components								
RF Charging Supply 34.5 Kv AC-8KV DC	1/36 m	Service Tunnel	4.0	4.0	2.8	0	0.3	1.2
Switching power supply 4kV 50kW	1/36 m	Service Tunnel	7.5	7.5	4.5	0	0.4	3.0
Modulator	1/36 m	Service Tunnel	7.5	7.5	4.5	0	0.4	3.0
Pulse Transformer	1/36 m	Service Tunnel	1.0	1.0	0.7	0	0.3	0.3
Klystron Socket Tank / Gun	1/36 m	Service Tunnel	1.0	1.0	0.8	0	0.2	0.2
Klystron Focusing Coil (Solenoid)	1/36 m	Service Tunnel		4.0	5.5	0	0.1	0.4
Klystron Collector	1/36 m	Service Tunnel	58.9	47.2	45.8	0	0.0	1.4
Klystron Body & Windows	1/36 m	Service Tunnel			4.2	0		
Relay Racks (Instrument Racks)	1/36 m	Service Tunnel	10.0	10.0	0	11.5	-0.2	-1.5
	2/36 m	Service Tunnel			0			0.0
	1/36 m	Service Tunnel			0			1.166
RF Distribution (Attenuators, Loads, Waveguide, Circulators all in series connection)	1/36 m	Penetration			0.676			
	1/36 m	Beam Tunnel			0.0	0		5.9
	26/36 m	Beam Tunnel			2.49	0		0.0
	24/36 m	Beam Tunnel			30.05			0.0
Subtotal RF unit Only			90	82	102.0			
Total RF			107	99	103.5	11.5		21.4

Total Heat load to Air/Chilled water in service tunnel (per RF)	32.9
Total Heat load to LCW (per RF)	103.5
Total Heat load to air in beam tunnel (ignore rock contribution for now)	5.9



1. Racks 11.5 kW
2. I^2R & Motor Loss 8.2 kW
3. Waveguides (B.T.) 5.9 kW
4. Switching P.S. 3.0 kW
5. Modulator 3.0 kW

Total of top 5 = 31.6 kW

82% of total (S.T.32.9+B.T.5.9 kW)

But are these loads real and cannot we reduce?…

Parametric Consideration

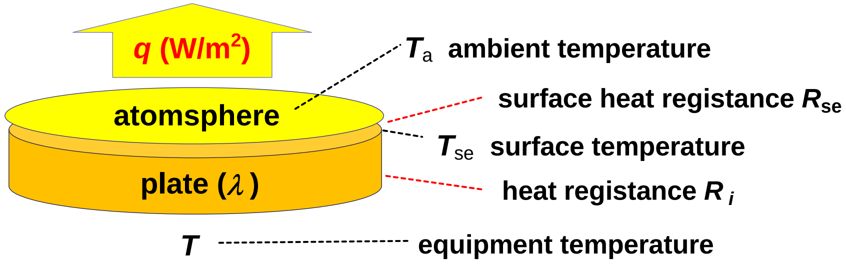
To understand heat loads to air, lets see how are heat diffusion and conduction..

Heat Diffusion from Plates

$$q(W/m^2) = U(\theta - \theta_a)$$

U: Heat transfer rate ($W/m^2/K$)
θ: Equipment temperature (C)
θ_a: Ambient temperature (C)

Heat diffusion by Radiation and Convection



$$U = (R_{se}+R_i)^{-1}$$

R_{se}: Surface heat resistance
R_i : Heat resistance of the material

$$R_{se} = (h_r + h_{cv})^{-1}$$

h_r: HTE by "Radiation"
h_r: HTE by "Convection"

$$h_r = \varepsilon\sigma(T_{se}^4 - T_a^4)/(T_{se} - T_a)$$

ε: Efficiency due to the material, ex. 0.30 (stainless steel), 0.94 (cement, cloth)
σ: Stefan-Boltsmann constant, $5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$
T_{se}: Surface temperature (K), T_a: Ambient temperature (K)

$$h_{cv} = \begin{cases} 3.26\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} & \text{upward-directed surface} \\ 2.28\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} & \text{doward-directed surface} \\ 2.56\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} & \text{vertical planes } (\Delta\theta>10K) \\ (3.61+0.094\Delta\theta)^{0.25}((w+0.348)/0.348)^{0.5} & \text{vertical planes } (\Delta\theta<10K) \end{cases}$$

