14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Achievement report of NEDO R&D Project on Innovative Thermal Management Materials and Technologies

Yoichi Fujita*, Tetsushiro Iwatsubo*

* Energy Conservation Technology Department, New Energy and Industrial Technology Development Organization (NEDO), 212-8554 Japan

Abstract

The importance of industrial heat pumps toward decarbonization has begun to be widely recognized worldwide. Japan has developed, and applied industrial heat pumps ahead in the world. This paper overviews the current technology and market status of industrial heat pumps in Japan. It reveals that heat-pumping technology has matured to some degree. However, it shows the importance of accelerating the adoption. This study also clarifies the issues for its widespread adoption by questionnaire survey and barrier analysis and discusses measures for the future.

Keywords: R&D Project; Thermal Management; Unutilized Thermal Energy; Industrial Heatpumps; High-temperature Heatpumps

1. Introduction

On October 2020, Japan declared that it would aim to realizing “carbon neutrality by 2050,” and in April 2021, Japan has also set a new target to reduce greenhouse gas emissions by 46% in FY 2030 from FY 2013 levels. Towards 2050, the new plan seeks to achieve energy transitions and decarbonization, considering the global momentum in this direction and in enforcement of the Paris Agreement, and to pursue all tenable options toward this end.

During Japan's energy distribution process, about 30% to 40% of primary energy, mainly fossil resources such as oil, coal, and natural gas, are lost when they are converted into electricity and fuel [1], and at the final consumption, and it is used only a small portion, so total 60% to 70% of primary energy is considered not to be used effectively but discarded as heat. Authors refer to such artificially discharged heat as “unutilized thermal energy,” and it is the key for realizing thorough energy efficiency to effectively reduce, reuse, and recycle this huge amount of unutilized thermal energy discharged into this environment, and it can be said to be a frontier.

Authors introduce an overview of a national R&D project “Research and Development Project for Innovative Thermal Management Materials and Technologies” which aims to realize thorough energy efficiency promoted by New Energy and Industrial Technology Development Organization (NEDO). Above all, they focus on R&Ds of new high-temperature heat pumps that make use of heat efficient in industrial fields by reusing unused thermal energy for process heating instead of boilers.

2. National R&D Project Overview

The goal of this project is to develop three Rs technology to effectively reduce (via insulation, thermal insulation, or heat storage), recover and reuse (via heat-pump technology), or recycle (via thermoelectric conversion or waste heat power generation) untapped thermal energy. The project also aims to develop basic crosscutting heat management technologies for effective reduction, recovery and reuse, or conversion of the

* Corresponding author. Tel.: +81-44-520-5281; fax: +81-44-520-5187.
E-mail address: thermal-energy@nedo.go.jp.

huge amount of unused heat released into the environment to achieve further energy conservation in the industrial, transportation, and consumer sectors.

Figure 1 shows Organizational chart of “Research and Development Project for Innovative Thermal Management Materials and Technologies”. The project had been excuted under industry-academia collaboration of the Thermal Management Materials and Technology Research Association (TherMAT).

In this way, this R&D project is intended for a wide range, but here authors introduce an R&D on high-temperature heat pumps, which are the core of this R&D project and can show high energy efficiency effect.

