

MAINS MASTERY 2026 · GS PAPER III · QUESTION 6 · STUDENT EDITION

Fast Breeders, Criticality and a Clean Energy Future

THE QUESTION, AS SET IN UPSC CSE MAINS 2026

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

Directive: Distinguish, Explain | 10 marks | 150 words

Science and technology: nuclear energy

1 **PYQ Deep Decode**
Demand, hidden demand, structure, form

2 **PYQ Intelligence**
2013 to 2026: nuclear power and clean energy

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Guranchal Ma'am, Founder, UPSC Gurus · upscgurus.in

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

1 PYQ Deep Decode

Read the question the way the examiner set it: the demand, the hidden demand, the structure that follows from both, and how the answer should be presented, opened and closed.

1.1 The demand

Three directives in one 10-mark question, each with its own object. First, **distinguish** a Fast Breeder Reactor from a thermal reactor: the differences must be set side by side, feature against feature. Second, **explain "criticality"**, not in the abstract but **in the context of the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam**, which attained first criticality on 6 April 2026. Third, draw out the **implications for India's clean energy future**. The marks lie in keeping the three parts distinct and in the right order, and in linking the third part to **breeding and thorium**, which is what makes a breeder different.

Words in the question	What they ask you to do	What goes wrong if you miss them
Distinguish between	Set out the differences, basis by basis: neutron energy, moderator, coolant, fuel, fissile balance, Indian examples. A table is the natural form.	Two separate descriptions that the examiner must compare for you.
Fast Breeder Reactor (FBR)	Fast neutrons, no moderator, liquid-sodium coolant, plutonium-uranium fuel, and a blanket that **breeds more fissile material than the core consumes**.	Calling it "a faster reactor" or omitting breeding, its defining feature.
thermal nuclear reactor	Neutrons slowed ("thermalised") by a moderator such as heavy or light water; India's PHWRs and the Kudankulam light-water units are examples.	Confusing "thermal reactor" with a coal-fired thermal power plant.
In the context of … prototype FBR at Kalpakkam	Anchor the definition in the event: the 500 MWe PFBR, designed by IGCAR and built by BHAVINI, reached **first criticality on 6 April 2026** after AERB clearance.	A textbook definition with no mention of the PFBR.
explain the term 'criticality'	The state in which the effective neutron multiplication factor **$k_{eff} = 1$**: the neutron population stays constant, on average, from one generation to the next, so the controlled chain reaction is self-sustaining. It is a reactor state, not a power level. Say what it proves and what it does not.	Treating criticality as an accident, or as the start of electricity supply.
its implications for clean energy future	"Its" points to the PFBR's criticality: what it means for fuel security, thorium, low-carbon baseload power and the 2047 nuclear target; a line on the conditions and challenges gives balance.	A general essay on renewable energy, or unqualified celebration.

THE DEMAND IN ONE LINE

Show, in a feature-by-feature comparison, why a fast breeder is not a thermal reactor; define criticality as $k_{eff} = 1$ through the PFBR's milestone; then show how it opens the door to fuller use of uranium and, in time, thorium for low-carbon power, and on what conditions.

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

1.2 The hidden demand

The question asks about **"first" criticality** and a **"prototype"**. Both words carry a quiet message: the reactor has proved that its core can sustain a controlled chain reaction, but it has not yet raised power, synchronised with the grid or run commercially. The clean energy future is therefore a **potential that depends on what follows**: power raising, the fast reactor fuel cycle facility that will recycle the bred plutonium, and replication in further FBRs. A strong answer shows the **promise** (breeding, thorium, low-carbon baseload) and the **conditions** (sodium safety, cost and time overruns, fuel-cycle readiness) in proportion.

Each implication should name the mechanism, the evidence, and the condition on which it depends. The last column is where the hidden demand begins.

Implication	Mechanism	What it still needs
Fuel security	U-238 in the blanket becomes Pu-239.	Reprocessing and refabrication of fuel at scale.
Thorium future	A thorium-232 blanket can breed uranium-233 for stage three.	A plutonium inventory built over years, and stage-three reactors.
Low-carbon baseload	Steady output to complement variable solar and wind.	Commercial operation and a fleet, not one prototype.