$\Delta\theta = |T_{se} - T_a|$
w: Air flow velocity (m/s)

$$R_i = d/\lambda$$

d: Thickness of the material (m)
λ : Thermal conductivity of the material ($Wm^{-1}K^{-1}$)

The order of "Surface Heat Resistance"

For T_a (ambient temperature) 29 C
and T_{se} (surface temperature) 34~54 C

(1) Heat Radiation

assume $\varepsilon = 1.0$

$h_r = \varepsilon\sigma(T_{se}^4 - T_a^4) / (T_{se} - T_a) = 6.4 \sim 7.1\ (Wm^{-2}K^{-1})$

(2) Air convection

assume w = 0.45 m/s (27 m/min)

$h_{cv} = 3.26\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} = 7.4 \sim 11.0\ (Wm^{-2}K^{-1})$ upward-directed surface

$h_{cv} = 2.56\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} = 5.8 \sim 8.7\ (Wm^{-2}K^{-1})$ vertical planes ($\Delta\theta$ >10 K)

(3) Overall heat diffusion from equipment surfaces

assume $\varepsilon = 1.0$ and w = 0.45 m/s (27 m/min)

$h = 12 \sim 18\ W/m^2/K$ (for $\Delta T = 5 \sim 25$ deg)

Suppress the Heat load to Air!

Heat load to air by RF equipment when LCW used

Estimated diffusion when ΔT = 5 deg, ε = 1, w = 0.45 m/s

T: Equipment temperature (34 C)

T_a: Ambient temperature (29 C)

		Heat Load	Load to Air/Chilled Water (@present)	Estimated Heat Difusion		
				Top panel (m2)	Side panel (m2)	Heat difussion (kW) @ΔT=5de
1	Racks	11.5	11.5	8.8	56.7	4.1
2	I^2R & Motor Loss	8.22	8.2			0.0
3	Waveguides (B.T.)	5.9	5.9	24.6	45.9	4.5
4	Switching P.S.	7.5	3	3.0	14.5	1.1
5	Modulator	7.5	3	4.6	21.3	1.6
	Total of top 5	40.62	31.6			11.3

Effects of Heat Insulator

----- 釈迦に説法 (Preaching Budda) -----

Heat radiation and convection

assume ε = 1.0 and w = 0.45 m/s (27 m/min)

h = 12 ~ 18 $W/m^2/K$ (for ΔT = 5 ~ 25 deg)

R_{se} = 0.056 ~ 0.083 $W^{-1}m^2K$

Heat resistance of insulator (1 mm)

$R_i = d/\lambda = 0.020\ W^{-1}m^2K$

d: Thickness of the material (0.001 m)

λ : Thermal conductivity of insulator (0.05 $Wm^{-1}K^{-1}$)

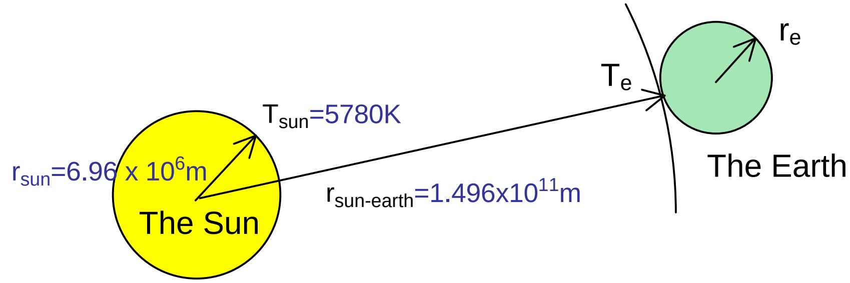
- A few mm of heat insulator is comparable to surface resistance
- A few cm of heat insulator is usually enough for completeness of water cooling system

Ambient Temperatures

Surface and Underground

Earth Temperature

-- as a short note --



Solar constant

$$q_{sun} = \sigma T_{sun}^4 \times 4\pi r_{sun}^2 / 4\pi r_{sun\text{-}earth}^2 = 1370\ W/m^2$$

Temperature of the earth

$$q_{sun}\ \pi r_e^2 = \sigma T_e^4 \times 4\pi r_e^2 \quad \text{(equilibrium)}$$

$$\Rightarrow \quad T_e = 279\ K\ (6\ C)$$

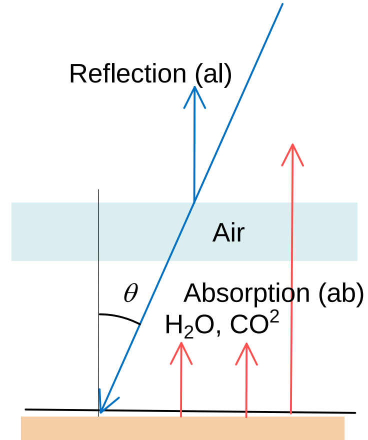
Temperture on the ground depends on site

