Histórico dos reatores rápidos e ciclo do tório no DCTA

Prof Lamartine Nogueira Frutuoso Guimarães*

Dr. Artur Flávio Dias**

*PG-CTE/ITA, CAP/INPE, UNIP/SJC

*,** Consultor

VI SENCIR – UFMG

10 de novembro de 2022

Publicações RR do IEAv.

1978	IEAV/RP-005/78	Compilação de parâmetros nucleares dos isótopos do tório, urânio e plutônio	Hélio Dias
1980	EAV/NT-014/80	Estudo inicial das características de regeneração dos GCFR com U233-Th	Yuji Ishiguro e Antonio Soares de Gouvea (IPEN)
1981	EAV/NT-003/81	Possíveis tipos de regeneradores com o ciclo do tório	Yuji Ishiguro
1981	LEA/NT-023/81	LMFBR with 233U/Th - fueled inner core	Yuji Ishiguro e Artur F. Dias
1981	IEAV/RP-026/81	Sodium-cooled thorium-cycle breeder reactor with coated particles	Yuji Ishiguro e Antonio S. Gouvea
1982	LEA/NT-002/82	Reatores regeneradores para o ciclo do tório	Yuji Ishiguro, Aydin Konuk, Antonio S. de Gouvea
1982	LEA/NT-004/82	Um LMFBR para a introdução do ciclo do tório	Yuji Ishiguro e Artur F.Dias
1982	LEA/NT-005/82	Um LMFBR para a introdução do ciclo do tório e o projeto das varetas de combutível de U233/Th	Yuji Ishiguro, Artur F. Dias e Antonio S. de Gouvea
1982	IEAV/RP-002/82	Fuel pins for thorium cycle LMFBR	Yuji Ishiguro e Ahmet Aydin Konuk (Oregon State University)
1983	IEAV/NT-003/83	A LMFBR fueling concept for Thorium utilization and improved inherent safety	Yuji Ishiguro
1985	IEAV/RP-017/85	Otimização do reator regenerador binário. III - Influência da altura do núcleo na reatividade de vazios no sódio	Jamil A. Nascimento, Artur F. Dias e Yuji Ishiguro
1985	IEAV/RP-025/85	Pequenos reatores a metal líquido para uma fase inicial da introdução de reatores regeneradores rápidos	Yuji Ishiguro e Jamil A. Nascimento

Publicações RR do IEAv.

1986	IEAV/NT-008/86	Estudo da sensibilidade de parâmetros integrais com relação às seções de choque do 232tório	L.N.Frutuoso Guimarães e Artur C. Menezes
1986	IEAV/RI-004/86	Sobre o desenvolvimento de reatores regeneradores rápidos e a utilização do tório no Brasil	Yuji Ishiguro
1986	IEAV/RP-010/86	Otimização do reator regenerador binário IV - concepção de combustível misto na parte central do núcleo	Artur F. Dias e Yuji Ishiguro
1986	IEAV/RP-014/86	Otimização do reator regenerador binário V - reatores regeneradores binários com duas e quatro zonas e um LMFBR - (Pu/U) convencional de duas zonas	Artur F. Dias e Yuji Ishiguro
1986	IEAV/RP-016/86	Otimização do reator regenerador binário VI - um projeto aceitável de reator regenerador binário	Artur F. Dias e Yuji Ishiguro
1986	IEAV/RP-023/86	Designs, characteristics and development of fast reactors for utilization of thorium	Y.Ishiguro, A.F.Dias, J.A. Nascimento
1987	EAV/RP-023/87	Otimização do reator regenerador binário VII - núcleos com combustíveis ^{233}U/ ^{238}U e Pu/ ^{238}U.	J.A.Nascimento, Artur F.Dias e Yuji Ishiguro
1987	IEAV/RP-025/87	O papel dos reatores regeneradores rápidos no contexto energético nacional do futuro	José Guilherme S.M. Senna
1987	IEAV/RP-030/87	Contribuição a metalurgia do uranio e ao estudo de suas ligas metálicas de utilização com combustível em reatores rápidos regeneradores	Carlos de Moura Neto

Publicações RR do IEAv.

