Startup of RAPID-L Lunar Base Reactor by Lithium Release Module*

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Abstract

The 200 kWe uranium-nitride fueled lithium cooled fast reactor concept RAPID-L to be combined with thermoelectric power conversion system for lunar base power system is demonstrated. Unique challenges in reactivity control systems design have been attempted in RAPID-L concept. The reactor involves the following innovative reactivity control systems: Lithium Expansion Modules (LEM) for inherent reactivity feedback, Lithium Injection Modules (LIM) for inherent ultimate shutdown, and Lithium Release Modules (LRM) for automated reactor startup. All these systems adopt lithium-6 as a liquid poison instead of conventional B_4C rods or Be reflectors. These systems are effective independent of the magnitude and direction of the gravity force. In 2006, however, the following design amendment has been made. 1) B_4C poison rods were added to ensure criticality safety in unintended positive reactivity insertion by LRMs due to fire in the launch phase accident; because LRM freeze seal melts at 800°C which result in positive reactivity insertion. 2) Lower hot standby temperature of 200°C was adopted instead of conventional 800°C to reduce the external power at the startup. In this paper, development of the LRM orifice which dominates the startup transient of RAPID-L is discussed. An attention was focused how to achieve sufficiently small flow rate of ^6Li in the orifice because it enables moderate positive reactivity insertion rate. The LRM orifice performance has been confirmed using 0.5 mm diameter SUS316 orifice/lithium flow test setup in the glove box.

Key words: Fast Reactor, Micro Nuclear Reactor, Reactor Startup, Lunar Base

1. Introduction

In previous fast reactors, all the reactor operations including startup, shutdown and power control should be achieved by control rods made of B_4C absorber and/or Be reflectors. Such control systems involve a number of specific issues; reliability of actuation and drive mechanisms, scram capability under seismic condition, and unprotected transient overpower (UTOP) mitigation potential. Furthermore, future fast reactor plants will have greater safety requirements and operational demands. Despite several approaches¹⁻³ to enhance inherent safety by self-actuated shutdown capability, no attempts except the inherent secondary shutdown system⁴ (ISSS) and the gas expansion module⁵ (GEM) have been made to apply measures without absorber rods. Both the ISSS and GEM are, by their own nature, effective for unprotected loss of flow (ULOF) but not for transients such as UTOP. Another issue to be considered in future fast reactors, especially in space reactors, is the simplicity of operation. So far, skillful operators are essential for reactor startup in

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conventional plants. Fully automated reactor startup has never been reported except for spacecraft nuclear reactors⁶.

This study concentrated on the establishment of operator-free fast reactor concept RAPID-L⁷, designed for lunar base activities. RAPID-L is one of the variants of fast reactor concept RAPID⁸ (Refueling by All Pins Integrated Design), which enable quick and simplified refueling 2 months after reactor shutdown. A significant advantage of RAPID-L is the introduction of the innovative reactivity control systems: lithium expansion module^{7,9} (LEM), lithium injection module^{7,9,10} (LIM) and lithium release module^{7,9} (LRM). LEM is the most promising candidate for improving inherent reactivity feedback. LEMs could realize burnup compensation and partial load operation. LIMs assure sufficient negative reactivity feedback in unprotected transients. LRMs enable an automated reactor startup by detecting the hot standby temperature of the primary coolant. All these systems utilize liquid poison of ⁶Li and are actuated by highly reliable physical property (i.e. volume expansion of ⁶Li for LEM, and freeze seal meltdown for LIM and LRM).

In the 2006 design phase¹¹, an attention has been focused on the criticality safety at launch phase accident, especially on the fire which results in unintended positive reactivity insertion by LRMs because LRM freeze seal melts at 800°C. In view of this, B₄C poison rods as well as LRM were introduced. A definite advantage of LRM over B₄C rod is that the former has no moving parts and requests no instrumentation, while the B₄C rod ensures criticality safety in all accidental situations. Therefore both LRM and B₄C rod is required.

