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RAPID-L and RAPID Operator Free Fast Reactor Concepts Without Any Control Rods

Mitsuru KAMBE[1*], Hirokazu TSUNODA[2], Kiyoshi NAKAZIMA[2] and Takamichi IWAMURA[3]
[1]Central Research Institute of Electric Power Industry (CRIEPI), 2-11-1, Iwado Kita, Komae-shi, Tokyo, 201-8511 Japan
[2]Mitsubishi Research Institute, Inc. 3-6, Otemachi 2-chome, Chiyoda-ku,Tokyo, 100-8141 Japan
[3]Japan Atomic Energy Research Institute, 2-4, Shirakata-shirane, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195 Japan

The 200 kWe uranium-nitride fueled lithium-cooled fast reactor concept "RAPID-L" for lunar base power system, and the 1000 kWe U-Pu-Zr metal fueled sodium-cooled fast reactor concept "RAPID" for terrestrial power system have been demonstrated. These reactors are characterized by RAPID (Refueling by All Pins Integrated Design) refueling concept, which enable quick and simplified refueling. The essential feature of RAPID concept is that the reactor core consists of an integrated fuel assembly (IFA) instead of conventional fuel subassemblies. In this small size reactor core, all the fuel pins are integrated altogether and encased in a fuel cartridge. Refueling is conducted by replacing an IFA. The reactor can be operated without refueling for up to 10 years.

Unique challenges in reactivity control systems design have been addressed in these reactors. They have no control rod, but involve 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 B4C rods. In combination with LEMs, LIMs and LRMs, RAPID-L and RAPID can be operated without operator. In this paper, design characteristics of RAPID-L and RAPID reactor concepts are discussed.

KEYWORDS: Fast Reactor, Operator-Free Reactor, Space Reactor, Lithium Cooled Reactor, Sodium Cooled Reactor

I. 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. 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. In spite of the inherent safety features of fast reactors 1), self-actuated shutdown system would be essential in the future plants from the view of redundancy. Despite several approaches 2-4) to enhance inherent safety by self-actuated shutdown capability, no attempts except inherent secondary shutdown system 5) (ISSS) and gas expansion modules 6) (GEM) have been made to apply measures without absorber rods. The ISSS concepts consist of small tantalum alloy balls that are hydraulically raised by the reactor coolant and inherently drop into the core zone in a unprotected loss of flow (ULOF) incident. The GEMs are empty assemblies, sealed at their top end and connected to the inlet coolant plenum at the bottom end. In case of ULOF, the neutron scattering sodium is removed and a neutron leakage path out of the core is provided. Both the ISSS and GEMs are, by their own nature, effective for ULOF but not for transients like UTOP. In addition, long-life reliability is as yet unconfirmed. Another issue to be considered in future fast reactors is the simplicity of operation. So far, skillful operators are essential for reactor startup in conventional plants. Fully automated reactor startup has never been attempted except for spacecraft nuclear reactors 7).

The author has established a 200-kW (electric) lithium-cooled fast reactor concept RAPID-L 8, 9) without any control rods, designed for lunar base activities. A significant advantage of RAPID-L is the introduction of the innovative reactivity control systems: lithium expansion module 8-10) (LEM), lithium injection module 8-10) (LIM) and lithium release module 8, 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 ^{6}Li and are actuated by highly reliable physical property (i.e. volume expansion of ^{6}Li for LEM, and freeze seal meltdown for LIM and LRM). This concept enables operator free reactor and exclude human error and terrorists intervention.

RAPID-L is characterized by RAPID 11) (Refueling by All Pins Integrated Design) refueling concept, which enable quick and simplified refueling 2 weeks after reactor shutdown.

RAPID-L is equipped with the thermoelectric (TE) energy conversion system instead of the conventional steam turbine generator. In spite of inferior conversion efficiency, TE system was adopted because of reliability, long-life performance, and survivability thoroughly demonstrated with over 40 years of failure-free space operation 12) by the

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[*] Corresponding author, Tel. +81-3-3480-2111, Fax. +81-3-3480-2493, E-mail: kambe@criepi.denken.or.jp

USA. The authors are developing TE system consists of the functionally graded material compliant pad [13-15) (FGM CP), bond-free compliant pad [14, 15) (BFCP) and liquid compliant pad [14, 15) (LCP). These pads provide (1) a high flux, direct conduction path to heat source and heat sink, and (2) the structural flexibility to protect the TE cell from high stress due to thermal expansion. The TE system equipped with such CPs enables approximately 3 times much power as that of conventional TE system.

In addition to RAPID-L design, a 1000-kW (electric) sodium-cooled fast reactor RAPID, designed for terrestrial applications, is also presented in this paper. This is one of the variants of the RAPID series. Potential uses for RAPID are in power plants in urban areas of industrialized nations to relieve the peak load, and for developing countries where remote regions cannot be conveniently connected to the main grid and where it is economical to provide local generation capacity. In addition RAPID can be used for seawater desalination process.

