OPTIMAL OPERATION OF A HVAC SYSTEM WITH A THERMAL STORAGE WATER TANK

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ABSTRACT

A methodology for the optimal operation of a HVAC system with a thermal storage water tank has been proposed by one of the authors[1)]. In the present paper improvement of the methodology is explained together with simulation results obtained by using real building data. The main results are as follows. 1) This method is sufficiently robust to be applied to a real HVAC system having time varying air-conditioning (AC) load. 2) Predicted AC load must include some error and it was found that storage operation ignoring the error often experiences shortage of thermal energy and as a result unsatisfied air-conditioning creating room air temperature deviation. To avoid the problem increasing in the load by taking the error level into account should be considered. 3) On peak load days daytime storage operation is normally necessary due to the limitation in tank capacity. The optimal operation method considering this constraint was developed and it was found that the performance is fine.

INTRODUCTION

Japanese government has controlled its electric industry in order to provide stable supply and to attain nationwide price uniformity. However the current worldwide movement known as restructuring of electricity market forced the government to change the policy drastically and the market has been partly opened in 2000. The issues in restructuring differ from country to country based on its constraints in energy resources and conditions of power plants, however, minimizing a large demand gap between the daytime and the nighttime is the Japanese top priority issue. Therefore nighttime low electricity price has been adopted before the current restructuring movement and the thermal storage systems for HVAC systems have been widely applied since 1960s mainly to large commercial buildings. In spite of the long experience in thermal storage system operation, however, operators still find difficulty in optimal operation of the system. One cause of the problem is immaturity in the control strategies developed without adequate understanding of system's sophistication. To cope with this problem development of new optimal operation strategy is needed, where enhancing the recent development of computer control technology and the fast price dropping of computer products will be key issues.

The authors have previously proposed a basic methodology for the optimal operation of a thermal storage water tank at the Building Simulation '99 conference utilizing simulation technology[1)]. In the present paper the following improvements added to the previous method and the investigation results related to the new development are explained.

1) Instability and local minimum occurrence in the process of optimization was found in the previous methodology, therefore, computational algorithm was improved.
2) The optimal operation was searched assuming that AC load prediction is perfect. If predicted load is smaller than the resultant load, satisfactory air-conditioning cannot be achieved, therefore, it is recognized that increasing the predicted load by some percentage is safer decision. In this study magnitude of the percentage defined as a safety margin is investigated and recommended.
3) In the previous study all the thermal energy required to manage AC load is stored during the nighttime. But in the actual system storage tank capacity is designed not to store whole energy for a peak day, that is, on heavy load days chillers must be operated even during the daytime and electricity used for this additional operation must be taken into account in optimization. In this research this is investigated and quasi-optimal operation strategy is proposed.
4) The aim of the optimization was to minimize electric power consumption, however, reduction of electricity cost is the most important aim for building users and the amount of CO_2 emission for global warming issue. The effect by the different objectives is analyzed and compared.
5) The AC loads used for investigation were typical periodic diurnal and artificially produced random loads. In the present investigation AC load taken

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from a real building and the load predicted are used additionally to demonstrate the feasibility of our method.

As shown in the previous report the total HVAC system including major components, such as a storage tank, air-handling units, cooling towers, and water pumps is modeled to simulate the performance on MATLAB/ SIMULINK environment (Figure 1). By this implementation wide variety of HVAC systems can be easily modeled by the aid of user-friendly graphical interface. The variables to be optimized are the chilled water temperature and the duration of chiller operation.

IMPROVEMENT OF OPTIMIZATION ALGORITHM

Several improvements were added to the previous optimizing algorithm in order to stabilize calculation, avoid local minimum occurrence and reduce computational time by applying more rationale constraints and more precise model for water circulation.

1) Improvement in determining required thermal storage

The required thermal storage for a following day is defined as follows.

$$Q_d = Q_p + Q_c + Q_l - Q_s \qquad (1)$$

Where,

Q_p : predicted building load

Q_c : generated heat by circulation pumps for chilled water

Q_l : heat loss through storage tank walls

Q_s : stored heat in a tank

Although Q_d is mainly subject to Q_p the impact of Q_c and Q_l on Q_d cannot be ignored. In the previous algorithm Q_c and Q_l were estimated as a given fraction of the predicted heat load Q_p but this caused instability of simulation when time varying real load was fed as the input for simulation. In the new algorithm those values are estimated based on simplified simulation and this improvement can reduce error level down to about 10% rather than the previous magnitude of 70%.