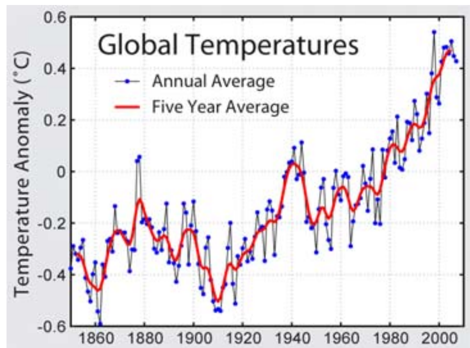
$$q_{sun} \times \cos\theta (1-al) = \sigma T_g^4 (1-ab) \quad \text{(equilibrium)}$$

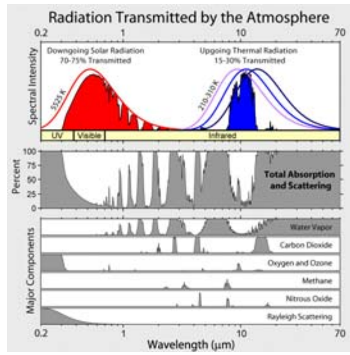
$$\cos\theta = \sin\Theta \cos\omega_d t \cos\omega_y t + \sin\Theta \sin\omega_d \cos\mu \sin\omega_y t + \cos\Theta \sin\mu \cos\omega_y t$$

Θ: latitude, μ=23.5 deg,

$\omega_d = 2\pi$/day, $\omega_y = 2\pi$/year







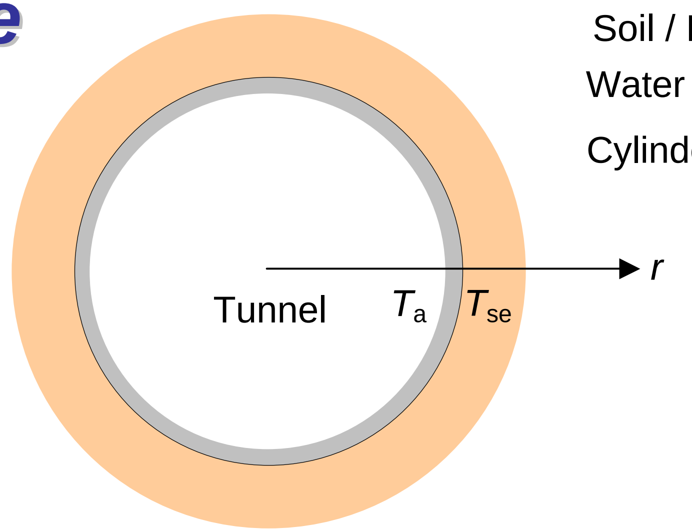
Temperatures affects surface cooling tower

Place	Altitude		Temperature Monthly Average												Annual Average	Statistical Peoriod
	d	m	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	sep	Oct	Nov	Dec		
Moscow-Dolgoprudnyj	55	50	-7.5	-6.7	-1.4	6.4	12.8	17.1	18.4	16.5	10.8	5.0	-1.6	-5.5	5.3	1971-2000
Chicago-Ohare	41	59	-5.6	-2.8	3.0	9.0	15.1	20.4	23.4	22.4	18.0	11.4	4.3	-2.2	9.7	1971-1999
Zurich-Town	47	23	0.3	1.3	5.1	8.1	12.8	15.6	18.0	17.7	14.0	9.3	4.1	1.5	9.0	1971-2000
Berlin-tempelhof	52	28	0.8	1.5	4.9	8.7	14.2	17.2	19.2	18.8	14.5	9.6	4.9	2.0	9.7	1971-2000
Morioka	39	42	-2.1	-1.6	1.8	8.4	13.8	18.2	21.8	23.2	18.3	11.8	5.7	0.8	10.0	1971-2000
Tokyo	35	41	5.8	6.1	8.9	14.4	18.7	21.8	25.4	27.1	23.5	18.2	13.0	8.4	15.9	1971-2000
Fukuoka	33	35	6.4	6.9	9.9	14.8	19.1	22.6	26.9	27.6	23.9	18.7	13.4	8.7	16.6	1971-2000