Another issue in conventional RAPID-L design is the external power required at the startup. Approximately 3420 kWh external power is required to heat up the reactor from cold equilibrium temperature (−100°C) to the hot standby temperature (800°C). To reduce such external power and to ensure criticality safety in any phase of the mission, poison rods are introduced in addition to above mentioned innovative control systems.

In this paper, development of the LRM orifice which dominates the startup transient of RAPID-L is discussed. The most important issue is how to achieve sufficiently small flow rate of ⁶Li in the orifice because it enables moderate positive reactivity insertion rate. The LRM orifice performance has been confirmed using 0.5 mm diameter SUS316 orifice/lithium flow test setup in the glove box.

2. Plant Concept

2.1 Overall Plant Design

The conceptual design of RAPID-L consists of a 5000 kWt-200 kWe uranium-nitride fueled, lithium cooled, fast spectrum reactor with lithium inlet and outlet temperature of 1030 and 1100°C, respectively. The reactor structure and the fuel cartridge are shown in Fig. 1. The reactor is basically a loop type configuration and a reactor vessel of 2 m in diameter and 6.5 m deep. The difference from conventional pool type reactor is the integrated fuel assembly. The core consists of approximately 2700 fuel elements. These entire elements are combined together by a core support grid and several spacer grids, and are assembled into a fuel cartridge as shown in Fig. 2. In this particular reactor concept, the reactor has neither diagrid nor core support structure because they are also integrated in a fuel cartridge.

From a general design standpoint, the integrity of the core support structure is of outstanding importance. Thus the most important in-service inspection (ISI) requirement is validation of the core support structure as this is entirely immersed in the coolant and therefore presents a difficult and currently unresolved problem. The RAPID concept makes it easier by adopting a combination of replaceable diagrid/core support structure and a permanent reactor vessel. Advantage has been taken of simple reactor vessel instead of conventional one with diagrid and core support structure; the simple reactor vessel would

make ISI easier than it would be with more complex diagrid and core support structure. ISI of the reactor vessel can be conducted in each refueling. In this concept, the design lifetime of the replaceable core support grid as well as the fuel cartridge can be reduced to 10 years, those located in the relatively high flux regions (i.e., 10^{22} n cm⁻² in 10 years). On the other hand, the reactor vessel can be designed as a permanent structure exposed to decreased neutron flux. To keep the final fluence of the reactor vessel under the design limit (i.e., 10^{21} n cm⁻² in 20 years), neutron shielding materials must be effectively provided in the lower section of the fuel cartridge.

Electromagnetic pumps and the fuel cartridge are connected by the connecting tubes. The reactor subsystem is

Fig.1 Reactor structure of RAPID-L

Fig. 2 Fuel cartridge detail

characterized by RAPID refueling concept to eliminate conventional fuel handling systems. A substantial reactor block mass savings of less than a half over comparable liquid metal cooled fast reactor systems can be estimated. Its compact design makes it possible to assemble a whole structure in the workshop prior to the launch.

The overall nuclear power system is illustrated in Fig. 3. The reactor is located in an excavated cylindrical hole which provides shielding of gamma and neutron radiation.

The power conversion system consists of 4 power conversion segments placed around the reactor. Each segment has a pumped lithium heat rejection loop connected to cesium heat pipe radiators. The eight radiator panels are arranged in a vertical configuration extended radially from the power conversion segments. A thermal apron is placed between the radiator panels to reduce the lunar surface temperature and thus, reduce required radiator area. Each segment comprises 18 thermoelectric (TE) modules. Each TE module consists of 720 TE units with 12 sodium heat pipes on the hot sides and 13 cesium heat pipes on the cold sides. The secondary lithium inlet temperature of 800 K with the temperature rise of 46 K was determined to realize the optimum trade-off between the energy conversion system and the waste heat radiator system to minimize the total mass of the power system. Based on the TE cell efficiency of current state of the art, net efficiency of the system is estimated to be 4%.

A performance breakdown of the nuclear power system is shown in Table 1.

