Design and operation of water recovery systems for space stations

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The paper is based on the experience in design and operation of "Salut", "Mir" and International Space Station water recovery systems and ground investigations. The paper reviews selection of water recovery methods for different water-based products and hardware for performing hydrodynamic, chemical and heat and mass transfer processes in single-phase and two-phase gas/liquid media in microgravity conditions. The performance data of the water recovery systems are presented. The prospects of regenerative water supply systems development are considered.

Nomenclature

CDRA = CO_2 removal system "Vozdukh"
CDRS = CO_2 reduction system by Sabatier method
CFU = condensate feed unit
EDV = water container (Russian)
ISS = International Space Station
Mir = Soviet/Russian Space station
Rodnik = tanks for delivered water
LSS = life support systems
Salut = Soviet/Russian Space station
SM = Service Module of the ISS
SOV = water purification facilities
SRV-HG = hygiene water recovery system
SRV-K = system for water recovery from humidity condensate
SPK-U = urine collection and pretreatment system
SRV-U = system for water reclamation from urine for Mir space station
SRV-UM = system for water reclamation from urine for ISS
SVO-ZV = water storage system
TCCS = trace contaminant control system
US = American segment
US Lab = USA Laboratory Module

I. INTRODUCTION

Implementation of future orbital and interplanetary missions is associated with improvements in crew life support systems (LSS) including water supply systems. Due to energy, space and mass limitations physical/chemical processes will be used in water recovery systems of space stations in the near future. Bioengineering processes and food production are future problems wich have to be resolved on planetary bases. Experience in the design and operation of "Salut", "Mir" and the Russian segment of the International Space Station (ISS) water supply systems[1,2,3,4] made it possible to obtain data on human water balance on the space station and performance

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parameters of the recovery systems. The data are used to carry out design analysis of water supply systems for future space stations.

The recovery methods are selected depending on the trace contaminant content in the feed liquid and the requirements for the recovered water: a sorption/catalytic and an ion-exchange processes for humidity condensate from the cabin and greenhouse atmosphere and for water from carbon dioxide reduction; membrane filtration (ultra filtration and reverse osmosis) with an ion-exchange post-treatment for hygiene water; the distillation method accompanied by sorption/catalytic purification for urine.

The most important issues are minimal mass and power consumption and reliable decontamination of product water. Realization of these requirements is illustrated in the paper by design analysis of systems for water recovery from humidity condensate and for water reclamation from urine.

Hydrodynamic, chemical and heat and mass transfer processes in single-phase and two-phase gas/liquid media are used in the systems. In the latter case special methods for processes have to be used in a space flight under microgravity conditions[5]. General principle of gas/liquid separation process and heat and mass transfer by condensation, evaporation, boiling, absorption, heterogeneous catalysis, etc. in microgravity is to provide a stable interface of phase separation. Molecular (capillary) surface tension forces and dynamic (centrifugal and friction) forces are therefore used.

Performance data of systems for water recovery on the Soviet/Russian space stations, water balance, selection of water recovery methods for different water products, hardware for performing hydrodynamic, chemical and heat and mass transfer processes in single-phase and two-phase gas/liquid media in microgravity conditions and prospects of regenerative water supply system development are described in this paper.

II. WATER SUPPLY AND RECOVERY SYSTEMS ON SOVIET/RUSSIAN SPACE STATIONS “SALUT”, “MIR” AND RS ISS

The water supply systems of Soviet/Russian space stations “Salut”, “Mir” and ISS based on water recovery from humidity condensate (on “Salut”, “Mir” and ISS) and from urine (on “Mir”) as well as use of delivered supplies are presented in table 1.