2) Avoiding local minimum in optimization

In the previous algorithm the optimal chilled water temperature θ was determined by searching the temperature itself and the duration of chiller operation T_{ch} simultaneously, however, this approach sometimes could not find the optimal values due to local minimum occurrence in optimization process. To avoid the problem it was found that the two variables should be searched independently. In the new algorithm θ and T_{ch} are searched starting from the initial value 5 °C and 10 hours respectively.

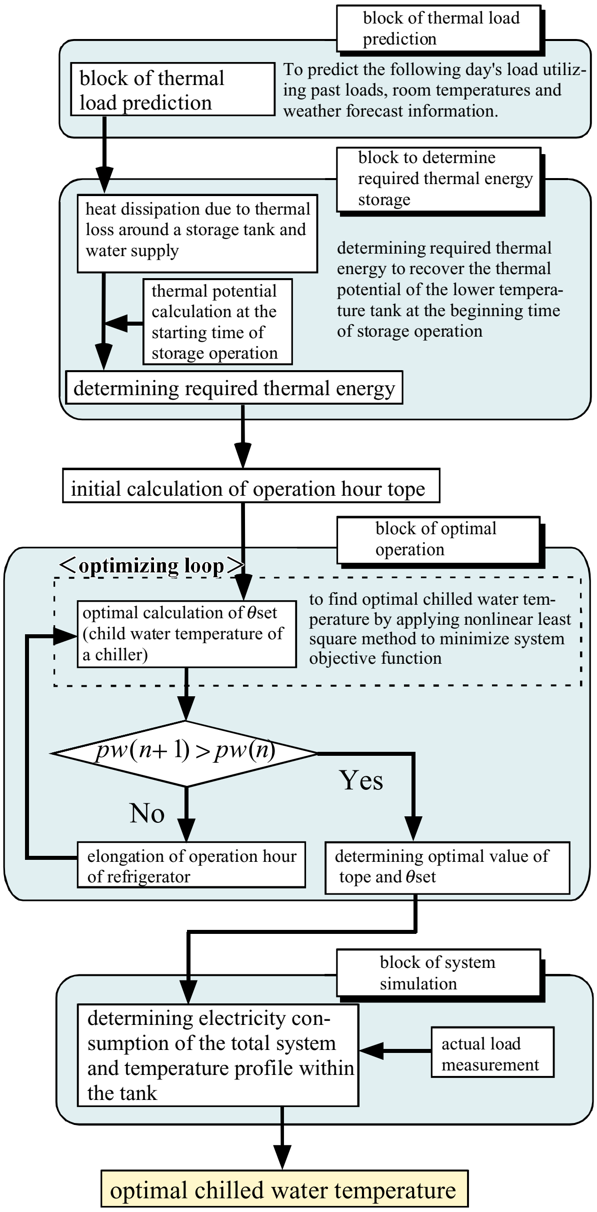

Figure 1 Improved optimal argolithm

3) Rationalization of constraints in optimization

The constraints in optimization are;

$$0 \le \dot{m} \le \dot{m}_d ,\ 0 \le T_{ch} \le 10 \text{ and } Q_{ch} \le Q_d$$

where

$\dot{m}$: chilled water flow rate

$\dot{m}_d$: design value of $\dot{m}$

T_{ch} : chiller operation time

Q_{ch} : total thermal energy production by chiller

Q_d : total chiller capacity based on design value

The second constraint is automatically satisfied by the new optimization search method mentioned above. To incorporate the first and the third constraint in optimization a penalty function method is used.

4) Improvement of water circulation model

The functions of bypass circuit of chilled water circulation system and on-off control of pump units are

Table 1 Reduction rate for three objective functions from the reference operation

load type	control method	reduction rate [%]		
		electricity consumption	electricity cost	CO_2 emission
light load	optimal electricity consumption	41.6	34.0	41.7
	optimal electricity cost	41.7	34.2	41.6
	optimal CO_2 emission	41.1	33.6	41.7
medium load	optimal electricity consumption	24.9	16.1	25.4
	optimal electricity cost	24.5	18.2	24.9
	optimal CO_2 emission	24.8	15.5	25.5
heavy load	optimal electricity consumption	11.7	3.1	11.7
	optimal electricity cost	10.7	6.9	11.4
	optimal CO_2 emission	11.6	4.8	11.8

incorporated to make the simulation model realistic. The characteristic curves of pumps are also improved to make the performance more precise.