Place	Altitude		Relative Humidity Monthly Average												Annual Average	
	d	m	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	sep	Oct	Nov	Dec		
Moscow-Dolgoprudnyj	55	50	80	76	73	67	64	63	69	74	78	79	82	82	74	1961-1967
Chicago-Ohare	41	59	72	72	70	65	64	66	69	71	71	69	73	76	70	1961-1990
Zurich-Town	47	23	85	80	75	72	73	74	73	77	81	84	84	85	79	1961-1990
Berlin-tempelhof	52	28	89	83	76	68	64	61	65	69	73	79	87	89	75	1961-1967
Morioka	39	42	73	71	68	66	69	76	81	80	81	78	74	74	74	1971-2000
Tokyo	35	41	50	51	57	62	66	73	75	72	72	66	60	53	63	1971-2000
Fukuoka	33	35	64	64	66	67	69	76	75	74	74	69	67	65	69	1971-2000

Detail design and comparison of site difference are the next step after the system optimizaton.

Beam Tunnel Temperature



Tunnel Air temperature without wall loss

$\Delta T = P/(Fc)$

P:heat load [W],
F: air flow [g/s],
c: specific heat capacity [J/(gK)]

When,
$P = 5.9$ kW x 104 = 0.61 MW,
$F = 7.16\ m^3/s$ ($= \pi \times 2.25^2\ m^2 \times 0.45$ m/s)
$\rho = 1184\ g/m^3$
$c = 1.020$ J/(gK) (hum~50%)
$\Delta T \sim 70$ deg!

Heat Diffusion into tunnel wall
$q = h\ \Delta T$

Assuming the tunnel surface heat resistance (1/h)
$h = 12 \sim 18\ W/m^2/K$ (for $\Delta T = 5 \sim 25$ deg)

$S = \pi \times 4.5$ m x 36 m ~ 500 m^2 (Tunnel wall / RF init)
$Sh = 6 \sim 9$ kW /K

How is Underground Temperature ?

Depend on the geology

Deeper than 10 m, the temperature is constant

Geothermal heat flow forward the surface ground

$$\sim 40 \times 10^{12} / 4\pi(6.4 \times 10^{6})^{2} = \sim 0.08\ W/m^{2}$$

the total geothermal heat of the earth (W) / the surface area of the Earth (m^2)

Temperature rise in deep underground

$$\sim 0.08 / (2\sim 8) = 0.01\sim 0.04\ K/m$$

Heat flow (W/m^2) / the thermal conductivity (W/mK)

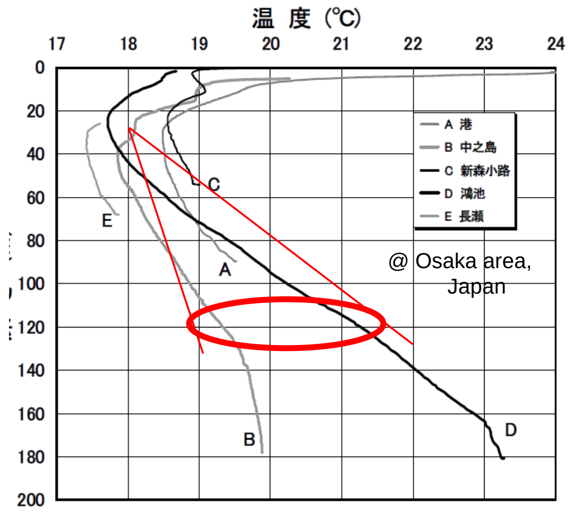
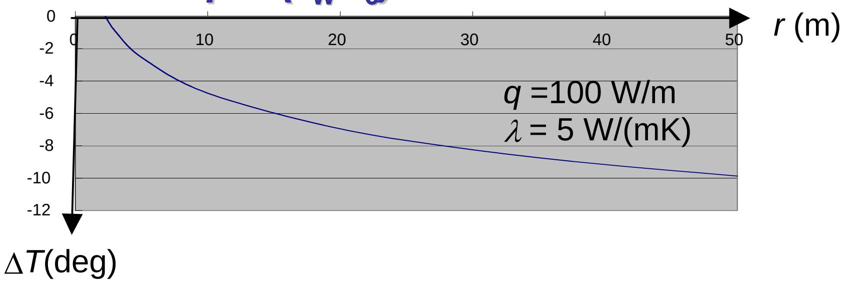


図-7 温度と深さの関係
(K.Kitaoka, Okayama university of science)

