APPLICABILITY OF PNEUMATIC CAPSULE PIPELINE SYSTEM TO RADIOACTIVE WASTE DIPOSAL FACILITY

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ABSTRACT

Various transport systems have been studied for the transportation of waste packages and buffer materials from the ground surface to the underground radioactive waste disposal facility, such as a lift (vertical shaft type) and a vehicle (inclined tunnel type)(1). This paper introduces pneumatic capsule pipeline system as a new method for the transportation. The system is designed to transport pneumatically waste packages and buffer materials between the surface and the underground as shown in Fig. 1. The system is also used to transport excavated debris, equipments and materials during construction. It is economical to utilize the system for air ventilation in addition to be used for transportation. The capsule moving in the shaft can be controlled at appropriate speed by adjusting the air pressure in the shaft. This paper discusses the applicability of the system to the geological disposal based on analytical simulation and experimental study.

Fig. 1. Image of Pneumatic Capsule Pipeline System

INTRODUCTION

A lift in the vertical shaft and a vehicle on the inclined tunnel have been studied to date for the deep geological

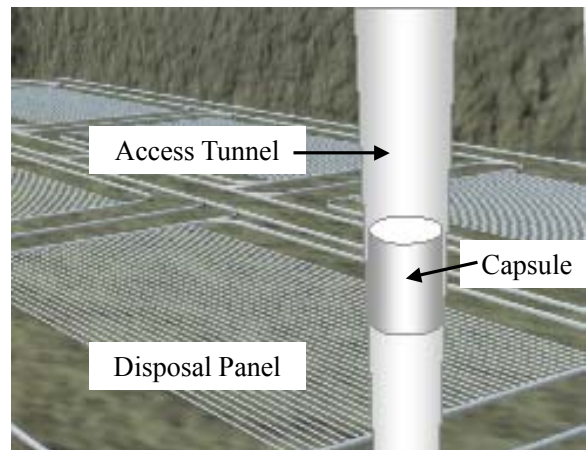disposal as a way of transporting waste packages and buffer materials from the surface to the underground facility. However, these types of transportation have been pointed out to have following disadvantages.

- When the carrying equipment does not function properly, there is a possibility that the radioactive waste package goes out of control in the tunnel, which might cause a terrible disaster.
- A lifting capacity will be reduced due to the increase of weight of the wire rope as the depth of the underground facility increases.
- Transport speed must be limited within a reasonable range in order to keep the stress of the wire rope below allowable level.
- These methods need costly devices to keep the reliability of the carrying equipment at required level.

In this paper, a pneumatic capsule pipeline system is presented as an alternative to the lift type and the vehicle type.

FEATURE OF THE SYSTEM

The same type of pneumatic capsule pipeline system has been used in the transportation of ore or soil through pipeline. The basic concept of the system is illustrated in Fig. 2.

The shaft in the system is excavated in the rock, installing liner and membrane inside the shaft to provide enough structural strength and air tightness for the transportation. The capsule transport velocity can be controlled by changing air pressure in the shaft i.e., making the pressure difference between upper and lower of the capsule. The difference is made by exhausting air from the top of the shaft and supplying air into the lower part in the transport pipeline.