WEAK

With the PFBR attaining criticality, India has achieved energy independence and a clean energy future based on thorium is now assured.

STRONG

The PFBR's first criticality validates India's indigenous fast reactor design and begins the second stage; whether it delivers fuel security and a path to thorium depends on power raising, a closed fuel cycle and a fleet of follow-on FBRs.

1.3 The structure

The question has **three explicit parts**, in a fixed order, and the hidden demand sits inside the third as a short line on conditions and challenges. The shares are of the body between the introduction and the conclusion; they are a teaching guide, not a UPSC rule.

Introduction | **1. FBR and thermal reactor** about a third | **2. Criticality, at Kalpakkam** about a quarter | **3. Implications, and conditions** about two-fifths | **Conclusion**

Part 1 ### FBR and thermal reactor *about a third*

Neutrons, moderator	Fast, unmoderated, against thermal, moderated.
Coolant, fuel	Liquid sodium and plutonium-uranium MOX, against water and natural or enriched uranium.
Fissile balance, examples	Breeds more than it burns (PFBR), against net consumption (Kakrapar PHWRs, Kudankulam).

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Part 2 **Criticality** about a quarter

Meaning	k_{eff} = 1: neutron population steady across generations; a self-sustaining, controlled chain reaction.
At Kalpakkam	First criticality on 6 April 2026, after AERB clearance; low-power tests, power raising and grid connection follow.

Part 3 **Implications and conditions** about two-fifths

Promise	Fuller use of uranium; gateway to thorium; low-carbon baseload; closed fuel cycle; 100 GW by 2047.
Conditions	Sodium safety, cost and delay, fuel-cycle readiness.

1.4 How to present it

The form follows the question. "Distinguish between" is a comparison, so Part 1 is a **three-column table** (basis, thermal reactor, FBR): it lets the examiner read every difference in one glance. "Explain the term" is a definition with context, so Part 2 is **two crisp points**, with k = 1 stated exactly. "Implications" are a set of consequences, so Part 3 is **headed points**, closing with the conditions. A small three-stage flow (stage 1, stage 2, stage 3) is a strong addition if you draw quickly.

Form	Fit here	Reason
Table, points, headed points	**Best**	Each part gets the form its directive calls for.
Three-stage flowchart in Part 3	Good	Shows the PFBR's place at a glance; costs a few words.
Continuous paragraphs	Weak	The comparison is lost and the parts blur.

1.5 The introduction and the conclusion

The introduction serves the whole question. It places the PFBR within India's three-stage programme and names the milestone, so that the comparison, the term and the implications all follow from it.

The conclusion settles the demand. It gives a view on the clean energy future: criticality proves the concept, and commercial operation, the fuel cycle and a fleet of FBRs will decide how far the promise is realised.

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2 PYQ Intelligence 2013 to 2026

The question's context in 2026, its place in a line of questions on nuclear and clean energy, and what to prepare next.

2.1 Why the subject was topical in 2026

The PFBR at Kalpakkam attained first criticality on 6 April 2026, more than two decades after construction began, and the Government described it as the start of the second stage of India's nuclear programme. It came after the Nuclear Energy Mission of the Union Budget 2025-26 and the SHANTI Act of December 2025 had set out a larger role for nuclear power. GS Paper III was held on 23 August 2026. UPSC never states why it sets a question, so treat this as **context, not cause**. Everything in this table predates the examination.