TOTALLY NIGHTTIME OPERATION

For a basic investigation the storage tank capacity is assumed large enough to store whole thermal energy required for air-conditioning on the following days. Although this assumption is not realistic in common building systems the investigation is useful to understand the basic performance and characteristics of the present operation method.

1) Comparison of Objective Functions with Periodic Load

To investigate the effect brought by the deferent objective functions which correspond to minimizing electricity consumption, electricity cost and CO_2 emission simulations were carried out using three standard and periodic AC loads; heavy, medium and light load. For the simulations the following conditions are used. The current electricity prices in the Tokyo region are 6 JPY/kWh for the nighttime (22:00 - 8:00), 20 JPY/kWh for the daytime (8:00 - 14:00, 16:00 - 22:00) and 22 JPY/kWh for peak hour (14:00 - 16:00). The larger the percentage of generation by nuclear power plants is, the less the CO_2 emission rate by unit electricity consumption is because nuclear power is believed to emit less CO_2. In the present research hourly CO_2 emission rates reported by Tokyo Electric Company are used. For the comparison of the results the reference operation is defined; namely non-optimal operation that corresponds to chilled water temperature of 7 ^{0}C (design value) and full storage without load prediction function. The reduction rates from the reference vale are shown in Table-1.

It can be seen that the reduction of all the three optimal operations is substantial. This says incorporating optimal operation is very beneficial. However the deference between the reduction rates of three objective functions is very small. The reasons of this result are as follows.

1) To reduce electricity cost daytime electricity usage should be minimized because daytime price is higher. Decreasing in chilled water temperature is the most effective way to achieve this because water circulation rate during daytime air-conditioning can be reduced and as a result electricity used for pumping is reduced. However decreasing the temperature requires more electricity due to COP drop in chiller operation. Due to these contradictory effects the temperature level defers from that of the operation for electricity consumption optimization.

2) Hourly CO_2 emission rates in unit electricity usage do not differ so significantly that much difference between two objective functions; electricity consumption and CO_2 emission, does not occur.

If we evaluate the total effectiveness of incorporating the optimal operation based on the medium load condition, about 25% in electricity consumption and CO_2 emission and 16% in electricity cost can be reduced.

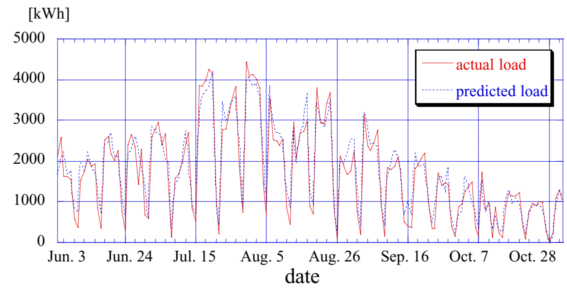

Figure 2 Air-conditioning load taken from a real building and the predicted load

2) Simulation using Real Air-Conditioning Loads

To verify the feasibility and the stability of the present method simulation using real air-conditioning loads measured at a real building was performed. The record of the integrated loads in daily basis is shown by the solid line of Figure 2. The period of air-conditioning is from June 3 to October 31 and the daily air-conditioning period is from 9:00 to 18:00. The dotted line in Figure 2 is

Table 2 Results of perfect prediction case for total period

	in average		power consumption [MWh]			
	operation hour [h]	set temperature [°C]	total	refregirator	secondary pump	others
maximum storage operation	5.4	7.0	96.8	73.7	5.0	18.1
optimal operation	3.5	15.2	67.3	49.1	6.4	11.8

Table 3 Monthly compumption and reduction rates in electricily

	maximum storage operation [MWh]	optimal operation [MWh]	reduction rate [%]
Jun	17.3	11.3	34.5
Jul	26.4	21.3	19.4
Aug	25.1	17.8	28.9
Sep	16.4	10.5	35.6
Oct	11.6	6.3	45.6
total	96.8	67.3	30.4

Table 4 Results of operation based on real load with prediction error

	in average		power consumption [MWh]			
	operation hour [h]	set temperature [°C]	total	refregirator	secondary pump	others
maximum storage operation	5.1	7.0	79.8	60.2	4.4	15.2
optimal operation	3.1	15.2	50.9	36.3	5.3	9.3

the predicted load by the method of the previous report [4]. The prediction error is 7.32% (a_0) of the maximum load. The a_0 is defined as EEP (Expected Error Percentage) value.