The total mass of the system, including power conditioning is 15.8 metric tones. The system was designed to be launched by conventional launch vehicle (i.e. payload geometric envelope: 3.7 m diameter and 10 m long, payload maximum weight: 10 t). Two launches are sufficient to bring the whole system.

Fig.3 Nuclear power system layout

2.2 Reactor Core Design

The reactor core is a homogeneous design with two regions. The active core region is 600 mm diameter and 600 mm high with a center channel 120 mm diameter. The fuel chosen for the inner and outer core consists of 40% and 50% enriched uranium-nitride. The uranium enrichments were adjusted to minimize both the burnup reactivity swing and the

radial peaking factor. The core performance parameters are shown in Table 2. The core Reynolds number is defined by the equivalent hydraulic diameter and the flow velocity in the pin bundle.

Table 1 Nuclear Power System Performance Parameters

Reactor thermal power (kWth)	5000
Gross electrical output (kWe)	240
Net electrical output (kWe)	200
Plant design lifetime (years)	20
Thermoelectric system	
inlet/outlet temperature (°C)	1065/550
Conversion efficiency (%)	5
Waste heat to reject (kWth)	4760
Radiator inlet/outlet temperature (°C)	573/527
Radiator area (m ²)	240

Table 2 Core Performance Parameters

Thermal nominal output (kW)	5000
Active core height (m)	0.6
Active core diameter (m)	0.6
Core volume fraction (fuel/coolant/structure)	52/32/16
²³⁵ U enrichment (%) (inner core/outer core)	40/50
Design lifetime (year)	10
Burnup reactivity swing (\$/10 year)	3.2
Fuel pin outer diameter (mm)	8.0
Fuel pin pitch (mm)	9.04
Number of fuel pins	2700
Peak linear power at BOL (W/cm)	52
Primary coolant	⁷ Li (99.99%)
Primary coolant flowrate (kg/s)	17.25
Core inlet/outlet temperature (°C)	1030/1100
Average coolant velocity in the core (m/s)	0.72
Core Reynolds number	5870
Gas plenum height (m)	0.5
Internal pressure of the fuel cladding at EOL core (MPa)	4

3. Reactivity Control Systems

In addition to the conventional B₄C poison rods, the reactor involves the following innovative reactivity control systems: Lithium Expansion Modules (LEM) for inherent reactivity feedback, Lithium Injection Modules (LIM) for inherent ultimate shutdown, and Lithium Release Modules (LRM) for automated reactor startup. All these systems adopt lithium-6 as a liquid poison. These systems are effective independent of the magnitude and direction of the gravity force.

3.1 Lithium Expansion Module (LEM)

The LEM is the most promising candidate for improving inherent reactivity feedback. The concept of LEM is illustrated in Fig. 4.

LEM is composed of an envelope of refractory metal in which liquid poison of 95% enriched ^6Li is enclosed. Lithium-6 is suspended in the upper part of the envelope by surface tension exerted on the gas-liquid interface. The

LEM is actuated by the volume expansion of ^6Li itself. If the core exit temperature increases, the gas-liquid interface goes down and negative reactivity insertion can be achieved. LEM is effective independent of the magnitude and direction of the gravity force.

RAPID-L is equipped with 4 quick LEMs and 24 slow LEMs. Figure 3 indicates the locations of the gas-liquid interface of both LEMs and corresponding core outlet temperatures. In the figure, quasi-steady-state temperature variation is supposed.

Fig.4 Elevation of the LEM gas-liquid interface

3.2 Lithium Injection Module (LIM)

The LIM is another innovative device installed in RAPID-L to assure inherent safety. The concept of LIM is illustrated in Fig.5. LIM is also composed of an envelope in which 95% enriched ^6Li is enclosed. In case that the core outlet temperature exceeds the melting point of the freeze seal, ^6Li is injected by pneumatic mechanism from upper to lower region to achieve negative reactivity insertion. In this way the reactor is automatically brought into a

permanently subcritical state and temperatures are kept well below the boiling point of lithium (1330°C). LIM is also effective independent of the magnitude and direction of the gravity force. According to our experiment¹⁰, the time required for reactivity insertion of LIM is 0.24 s, which is quite shorter than that of free drop of the conventional scram rods (i.e. as much as 2 s on the earth¹). Detail of the freeze seal design is discussed in the former paper⁹⁻¹⁰.