II. Plant Concepts

1. Overall Plant Design

(1) RAPID-L

Because no cooling water is available on the lunar surface, waste heat of the RAPID-L power plant should be rejected by radiator panels. Another characteristic of the plant is thermoelectric (TE) power conversion system instead of the conventional steam turbine generator. Based on the TE cell efficiency of current state of the art, the net efficiency of the system is estimated to be 4%. The radiator panel temperature of 550ºC was selected to minimize the overall weight of the system. Accordingly, the reactor must be operated over 1000ºC. To meet this design requirement, lithium was adopted as the reactor coolant instead of sodium, and molybdenum rhenium (MoRe) alloy as the reactor structure instead of austenitic steel.

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 1,030 and 1,100ºC, 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 2,700 fuel elements. All these element are combined together by a core support grid and several spacer grids, and are assembled into a fuel cartridge. The fuel cartridge also comprises 28 LEMs, 16 LIMs, 16 LRMs, a radial reflector and a shield plug. In this particular reactor concept, the reactor has neither diagrid nor core support structure because they are also integrated in a fuel cartridge.

The overall nuclear power system is illustrated in Fig. 2. The reactor is coupled to 4 TE power conversion segments[11] placed around the reactor. Each segment has a pumped lithium heat rejection loop connected to mercury heat pipe radiators. The 8 radiator panels are arranged in a vertical configuration extended radially from the power conversion segments. The reactor is located in an excavated cylindrical hole which provides shielding of gamma and neutron radiation. A performance breakdown of the nuclear power system is shown in Table 1.

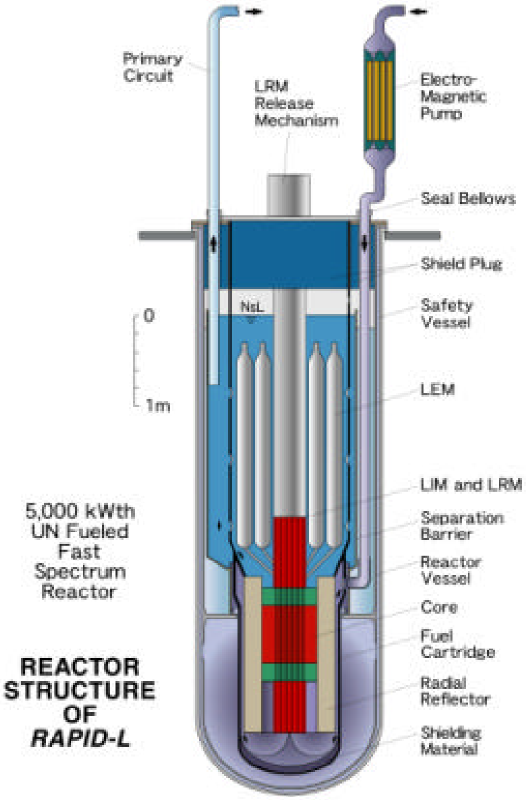

Fig. 1 Reactor structure of **RAPID-L**

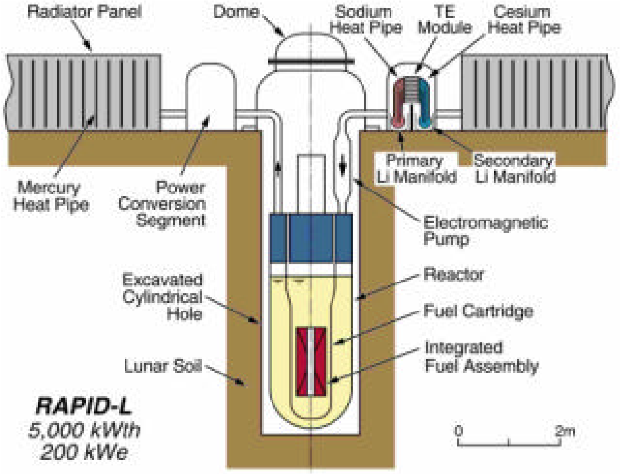

Fig. 2 Power system layout of **RAPID-L**

Table 1 Nuclear Power System Performance Parameters of **RAPID-L**

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)	4560
Radiator inlet/outlet temperature (°C)	573/527
Radiator area (m^2)	240

(2) RAPID

Water is used to reject the waste heat of the terrestrial power plant RAPID. Therefore conventional sodium cooled fast reactor design and austenitic steel as the reactor structure can be applied. While the TE system is also adopted in view of simpler operation and maintenance. In this design, the advanced TE system to be developed by 2010 is adopted. The net efficiency of the system is estimated to be 12%.

The conceptual design of RAPID consists of a 10 MWt-1 MWe U-Pu-Zr metal fueled, sodium cooled, fast spectrum reactor with lithium inlet and outlet temperature of 530 and 380°C, respectively.

The reactor structure is shown in Fig. 3. The reactor is basically a loop type configuration and a reactor vessel of 2.6 m in diameter and 7.0 m deep. The basic concept is similar to that of RAPID-L, however, considerable attention has been paid to reduce the fuel cartridge size from the view of spent fuel handling. The fuel cartridge, 1.6 m in diameter and 3.9 m long, involves approximately 13,000 fuel elements, 12 LIMs and 9 LRMs. However, the radial shield is not encased in the fuel cartridge, but placed on the core support platform. Difference from the RAPID-L design is that the 41 LEMs can be withdrawn by the upper internal structure prior to the refueling.