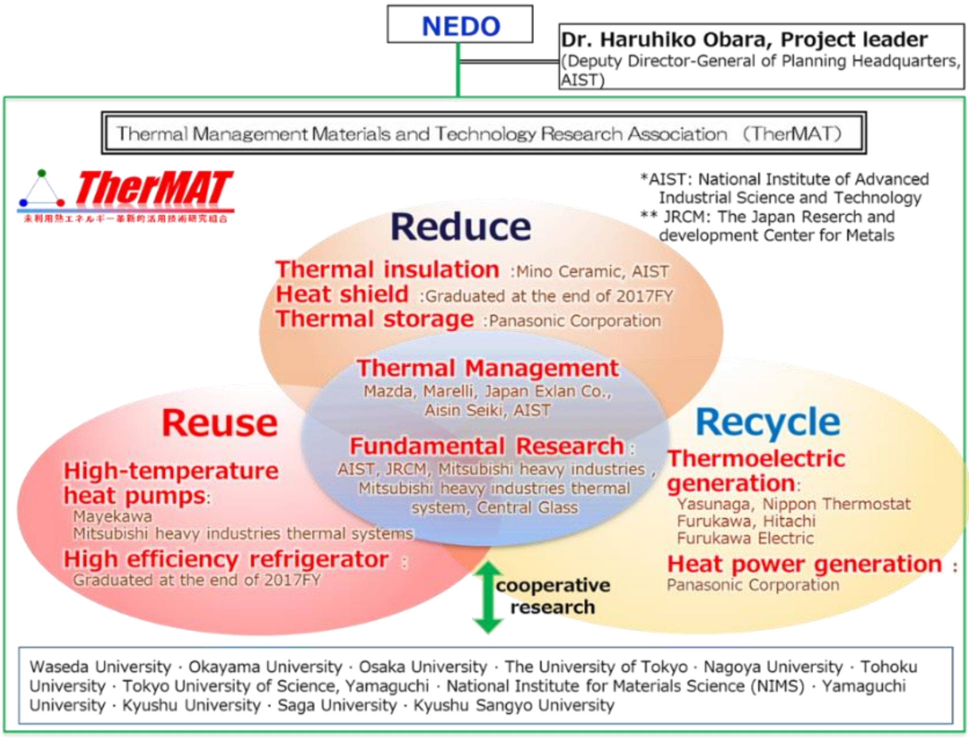

Fig. 1. Organizational chart of “Research and Development Project for Innovative Thermal Management Materials and Technologies”

Figure 2-1 shows the estimated amounts of nationwide unutilized thermal energy, by sector and temperature based on the survey result from 1,273 factories of 15 industries. The nationwide estimation of the amount of unutilized thermal energy (exhausted as gas) was based on results of questionnaires, approximation calculated by the correlation between energy inputs to factories and unutilized thermal energy as exhaust gas by industry, and FY2015 energy consumption statistics of manufacturing industries. [2]

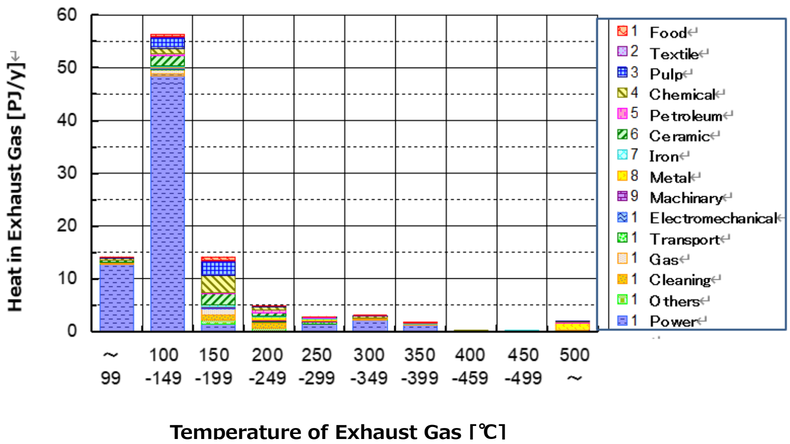

Figure 2-1: Estimation of amount of heat in exhaust gas from industry by temperature range

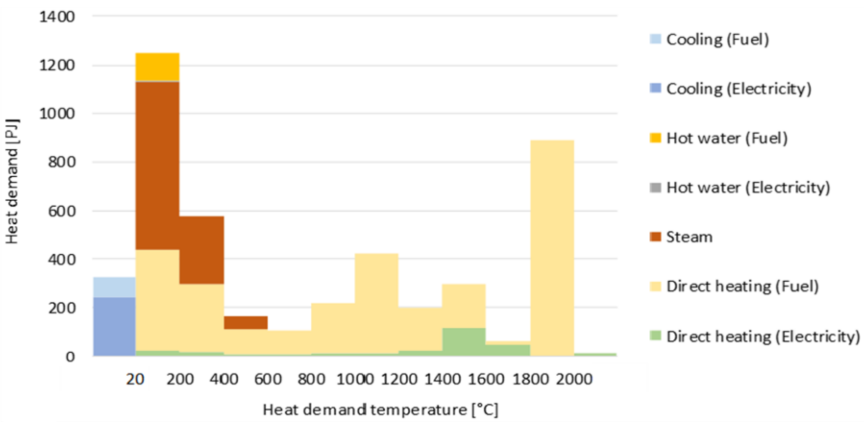

Figure 2-2: Heat demand in the Japanese industry by heat use form

On the other hand, Figure 2-2 shows the estimated amounts of heat demand, by heat form and temperature based on the survey result from 1,155 factories of 15 industries. [3] This heat demand area below 200°C becomes 1250 PJ (= 347 TWh) and accounts for 28% of the total industrial heat demand. Another feature is that temperature distribution of exhaust heat and heat demand are overlapping each other.