A waste package and buffer materials are put in a container made of thin stainless steel for encapsulating. Then the container is inserted to the transport pipeline from the attach and detach device at the top of the shaft. The capsule is transported through the ascending air current to the bottom of the shaft by controlling a pressure difference between upper and lower of the capsule using a blower at the top of the shaft. The container is dismounted from the attach and detach device at the bottom of the shaft, then the capsule is transferred to the planed location for emplacement.
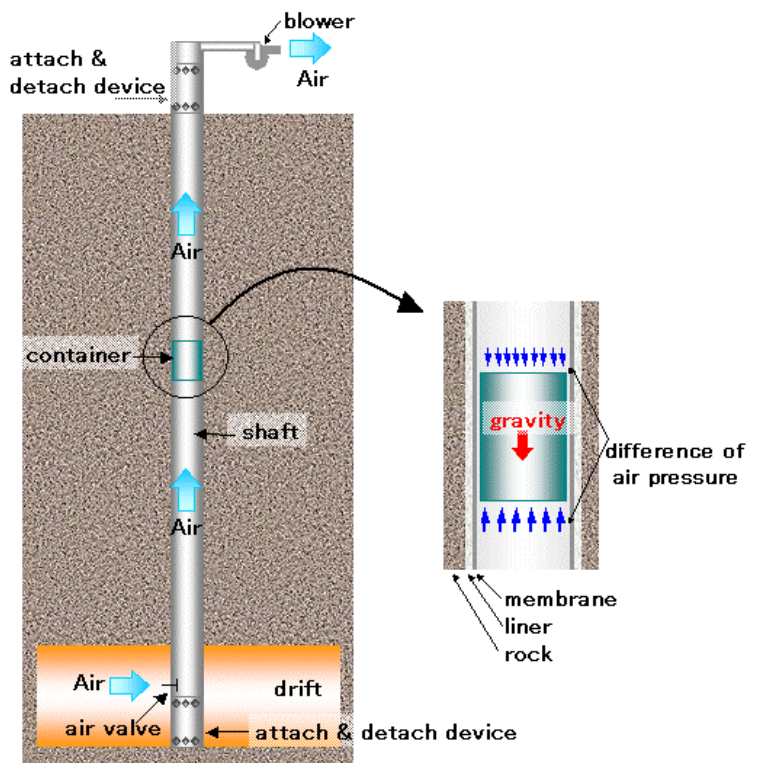

Fig. 2. Basic Concept of this System

The advantages of the system are mentioned as follows.

-Transportation without wire rope

The transportation system using wire rope makes it difficult to transport loads to the very deep underground since the weight of the wire rope becomes heavier with the increase of the depth. On the other hand, the pneumatic transportation system utilizing air pressure can transport loads without regard to the depth of the repository.

- High Usability

A waste package and buffer materials can be transported as an assembled capsule. The containers can be used to convey other loads, such as equipment, materials (ex. concrete), and excavated debris during construction.

- Applicability of Shaft Layouts

The shaft for transportation does not need to be vertical. The inclined or curved tunnel is also applicable when it is curved enough to pass through a transport capsule.

- Substitute for Ventilation Shaft

The system can be used for air ventilation in the underground facility, which results in cost-effectiveness.

- Safety

The air valve installed in the lower part of the shaft prevents air leakage from the shaft into the underground facility. Even when power supply is accidentally terminated, the air in the pipe prevents a sudden fall of a container, behaving like an air damper.

ANALYTICAL STUDY

In order to study the applicability of the system to the disposal facility, an analytical study is performed to simulate the behavior of the capsule when it is transported from the surface to the deep underground. Theory of the air transportation system is reviewed, and analytical simulation is performed. The dimension and weight of the materials and the transport distance for the simulation were determined according to Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan prepared by Japan Nuclear Fuel Cycle Institute (1999).

Theory of capsule transportation

The capsule moves upward by making a pressure difference between upper and lower of the capsule. The theory of this system is described below (2).

We define the direction of x (capsule position measured from the bottom of pipeline) and v (velocity of capsule) as shown in Fig. 3.

$$\frac{dx}{dt} = v$$

The incremental displacement is given by

$$\Delta x = v \cdot \Delta t \qquad \text{(Eq.1)}$$

The equation of capsule motion is given by

$$M \frac{dv}{dt} = (P_u - P_e)A_c - Mg$$

Where;

    M : mass of the capsule

    P_u : pressures acting on the bottom of capsule

    P_e : pressures acting on the top of capsule

    A_c : pressure bearing area

    g : acceleration of gravity

The velocity increment is

$$\Delta v = \left\{ \frac{(P_u - P_e)A_c}{M} - g \right\} \Delta t \qquad \text{(Eq.2)}$$

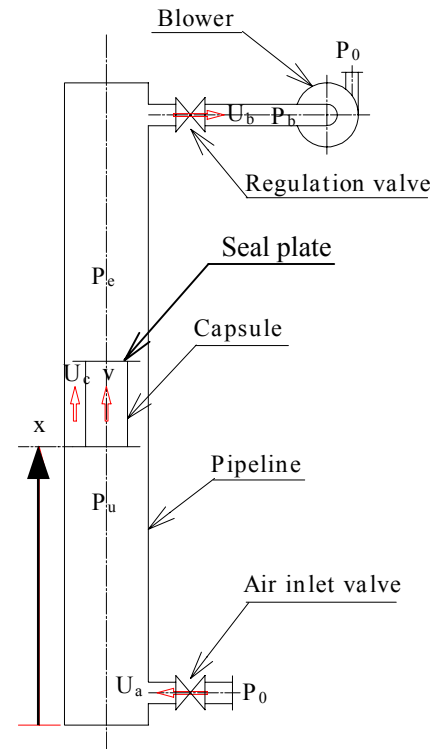When U_c is defined as the velocity of the air through the gap between capsule and pipe wall,