Table 2 Nuclear Power System Performance Parameters of **RAPID**

Reactor thermal power (MWth)	10
Gross electrical output (MWe)	1.2
Net electrical output (MWe)	1
Plant design lifetime (years)	30
Thermoelectric system	
inlet/outlet temperature (°C)	510/40
Conversion efficiency (%)	12

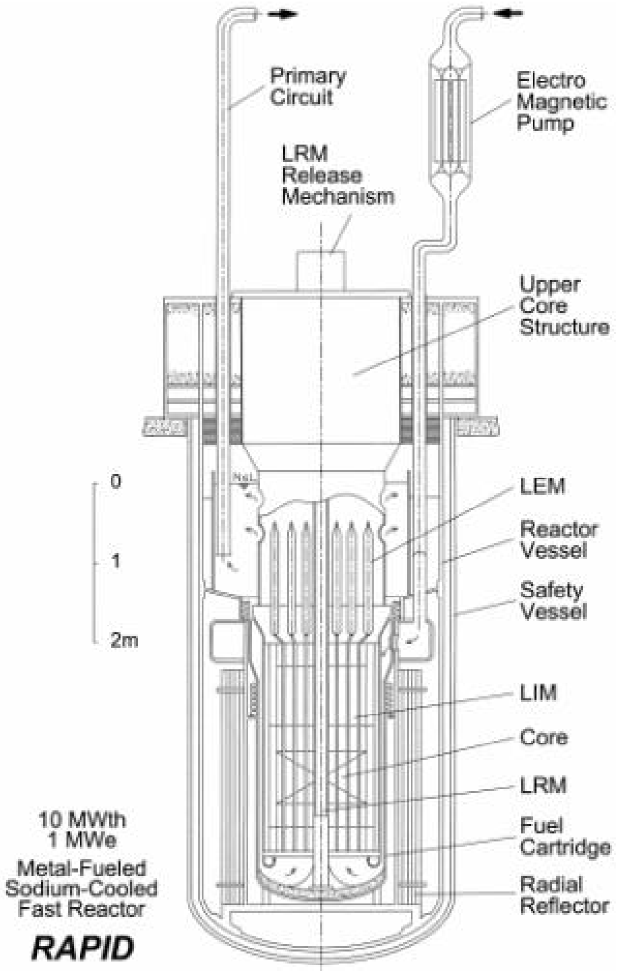

Fig. 3 Reactor structure of **RAPID**

2. Reactor Core Design

(1) RAPID-L

The reactor core of RAPID-L 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 3. As shown in Fig. 4, the core comprises LEMs for reactivity control, LIMs for ultimate shutdown and LRMs for automated startup instead of conventional control rods.

(2) RAPID

Also the reactor core of RAPID is a homogeneous design with two regions. Two dimensional R-Z model of the core is shown in Fig. 5. The active core region is 1150 mm diameter and 1000 mm high with a center channel 220 mm diameter. The fuel chosen for the inner and outer core consists of 14% and 19% enriched U-Pu-Zr metal. The core performance parameters are shown in Table 4. The location of LEMs, LIMs and LRMs are presented in Fig. 6.

Table 3 Core Performance Parameters of **RAPID-L**

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
Fuel	UN
^{235}U enrichment (%) (inner core/outer core)	40/50
Design lifetime (year)	10
Burnup reactivity swing ($/10 year)	−3.0
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)	4.1

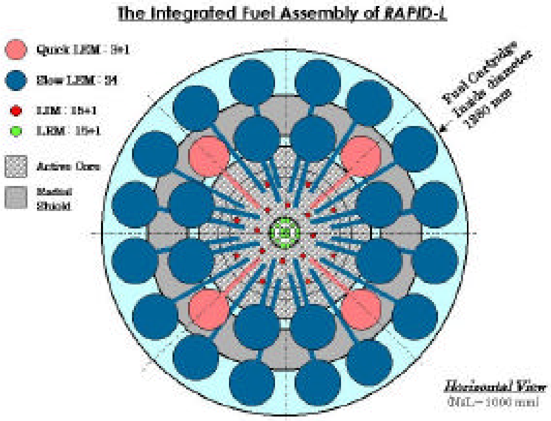

Fig. 4 Integrated fuel assembly of **RAPID-L**

Table 4 Core Performance Parameters of **RAPID**

Thermal nominal output (kW)	10000
Active core height (m)	1.0
Active core diameter (m)	1.15
Core volume fraction (fuel/coolant/structure)	52/32/16
Fuel	U-Pu-Zr metal
Pu enrichment (%) (inner core/outer core)	14/19
Design lifetime (year)	10
Burnup reactivity swing ($/10 year)	−2.9
Breeding gain	1.05
Fuel pin outer diameter (mm)	8.0
Fuel pin pitch (mm)	9.04
Number of fuel pins	13000
Peak linear power at BOL (W/cm)	43
Primary coolant	Sodium
Core inlet/outlet temperature (°C)	380/530

