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ORIGINAL ARTICLE

An ambitious step to the future desalination technology: SEAHERO R&D program (2007–2012)

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Abstract In Republic of Korea, seawater engineering and architecture of high efficiency reverse osmosis (SEAHERO) research and development (R&D) program started from 2007 to lead the top seawater reverse osmosis (SWRO) plant technologies for desalination with the fund of US $165 million for 6 years including test-bed plant construction. There are three technical strategies for SEAHERO R&D program called 3L, which represents large scale, low fouling, and low energy, respectively. Large scale means design, construction, and operation of the largest unit SWRO train [daily water production rate = 8 MIGD (36,000 m^3/day)] in the world. Low-fouling strategy targets the decrease of RO membrane fouling by 50%. The specific target for low energy is total energy consumption of whole SWRO plant (including intake, pretreatment, SWRO systems, and so on) less than 4 kWh/m^3. The core parts for SWRO plant, such as 16 in. diameter RO membrane and energy recovery device, were developed and will soon be introduced to a test-bed including the largest unit SWRO train. The next step of SEAHERO is real field scale test-bed application of the unit technologies developed for the past 4 years (2007–2010) such as strategic pretreatment, energy-saving technology, and reliable system monitoring.

Keywords Desalination · Reverse osmosis · SEAHERO · Large scale · Low fouling · Low energy

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Introduction

Korean government (especially ministry of Land, Transport and Maritime affairs) selected seawater reverse osmosis (SWRO) desalination technology as one of global top 5 technologies which will bloom Korean economy in 2006. Center for Seawater Desalination Plant (CSDP) funded by Korean government launched SEAHERO research and development (R&D) program from August 31st, 2007. SEAHERO is an abbreviation for seawater engineering and architecture of high efficiency reverse osmosis. SEAHERO R&D program (SEAHERO hereafter) is targeting to get the top level of SWRO plant technologies in the world and will be carried out with the fund of US $165 million for 5 years (Kim et al. 2009a).

SEAHERO consists of four core technology (CT) projects, including development of platform technologies for SWRO plant construction (CT 1: platform technology), development of SWRO membranes and high pressure pump component manufacturing and system optimization technologies (CT 2: plant units localization and system

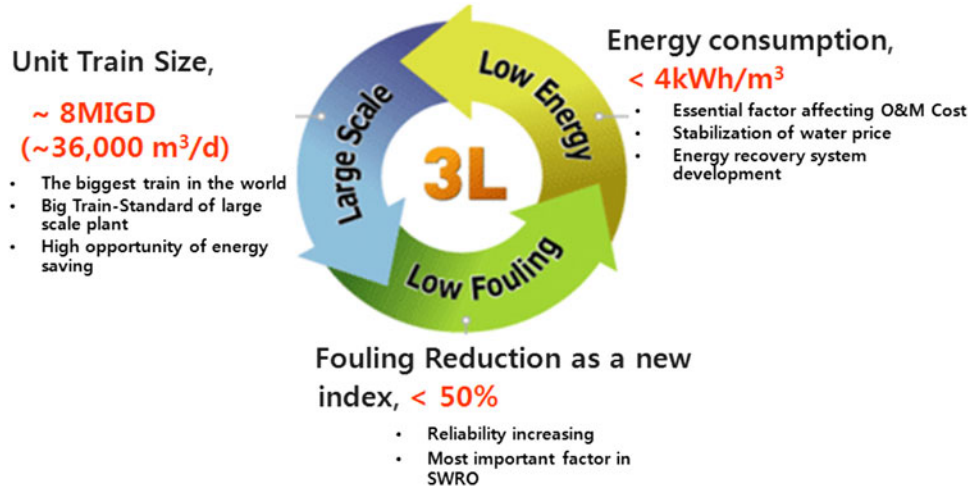

Fig. 1 The 3L strategies in SEAHERO R&D program

optimization), development of large-scale SWRO plant design and construction technology [CT 3: engineering–procurement–construction (EPC)], and development of innovative operation and maintenance (O&M) technology for large-scale SWRO plant (CT 4: O&M). More detailed information about the four CTs can be obtained from the official web page of SEAHERO (http://www.seahero.org).