2-1) Simulation with Perfect Prediction

Load prediction is not perfect in a real situation; however, basic investigation was made assuming perfection. The results for the whole period of simulation are shown in Table-2 compared with the reference operation defined at the previous investigation. It is found that substantial conservation 33.1MWh (=96.8 - 63.7MWh) can be attained, that corresponds to 31% reduction. This is mainly due to chiller COP increase with high chilled water temperature of 15.2 °C in average. Table-3 shows monthly results. It can be found that the reduction rates are larger in intermittent season. This is why in heavy load period the temperature must be low to manage large AC load and as a result COP decreases.

2-2) Simulation with Prediction Error

Taking the real situation into account simulation with load prediction error was carried out. Namely thermal storage operation is performed based on the predicted load and consumption of the thermal energy or air-conditioning operation is achieved based on real loads. As mentioned previously the EEP value of the present example is 7.32%. Therefore due to the existence of the prediction error the stored thermal energy is not necessarily sufficient to manage air-conditioning for a whole day on certain days. The shortage of thermal energy results in the increase of stored chilled water temperature, and consequently room air temperature becomes higher than the set point for some hours. Such a day is defined as an insufficient storage day. In the present study the number of such days was 17. Table-4 shows the results and it can be seen that the reduction rate (36%) excluding the insufficient storage days is similar to that of the perfect prediction case (32%). But the existence of 17 days of insufficient air-conditioning would be a serious problem to building users. Furthermore it was found that inadequate temperature disturbance in the tank is produced and this causes unstable air-conditioning operation.

3) Simulation Considering Prediction Error

Two points are considered in the investigation of prediction error; the effect of prediction error EEP level and the effect of a margin of safety to reduce occurrence of faulty air-conditioning days.

3-1) EEP level of prediction error

The EEP level of prediction error of the present example is 7.32% as shown previously, however, according to the benchmark trials operated by SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineering of Japan) the average EEP level of the best methods was around 5%. Therefore in the present investigation predicted loads with three levels of EEP, namely 5% (average), 10% (2 times) and 20% (4 times), were generated by the following method and the simulation using them was performed.

$$e_d(n) = Q_{r,d}(n) - Q_{p,d}(n) \tag{2}$$

$$k(n) = \frac{(a_L/a_0)\cdot e_d(n) - Q_{r,d}(n)}{Q_{p,d}(n)} \tag{3}$$

$$q_{p,L}(n,j) = k(n) \cdot q_p(n,j) \quad (4)$$

where,

$e_d(n)$: prediction error in day total
$Q_{r,d}$: actual load in day total
$Q_{p,d}$: predicted load in day total
$q_{p,L}$: predicted hourly load
n : indication of day
j : indication of hour
a_L : EEP level (a_1 : 5%, a_2 : 10%, a_3 : 20%)

As shown in Table-5 the optimal chilled water temperature decreases and the number of days of insufficient storage or unsatisfactory air-conditioning increases substantially with EEP, although electricity consumption does not increase significantly. When EEP level is 10% 20 days out of 122 days or 16% of cooling season days will have unsatisfactory air-conditioning. This figure will not be acceptable by buildings users.

3-2) Operation with a margin of safety

Increasing the stored thermal energy by a margin of safety for the predicted load can decrease the number of unsatisfactory air-conditioning days. To investigate the effect of margin level simulation was performed with five levels; 0%, σ (=7.32%), 2σ, 4σ and 8σ. As shown in Table-6 no unsatisfactory air-conditioning day occurs by applying the margin level greater than 4σ, nevertheless the electricity consumption increases very little (3%).

PARTLLY DAYTIME STORAGE OPERATION

According to a design guide a standard storage tank should be sized so that chillers are operated for 10 hours both in the nighttime and the daytime on the day of maximum load condition. This implies maximizing the duration of chiller operation and consequently minimizing chiller capacity. In other words the tank capacity is designed so as to store a half of the maximum day total load, although this does not necessarily ensure optimal size. When daytime storage operation takes place the conditions concerning optimal operation become more sophisticated. On a day when total air-conditioning load is less than the tank capacity nighttime operation meets the requirement and the operation strategy can be the same as explained for the totally nighttime operation. However when total load exceeds the tank capacity optimal operation becomes more complex because other variables such as operation schedule of chillers in addition to the chilled water temperature must be considered. In the present study four conditions are analyzed with different levels as listed in Table-7. They are chiller operation schedule, chilled water temperature set point, reference tank temperature, and a margin of safety for storage. Eleven scenarios (S1 -- S7, S11 -- S14 shown in Table-8) based on different combinations of the four conditions and levels were investigated as potential optimal strategies. For example each scenario is abbreviated such as S1(σ), if the scenario is S1 and the safety margin is σ. Simulation was carried out by taking electric power consumption as the objective function and daytime chilled water temperature was optimized. To evaluate the results of the scenarios the performance of non-optimal operation is taken as the reference, that is, the chilled water temperature in the nighttime is set at 7 °C and the temperature of the last tank is maintained between 8 and 9 °C by on-off control of chillers. The reduction rates shown in Table-9 mean the reduction from the reference value. As seen they range from 11 to 18 % with 15 % in average.