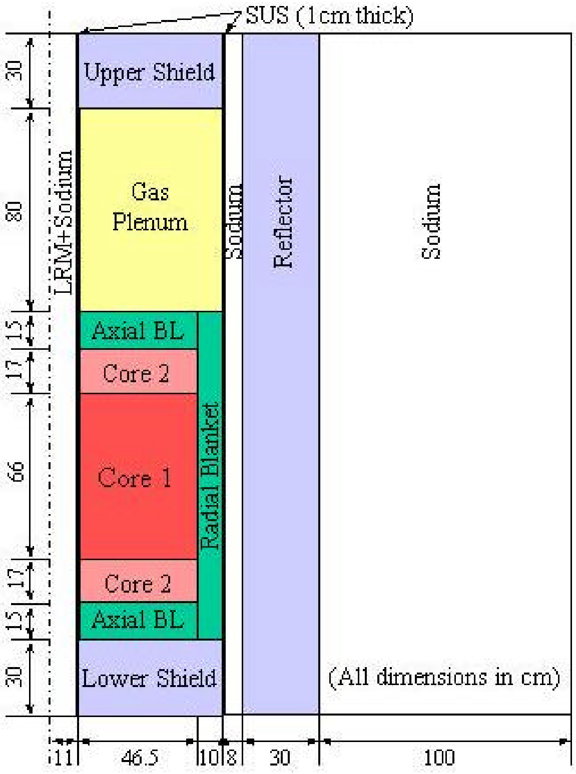

Fig. 5 Two dimensional R-Z model of **RAPID** core

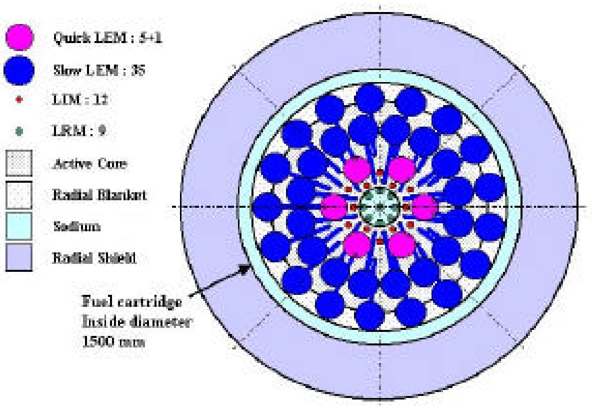

Fig. 6 Integrated fuel assembly of **RAPID**

3. The RAPID Refueling Concept

(1) RAPID-L

Refueling is conducted every 10 years. The refueling procedure is illustrated in Fig. 7. The RAPID concept[10, 12] enables quick and simplified refueling after 2 weeks of reactor shutdown at which decay heat of the core is 10 kW. In case of refueling, a lithium filled fuel cartridge is removed from the reactor and loaded into a lithium filled on-site storage cask (OSSC) waiting besides the reactor. After having received a spent fuel, the OSSC is equipped with a heat pipe radiator for decay heat removal. It is stored in an excavated cylindrical hole to minimize the dose rate of astronauts involved. Dissipation of decay heat will solidify lithium in the OSSC one year after the refueling. Then spent fuel together with the OSSC could be disposed into deep space.

(2) RAPID

Refueling concept is similar to that of RAPID-L, however, refuelling should be conducted in inert gas atmosphere. This is an open vessel hot cell refueling concept. Just prior to the refueling, a movable inerted cell (MIC) is placed above the reactor, and the LEMs' cartridge is removed from the reactor. Then sodium filled fuel cartridge is removed from the reactor and loaded into a sodium filled on-site storage cask (OSSC) waiting in the MIC. After having received a spent fuel, the OSSC is equipped with a heat pipe radiator for decay heat removal. It is stored in the spent fuel storage station adjacent to the reactor building. Refueling can be carried out 2 weeks after reactor shutdown at which decay heat of the core is 20 kW. Dissipation of decay heat will solidify sodium in the OSSC two years after the refueling. Then spent fuel together with the OSSC could be transported to the reprocessing plant without any intermediate steps.

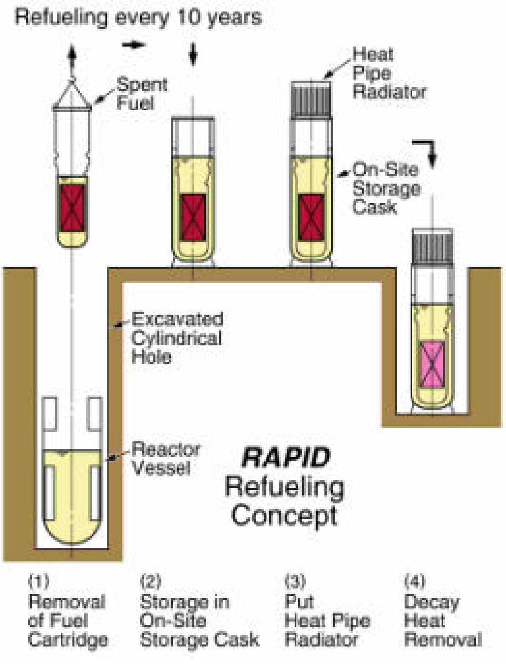

Fig. 7 RAPID refueling concept (**RAPID-L**)

III. Lithium Expansion Module (LEM)

1. LEM for RAPID-L

The LEM is the most promising candidate for improving inherent reactivity feedback. The concept of LEM is illustrated in Fig. 8. LEM is composed of an envelope of refractory metal in which liquid poison of 95% enriched ^{6}Li 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 ^{6}Li itself. If the core exit temperature increases, the gas-liquid interface goes down and negative reactivity insertion can be achieved.