Fig.5 LIM concept

3.3 Lithium Release Module (LRM)

An automated reactor startup can be achieved by LRM. Figure 6 represents the basic concept. LRM is similar to LIM; however, ^6Li is reserved in the active core level prior to the reactor startup. The LRM should be placed in the active core region where the local coolant void worth is positive, as is also the case with LEM and LIM. RAPID-L is equipped with an LRM bundle in which 16 LRMs are installed. The reactivity worth of an LRM bundle is +3.7 \$ in the case that 95% enriched ^6Li is enclosed in each 20-mm-diam envelope. An automated startup can be achieved by gradually increasing the primary

coolant temperature by the primary pumps circulation. Then the freeze seal of LRMs melt down at melting temperature of the freeze seal, and ${}^6\text{Li}$ is released from lower level (active core level) to upper level to achieve positive reactivity addition. In case the freeze seal support material of

Fig.6 LRM concept

Ag-72Cu is adopted, the injection starts at 800°C. Because Ag-Cu alloy has various range of melting temperature depending on the composition, LRM of desired trigger temperature could be available. Fortunately injected Li stays over the active core region which is colder than the active core region, condensation of Li into the hot side will not occur. Even if condensation occurs, mass transfer through a 0.5 mm diameter orifice would be negligible.

Detail of the LRM freeze seal as well as the orifice is shown in Fig. 7. To, achieve moderate reactivity insertion rate LRM is equipped with an orifice of 0.5 mm diameter. In the reactor startup, lithium in the LRM melts at 181°C while the freeze seal still remain solid to isolate top and bottom chambers until its melting temperature (800°C or 1030°C, for detail, refer to chapter 4). Performance of the orifice is discussed in chapter 5.

3.4 Location of the Reactivity Control Systems in the Fuel Cartridge

As mentioned earlier, the conventional B_4C poison rods are also equipped in RAPID-L. The role of B_4C rods is to ensure the criticality safety at launch phase accident, especially on the fire which results in unintended positive reactivity insertion by LRMs because LRM freeze seal melts at 800°C. Location of these devices in the fuel cartridge is shown in Fig. 8 which illustrates the horizontal cut section of the fuel cartridge at 1 m below the NsL (Normal System Level). Specifications of these systems are summarized in Table 3.

Fig.7 Detail of the freeze seal and orifice

Table 3 Design parameters of the RAPID-L reactivity control systems

Reactivity control system	Envelope inner diameter (mm)	Number
B_4C poison rod	20	8
LRM	20 [40 or 60] *	16 [TBD]*
Slow LEM	20	24
Quick LEM	20	4
LIM	20	16

*) In case envelope inner diameter of the LRM is 40 or 60 mm as shown in chapter 5.1, number of such LRMs would be less than 16.

Fig.8 RAPID-L reactivity control systems

4. Reactor Startup

4.1 Startup Sequence

In the startup sequence adopted here¹¹, heat up the reactor from -100°C to $+200^{\circ}\text{C}$ is done by external heat source, while heat up the reactor from 200°C to 1100°C is achieved by reactor power itself, as shown below.

from 200°C to 800°C by pulling the B₄C poison rods

from 800°C to 1030°C by the first LRMs ($1.35 \text{ } \$/2 \text{ hr} = 1.13 \text{ } \phi/\text{min}$)

from 1030°C to 1100°C by the second LRMs ($1 \text{ } \$/7 \text{ hr} = 0.24 \text{ } \phi/\text{min}$)

To achieve this startup sequence, the melting temperatures of the first and second LRM freeze seals are 800°C and 1030°C , respectively.

4.2 Plant Dynamics Analysis of the Startup Transient

Results of the plant dynamics analyses¹¹ are shown in Fig. 9. The reactor startup is done as follows.