As shown in Figure 2-2, main heat source is steam below 200°C and usually boilers using fossil resources are used as heat sources as steam for industrial heating applications, and unutilized thermal energy is discharged from each heating process. By reusing this waste heat as a heat source, it is expected to regenerate it to a higher temperature and replace the heat sources from conventional boilers with high-temperature heat pumps.

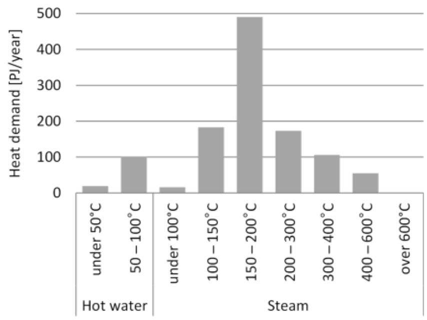

Figure 2-3: Heat demand of hot water and steam

Figure 2-3 shows the graph picking up the heat demand of hot water and steam from Figure 2-2. The applicable potential of heat pump expands as its supply temperature rises. Although it is largest demand at 150°C to 200°C range, unfortunately there is no heat pump which can supply above 150°C.

In this project, it aims to develop high-temperature heat pumps which can supply high-temperature heat about from 160°C to 200°C with high efficiency (e.g. COP: 3.5 or higher), recovering from waste heat of 80°C or 100°C which is discarded from industrial manufacturing processes, and as the result of penetrating them as alternatives to steam boilers, can contribute to use primary energy efficiently and reduce CO_2 emissions.

Figure 3 shows comparison of primary energy basis efficiency between boiler and high-temperature heat pump. Typical conventional heat systems supply steam by boiler with 90% of efficiency. On the contrary COP (Coefficient of Performance) of high-temperature heat pump reaches 3.5, and generation efficiency of thermal power plant is 45%. Therefore, total efficiency of high-temperature heat pump system reaches 158%, which is 1.75 times more efficient than conventional boiler system. It is expected that high-temperature heat pump will prevail by economical advantage.

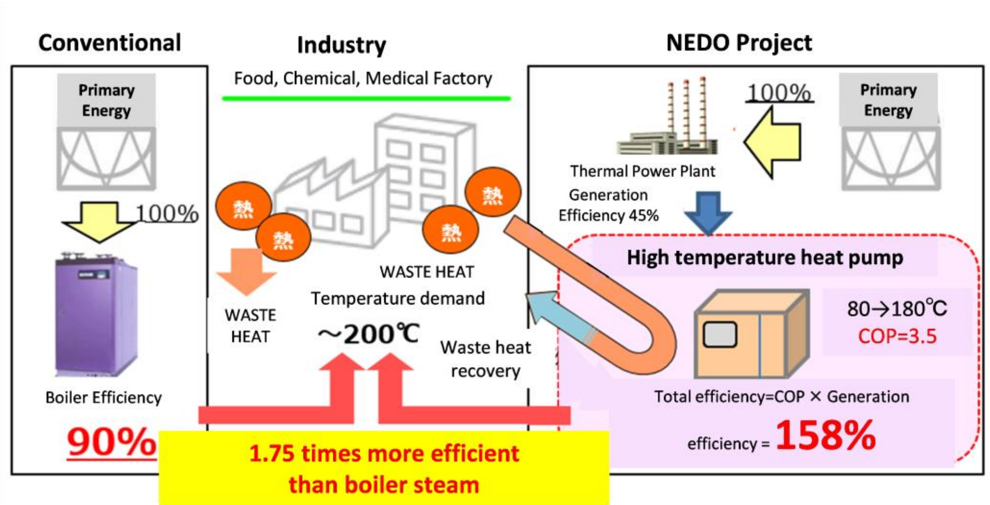

Figure 3: Comparison of efficiency between boiler and high-temperature heat pump

3. Development of industrial high-efficiency and high-temperature heat pump capable of supplying maximum 200°C

3-1. Development target

In this project, Mayekawa Mfg. Co., Ltd. who is the member of TherMAT, is developing heat pump systems with having the target that can meet the supply temperature range up to 200°C and achieve COP: 3.5 or higher by heating from 80°C to 180°C. [4]