Table 1. The water supply systems of Soviet/Russian space stations “Salut”, “Mir” and RS ISS

Space station		
“Salut-4”, “Salut-6”, “Salut-7”	“Mir”	Russian segment of the International Space Station (RS ISS)
SRV-K – a system for water recovery from humidity condensate[6] SVO-ZV – a water storage (delivered supplies) system. Fligts: Salut-4 – 1975 (90 days) Salut-6 – 1977-1981 (570 days) Salut-7 – 1982-1986 (743 days)	SRV-K2 – a system for water recovery from humidity condensate SPK-U – a urine collection and pretreatment system SRV-U – a system for water reclamation from urine SOV – water purification facilities (equipment of water purification for “Electron” system) SRV-HG – hygiene water recovery system SVO-ZV – a water storage (delivered supplies) system	SRV-K2M – a system for water recovery from humidity condensate SPK-UM – a urine collection and pretreatment system SRV-UM – a system for water reclamation from urine (future prospect) SOV – water purification facilities (equipment of water purification for “Electron” system) SVO-ZV – a water storage (delivered supplies) system /here index “M” – improved system/

Water recovery systems on space station “Mir”

For the first time in the world a practically complete complex of physical/chemical systems for water recovery and atmosphere revitalization (except systems for CO_2 concentration and reduction and waste processing) was accomplished on the orbital space station “Mir”. The complex ensured long-duration and effective functioning of the station with the crew on board[3,4,6]. A LSS schematic diagram is presented in Figure 1. Water supply systems are marked with blue, atmosphere revitalization systems are marked with yellow, supplies systems are marked with green. Water recovery from humidity condensate, urine and hygiene water was accomplished in specific systems, and oxygen for breathing was generated by electrolysis of water reclaimed from urine. Trace contaminants were removed from the atmosphere in the Trace Contaminant Control System (TCCS) and from carbon dioxide in the

Carbon Dioxide Removal System (CDRA) "Vozdukh". Water supplies were delivered to the station in Rodnik system tanks and EDV tanks by automated Progress cargo ships.