Fig. 3. Pneumatic Capsule Pipeline Model

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$$P_u - P_e = \frac{\rho}{2}\frac{(U_c - v)^2}{\varphi^2} \qquad \text{(Eq.3)}$$

where;

ρ : air density

φ : leak rate, which is given by

$$\varphi = \frac{1}{2}\left(\frac{A}{A_c} - 1\right)$$

where;

A : sectional area of pipeline

When U_b is defined as the velocity of the air based on the inside diameter of pipeline through the regulation valve of which Resistance factor is ζ_b,

$$P_b = P_e - \zeta_b \frac{\rho}{2}\left(\frac{A}{A_b}U_b\right)^2 = P_e - a_2 U_b^2$$

where;

A_b : sectional area of regulation valve

a_2 : factor derived from pressure losses

By using constant factor a_0 and a_1, inlet pressure of blower, P_b, is approximated by

$$P_b = a_0 - a_1 U_b^2$$

Then we have

$$P_b = \frac{a_1 P_e - a_2 a_0}{a_1 - a_2} \qquad \text{(Eq.4)}$$

and

$$U_b = \sqrt{\frac{a_0 - P_e}{a_1 - a_2}} \qquad \text{(Eq.5)}$$

By using resistance factor of the inlet valve, ζ_a, air velocity through the inlet valve, U_a, is given by

$$U_a = \sqrt{\frac{1}{\zeta_a}\frac{2}{\rho}(P_a - P_u)} \qquad \text{(Eq.6)}$$

When the pressure at the capsule bottom is smaller than the atmosphere pressure, the change in the state of air in the region below the capsule is given by

$$(P_u + \Delta P_u)A(x + \Delta x) = P_u A(x + v\Delta t) - \frac{P_u + P_e}{2}AU_c\Delta t + \frac{P_u + P_0}{2}AU_a\Delta t$$

Then we have

$$P_u = -\frac{\Delta t}{2x}\{(P_u + P_e)U_c - (P_u + P_0)U_a\}$$ (Eq.7)

The change in the state of air in the region above the capsule is given by

$$(P_e + \Delta P_e)A\{(L - x) + \Delta(L - x)\} = P_e A\{(L - x) - v\Delta t\} + \frac{P_u + P_e}{2}AU_c\Delta t - \frac{P_e + P_b}{2}AU_b\Delta t$$

Then we have

$$P_e = -\frac{\Delta t}{2(L - x)}\{(P_e + P_b)U_b - (P_u + P_e)U_c\}$$ (Eq.8)

By using these equations, the specifications of the blower, regulation valve and inlet valve can be determined according to the required performance of capsule transportation. The theoretical review mentions the capsule moving upward. The theory for downward can be developed similarly.

Analytical Simulation

To study on applicability of the system to the geological disposal with 1000m-depth shaft, an analytical simulation is performed to confirm the following points.
  - Variation of landing velocity of the capsule depending on the fluctuation of seal diameter
  - Influence of leak rate on the velocity of the capsule in the vertical shaft.

- Analytical Conditions

The velocity of the capsule in the vertical shaft is analyzed with the following conditions.
  - An assembled package
  A waste package with 820mm diameter and 1,730mm height, surrounded by the buffer materials with 700 mm thickness.

  Diameter: 2,220 mm
  Height: 3,130 mm
  Weight: 23,980 kg

- Capsule

Dimensions of the capsule are specified so that it can encapsulate the assembled package to be transported. The weight was assumed based on the capsule system used in the experimental test to be described in the EXPERIMENTAL STUDY section.

   Seal plate diameter (Design value): 2,931 mm

   Capsule body: 2,500 mm

   Weight: 3,677 kg

- Pipeline

The diameter of the pipeline was specified 2,992mm for the velocity of 5.0 m/second as steady speed. The length of the pipeline was specified 1,000m.