The 3L is a title to represent the three main technical strategies as shown in Fig. 1. Each L means *large scale* plant construction, maintenance by *low fouling*, and *low energy* consumption of plant, respectively, which are closely related to the economical efficiency of SWRO desalination plant.

The specific objectives for 3L are as follows:

1. *Large scale* To design and construct the largest unit SWRO train [daily water production rate = 8.0 MIGD (36,000 m^3/day)] in the world. The daily production rate of the largest unit train at the moment is 5.2 MIGD, and it is in Point Lisas SWRO plant, Trinidad and Tobago (GWI 2007) and a desalination plant with unit train size of 6.84 MIGD (31,000 m^3/day) will soon be constructed in Antofagasta, Chile (GWI 2009a).
2. *Low fouling* To reduce membrane fouling by 50% in terms of silt density index (SDI) and a new fouling index developed through CT 1 project.
3. *Low energy* To lower energy consumption of whole SWRO plant (including intake, pretreatment, SWRO systems, and so on) less than 4 kWh/m^3.

The 3L is finally accomplished by designing, constructing, and operating a test-bed, which is defined as a whole system for the real field application of developed unit technologies. The capacity of the test-bed is 10 MIGD (45,000 m^3/day). The test-bed will include an 8 MIGD unit SWRO train, which will be the largest unit train in the world.

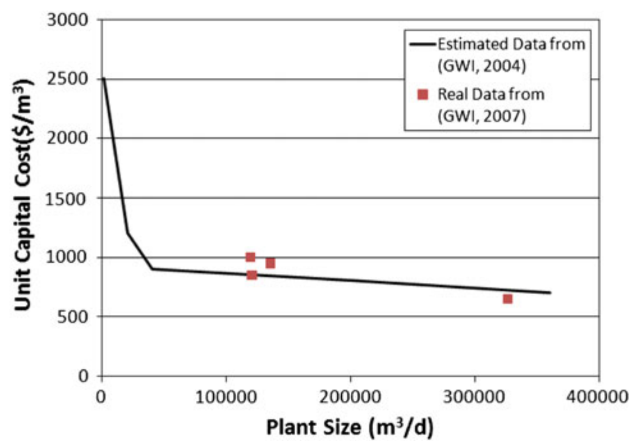

Fig. 2 SWRO plant size and capital cost

Large scale

Scale-up is one of 3L (i.e., large scale) strategies and regarded as the most important goal of SEAHERO program. Plant scale-up of SWRO is advantageous in terms of economies-of-scale, which can contribute to a considerable reduction in the cost of water production as shown in Fig. 2 (GWI 2004, 2007).

The plant size is one of the most influential factors to determine the water production cost although there are many other parameters, for example, total dissolved solid (TDS) of feed seawater, water production quality (i.e., permeate TDS), seawater temperature, seawater quality, and so forth. Large SWRO plants are able to use larger, more efficient high pressure (HP) pump units and energy recovery devices (ERD) contributing to the lower energy/operating costs of the system, which is another benefit of scale-up as shown in Table 1, which is an estimated result of energy consumption as a function of plant size (GWI 2009b).

Table 1 Energy consumption in SWRO plant as a function of plant size

	0.3 MGD (1,135 m^3/day)	10 MGD (37,850 m^3/day)	50 MGD (189,250 m^3/day)
RO process	10.5 (2.78)	8.6 (2.27)	7.6 (2.0)
Intake	2.01 (0.53)	1.74 (0.46)	1.72 (0.45)
Pre-treat	1.06 (0.28)	0.91 (0.24)	0.90 (0.24)
Post-treat	0.23 (0.06)	0.17 (0.05)	0.16 (0.04)
Distribution	1.17 (0.31)	0.86 (0.23)	0.85 (0.23)
Total energy	15.0 (3.96)	12.3 (3.25)	11.3 (2.99)

All values in kWh/kgal (kWh/m^3)

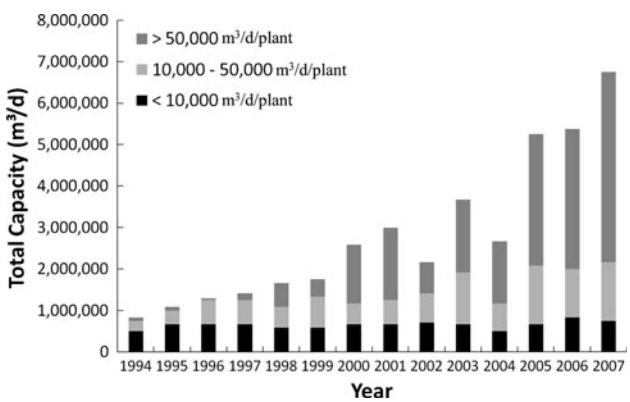

Fig. 3 Statistics of world market for SWRO plant and the market shares by plant size

Because of these benefits of scale-up, the share of large SWRO plant becomes bigger in the world desalination market as shown in Fig. 3 (GWI 2009b).