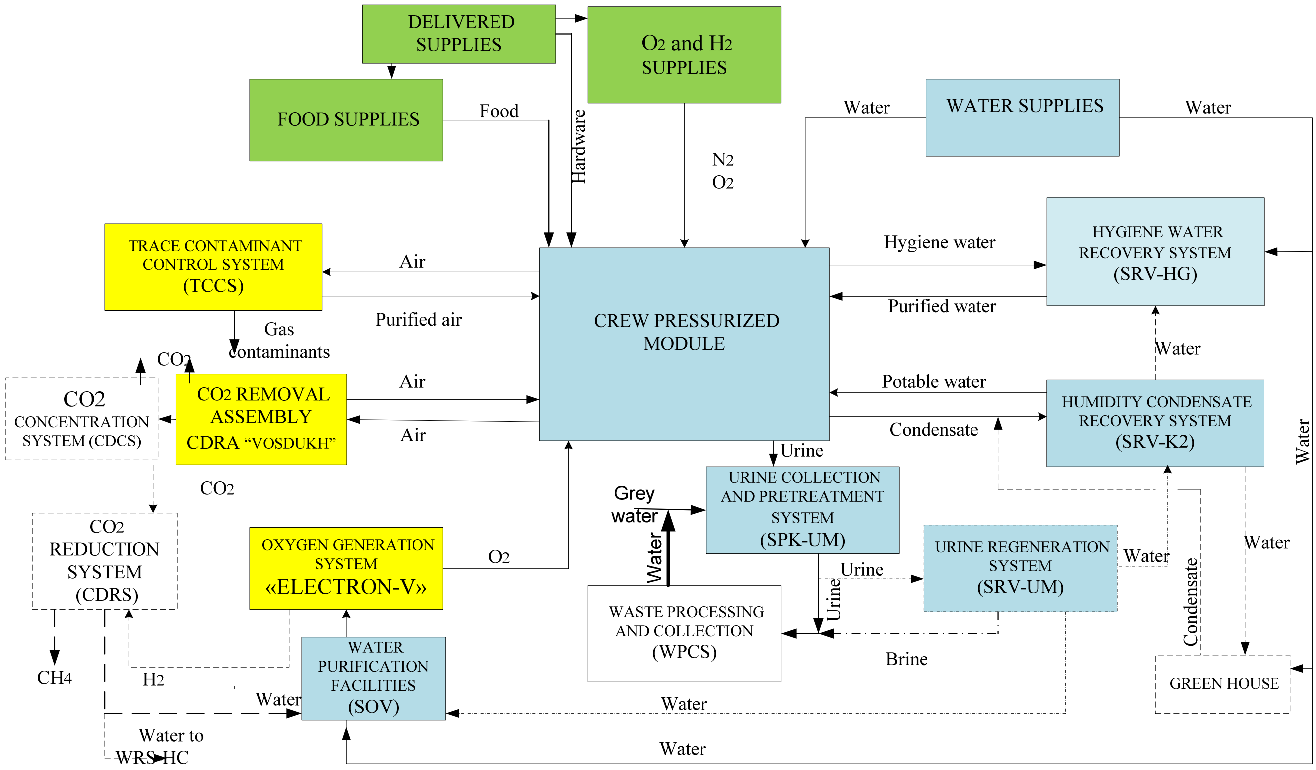

Fig.1. Schematic illustration of space station "Mir" life support systems.

Table 2. Main results of the space station "Mir" water recovery systems performance

Parameters \ System	SRV-K2	SPK-U	SRV-U	SRV-HG	SOV
Water flow rate, kg/hr	0.5	3	0.3	0.9	40
Water recovery coefficient, %	100	---	80	98	100
Initial weight, kg	104	90	100	230	25
Specific mass requirements (including of replacing the outdated equipment) for production of 1 liter of water, kg/kg H2O	0.14	0.11	0.23	0.08	0.025
Average power consumption for 3 crew members per day, W	0.4	5	266	7	0.05
Specific energy consumption for providing 1 liter of water, W-hr/kg	2	20	1200	8	0.3
Total amount of provided water, kg	15500	13750*	6000	—	—
Saving of mass delivery, kg	17200	4900	6150	—	—

*Pretreated urine with flush water.

After beginning of Russian-US cooperation the water generated in Shuttle fuel cells was transferred to space station "Mir" for drinking and oxygen generation by water electrolysis. The recovery systems provided water and oxygen as well as atmosphere revitalization to needs of cosmonauts during the whole period of the station orbital flight. Some system performance data are given in Table 2. SRV-K2 system performed in the base module for the whole period of manned flight from March16th, 1986 till August 27th, 1999; SPK-U and SRV-U systems performed in Kvant-2 module from January 16th, 1990 till August 27th, 1999; SRV-HG system was in operation for a short period of time only for verification of its serviceability.

Basic parameters of the space station "Mir" water regeneration systems are presented in table 2. It shows that mass requirements for water recovery are less than those for delivery to the space station. Specific mass with water recovered from humidity condensate is 0.14 kg of system mass per 1 kg of recovered water. The mass requirements per 1 kg of delivered water are 1.25 kg/liter H_2O including tank mass. During Mir performance the water recovery systems provided for mass savings of goods delivered to the station in sum of 28250 kg. It should be noted very low power consumption especially of the SRV-K2 water recovery system which was 2 W-hr per 1 liter H_2O.

Water recovery systems on the Russian segment of International Space Station (RS ISS)

A similar life support complex including CO_2 reduction and concentration systems, a vitamin greenhouse and water recovery from these systems was expected to incorporate on the ISS[2, 3, 7, 8] step-by-step. At present improved systems of water recovery from humidity condensate (SRV-K2M), urine collection and pretreatment system (SPK-UM is the 1st part of the system for water reclamation from urine), equipment of water purification for "Electron" system (SOV), a water storage (delivered supplies) system (SVO-ZV) have been incorporated. The system for water reclamation from urine (SRV-UM) will operate in a new Russian module MLM. A scheme of ISS water supply system[9] is presented in Figure 2. Some system performance data for the period from November 2nd, 2000 (the onset of manned flight) till February 1st, 2016 are given in Table 3. Water balances on "Mir" station and ISS above mentioned flight periods are given in Table 4.