1) Daytime chiller operation schedule

To evaluate the schedule of daytime chiller operation

Table 5 Comparison of optimal operation with different levels of EEP

EEP value	set temperature [°C]	power consumption [MWh]	power consumption increase rate [%]	insufficient storage day	storage needless day
0%	15.9	42.1	0.0	0	0
5%	15.4	43.1	2.2	11	5
10%	14.7	43.2	2.4	20	12
20%	13.2	43.7	3.6	27	27

Table 6 Results of operation with a margin of safety

	power consumption [MWh]				insufficient storage day	storage needless day	reduction effect [%]
	total	refregirator	secondary pump	others			
0	56.0	40.1	5.7	10.2	11	5	35.0
s	56.5	40.8	5.5	10.3	9	5	34.4
2s	57.3	41.6	5.3	10.4	5	6	33.6
4s	58.6	43.0	5.2	10.5	0	6	32.0
8s	61.2	45.6	4.9	10.7	0	5	29.0
full storage	86.2	65.3	4.6	16.3	0	0	0.0

the performance of early time operation (OE) and late time operation (OL) were compared. The OE means that chillers are operated without break after nighttime operation, namely, operated in the morning. On the contrary OL is reverse or operation in the afternoon. Heat loss is reduced by OL operation but the possibility of the occurrence of thermal energy shortage is higher. Although the difference between the two strategies is negligible as shown in S1(0) for OE and S2(0) for OL of Table-9.

2) Chilled water temperature in the nighttime

In the nighttime chillers are operated at maximum capacity in partially daytime storage operation. To investigate the effect of the chiller temperature set point in the nighttime operation, simulations were performed at three levels of set point; namely 7, 9 and 11 °C. They are abbreviated as S1, S4 and S5 respectively and the effect of three levels of safety margin for load prediction is analyzed together. Fundamentally the set point should be the design value of 7 °C to store maximum thermal energy during night, however, it can be set higher in real operation. In this case the stored energy will be consumed excessively in the daytime and the risk of unsatisfactory air-conditioning or insufficient storage increases. In addition to the three scenarios the scenario S3 in which the set point was optimized as a uniform value for day and night was performed. The results are shown in Table-9. All the scenarios of S3 show good reduction in power consumption, however, electricity cost increases and the number of insufficient storage days is large. This is because the chiller operation is mostly in the daytime. The differences between S1, S4 and S5 are not significant, but comparing three aspects of power consumption, cost and CO_2 emission the S4(2σ) would be decided as an optimal scenario and reductions of 12.9% in power consumption, 6.8% in cost and 12.4% in CO_2 emission can be attained.

3) Reference temperature change with month

As investigated previously by changing the tank reference temperatures with month the system efficiency will increase. To investigate this effect simulation S6 and S7 were performed. By comparing with the best given result S4(2σ) it can be found that additional reductions of 3.5% in power consumption, 2.5% in cost and 3.2% in CO_2 emission is possible.

4) Difference in objective function

The objective function of the above studies is the electric power consumption. To investigate the effect of applying different objective functions simulations through S11 to S14 were performed. It can be seen that the effect is very little, therefore taking the electric power consumption as the objective function is acceptable.

CONCLUSIONS

An optimal operation method for a HVAC system equipped with a water storage tank was proposed by the author's in the previous work[1)]. In the present report improvement of the methodology is explained and the effect and the feasibility of the method is investigated and evaluated. The evaluation is made in terms of

Table 7 Conditions for partial daytime operation

investigated condition	a	b	c	d
1. operation schedule	earlier time operation (OE)	later time operation (OL)		
2. set temperature	night time: 7°Cday time: optimizing for day time (T7)	optimizing for whole day (TW)	night time: 9°Cday time: optimizing for day time (T9)	night time: 11°C day time: optimizing for day time (T11)
3. reference temperature	same for all months (SA)	setting for each month (SE)		
4. margin for storage safety	0	σ	2σ	