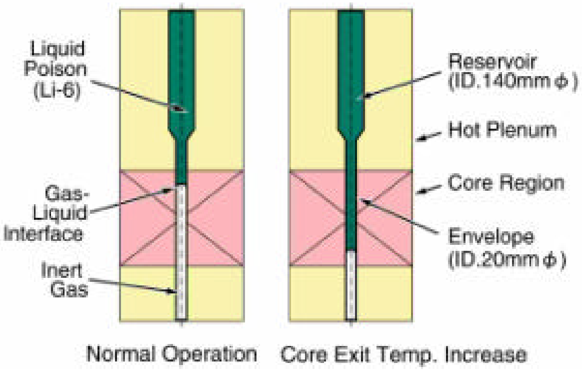

Fig. 8 Concept of LEM for **RAPID-L**

RAPID-L is equipped with 4 quick LEMs and 24 slow LEMs. Figure 9 indicates the locations of the gas-liquid interface of both LEMs and corresponding core outlet temperatures. In Fig.9, quasi-steady-state temperature variation is supposed.

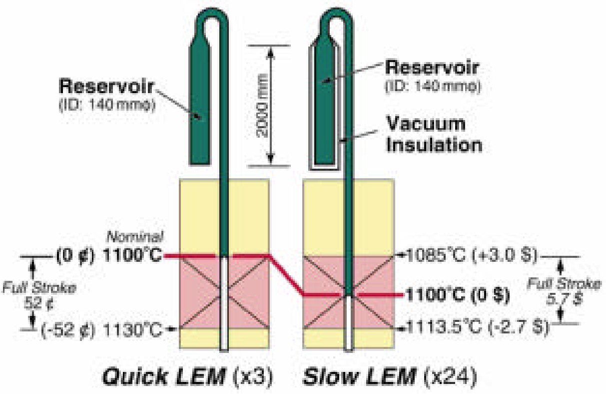

Fig. 9 Elevation of the LEM gas-liquid interface (**RAPID-L**)

A quick LEM is characterized by a quick response. It can provide only a negative reactivity insertion. Three (out of 4) quick LEMs ensure −50¢. Accordingly it is effective to mitigate the anticipated transient without scram. The gas-liquid interface in the nominal operation is placed at the active core top. In case the core outlet temperature decreases, the gas-liquid interface goes up and no positive reactivity insertion is expected.

Slow LEM can provide both negative and positive reactivity insertion with moderate thermal response. Reactivity varies between −2.7 $ and +3.0 $ by 24 slow LEMs. Slow LEMs have a role of automated burnup compensation. In addition, slow LEMs also realize partial load operation in accordance with the primary flow rate. The gas-liquid interface in the nominal operation is placed in the active core region as shown in Fig. 9. In case the core outlet temperature decreases, the gas-liquid interface goes up, and positive reactivity is added, and vice-versa. To avoid quick positive reactivity addition, slow LEMs have a reservoir of double envelopes for vacuum insulation. Therefore, slow LEMs are affected only by moderate thermal transients resulting from burnup reactivity swing and primary flow rate control. Design parameters of LEMs are described in Table 5.

In case of sudden increase of the primary flowrate, the reactor power will increase and approaches gradually to the value that is roughly proportional to the primary flowrate. Only an acceptable overpower is expected in the transient as shown in Fig. 10. The most severe example here is the primary flowrate increase from 100% to 110% in 2 seconds. The maximum power in the transient is 15%.

Table 5 Design parameters of quick and slow LEMs for **RAPID-L**

	Quick LEM	Slow LEM
Envelope		
Inner diameter (mm)	20	20
Full stroke (mm)	640	640
Material	MoRe	MoRe
Reservoir		
Inner diameter (mm)	140	140
Length (mm)	2000	2000
Total LEM sensitivity (¢/K)	2.3	16.7
Single LEM sensitivity (¢/K)	0.77	0.77

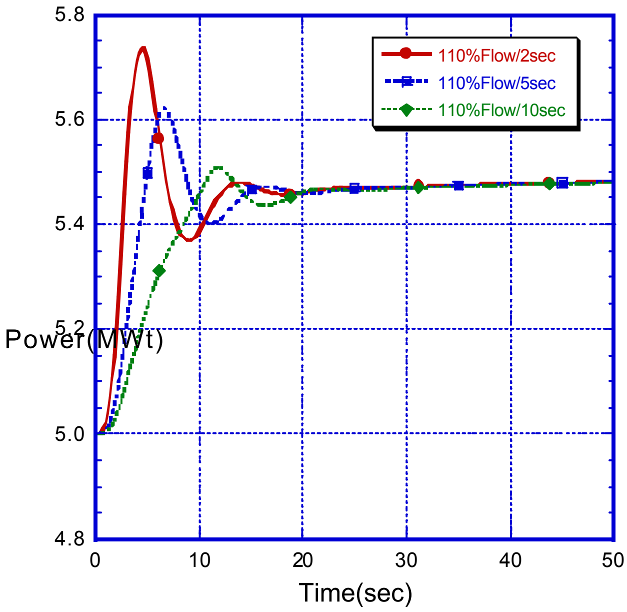

Fig. 10 Transient response in case of primary flow rate increase (**RAPID-L**)