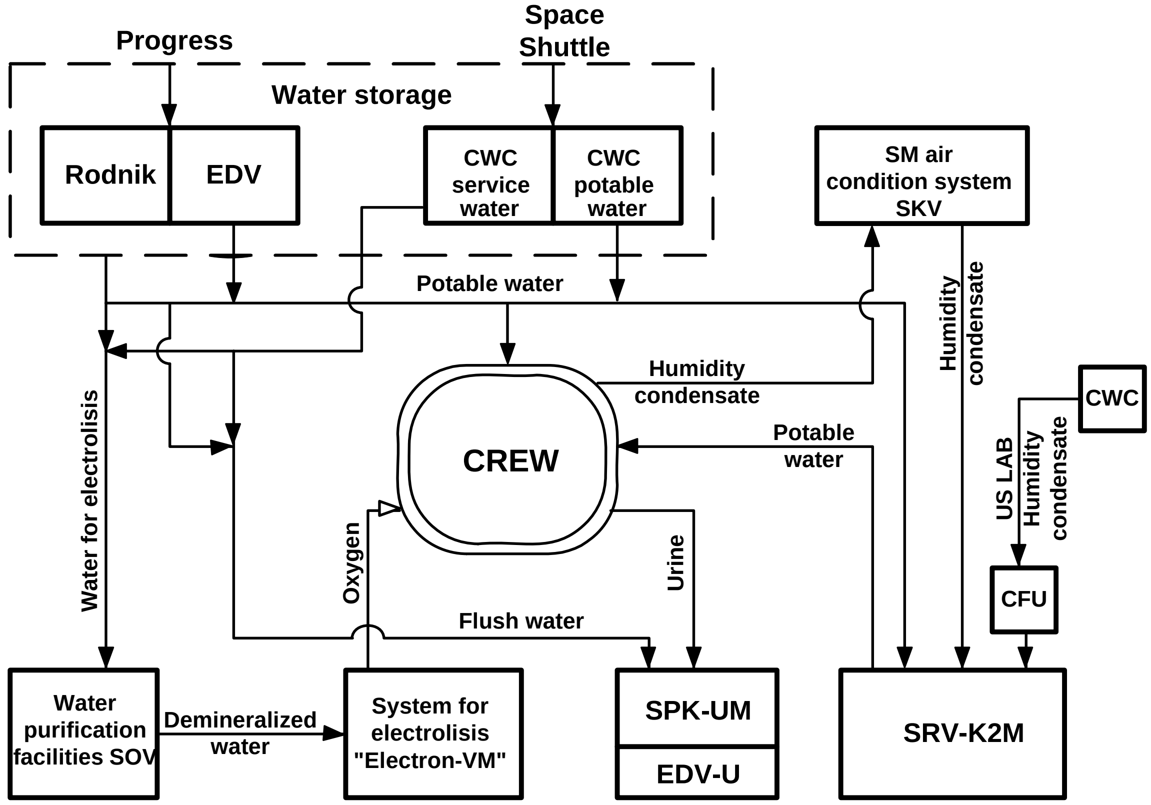

Fig. 2. Schematic illustration of ISS water supply

Table 3. Main results of the ISS water recovery systems performance (flight period from November 2nd, 2000 up to February 1st, 2016)

Parameters / System	SRV-K2M	SPK-UM	SOV
Water flow rate, kg/hr	1	3	40
Water recovery coefficient, %	100	---	100
Initial weight, kg	115	75	25
Specific mass consumption (taking into account replacing the outdated equipment) for providing 1 liter of water, kg/kg H2O	0.08	0.07	0.025
Average power consumption for 3 crew members per day, W	0.4	5	0.05
Specific energy consumption for production of 1 one liter of water, urine*, W-hr/kg	2	20*	0.3
Total amount of obtained water/ urine*, kg	17860	25580*	10525
Saving of mass delivery, kg	20900		—

* Pretreated urine with flush water.