There are 2 type of high-temperature heat pump in accordance with heating methods. Type-1 is steam supply circulating type with small temperature glide by Vaper compression cycle as shown in Figure 4-1. There is constant temperature during heating process which water is changed phase to steam. It is difficult to generate above 150°C of steam with presently available refrigerant. Type-2 is thermal oil or air supply transient type with large temperature glide by trans critical cycle as shown in Figure 4-2. There is no constant temperature during heating process. It is possible to generate above 150°C with presently available refrigerant. Therefore, Type-2 was adopted to achieve 180°C for this development.

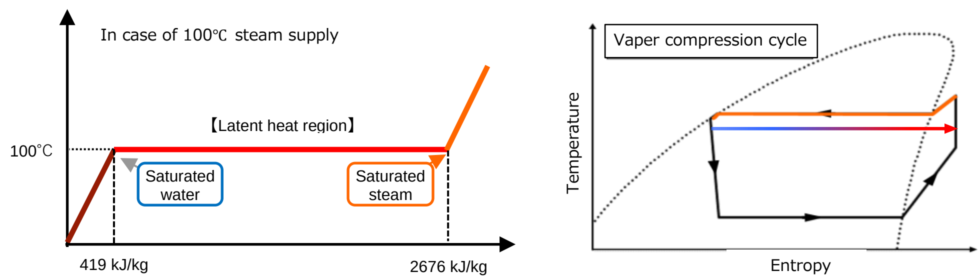

Figure 4-1: Type-1 Steam supply circulating type

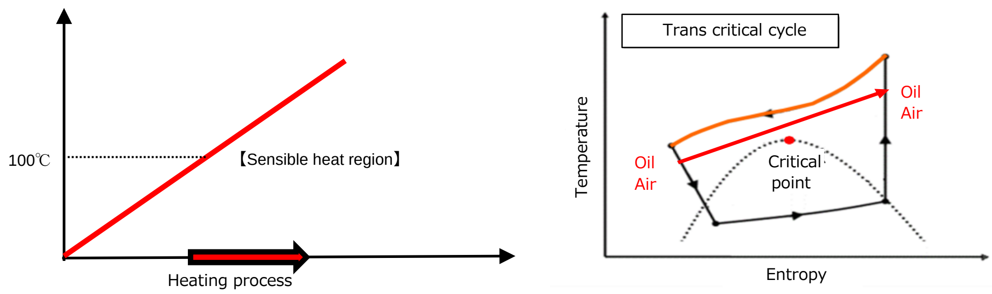

Figure 4-2: Type-2 Thermal oil or air supply transient type

Figure 5 shows the flow diagram of the system. The system consists of heat exchangers, compressors, expansion valve and connecting pipes. The heat exchangers are an evaporator, a gas cooler, and a liquid-gas heat exchanger. Approximately 80°C of waste heat is extracted by the evaporator as the heat source to evaporate the refrigerant which is then compressed and heated to about 200°C in the compressor. The heating medium flowing through the gas cooler is thermal oil with flash point temperature of more than 250°C which is classified as nonhazardous material by the fire service act.