In principle, there are two approaches of system scale-up. One is the increase of size of a single component which constitutes the system, and the other is the increase of the number of the components. The three important components for SWRO system scale-up are SWRO membrane, HP pump, and ERD. HP Pump supplies relevant trans-membrane pressure and flow rate to SWRO unit train, which is defined as a physically packed group of pressure vessels arranged in parallel. An HP pump unit consists of one HP pump or several HP pumps, and a pressure vessel generally consists of 6–8 membrane modules (Jacangelo 2006; Bruno 2007; Wilf 2009). ERD transfers the energy from the concentrate stream directly to feed flow to RO unit train. The capacity of HP pump and ERD is highly related to the size of SWRO unit train. Therefore, the key factor to increase SWRO plant size is dependent upon selecting appropriate the size of SWRO unit train. According to a rigorous technical review in a previous research (Kim et al. 2009a), the most efficient way to increase SWRO plant size turns out to be increasing the size of SWRO unit train. The trend of change in the unit train size from 1982 supports this conclusion as shown in Fig. 4 (GWI 2007). The test-bed of SEAHERO contains the biggest SWRO unit train (size = 8 MIGD or 36,000 m^3/day).

Introduction of 16 in. diameter SWRO membrane will accelerate the economies-of-scale in large SWRO plant. A 16 in. diameter SWRO module can produce more than three times larger amount of fresh water than an 8 in. diameter module, which is current market standard of spiral wound RO module (Kim et al. 2009a). The diameter of 16 in. RO module assures more than 10% of capital cost saving compared to the case of 8 in. diameter module (Hallan et al. 2008). One of the most splendid products of SEAHERO is the production of 16 in. SWRO membrane module with high permeability. The production rate and the nominal salt rejection of the module is 136.1 m^3/day and 99.7% in the test condition of 32,000 mg/l sodium chloride solution, 8% of recovery, 25°C of temperature and 6.5–7.0 of pH as reported in the web page of CSM filter (http://www.csmfilter.com/upload/csm/swe/prod1_2010114134121.pdf), which is a company member of SEAHERO. This SEAHERO-brand SWRO membrane module will be installed in the test-bed.

In summary, SEAHERO focuses on the two approaches to achieve the large-scale objective; the increases in the unit SWRO train size and the RO module diameter were shown in Fig. 5.

Low fouling

Membrane fouling has been a critical problem in world-wide desalination plants using RO membrane to separate salts from seawater (Barger and Carnahan 1991). Since the membrane fouling leads to performance deterioration such as lowered permeate flux and salt rejection, it has been hindering RO application (Tang et al. 2010). In order to reduce the membrane fouling, numerous research topics have been studied such as mechanism of membrane