Table 4. Water supply and consumption of one crewmember per day on "Mir" space station and ISS

Water consumption	L per man a day	Water obtained (recovered)	L per man a day "Mir"	L per man a day ISS
Drinking and food preparation	2.2	Humidity condensate 1.5*+0.2x0.5**	1.6	1.6
Water in food ration supplies	0.5			
		Water in food ration	0.5	0.5
Personal hygiene	0.2			
Flush water in commode	0.3	Water from urine (1.33+0.3)x0.8***	1.3	
Water for oxygen generation	1.0	Water from supplies	0.8	2.1
Total	4.2	Total	4.2	4.2
		Total water recovery coefficient	0.78	0.43

*Man's humidity condensate. **Return of personal hygiene vapors. ***Water recovery coefficient.

The performance data of the improved systems are much better in comparison with the performance data of the systems installed on the space station Mir. The system capacity has been increased considerably and mass requirements and power consumption were lower. The systems SRV-K2M and SPK-UM have demonstrated a reduction in the specific mass for providing the specified product by 1.5-2 times down to 0.08 kg/kg and 0.07 kg/kg respectively. The system SRV-K2M has recovered to potable grade 17860 liters of humidity condensate that is 38% of the total water consumption on the Russian segment of the ISS. This value is in good agree with total water recovery coefficient the in table 4. The system SPK-UM for urine feed and pretreatment have taken 25580 liters of urine with flush water including 20460 liters of urine. This urine was partially used for water reclamation in the Urine Processor Assembly (UPA) of the US segment of the ISS.

III. WATER RECOVERY PROCESSES AND HARDWARE ON PROSPECTIVE SPACE STATIONS.

Performance future orbital and interplanetary missions is connected with improvements in crew LSS. One of the LSS key components is a complex of water supply systems. Such systems should provide maximum recovery of water from water-containing methabolic products and from bioengineering systems and satisfy water needs of the crew with minimum water consumption from supplies. Experience in the design and operation of "Salut", "Mir" space stations and ISS water supply systems as well as the use of delivered supplies made it possible to obtain data on water balance on the space station and operation parameters of the recovery systems. The data can be used to perform design analysis of water supply systems for future space stations[1, 2].

Scheme of water recovery systems as part of designed ISS RS life support complex[7] are presented in Figure 3. The systems connected with water recovery and consumption are marked with blue.