Table 8 Combination of conditions for each scenario

operation senario	operation schedule	set temperature	reference temperature	margin for storage safety	objective function
S1	OE	T7	SA	0, s , 2s	power consumption
S2	OL	T7	SA	0	power consumption
S3	OE	TW	SA	0, s , 1s	power consumption
S4	OE	T9	SA	0, s , 0s	power consumption
S5	OE	T11	SA	0, s , 1s	power consumption
S6	OE	T7	SE	0, s , 2s	power consumption
S7	OE	T9	SE	0, s , 2s	power consumption
S11	OE	T7	SE	2s	power cost
S12	OE	T7	SE	2s	CO_2 emission
S13	OE	TW	SA	2s	power cost
S14	OE	TW	SA	2s	CO_2 emission

electricity consumption, electricity cost and CO_2 emission based on the present electricity tariff and diurnal variations in CO_2 emission for unit electricity usage taking nuclear power generation into account.

Firstly totally nighttime operation is investigated. This is the case that the tank capacity is designed large enough to store whole energy to satisfy air-conditioning of a peak day. If air-conditioning load is predicted perfectly the reduction of electric power consumption from non-optimized operation can be about up to 30%. In reality perfect prediction is not possible and if the error level is 5% the system encounters 11 days of unsatisfied air-conditioning or insufficient storage. In general this figure may not be accepted by building users. Therefore the cases in which predicted load is increased with a margin of safety are investigated and it is found that no insufficient storage day occurs with 20% of a margin of safety. Nevertheless reduction effect remains at about 30%.

Secondary more common operational condition is investigated, that is, partially daytime storage operation. According to a design guide the tank capacity is sized so that chillers are operated 10 hours both in the nighttime and the daytime on a peak load day. Consequently the tank is in storing mode only for nighttime on the days of light load. On these days the optimal strategy can be the same as for the totally nighttime operation. On the contrary storing operation must be done during daytime also on the days of heavy load, then conditions becomes complex. Eleven scenarios are made as feasible combinations of conditions and they are evaluated. In conclusion the following scenario is the best; nighttime storage operation at 9 ºC followed by daytime operation in the morning, monthly varied reference temperatures for storage and 10% of a margin of safety for load prediction. Approximate reduction by this near-optimal operation is 15% in power consumption, 9% in cost and 14% in CO_2 emission. The effect of different objective function is also analyzed but not so significant effect is detected.

ACKNOWLEDGEMENT

The authors acknowledge the favor of Tonetsu Co. in providing measured data from a real building.

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Table 9 Comparison of different scenarios for partially daytime operation

operation senario	margin for storage safety	power consumption [MWh]	power consumption reduction rate [%]	electricity cost [JPY*1000]	electricity cost reduction rate [%]	CO_2 emission [kgC]	CO_2 emission reduction rate [%]	insufficient storage day
S1	0	79.9	12.7	740	0.3	6450	11.1	0
	s	80.3	12.2	699	5.8	6411	11.6	0
	2s	81.1	11.4	689	7.1	6450	11.1	0
S2	0	80.1	12.4	744	-0.2	6470	10.8	1
S3	0	76.6	16.3	870	-17.2	6451	11.1	1
	s	76.7	16.2	849	-14.4	6428	11.4	12
	2s	77.1	15.7	855	-15.2	6468	10.8	13
S4	0	78.4	14.3	731	1.5	6340	12.6	0
	s	78.7	13.9	691	6.9	6297	13.2	0
	2s	79.6	12.9	692	6.8	6358	12.4	0
S5	0	77.3	15.5	764	-2.9	6308	13.0	0
	s	77.7	15.1	747	-0.6	6310	13.0	1
	2s	78.3	14.4	771	-3.9	6397	11.8	3
S6	0	77.2	15.6	733	1.2	6265	13.6	5
	s	76.5	16.4	677	8.8	6130	15.5	7
	2s	78.0	14.8	674	9.2	6224	14.2	1
S7	0	75.7	17.3	722	2.7	6148	15.3	5
	s	75.1	17.9	671	9.7	6025	17.0	7
	2s	76.4	16.4	673	9.3	6121	15.6	1
S11	2s	78.0	14.8	672	9.4	6221	14.3	1
S12	2s	78.1	14.7	674	9.3	6221	14.3	1
S13	2s	79.9	12.7	697	6.1	6377	12.1	0
S14	2s	79.4	13.2	718	3.3	6369	12.2	0

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