- 1) After having been installed the reactor on the lunar base, the primary coolant lithium is circulated at its nominal flow rate, and poison rods are released by drive motor, then criticality is attained at 200°C .
- 2) Further release of the poison rods will result in increase of the core exit temperature up to 800°C . Then the first LRM freeze seal melts, and positive reactivity insertion by the first LRM ($1.35 \text{ } \$/2 \text{ hr} = 1.13 \text{ } \phi/\text{min}$) takes place. This reactivity insertion rate is as moderate as that manually inserted by control rods in conventional fast reactors. During this period, greater variation of the reactor power is perceived because of negative reactivity feedback of the fast reactor core.

- 3) Positive reactivity addition by the first LRM will result in increase of the core exit temperature up to 1030°C. Then the second LRM freeze seal melts, and positive reactivity insertion by the second LRM ($1 \text{ } \$ / 7 \text{ hr} = 0.24 \text{ } \phi / \text{min}$) takes place. In the reactivity vs. time relation in Fig. 9, reactivity of the second LRM starts from 0 ϕ at 5 hr from the startup, however, the first LRM keeps 530 ϕ even after the second LRM initiated the injection.
- 4) LRM release is completed and the nominal core exit temperature of 1100°C is attained. In this final sequence, slow LEMs and quick LEMs have important roles. Slow LEM would provide negative reactivity feedback beyond 1085°C (refer to Fig. 4) to counterbalance positive reactivity addition by LRMs. Final negative reactivity feedback by slow LEM would be 3 $\$$ which compensate the excess reactivity of the beginning-of-life (BOL) core. In the final approach to the nominal power, especially 6-7 hr from the reactor startup, quick LEMs would be also actuated to provide negative reactivity feedback to restrict reactor overpower. Negative reactivity feedback of slow LEM would gradually decrease as burnup goes on to keep the reactor power as nominal as possible.

Fig. 9 Plant dynamics analyses of the RAPID-L startup sequence ¹¹

5. Development of the Lithium Release Module (LRM)

5.1 Requirements on the LRM Orifice

Our primary concern in the LRM design is how to achieve sufficiently small flow rate of ${}^6\text{Li}$ in the orifice because it enables moderate positive reactivity insertion rate. To realize startup sequence presented in the former chapter, requirements for the orifice flow rate of the first and second LRMs are given as follows.

1) First LRM

Required reactivity insertion rate:	1.35 $\$/2$ hr = 1.13 ϕ/min
Active core height:	600 mm
LRM envelope inner diameter:	40 mm
Volume of ${}^6\text{Li}$ in the envelope:	$(\pi/4) \times 4^2 \times 60 = 754 \text{ cm}^3 = 754 \times 10^{-6} \text{ m}^3$
Specific weight of Li:	510 kg/m^3 at 200°C 450 kg/m^3 at 800°C
Weight of ${}^6\text{Li}$ in the envelope:	385 g (=754 $\text{cm}^3 \times 0.51$) at 200°C
Required mass flow rate:	385 g/2 hr = 3.2 g/min

2) Second LRM

Required reactivity insertion rate:	1 $\$/7$ hr = 0.24 ϕ/min
Active core height:	600 mm
LRM envelope inner diameter:	60 mm
Volume of ${}^6\text{Li}$ in the envelope:	$(\pi/4) \times 6^2 \times 60 = 1696 \text{ cm}^3 = 1696 \times 10^{-6} \text{ m}^3$
Specific weight of Li:	510 kg/m^3 at 200°C 430 kg/m^3 at 1030°C
Weight of ${}^6\text{Li}$ in the envelope:	865 g (=1696 $\text{cm}^3 \times 0.51$) at 200°C
Required mass flow rate:	865 g/7 hr = 2.1 g/min

5.2 Measurement of the Orifice Flow Rate

To confirm the orifice performance specified above, an orifice of 0.5 mm diameter and 15 mm long made of SUS316 was adopted as shown in Fig. 10. In view of the compatibility with lithium over 800°C, however, orifice made of MoRe or NbZr alloy is requested. Either boring by spark erosion or mechanical drilling could manufacture such small diameter orifice made of these refractory metals. This manufacturing is a proven technology and it is easy to provide such orifice of sufficient accuracy. Lithium of “battery grade” was used to avoid plugging of the impurities in such a small diameter orifice.