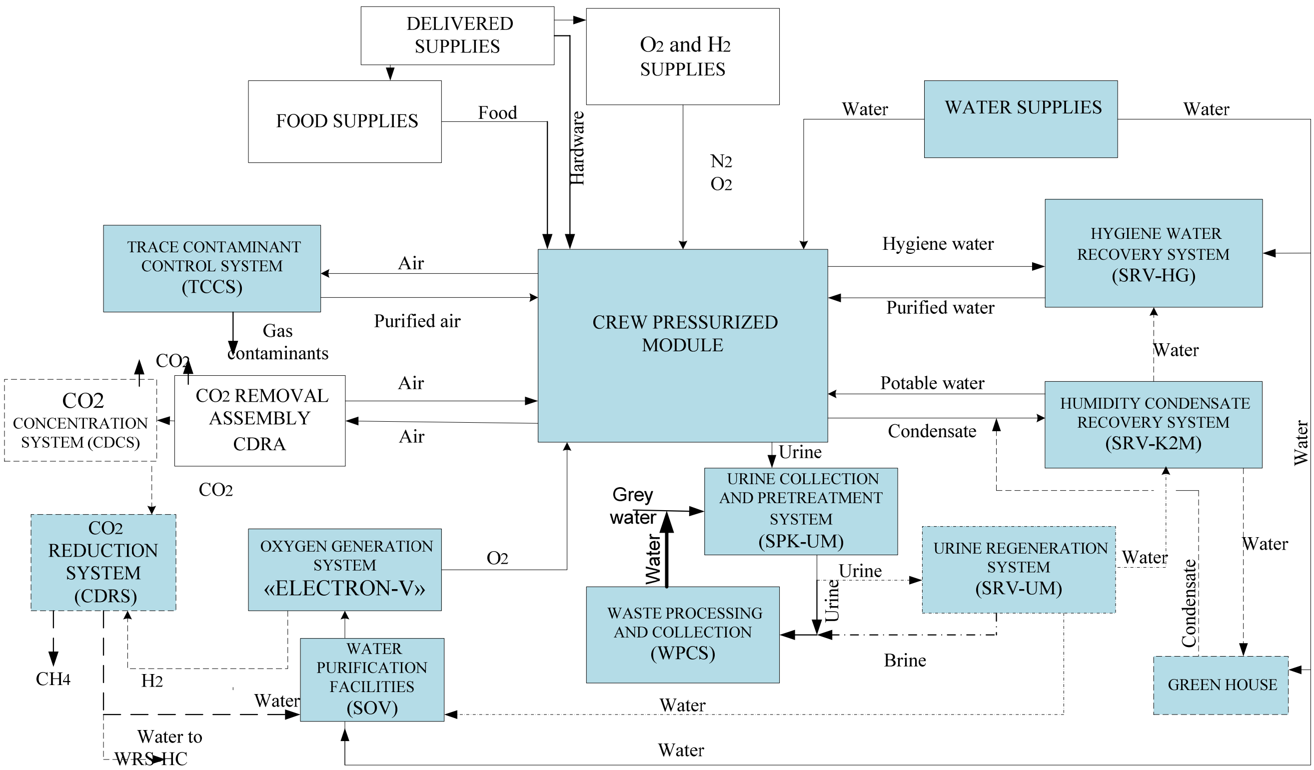

Fig. 3. Water recovery systems as part of future ISS RS life support schematic

For the Russian segment, firstly, it is necessary to implement a system for water reclamation from urine SRV-UM, a system for CO_2 concentration and a system for CO_2 reduction based on Sabatier reactor. The additional recovered water will be purified in the SRV-KM system. Hereafter it is reasonable to extract water from concentrated urine (brine) and from solid waste. With implementation in LSS hygiene hardware (shower, washing machine) a close cycle of hygiene water processing (recovery) with SRV-HG system will be included. With the implementation in LSS a greenhouse it is necessary to accomplish in SRV-KM system water recovery from vapor condensate from plants evaporation and from biomass drying. The balance of water supply and consumption for one crewmember is presented in table 5. It is evident from the table that water recovery coefficient of the life support complex depends on the structure of the complex and the water recovery coefficient of each system. The water recovery coefficient of the life support complex amounts to 0.91 instead 0.43 in the table 4.

In the near future the water recovery systems will be based on physico-chemical processes. The systems will use hydrodynamic, chemical and heat and mass transfer processes in single-phase and two-phase gas liquid mixture. For two-phase media special methods for processes have to be used in space flight under microgravity conditions. The most reliable processes on which the water recovery systems can be based are presented in the table 6.