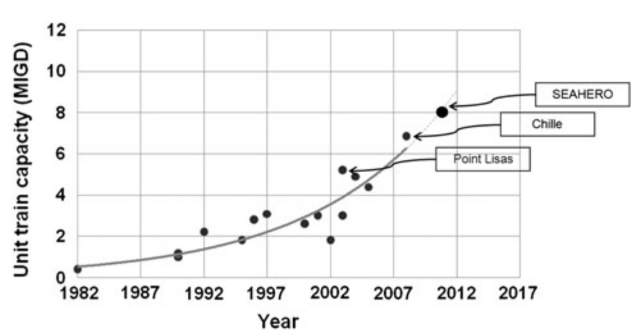

Fig. 4 The increase in the size of SWRO unit train

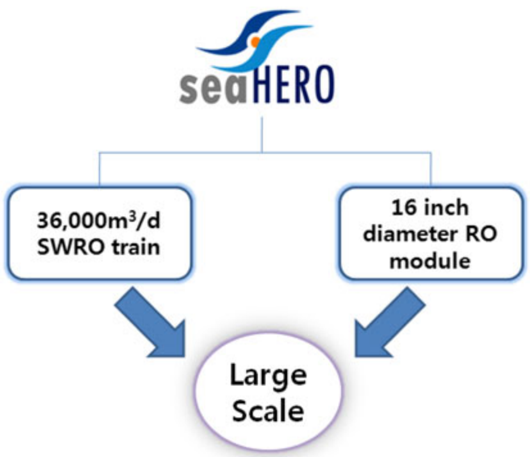

Fig. 5 The large-scale strategy in SEAHERO

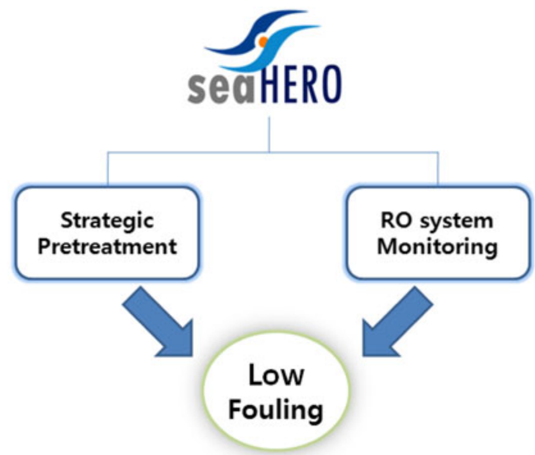

Fig. 6 The low-fouling strategy in SEAHERO

fouling, optimization pre-treatment process or system, development of cleaning method or materials, development of membrane fouling index, and others (Prihasto et al. 2009).

In SEAHERO, the specific target for the low-fouling strategy is 50% of fouling reduction as mentioned in "Introduction" part of this paper. Fouling reduction in principle can be interpreted to the increase in membrane replacement period. The assurances of 50% increased membrane replacement period can be a reasonable specific target for low fouling. However, the membrane replacement period (usually more than 5 years) cannot be estimated during the R&D period of SEAHERO until 2012. The product of SEAHERO should be estimated by Korean government at the end of the R&D period since SEAHERO is a government-funded R&D program. Therefore, 50% reduction of silt density index (SDI) and a new fouling index developed in SEAHERO is selected as a specific target for low fouling instead the increase in membrane replacement period.

A number of technologies for fouling reduction can be categorized into three parts: (1) pretreatment, (2) system monitoring, and (3) manufacturing low-fouling membrane. A strategic selection of pretreatment increases the quality of RO feed water to reduce fouling. A reliable system monitoring detects fouling in early state to avoid severe irreversible fouling. Low-fouling membrane is more resistant to the attachment of foulants such as particles, organic matters, and microbes. Among these three strategies, SEAHERO focuses on pretreatment and system monitoring as shown in Fig. 6.

There are lots of unit processes for pretreatment system. The most important thing in design of pretreatment system is to select best combinations of these unit processes targeting highest RO feed water quality with lowest cost, which can be called strategic pretreatment. Selection of good combinations of pretreatment processes depends on field conditions such as feed water quality, temperature, and fouling durability of RO membrane. In SEAHERO program, factors affecting design of optimal pretreatment strategies and the economic evaluation of SWRO system with regard to various antifouling strategies were investigated (Prihasto et al. 2009; Choi et al. 2009a, b, c; Jeong et al. 2010).

Reliable system monitoring technologies for SWRO system can be applied to avoid severe troubles such as irreversible fouling, scaling, and unexpected system failures, which will be more promising. In SEAHERO program, estimation technologies of system performance by using plant operation data (i.e., pressure, flow rate, temperature, total dissolved solids concentration, and pH) were developed (Kim et al. 2009f, 2011), and application of biosensor to select the most problematic biofoulant in SWRO processes were investigated (Lee et al. 2009a, b).