- Deviation of seal diameter

Seal plate is produced under control of circumferential length. Based on the quality data, the standard deviation of seal diameter, σ, becomes 1.7mm.

The location of braking valve (inlet valve) was determined to be 5 m upper from the bottom of the pipeline, so that the landing velocity becomes 0.1 m/second at the condition of design value of seal diameter.

Seven cases of simulation were performed as shown in Table I.

Table I. Cases of Simulation

Case	1	2	3	4	5	6	7
Deviation	-3σ	-2σ	$-\sigma$	design value	$+\sigma$	$+2\sigma$	$+3\sigma$
Seal plate diameter (m)	2.9256	2.9273	2.9290	2.9306	2.9323	2.9340	2.9357
Leak rate: ϕ (-)	0.0228	0.0222	0.0216	0.0210	0.0204	0.0198	0.0192

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Results

- Variation of landing velocity of the capsule depending on the fluctuation of seal diameter

When the capsule is descending in the pipeline and after passing the air inlet valve, the air pressure in the space between the capsule and the end of the pipeline is increased, which then the velocity is decreased. The results of the study on the behavior of the capsule depending on the fluctuation of the seal diameter are shown in Fig. 4.

When the seal diameters are less than designed value (-σ, -2σ, -3σ), with large leak rate, landing velocities are 0.6, 1.1 and 1.4 m/sec respectively.

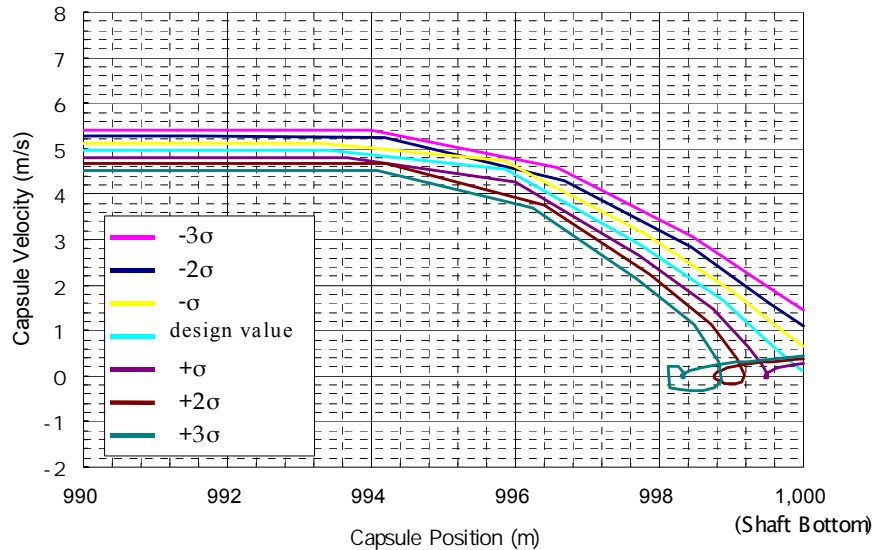
Fig. 4.   Capsule Velocity near the Bottom

When the seal diameters are more than designed value (+σ, +2σ, +3σ),   with small leak rate, the movement of the capsule was reversed and then descended again, which resulted landing velocity of 0.3, 0.4 and 0.4 m/sec respectively. It indicates that braking effect depends largely on precision of the seal diameter.

- Influence of leak rate on the velocity of the capsule in the vertical shaft

The influence of the seal diameter on the behavior of the capsule was studied for the seal diameter of 2,931 mm (98% of the diameter of the pipeline, ϕ=0.021) and 2,892 mm (96.7 % of the diameter of the pipeline, ϕ=0.035). The results are shown in Fig. 5 and Fig. 6. In each case, the capacity of the blower is set up so that the steady speed of 5 m/sec will be achieved.

In the case of the larger seal diameter (Fig. 5), the capsule velocity has reached the steady velocity soon after the start and its fluctuation is small. On the other hand, in the case of the smaller seal diameter (Fig. 6), the capsule velocity is increased after the start up to 20 m/sec or larger, then decreased to as small as 1 m/sec, and then reached steady velocity of 5.0m/sec. This indicates that the seal diameter needs to be as large as possible to achieve a smooth transport of a capsule; the pipeline should be manufactured as precisely as possible.