1988	IEAV/RP-005/88	Otimização do reator regenerador binário. VIII núcleo com combustíveis ^{233}U-^{238}U e Pu-^{238}U	J.A.Nascimento e Yuji Ishiguro
1988	IEAV/RP-051/88	Reator regenerador binário com núcleo anular	J.A.Nascimento e Yuji Ishiguro
1989	IEAV/RP-012/89	Necessidade de reatores regeneradores rápidos e possibilidade de méritos de utilização do tório	Yuji Ishiguro
1991	IEAV/NT-006/91	Extensão da cadeia de queima do Th232 na biblioteca do programa WIMDS/4	Alexandre D. Caldeira
1991	IEAV/RP-017/91	Reator regenerador rápido de 3.000 MWt iniciado com U-Zr	Jamil A. Nascimento e Yuji Ishiguro
1997	IEAV/RP-013/97	Metodologia de cálculo de blindagens para reatores nucleares regeneradores rápidos	Luiz H.Claro, Wilson J. Vieira, Artur F. Dias e Shizuca Ono

Publicações RR do IEAv.

- 27 publicações.
- Entre 1978 à 1997.
- 19 publicações entre 1981 e 1987.
- Todo o trabalho realizado envolveu análise computacional.
- Havia um forte sentimento de que este caminho levaria à construção.
- A análise computacional produziu núcleos de reator de 3000, 1000 e de 100 MWth.
- A intenção, para construir, era começar com os de mais baixa potência e “provar” a segurança (nuclear) para o público e gradativamente aumentar a potência térmica.
- A utilização de tório não era opção, era certeza (15 títulos com tório).

Publicações RR do IEAv.

- Apesar de se almejar demonstrar a segurança dos reatores rápidos, nunca foi elaborada uma estratégia efetiva para se chegar a esta demonstração. (Em nenhum lugar do mundo.)
- Importante observar que houve um esforço análogo no IEN, o trabalho se concentrou mais em sistemas experimentais.
- Operação de loops termo hidráulicos.
- Mas nunca houve uma sinergia entre os dois grupos.
- Houve mais uma competição nociva e destrutiva.

1º reator rápido Naval. US Navy, SSN 575 SEAWOLF.

- Utilizava um reator rápido refrigerado a sódio líquido.
- Construção iniciada em 07 de setembro de 1953.
- Lançado em 21 de Julho de 1955.
- Comissionado em 30 de Março de 1957.
- Devido a vários vazamentos de sódio em 12 de Dezembro de 1958 iniciou troca do reator para um PWR.
- Relançado em 30 de Setembro de 1960.
- A US Navy nunca mais empregou LMFR.

Decommissioned reactors

- **United States**
- Clementine was the first fast reactor, built in 1946 at Los Alamos National Laboratory. It used plutonium metal fuel, mercury coolant, achieved 25 kW thermal and used for research, especially as a fast neutron source.
- Experimental Breeder Reactor I (EBR-I) at Argonne West, now Idaho National Laboratory, near Arco, Idaho, in 1951 became the first reactor to generate significant amounts of power. Decommissioned in 1964.
- Fermi 1 near Detroit was a prototype fast breeder reactor that powered up in 1957 and shut down in 1972.
- Experimental Breeder Reactor II (EBR-II) at Idaho National Laboratory, near Arco, Idaho, was a prototype for the Integral Fast Reactor, 1965–1994.
- SEFOR in Arkansas, was a 20 MWt research reactor that operated from 1969 to 1972.
- Fast Flux Test Facility (FFTF), 400 MWt, operated flawlessly from 1982 to 1992, at Hanford Washington. It used liquid sodium drained with argon backfill under care and maintenance.
- SRE in California, was a 20 MWt, 6.5 MWe commercial reactor operated from 1957 to 1964.
- LAMPRE-1 was a molten plutonium fueled 1 MWth reactor. It operated as a research reactor from 1961-1963 at Los Alamos national Lab.