2. LEM for RAPID

The quick and slow LEMs of RAPID is similar to those of RAPID-L. Only the difference is the envelope and reservoir dimensions. The inside diameter of LEM envelope for RAPID is 12 mm, smaller than that for RAPID-L, because it depends on the gravity force. On the lunar surface where the gravity force is one-sixth of the earth, the 20 mm diameter envelope is possible, while on the earth, the gravity force of 0.3 g as well as 1 g (9.8 m/s^2) should be supposed on considering the earthquake. Principle of LEM was demonstrated by using specimen of 12 mm envelope as shown in Fig. 11. RAPID is equipped with 6 quick LEMs and 35 slow LEMs. Figure 12 indicates the locations of the gas-liquid interface of both LEMs. Design parameters of LEMs are described in Table 6.

Fig. 11 LEM specimen

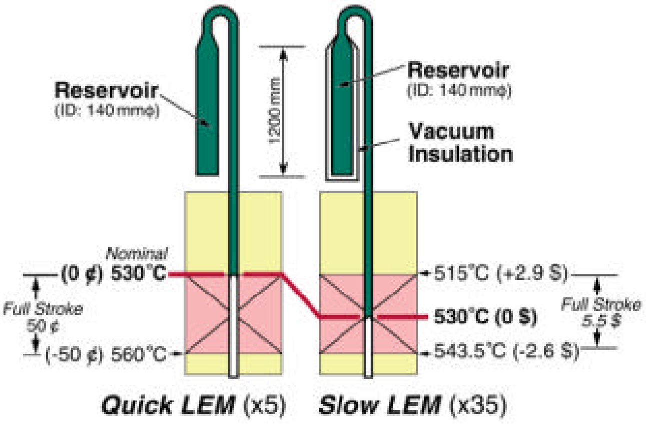

Fig. 12 Elevation of the LEM gas-liquid interface (**RAPID**)

Table 6 Design parameters of quick and slow LEMs for **RAPID**

	Quick LEM	Slow LEM
Envelope		
Inner diameter (mm)	12	12
Full stroke (mm)	1000	1000
Material	MoRe	MoRe
Reservoir		
Inner diameter (mm)	140	140
Length (mm)	1200	1200
Total LEM sensitivity (¢/K)	1.7	19.3
Single LEM sensitivity (¢/K)	0.33	0.55

IV. Lithium Injection Module (LIM)

1. LIM for RAPID-L

The LIM is another innovative device installed in RAPID-L to assure inherent safety. The concept of LIM is illustrated in Fig. 13. LIM is also composed of an envelope in which 95% enriched ^{6}Li is enclosed. In case that the core outlet temperature exceeds the melting point of the freeze seal, ^{6}Li 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). Time required for reactivity insertion of LIM is 0.24 sec, which is quite shorter than that of free drop of the conventional scram rods (i.e. as much as 2 sec) on the earth. To provide the shutdown margin of −0.5 $, the total reactivity worth of −3.7 $ is required for LIMs to counterbalance the slow LEMs' feedback (+3.0 $) and the power defect reactivity of the core (+0.2 $). 16 LEMs of 20-mm-diam envelope are sufficient to achieve it. Similarly to LEMs, LIMs assure sufficient negative reactivity feedback in unprotected transients. The role of LIM is to provide with variety and redundancy of inherent safety in unprotected transients. Either LEMs or LIMs can meet such transients independently. The difference between LEM and LIM is that the former can achieve both negative and positive reactivity feedbacks reversibly, and the latter only negative feedback permanently. Freeze seal design is the key issue to ensuring the accurate injection temperature over the design lifetime. The freeze seal segment consists of CuNi alloy (trade name: L-30) to assure the injection temperature of 1240°C. A cut view of the freeze seal is shown in Fig. 14. A molybdenum rhenium (MoRe) rupture foil of 50μm thick separates the top chamber (lithium-6) and bottom chamber (vacuum). In case CuNi support melts, the rupture foil will be broken by the top chamber pressure. Boron nitride (BN) diffusion barrier is inserted between the rupture foil and support to avoid the formation of intermetallide due to diffusion at operating temperature. The freeze seal parts of LIM are shown in Fig. 15.