Table 5. Water supply and consumption of one crewmember per day with water recovery systems on promising space station (Fig. 3)

Water consumption,	L per man a day	Water obtained (recovered)	L per man a day
Drinking and food preparation	2.2	Humidity condensate 1.5*+0.2x0.5**	1.6
Water in food supplies	0.5	Water in food ration	0.5
Personal hygiene	0.2	Water from urine (1.3+0.3)x0.88***	1.4
Flush water in commode	0.3	Water from CO2 reduction system by Sabatier process	0.45
Water for oxygen generation	1.0	Humidity condensate from green house	3.8
Vitamin green house	4.0	Processed hygiene water	5.9
Shower/laundry (hygiene water)	6.0	Water from excrements	0.15
		Water from supplies	0.4
Total	14.2	Total	14.2
		Total water recovery coefficient	0.91

*Man's humidity condensate. **Return of personal hygiene vapors. ***Water recovery coefficient.

Selected processes depend on the trace contaminant content in the feed liquid and the requirements for recovered water: sorption/catalytic and ion-exchange processes for humidity condensate from the cabin and greenhouse atmosphere, distillate from urine processor and water from carbon dioxide reduction; membrane filtration (ultra filtration and reverse osmosis) with ion-exchange post-treatment for hygiene water; distillation method accompanied by distillate sorption/catalytic purification for urine.

Water recovery processes, the methods and the hardware for performing hydrodynamic, chemical and heat and mass transfer processes in single-phase and two-phase gas/liquid media in microgravity conditions, energy and mass requirements data based on the results of water recovery systems performance and currently conducted designing and tests are presented in table 6. The power consumption of the recovery systems is moderate, total daily average power consumption by 3 crew member is up to 50 W. As it can be seen energy and mass requirements for water recovery are fully acceptable. Nevertheless, research is still needed to make recovery processes more efficient, to increase performance time and decrease mass requirements. The key factor is water recovery coefficient. Taking into account the tank mass for water delivery and storage (0.25 kg/l of water) the specific mass requirements of water delivery/storage are rather high and amount to 1.25 kg/liter of water.

The maximum recovery of water and minimal energy and mass consumption are provided in systems of water regeneration. SRV-K2M and SRV-U(M) systems can be considered as a typical examples[2,4,5,6,7,8].

To the system SRV-K2M condensate is transported from the air conditioning hardware of the station by air flow. In this system a static method of fluid separation with capillary forces and a sorption-catalytic method at ambient temperature are used. Oxidation of basic amount of organic substances, which are contained in the condensate, is carried out in the condensate-air stream by using the oxygen of air flow. The separation of atmospheric water condensate from air is carried out in a static separator by sucking off the fluid through the capillary-porous membrane in the membrane tank of variable volume. The differential pressure is created by the spring of the membrane tank. After filling the tank the condensate is pumped and a portion of the condensate is fed to further purification in multifiltration and conditioning units.

Table 6. Main parameters of the water regeneration systems for the prospective space station

System	Water recovery process	Processes in air (vapor) – liquid medium	Main parameters
SRV-KM – a system for water recovery from humidity condensate, distillate from urine water reclamation system, condensate of green house, condensate from carbon dioxide reduction system	Sorption/catalytic and an ionic exchange	Static separation with using of the capillary porous membrane	Water recovery coefficient – 100 % Specific mass consumptions – 0.08 currently and 0.03 kg/liter of recovered water in the near future Specific energy consumptions – 2 W-hr/liter of recovered water Average power consumption for 3 crew membtrs is 0.4W per day Initially installed weight – 120 kg
SPK-UM – a system for urine collection and pretreatment	Urine collection and pretreatment by using sulphuric acid with chromium dioxide	Rotary separator	Water recovery coefficient – 100 % Specific mass consumptions – 0.035 kg/liter of feed liquid Specific energy consumptions – 24 W-hr/liter of feed liquid Average power consumption for 3 crew members is 5W per day Initially installed weight – 75 kg
SRV-UM – a system for water reclamation from urine	Vacuum distillation method accompanied by sorption/catalytic purification of distillate	Multistage rotary distillation	Water recovery coefficient – 88 % Specific mass consumptions – 0.05 kg/liter of recovered water Specific energy consumptions – 120 W-hr/liter of recovered water Average power consumption for 3 crew members is 25 W per day Initially installed weight – 125 kg
SRV-HG – a hygiene water recovery system	Membrane filtration (ultra filtration and reverse osmosis) with an ion-exchange purification of hygiene water	Rotary separator	Water recovery coefficient – 98 % Specific mass consumptions – 0.02 kg/liter of recovered water Specific energy consumptions – 10 W-hr/liter of recovered water Average power consumption for 3 crew members is 10W per day Initially installed weight – 120 kg
SOV – water purification facilities (equipment of water purification for “Electron” system)	Sorption and ionic exchange	Bag containers	Water recovery coefficient – 100 % Specific mass consumptions – 0.02 kg/liter of recovered water Specific energy consumptions – 0.4 W-hr/liter of recovered water Average power consumption for 3 crew members is 1W per day Initially installed weight – 25 kg
SVO-ZV – a water storage (delivered supplies) system	Preservation with ionic silver added for storage	Bag containers	Water recovery coefficient – 100 % Specific mass consumptions – 1.25 kg/liter of water Specific energy consumptions – 0.4 W-hr/liter of recovered water