Decommissioned reactors

- **Europe**
- Dounreay Loop type Fast Reactor (DFR), 1959–1977, was a 14 MWe and Prototype Fast Reactor (PFR), 1974–1994, 250 MWe, in Caithness, in the Highland area of Scotland.
- Dounreay Pool type Fast Reactor (PFR), 1975–1994, was a 600 MWt, 234 MWe which used mixed oxide (MOX) fuel.
- Rapsodie in Cadarache, France, (20 then 40 MW) operated between 1967 and 1982.
- Superphénix, in France, 1200 MWe, closed in 1997 due to a political decision and high costs.
- Phénix, 1973, France, 233 MWe, restarted 2003 at 140 MWe for experiments on transmutation of nuclear waste for six years, ceased power generation in March 2009, though it will continue in test operation and to continue research programs by CEA until the end of 2009. Stopped in 2010.
- KNK-II, in Germany a 21 MWe experimental compact sodium-cooled fast reactor operated from Oct 1977-Aug 1991. The objective of the experiment was to eliminate nuclear waste while producing energy. There were minor sodium problems combined with public protests which resulted in the closure of the facility.

Decommissioned reactors

- **USSR/Russia**
- Small lead-cooled fast reactors were used for naval propulsion, particularly by the Soviet Navy.
- BR-5 - was a research-focused fast-neutron reactor at the Institute of Physics and Energy in Obninsk from 1959-2002.
- BN-350 was constructed by the Soviet Union in Shevchenko (today's Aqtau) on the Caspian Sea, It produced 130 MWe plus 80,000 tons of fresh water per day.
- IBR-2 - was a research focused fast-neutron reactor at the Joint Institute of Nuclear Research in Dubna (near Moscow).
- RORSATs - 33 space fast reactors were launched by the Soviet Union from 1989-1990 as part of a program known as the Radar Ocean Reconnaissance Satellite (RORSAT) in the US. Typically, the reactors produced approximately 3 kWe.
- BES-5 - was a sodium cooled space reactor launched as part of the RORSAT program which produced 5 kWe.
- BR-5 - was a 5 MWt sodium fast reactor operated by the USSR in 1961 primarily for materials testing.
- Russian Alpha 8 PbBi - was a series of lead-bismuth cooled fast reactors used aboard submarines. The submarines functioned as killer submarines, staying in harbor then attacking due to the high speeds achievable by the sub.
- The BN-600 reactor, a sodium-cooled fast reactor has been in operation since 1980 and produces power to this day.
- The BN-800 reactor, of similar design, is the largest fast reactor operating in the world today and has operated since 2016. It produces 880 MW of electrical power from 2100 MW thermal power, with a conversion efficiency of 42%.
- In November 2021, the foundation was finished for the BREST (reactor), which will be a molten lead cooled fast reactor. Operation is expected to commence in 2026.[19]

Decommissioned reactors

- **Asia**
- Monju reactor, 300 MWe, in Japan, construction 1986, first criticality April 1994, was closed in 1995 following a serious sodium leak and fire. It was restarted on May 6, 2010 but in August 2010 another accident, involving dropped machinery, shut down the reactor again. As of June 2011, the reactor had generated electricity for only one hour since its first test two decades prior.
- Aktau Reactor, 150 MWe, in Kazakhstan, was used for plutonium production, desalination, and electricity. It closed 4 years after the plant's operating license expired.

Never operated, active and under repair

- **Never operated**
- Clinch River Breeder Reactor, United States
- Integral Fast Reactor, United States. Design emphasized fuel cycle based on on-site electrolytic reprocessing. Cancelled in 1994 without construction.
- SNR-300, Germany
- **Active**
- BN-600 - a pool type sodium-cooled fast breeder reactor at the Beloyarsk Nuclear Power Station. It provides 560 MWe to the Middle Urals power grid. In operation since 1980.
- BN-800 - a sodium-cooled fast breeder reactor at the Beloyarsk Nuclear Power Station. It generates 880 MW of electrical power and started producing electricity in October 2014. It reached full power in August 2016.
- BOR-60 - a sodium-cooled reactor at the Research Institute of Atomic Reactors in Dimitrovgrad, Russia. In operation since 1968. It produces 60MW for experimental purposes.
- FBTR - a 40MWt,13.2MWe experimental reactor in India which focused on reaching significant burnup levels.
- China Experimental Fast Reactor, a 60 MWth, 20 MWe, experimental reactor which went critical in 2011 and is currently operational. It is used for materials and component research for future Chinese fast reactors.
- KiloPower/KRUSTY is a 1-10 kWe research sodium fast reactor built at Los Alamos National Laboratory. It first reach criticality in 2015 and demonstrates an application of a Stirling power cycle.
- **Under repair**
- Jōyō (常陽), 1977–1997 and 2004–2007, Japan, 140 MWt is an experimental reactor, operated as an irradiation test facility. After an incident in 2007, the reactor was suspended for repairing, recoworks were planned to be completed in 2014.[21]