In SEAHERO, a new fouling index was developed in order to support to achieve the strategic pretreatment and reliable system monitoring. It gives information on fouling potential by particles, hydrophilic organic matters, and hydrophobic organic matters, respectively (Choi et al. 2009a, b, c; Yu et al. 2010; Hong et al. 2010). The new fouling index is expected to be more useful than common indices such as silt density index (SDI) and modified fouling index (MFI) as well as MFI-UF and MFI-NF. In addition, more fundamental efforts to elucidate fouling mechanisms were made by developing new and advanced membrane characterization techniques such as atomic force microscopy (AFM) and dynamic hysteresis analysis (DH) (Yang et al. 2010; Lee et al. 2011).

Low energy

Low energy can be considered as an ultimate goal of SWRO plant. Moreover, the major contributions of large scale and low fouling are saving energy consumption. The power demand of SWRO system can be affected by internal parameters (e.g., membrane permeability, HP pump, ERD, and plant size) and external parameters (e.g., seawater temperature). Higher membrane permeability assures larger amount of fresh water production per unit applied pressure, which results in less energy consumption per unit water production. The higher efficiencies in HP pump and ERD play important roles to save energy in SWRO plant. HP pump efficiency is a function of its capacity. The most efficient HP pump is installed in Ashkelon SWRO plant with efficiency of 88.5% and capacity of 12.5 MIGD (Bruno 2007). There are two types of ERD: turbine type and isobaric. Isobaric ERD has higher efficiency than turbine type ERD as shown in Table 2 (Stover 2006) although the former is more expensive than the latter in a small system. Larger plant size is more advantageous to save energy as shown in Tables 1 and 2. High seawater temperature increases the membrane permeability to decrease the amount of energy consumption per fresh water production.

In SEAHERO, specific target for low energy is energy consumption of the test-bed including intake, pretreatment, and SWRO system less than 4 kWh/m^3, which is not the smallest value among SWRO plants in the world. There are several SWRO plants whose total power demands are less than 4 kWh/m^3. These plants are large in capacity and under the high temperature condition (e.g., higher than 25°C). Considering the test-bed size is rather small and seawater temperature in South Korea varies from 2 to 28°C, the target of 4 kWh/m^3 can be a challenging objective. Moreover, the power demand of Fukuoka SWRO plant with capacity of 50,000 m^3/day, which is exactly the same as the SEAHERO test-bed, was reported as 5.5 kWh/m^3 (GWI 2007).

Figure 7 shows the strategy of SEAHERO to achieve the low-energy objective. SEAHERO focuses on the development of high efficiency HP pump and ERD, highly permeable SWRO membrane, and system optimization. In addition, large scale and low-fouling strategies supports to achieve the low-energy objective. SEAHERO developed an HP pump and a non-rotating isobaric ERD with efficiencies more than 85 and 95%, respectively. As discussed earlier, the SEAHERO-brand 16 in. diameter SWRO module with high permeability was developed to decrease energy consumption per water production. The simulated energy consumption of the SEAHERO test-bed using these membranes was about 3.8 kWh/m^3.

System optimization is based on the fundamental understanding of SWRO system, and a good simulator can give a good strategy for energy saving such as control of operation conditions (i.e., selection of optimal recovery rate and trans-membrane pressure in accordance with feed water quality and temperature). In SEAHERO program, various types of simulators for monitoring and prediction of SWRO process performance and cost estimation were developed (Kim et al. 2009b, c, d, e; Lee et al. 2009a, b; Oh et al. 2009). Using these simulators, several energy-saving methodologies were suggested using stochastic control approaches which considered feed water temperature and operating pressure as control parameters. The methodologies showed how to improve the performance of SWRO desalination process as well as how to save the energy during the operation of the SWRO systems.

Together with the simulation techniques, an IT-based technology for real-time monitoring of energy consumption in SWRO plants has been developed in SEAHERO program, which enables a precise control of energy usage. Small-size digital power meters coupled with a wireless communication module were designed and developed to send real-time information on electricity usage of important equipments (i.e., high pressure pump, ERD booster pump, intake, and pretreatment pumps, etc.). The information obtained by these wireless power meters can be used to operate a SWRO plant with the optimized energy consumption. Furthermore, a preventive maintenance of

Table 2 Energy consumption (kWh/m^3) of SWRO system according to ERD type and system size

ERD type	Small SWRO system	Large SWRO system
Turbine type	4.29–4.35	2.42–3.19
Isobaric	3.45	1.92–2.79