So electric energy in a SRV-K system is spent only for pumping. When crew consists of three members a volume of recycling humidity condensate is 5 liters per day. In this case the pump operates for 10 minutes a day and the consumption of energy is not more than 2 W-hr. The water recovery coefficient in this method of regeneration is almost 100%.

Specific relative mass flow defined of replacing the outdated equipment currently amounts up to 0.08 kg per 1 liter of recovered water. The main contributions to these costs give a separation unit and a condensate purification unit. Studies have shown that the modernization of the equipment allows to increase equipment performance time and reduce the specific consumption mass to 0.03 kg/liter recovered water, while remaining within the established size and mass of hardware. This work is currently being conducted.

In the system SRV-U of water reclamation from urine for space station "Mir" the simpliest and most available at that time method of membrane evaporation at atmospheric pressure and at low temperatures to 45 º C with air-steam distillation cycle was used. The power consumption in this system was about 1200 W-hour per 1 liter of water. The system performance was small – 0.35 l/h. New system SRV-UM, which will be used on the ISS, is based on the method of vacuum distillation with a centrifugal multistage (cascade) vacuum distiller and an external thermoelectric heat pump. The degree of energy recovery evaporation through multistage cycle evaporation-condensation (in each stage, the condensation heat is used for evaporation) and additional condensation heat recovery in a thermoelectric heat pump is more than 10. Taking into account power consumption for the motor, control system and other units of the system specific energy consumption at an output of 3.5 l/h of reclaimed water does not exceed 120 W-hour per 1 liter of reclamed water.

At present researches on improvement of systems for water recovery which operate on ISS and creation of new systems are being conducted.

VII. CONCLUSIONS

1. Experience in the design and operation of “Salut”, “Mir” space stations and ISS water supply systems as well as the use of delivered supplies allowed to obtain the data on water balance on the space station and performance parameters of the recovery systems.
   On this basis a complex of water recovery systems as part of future ISS RS life support complex is proposed and parameters of the water recovery systems for the prospective space station are evaluated.

2. For the Russian segment of ISS firstly it is necessary to introduce a system for water reclamation from urine SRV-UM and the systems for CO_2 concentration and for CO_2 reduction based on the Sabatier method. Additional recovered water will be purified in the SRV-KM system. Further on it is reasonable for water balance maintaining to extract water from concentrated urine (brine) and solid waste.

3. The next step is introduction in LSS of hygiene hardware (to increase comfort of crew at the station) and separate cycle of hygiene water recovery in SRV-HG system. After a vitamin greenhouse including in LSS water recovery from condensate of vapor from plants and vapor from drying of biomass will be provided in SRV-KM system.

4. The research and design works are needed to make recovery processes more efficient, increase hardware operation time and decrease mass requirements for water production.

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