A schematic of the test setup is shown in Fig. 11. To realize situation in the LRM, the orifice specimen is connected to the lithium reservoir to which an Ar gas circuit is connected to exert difference pressure. Another end of the orifice is connected to the lithium discharge line from which lithium droplet comes out as shown in Fig. 12. The test setup is placed in the glove box and heated over 200°C using trace heater. Weight of lithium coming out is measured with respect to time to calculate lithium flow rate in the orifice. The actual operating temperature of LRM is 800 to 1100°C as shown in the chapter 4.1; however, lower temperature of the test setup is sufficient so long as correction on the lithium property is done.

One of the test results is shown in Figs. 13 and 14. As shown in chapter 5.1, required mass flow rate is 3.2 g/min for the first LRM and 2.1 g/min for the second LRM. Orifice difference pressures to achieve such flow rate are given in Fig. 14. The orifice difference pressure in Fig. 13 is slightly different between Run 1 and 2. However, both data coincides well on the orifice difference pressure vs. mass flow rate relation as shown in Fig. 14.

Fig. 10 Orifice specimen

Fig. 11 Schematic of the test
setup

Fig. 12 Test setup in the glove box

Fig. 13 Orifice test result

Fig. 14 Orifice difference pressure vs. mass flow rate

The orifice coefficient is the most important parameter in the LRM design because the orifice coefficient together with the difference pressure determines the orifice flow rate, i.e. positive reactivity insertion rate. The orifice is characterized by the following basic equations. As shown in equation (1), the orifice performance does not depend on g (acceleration of the gravity) but on ρ ($= \gamma/g$: viscosity of Li).

$$V = C (2g\Delta P_o / \gamma)^{1/2} \quad (1)$$

$$(\pi d^2 / 4) V t \gamma = W \quad (2)$$

where

V : flow velocity in the orifice (m/s)

C : orifice coefficient (<1)

g : acceleration of the gravity ($=9.8 \text{ m/s}^2$)

ΔP_o : orifice difference pressure

γ : specific weight of Li (510 kg/m^3 at 200°C , depends on the temperature)

π : ($=3.14$)

d : orifice diameter ($=0.5 \text{ mm} = 0.5 \times 10^{-3} \text{ m}$)

t : duration of injection (s)

W : weight of Li injected (kg)

Orifice coefficient C is given by the equations (1) and (2).

$$C = V / (2g\Delta P_o / \gamma)^{1/2} = W / [(\pi d^2 / 4) t \gamma (2g\Delta P_o / \gamma)^{1/2}] \quad (3)$$

However, pressure loss due to hydrodynamic friction in the orifice: ΔP_{Fric} should be also taken into account. It is estimated by the following equations. Friction coefficient λ is available by equation (5) so long as lithium in the orifice is laminar flow (i.e. Reynolds number less than 2320). Then the orifice coefficient C is calculated using the effective orifice difference pressure: ΔP_o given by the equation (6). The orifice coefficient calculated is listed in Table 4. The orifice coefficient defined in equation (1) was 0.17 and 0.12 for the first and second LRM, respectively. It seems that the orifice coefficient is not always constant, but depends on the flow rate. The hydrodynamic friction is less than 20% of the total difference pressure.

$$\Delta P_{\text{Fric}} = \lambda \times (L/d) \times (V^2 \gamma / 2g) \quad (4)$$

$$\lambda = 64 / \text{Re} \quad (5)$$

$$\Delta P_o = \Delta P_{\text{Total}} - \Delta P_{\text{Fric}} \quad (6)$$

where

V: flow velocity in the orifice (m/s)

Re: Reynolds number ($= Vd/\nu$)

d: orifice diameter ($= 0.5 \text{ mm} = 0.5 \times 10^{-3} \text{ m}$)