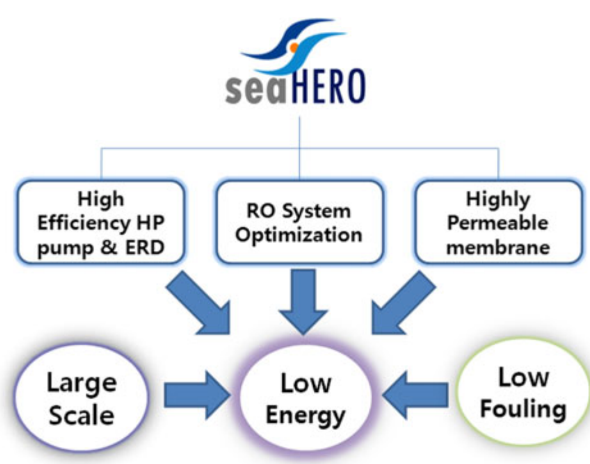

Fig. 7 The low-energy strategy in SEAHERO

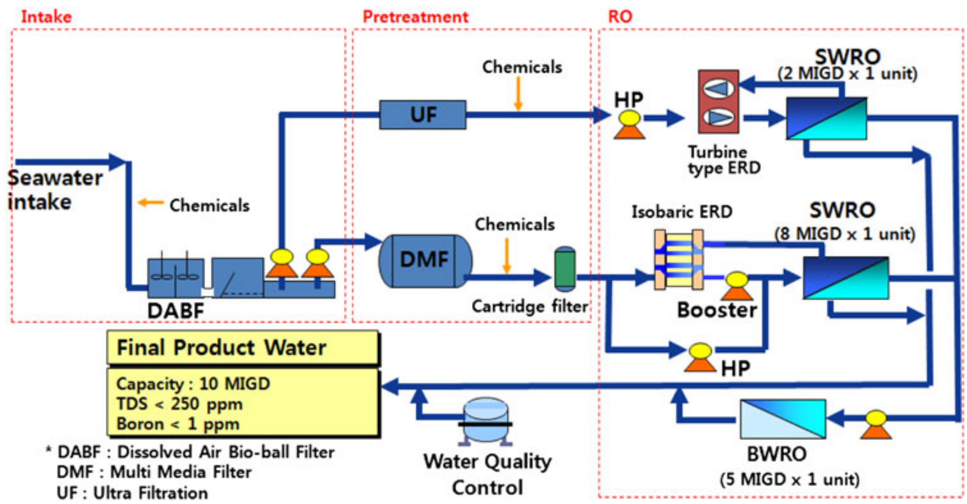

Fig. 8 The flow diagram of the SEAHERO test-bed

the equipments is possible by analyzing this real-time energy usage information.

In order to get further, SEAHERO carried out the researches on the combination of RO and forward osmosis (FO). As a result, application of FO to brine treatment was investigated (Tang and Ng 2008; Tan and Ng 2008), and the combination of RO and FO can result in more energy-saving compared to conventional RO system (Choi et al. 2009a, b, c).

Conclusion: the next step of SEAHERO

SEAHERO achieved fruitful results targeting 3L (i.e., large scale, low fouling, and low energy) of SWRO plant so far and is going to leap to the world best R&D program for seawater desalination. The next step of SEAHERO program is real field application of the 3L technologies to the SEAHERO test-bed. The capacity of the test-bed is 10 MIGD (45,000 m^3/day). The test-bed will include an 8 MIGD unit SWRO train, which will be the largest unit train in the world. Currently, the test-bed is ready to be constructed in Busan, South Korea by Doosan heavy industries and construction Co. Ltd, which is in charge of CT 3 (EPC) and CT 4 (O&M) in SEAHERO. Various pretreatment options such as coagulation, flotation, media filtration and membrane filtration, and different types of ERD (i.e., turbine type and isobaric) will be tested using the test-bed as shown in Fig. 8. Besides, process optimization based on system monitoring technologies will be verified.

The SEAHERO test-bed has two distinguished features. First, it has the world largest unit RO train as discussed earlier. Second, it will be the first SWRO plant in the world, which is firstly constructed for the R&D purpose and then used for a drinking water production facility after the R&D period. SEAHERO is going to develop the future desalination technology step by step, remaining footprints such as the leading-edge 3L technologies and the distinguished test-bed.

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