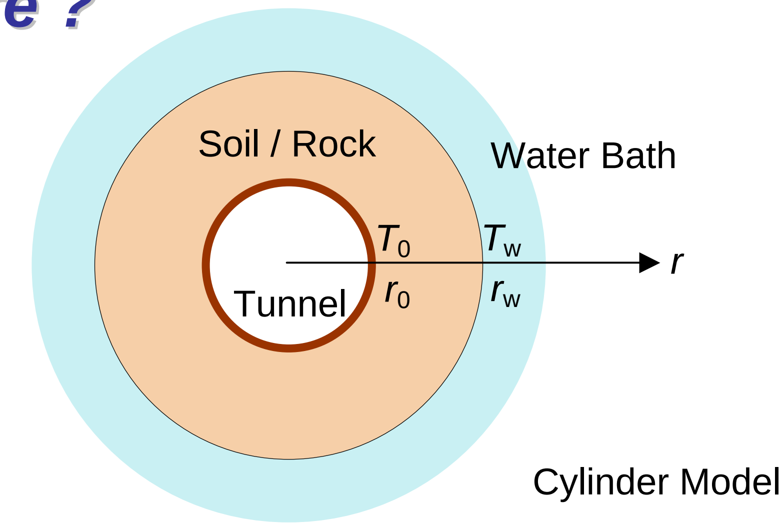
How is tunnel wall Temperature ?

Cylinder Model

$\Delta T = -q \ln (r_w/r_0) / 2\pi\lambda$

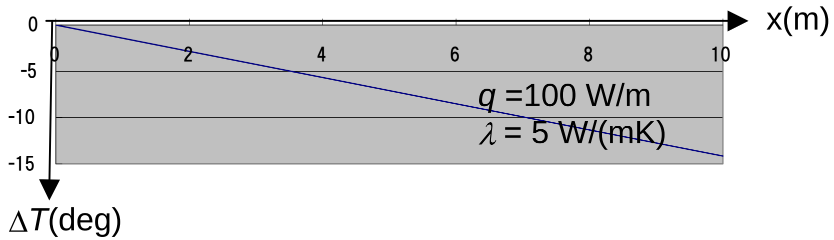


Assuming a bath, r_w-r_0 = 50 m, ΔT = 10 deg, 100 W/m could be removed from the tunnel

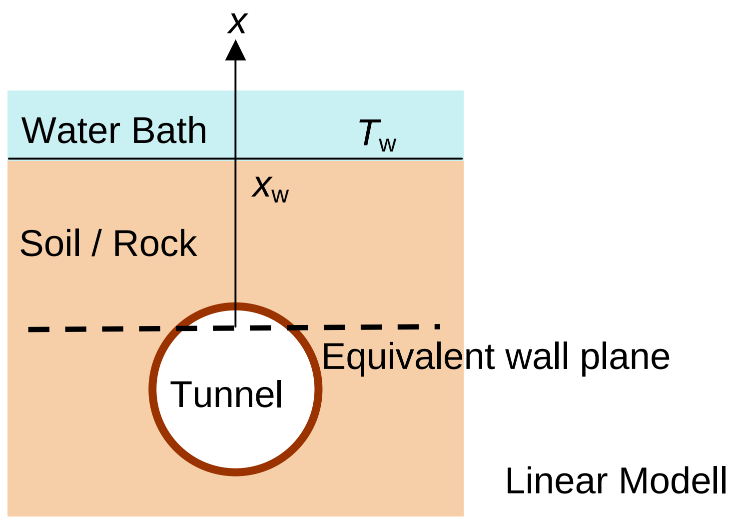


Linear Model

$\Delta T = -Q\, x / \lambda, \quad Q = q \times 2\pi r$ (guess)



Assuming a bath, r_w-r_0 = 7 m, ΔT = 10 deg, 100 W/m could be removable



Summary at Dubna

(1) Delta T increase and Chilled Water Decrease are potential measures to reduce cooling costs.

(2) Effect of high ΔT to room T may be suppressed by insulator with relative low cost.

(3) Effect of high ΔT to equipment and beam instability should be studied separately.

(4) Alternative air cooling system using package air conditioner is under consideration.

(5) More investigation and effort to decrease heat load to air are necessary.

(6) Cooling effect by tunnel wall depends on geology of the site, though an order of ~100 W/m may be cooled under some conditions.

(7) LCW skid loop with complicated piping is another impact to raise cooling cost but the study is a subject to be solved hereafter.