The theoretical power required for the operation of the blower in the case of larger seal diameter is 130 kW, and that in the smaller diameter is 1000 kW. The seal diameter and precision of the pipe are extremely important factors in terms of the power of the blower.
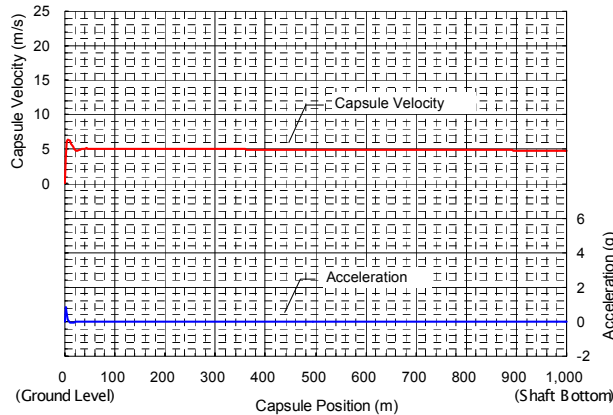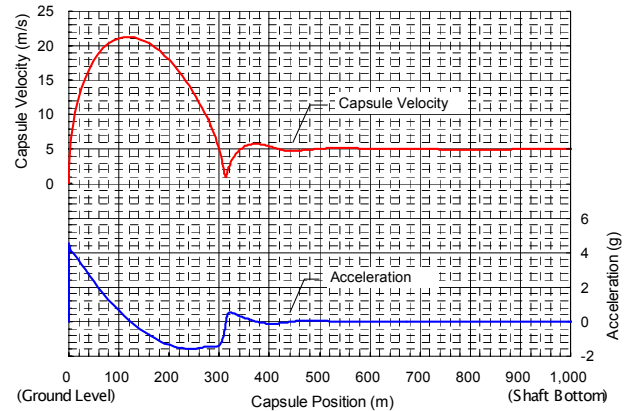
Fig. 5. Capsule velocity (ϕ 0.021)

Fig. 6. Capsule velocity (ϕ 0.035)

EXPERIMENTAL STUDY

To verify the applicability of the system to an actual plant, an experimental study was performed in Hiroshima prefecture, Japan (see Fig. 7). In the experimental facility whose length of pipe is 19m long using a capsule with 1m^3 capacity, 30 m^3 muck was successfully conveyed upward per hour, which is equivalent to designed volume. Following this experimental test, a sewage tunnel construction started in November 2001 using the system to transport muck upward. The specification of the system used in the experimental tests and the actual tunnel construction are shown in Table II. The construction has been progressed without any problem.

This experiment ensured the performance of the system for carrying loads upward. It is thought that other experiments are required to ensure the performance of transportation such as downward transportation and deep transportation.

Table II.   Specification of Facilities

		Experimental test	Tunnel construction
Cross section of pipe		1,004 mm	
Transportation capacity		30 m^3/h	
Pipeline	Cross sectional area	0.792m^2	
	Total length	19 m	33 m
Capsule	Volume	1.0 m^3	
	Tare mass	400kg	
	Payload	1,700 kg	
	Seal plate area	0.776 m^2	
Blower	Flow rate	300 m^3/min	
	Delivery pressure	3,000mmAq	
	Power consumption	200 kW	
Transportation speed	Upward run	2.0 m/s	
	Downward run	5.0 m/s	

Fig. 7. Facility for Experimental Study

CONCLUSION

The applicability of the pneumatic capsule pipeline system to the underground radioactive waste disposal is shown based on the results of the analytical simulation and experimental study. Following results are also obtained through analytical study.

- Accuracy of the seal diameter is an important factor to reduce landing velocity of the capsule.

- In terms of blower capacity, effectiveness of power and smooth transportation, it is important to keep precision of pipe dimension and to make seal diameter as large as possible.

REFERENCES

1. Japan Nuclear Fuel Cycle Institute, Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC TN 1400(1999).
2. S. KOSUGI, K. SAITOU, N. MATSUI, and Y. TOMITA, Development of Vertical Pneumatic Capsule Pipeline System for Deep Underground, 2nd International Symposium on Underground Freight Transportation by Capsule Pipelines and Other Tube/ Tunnel Systems(2000).