ν : dynamic viscosity of Li ($= 1.1 \times 10^{-6} \text{ m}^2/\text{s}$ at 200°C)

λ : friction coefficient ($= 64/\text{Re}$ in case $\text{Re} < 2320$)

ΔP_{Total} : overall orifice difference pressure

ΔP_{Fric} : pressure loss due to hydrodynamic friction

ΔP_o : effective orifice difference pressure with respect to the orifice coefficient ($= \Delta P_{\text{Total}} - \Delta P_{\text{Fric}}$)

C: orifice coefficient

g: acceleration of the gravity ($= 9.8 \text{ m/s}^2$)

Table 4 Orifice coefficient

	V (m/s)	Re	λ	ΔP_{Total} (mbar)	ΔP_{Fric} (mbar)	ΔP_o (mbar)	C
First LRM	0.50	230	0.28	28	5.5	22.5	0.17
Second LRM	0.35	160	0.40	26	3.8	22.2	0.12

In order to achieve required flow rate, the initial filling pressure of the LRM bottom chamber is calculated based on the Boyle-Charles law. As shown in Table 5, quite lower absolute pressure is required for the initial filling pressure that could be achieved by adjusting the pressure of laser welding chamber in which LRM bottom chamber is sealed.

Table 5 Required initial filling pressure of the LRM bottom chamber

	Required flow rate (Flow velocity in the orifice: V and orifice coefficient: C)	Required operating condition	Initial filling pressure at 20°C
First LRM	3.2 g/min ($V=0.50 \text{ m/s}$, $C=0.17$)	28 mbar at 800°C	7.6 mbar
Second LRM	2.1 g/min ($V=0.35 \text{ m/s}$, $C=0.12$)	26 mbar at 1030°C	5.8 mbar

6. Conclusion

An operator-free fast reactor concept RAPID-L has been demonstrated by adopting innovative reactor control systems LEM, LIM and LRM. In our latest design, B_4C poison

rods are also introduced to ensure criticality safety in all accidental situations. Requirements on the lithium release module (LRM) to startup RAPID-L has been discussed, and the LRM orifice performance has been confirmed using 0.5 mm diameter SUS316 orifice/lithium flow test setup in the glove box.

The following results have been obtained:

- 1) Sufficiently small flow rate (3.2 and 2.1 g/min for the first and second LRMs, respectively) of ^6Li in the LRM orifice is required to achieve moderate positive reactivity insertion rate (1.13 and 0.24 $\text{¢}/\text{min}$ for the first and second LRMs, respectively).
- 2) The orifice coefficient of 0.5 mm diameter SUS316 orifice was 0.17 and 0.12 for the first and second LRM, respectively. It seems that the orifice coefficient is not always constant, but depends on the flow rate.
- 3) In order to achieve required flow rate of the orifice, the initial filling pressure of the LRM bottom chamber is calculated. Quite lower absolute pressure (7.6 and 5.8 mbar for the first and second LRMs, respectively) is required for the initial filling pressure that could be achieved by adjusting the pressure of laser welding chamber in which LRM bottom chamber is sealed.
- 4) After reactor coolant is heated up to 800°C by means of the B_4C poison rods, reactor startup can be performed by the first and second LRMs automatically.

Further development on the LRM is focused on the freeze seal to achieve startup temperature of 800 and 1030°C for the first and second LRMs, respectively.

The definite advantage of RAPID-L is that it can exclude human error. The design concept outlined above offers a substantial inherent safety, and will meet the future space power requirements.

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Nomenclature

RAPID: Refueling by All Pins Integrated Design

RAPID-L: Refueling by All Pins Integrated Design-Lunar base

LEM: Lithium Expansion Module

LIM: Lithium Injection Module

LRM: Lithium Release Module

UTOP: Unprotected Transient Overpower

ISSS: inherent secondary shutdown system

GEM: gas expansion module

ULOF: unprotected loss of flow

ISI: In-Service Inspection

TE: Thermoelectric

NSL: Normal System Level

Re: Reynolds number