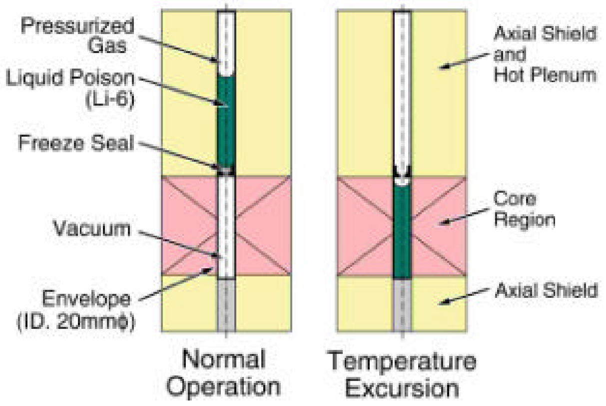

Fig. 13 LIM concept

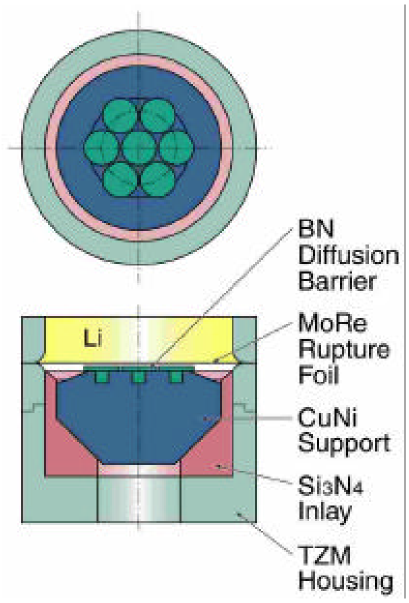

Fig. 14 LIM freeze seal of **RAPID-L**
(Injection temperature: 1240°C)

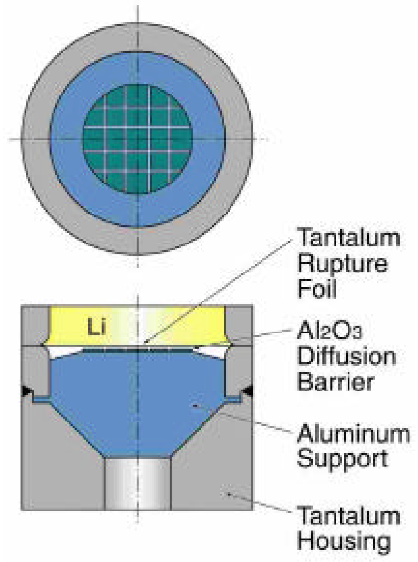

Fig. 16 LIM freeze seal of **RAPID**
(Injection temperature: 660°C)

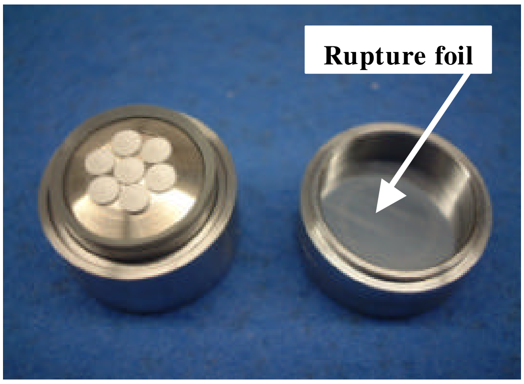

Fig. 15 LIM freeze seal before assembling
(**RAPID-L**)

Fig. 17 Cut section of the freeze seal after 2000 hours operation (**RAPID**)

2. LIM for RAPID

A cut view of the freeze seal is shown in Fig. 16. A tantalum (Ta) rupture foil of 20μm thick is adopted as a rupture foil. To ensure the injection temperature of 660°C, aluminum (Al) support is adopted. An alumina (Al_2O_3) coating of 0.2 mm thick on the support acts as a diffusion barrier.

The integrity of the freeze seal during design lifetime is of utmost importance. Figure 17 shows a cut section of the freeze seal after 2000 hours of heating at 600°C, which simulates the hot channel temperature at nominal operation. No creep deformation is perceived. The pressure load exerted on the support was 0.46 MPa which is quite smaller than the yielding stress of Al. Therefore we are optimistic about the long life durability of 10 years. No diffusion through the alumina diffusion barrier has been verified by the SEM (Scanning Electron Microscopy) inspection.

V. Lithium Release Module (LRM)

1. LRM for RAPID-L

Fully automated reactor startup can be achieved by LRM. Figure 18 represents the basic concept. LRM is similar to LIM; however, ^{6}Li 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 assembled. The reactivity worth of an LRM bundle is +3.7 \$ in the case that 95% enriched ^{6}Li is enclosed in each 20-mm-diam envelope. An automated startup can be achieved by gradually increasing the primary coolant temperature by the primary pump circulation. The freeze seal of LRMs melt down at the hot standby temperature (approximately 780°C), and ^{6}Li is released from lower level (active core level) to upper level to achieve positive reactivity addition. The freeze seal support material of Ag-72Cu is adopted to ensure the startup at 780°C. Automated reactor startup from subcritical was to insert reactivity at a constant rate (0.008¢/sec). This reactivity insertion rate is as moderate as that manually inserted by control rods in conventional fast reactors. An automated startup is completed in 11 hours.

Prior to the refueling, the LRM bundle should be released in lower part of the core so as that liquid poison should locate in the active core region again. In this case, the LRM bundle acts as a poison rod. Once released, it is clumped at the bottom and is impossible to pull out again. This is the design in conformance with space reactor safety criteria ruled in the USA. The reactor startup is only possible by installing a new fuel cartridge.