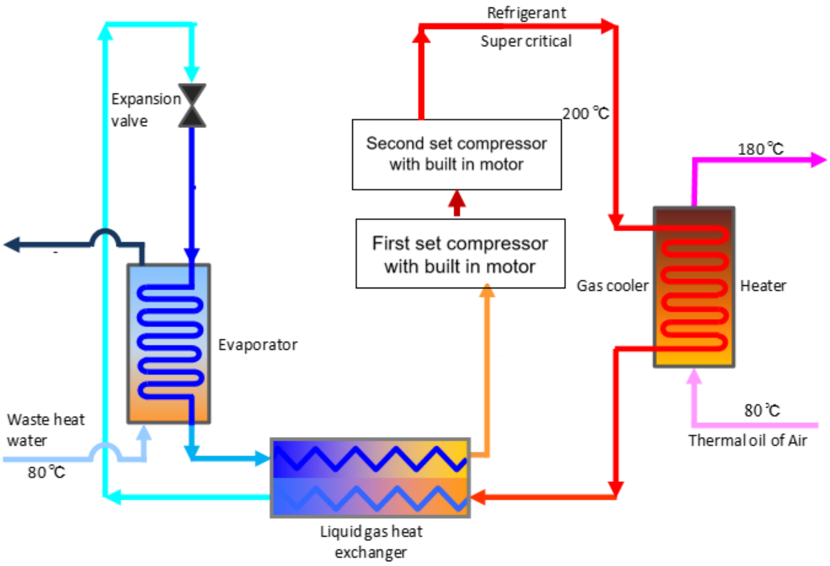

Figure 5: Schematic diagram of the high-temperature heat pump system

3-2. Development of compressor technology

To achieve the development target, it was necessary to develop an epoch-making compressor that had never existed before and to achieve the maximum operating temperatures of 200°C or higher. Due to the high operating temperatures, the conventional lubricating oil was difficult to use. Therefore, an oil-free centrifugal compressor with magnetic bearings is adopted. To improve efficiency, an optimally designed compressor rotor and a high-speed built-in motor are being used.

Magnetic bearings and built-in motors are one of the most important components in the development of this compressor. The magnetic bearings control the attractive force of the electromagnet and supports the rotating body in a non-contact manner. The built-in motor is located between the magnetic bearings at both ends. In consideration of the maximum operating temperature of 200°C, a three-phase induction motor with high heat resistance was adopted.

3-3. Development of the second prototype

NEDO had reported about 300kW of the first prototype which used R600 (n-butane) as refrigerant in the 13th IEA Heat Pump Conference 2020. [5] R600 which is a hydrocarbon-based refrigerant was adopted with a small GWP and high COP. However, R600 is a highly flammable and the test unit had to be enclosed in a casing to provide 24-hour ventilation and explosion-proof specifications. In recent years, it has become clear that new nonflammable low GWP refrigerants such as HFO (Hydro-fluoro-olefin) are available in the market and the rotation speed of the compressor is expected to be lower than that of R600 refrigerants. Therefore, HFO refrigerant is adopted for the second prototype. Table 1 and Figure 6 shows the main changes between the first prototype and the second prototype.

The second prototype comprises of two sets of compressors each with two stages, which makes it four stages compression compared with three stages compression of the first prototype according to fluid analysis result for different refrigerant. The two impellers being back-to-back structure was adopted with the second prototype to reduce thrust load of axial disk in comparison with the two impellers being same direction structure of the first set compressor of the first prototype.

The gas cooler with a capacity of 300 kW consists of two heat exchangers connected in parallel. The heating medium used is thermal oil and exchanges heat with the refrigerant in super critical state in trans critical cycle.

Table 1 The main changes of the first prototype compressor and second prototype compressor

	First prototype compressor	Second prototype compressor
Refrigerant	R600	R 1336mzz(Z)
Number of compression stage	Three stages	Four stages
Rotated speed[rpm]	45,000 (First set) 70,000 (High pressure side)	16,000 (First set) 15,000 (High pressure side)