Under construction

- PFBR, Kalpakkam, India, 500 MWe reactor with criticality planned for 2021. It is a sodium fast breeder reactor.
- CFR-600, China, 600 MWe.
- MBIR Multipurpose fast neutron research reactor. The Research Institute of Atomic Reactors (NIIAR) site at Dimitrovgrad in the Ulyanovsk region of western Russia, 150 MWt. Construction started in 2016 with completion scheduled for 2024.
- BREST-300, Seversk, Russia. Construction started at 8 June 2021.

Expectativa Futura

- **In design**
- BN-1200, Russia, built starting after 2014,[23] with operation planned for 2018–2020,[24] now delayed until at least 2035.[25]
- Toshiba 4S was planned to be shipped to Galena, Alaska (USA) but progress stalled (see Galena Nuclear Power Plant)
- KALIME is a 600 MWe project in South Korea, projected for 2030.[26] KALIMER is a continuation of the sodium-cooled, metal-fueled, fast-neutron reactor in a pool represented by the Advanced Burner Reactor (2006), S-PRISM (1998-present), Integral Fast Reactor (1984-1994), and EBR-II (1965-1995).
- Generation IV reactor (helium·sodium·lead cooled) US-proposed international effort, after 2030.
- JSFR, Japan, a project for a 1500 MWe reactor began in 1998, but without success.
- ASTRID, France, canceled project for a 600 MWe sodium-cooled reactor.
- Mars Atmospherically Cooled Reactor (MACR) is a 1 MWe project, planned to complete in 2033. MACR is a gas-cooled (carbon dioxide coolant) fast-neutron reactor intended to provide power to proposed Mars colonies.
- TerraPower is designing a molten salt reactor in partnership with Southern Company, Oak Ridge National Laboratory, Idaho National Laboratory, Vanderbilt University and the Electric Power Research Institute. They expect to begin testing a loop facility in 2019 and is scaling up their salt manufacturing process. Data will be used to assess thermal hydraulics and safety analysis codes.[27]
- Elysium Industries is designing a fast spectrum molten salt reactor.[28]
- ALFRED (Advanced Lead Fast Reactor European Demonstrator) is a lead cooled fast reactor demonstrator designed by Ansaldo Energia from Italy, it represents the last stage of the ELSY and LEADER projects.[29]
- **Planned**
- Future FBR, India, 600 MWe, after 2025[30]

Observações para discussão

- Apenas o caráter de engenharia não tranquiliza o público sobre a segurança nuclear.
- A segurança nuclear completa não pode ser provada.
- A invasão da Ucrânia pela Rússia gerou uma sensação de pânico com relação a segurança energética.
- Neste aspecto o risco do uso da energia nuclear parece ter sido aceito por alguns grupos, os quais não o aceitava anteriormente.
- O histórico de funcionamento dos LWR é bem melhor que o dos reatores rápidos.
- “Prove que é seguro.” Versus “É suficientemente seguro?.”
- Estamos numa bolha de momento bom para o nuclear em geral.
- Problemas do sódio continuam.
- Reator rápido precisa de Pu-239, isto implica em reciclagem. Reciclagem é proliferante.
- O Th-232 é fissionável, o U-233 é físsil. U-233 é produzido quase puro. É como trabalhar HEU, ou seja proliferante.
- As dificuldades são grandes, só unidos temos chances de superá-las.