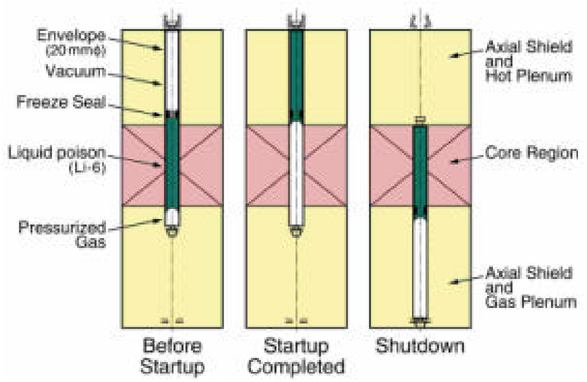

Fig. 18 LRM concept (**RAPID-L**)

2. LRM for RAPID

The concept of LRM for RAPID is essentially the same as that of RAPID-L. The hot stand-by temperature is 380°C in this case. In the center channel of the core, there is an LRM bundle in which 9 LRMs are installed.

The RAPID can be operated 10 years without shutdown. The reactor shutdown could be made by releasing the LRM bundle, however, it is better to operate the RAPID continuously during 10 years. The reactor startup is only possible by installing a new fuel cartridge. In view of the plant availability, periodic inspection of the reactor plant should be planned during a refueling shutdown. Such an interval of periodic inspections would be reasonable in future reactors, especially an operator free reactor RAPID because no moving parts is involved in the safety system.

VI. Conclusion

.An operator-free fast reactor concept RAPID-L and RAPID without any control rods has been demonstrated by adopting innovative reactor control systems LEM, LIM and LRM. Reactivity worth of these control systems are summarized in Table7 and 8. The reactivity worth range of the slow LEM is determined to compensate the burnup reactivity swing of each core.

The following results have been obtained:

1) An automated reactor startup can be performed by LRMs.
2) Burnup compensation can be achieved by slow LEMs.
3) Partial load operation can be done by slow LEMs and quick LEMs those are actuated by the primary flowrate control.
4) Transient mitigation can be made by quick LEMs.
5) Ultimate shutdown in unprotected transient is assured by LIMs.
6) An intended shutdown is possible by releasing the LRM bundle.

The advantage of RAPID-L and RAPID concept is illustrated in Fig. 19. The conventional reactors have several instrumentations to monitor the reactor. The process data available from such instrumentations are monitored, and the control /shutdown rods are actuated, if necessary. In this system, a failure of the system, human error and terrorist's intervention would result in unnecessary reactor shutdown and reduce the plant availability. Maintenance of the instrumentation and monitoring system is therefore important. In contrast to such conventional reactors, the RAPID-L and RAPID are controlled by LEMs, LIMs and LRMs.

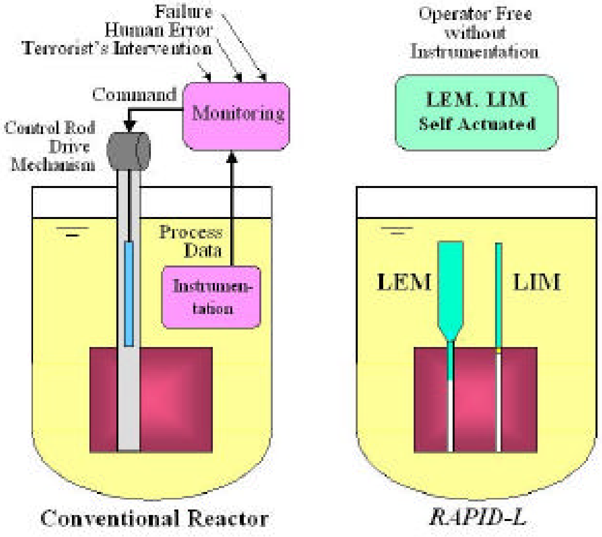

Fig. 19 Advantage of **RAPID-L** and **RAPID**

This concept excludes conventional instrumentation-monitoring system to assure the reactor safety. As a matter of fact, RAPID will be equipped with the primary flow meter and thermocouples to monitor the reactor. The former is necessary for partial load operation. However, these instrumentations are nothing to do with LEM, LIM and LRM. This is the definite advantage of RAPID-L and RAPID. The design concept outlined above offers a substantial inherent safety, and will meet the future power requirements.

Table 7 **RAPID-L** reactivity control system

Reactivity Control System	Envelope Inner Diameter (mm)	Number	Reactivity Worth Range ($)
Quick LEM	20	3+(1)	−0.52 to 0
Slow LEM	20	24	−2.7 to +3.0
LIM	20	16	−3.7
LRM	20	16	+3.7

(1): supplement in view of redundancy

Table 8 **RAPID** reactivity control system

Reactivity Control System	Envelope Inner Diameter (mm)	Number	Reactivity Worth Range ($)
Quick LEM	12	5+(1)	−0.5 to 0
Slow LEM	12	35	−2.6 to +2.9
LIM	20	12	−3.6
LRM	20	9	+3.6

(1): supplement in view of redundancy

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