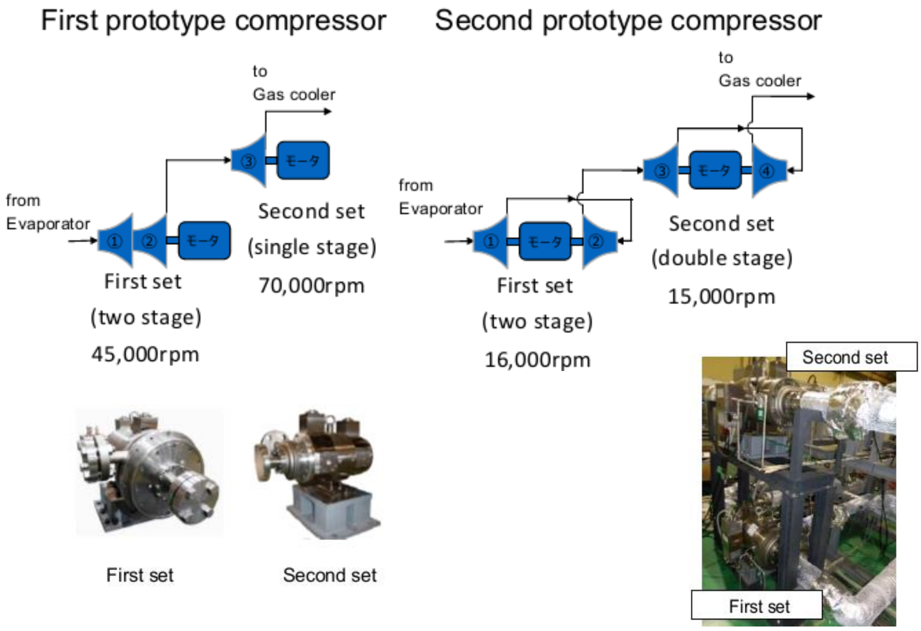

Figure 6: Comparison of the first prototype compressor and the second prototype compressor

Table 2 shows specifications of second prototype heat pump and Figure 7 shows the appearance. Currently, performance and reliability tests are conducted with the second prototype. According to comparison of theoretical values and actual measurements, there is prospect of achieving COP=3.5

Based on the test results, the elemental technologies such as compressors and heat exchangers are optimized, and then it is planned to be put on the market from around 2025.

Table 2 Specifications of test apparatus

Gas cooler	Type	Brazed plate
	Capacity	300 kW
Compressor	Type	Centrifugal
	Oil	Oil free
Refrigerant		R 1336mzz(Z)
Design pressure		5.2 MPaA
Rotation frequency	Low pressure compressor	16,000 rpm
	High pressure compressor	15,000 rpm
Thermal oil inlet temperature		80°C
Thermal oil outlet temperature		180°C

(a) Casing

(b) Inside

Figure 7: Test apparatus of high- temperature heat pump

3-4. Next steps

Toward introduction of the heat pumps after the end of R&D, it would be one of most important initiatives to see the effect or value when they apply to actual heat utilization equipment in factories. Especially it will be even more difficult to conduct verification to grasp the energy efficiency effect in the actual environment using the existing systems. Therefore, authors will proceed with activities of model cases studies, assumed actual heat utilization facilities, and based on the results of this studies, calculation and quantitatively evaluation of the effect or value including energy efficiency, cost merit and heat pump system configuration post introduction. As the result of the activities, "visualization" of introduction effect will be progressed and it will be possible to share the installation image of heat pumps in industrial heating processes with customers, which will be able to lead to acceleration of the commercialization.

On this project, NEDO plans to construct equipment utilizing systems with high- temperature heat pumps including attached facilities, proceed with model case verifications that examine optimal applied processes and clarify economic effects, and studies on "visualization" of introduction effect. Through these activities, the newly developed industrial high-efficiency and high-temperature heat pumps will be properly arranged and used for process heating instead of boilers, thereby promoting energy efficiency in factories and contributing to solving energy and environmental problems in the future.

4. Conclusion

"Energy efficiency" is the primary expectation for the realization of "3E + S" (simultaneously achieving Energy Security, Economic Efficiency and Environment, with coming Safety always at first) in Japan and global carbon neutrality by 2050, but most of primary energy is still discharged as unutilized thermal energy without being effectively used, even though various measures have been taken so far. Among energy forms such as fuel, electricity, and hydrogen that are expected to be used in the future, the last remaining form is heat, and decarbonization of all sectors that use this heat can be the key to construct the sustainable recycling society.

Now all the relevant people are required to promote to implement technologies for effectively reducing or recovering a large amount of unutilized thermal energy discharged into the environment including high-temperature heat pumps, to the society with economic rationality, realize significant energy efficiency of the entire society and a "circular economy", and there can be no doubt that this R&D project had been a driving force for it.

References

[1] Agency for Natural Resources and Energy, *FY2017 Energy Supply and Demand Report*, (2019) (in Japanese).
[2] NEDO, TherMAT, *Industrial Waste Heat Survey Report*, (2019) (in Japanese)
[3] Mitsubishi Research Institute, *FY2017 Heat supply and demand report*, (2018) (in Japanese)
[4] Kimura, *International Symposium on New Refrigerants and Environmental Technology 2021*.
[5] Kondo, *NEDO R&D project "Research and Development Project for Innovative Thermal Management"* ; HPC2020.