When	What happened	Why it matters for this question
2004	Construction of the **500 MWe PFBR** begins at Kalpakkam, with completion originally targeted for 2010.	The baseline for the delay.
4 March 2024	The Prime Minister witnesses the **commencement of core loading** at the PFBR.	The first step towards criticality.
July 2024	The **Atomic Energy Regulatory Board** permits the "First Approach to Criticality": loading of fuel into the core and the start of low-power physics experiments.	The first regulatory clearance for the milestone.
16 October 2025	After issues with fuel handling during commissioning, AERB issues **fresh permission** for initial fuel loading, the first approach to criticality and low-power physics experiments; loading of fuel sub-assemblies follows (DAE, Rajya Sabha, 4 December 2025).	The clearance under which criticality was reached.
1 February 2025	Union Budget 2025-26 announces a **Nuclear Energy Mission**: ₹20,000 crore for research on Small Modular Reactors, at least five indigenously designed SMRs operational by 2033, within a target of **100 GW of nuclear capacity by 2047**.	The national ambition the PFBR feeds.
July 2025	The Minister of State for Atomic Energy tells Parliament that "first-of-a-kind" technological issues arose in the integrated commissioning of the PFBR.	Why a prototype takes time.
17 to 20 December 2025	Parliament passes the **SHANTI Bill** (Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India), and it receives Presidential assent on 20 December. The Act provides for replacing the Atomic Energy Act, 1962 and the Civil Liability for Nuclear Damage Act, 2010, for licensed private participation in power generation, and for statutory recognition of the AERB. Enrichment	The legal frame for scaling nuclear power.

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When	What happened	Why it matters for this question
	and isotopic separation, spent-fuel management and heavy-water production are reserved to the Central Government, although licensees may enrich uranium-235 up to a threshold the Government notifies; exploration of uranium and thorium stays under Government control or the conditions it sets. Its working depends on the rules and notifications made under it.	
December 2025	The Department of Atomic Energy reports **24 reactors, 8,780 MW** in operation, and a projected 22,480 MW by 2031-32 (other DAE statements put it at 22,380 MW).	The base from which 100 GW must be built.
6 April 2026	The PFBR attains **first criticality at 8:25 pm**, after meeting AERB stipulations (DAE Press Release No. 2/2026).	The event the question names.
May 2026	BHAVINI tells a Southern Regional Power Committee meeting that the reactor is in **stage-wise commissioning**, with phased power injection into the grid planned from December 2026 (as reported by DT Next).	Criticality is not yet electricity.
July 2026	The Department of Atomic Energy tells Parliament that the PFBR is being commissioned, with **full commissioning expected by March 2027** and an estimated completion cost of ₹8,181 crore (as reported). This is a projection, not grid synchronisation or commercial operation.	An official timeline stated before the examination; still a projection.

2.2 The skill UPSC keeps testing

The closest precedents are 2013, 2017, 2018 and 2025: raw materials for atomic energy, the advantage of the fast breeder programme, the facts and fears of nuclear power, and the implications of a new energy technology. Questions are verbatim.

Year	The question as UPSC set it	What it asked of you	What changed in 2026
2013 GS I · Q24 10 marks	With growing scarcity of fossil fuels, the atomic energy is gaining more and more significance in India. Discuss the availability of raw material required for the generation of atomic energy in India and in the world.	Uranium and thorium resources.	The resource case now meets the reactor that unlocks it.
2017 GS III · Q16 15 marks	Give an account of the growth and development of nuclear science and technology in India. What is the advantage of fast breeder reactor programme in India ?	The FBR's advantage, within the programme's history.	The closest precedent: the advantage is now tested by a real milestone.
2018 GS III ·	With growing energy needs should India keep on expanding its nuclear energy programme?	A balanced view of nuclear power.	The balance now sits inside Part 3, as conditions.

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Year	The question as UPSC set it	What it asked of you	What changed in 2026
Q16 15 marks	Discuss the facts and fears associated with nuclear energy.		
2025 GS III · Q5 10 marks	The fusion energy programme in India has steadily evolved over the past few decades. Mention India's contributions to the international fusion energy project — International Thermonuclear Experimental Reactor (ITER). What will be the implications of the success of this project for the future of global energy ?	A technology, then its implications for energy.	The same "implications" demand, now for fission and for India.
2025 GS III · Q6 10 marks	How can India achieve energy independence through clean technology by 2047 ? How can biotechnology can play a crucial role in this endeavour ?	Clean technology and the 2047 horizon.	Nuclear breeding as one path to that goal.
2026 GS III · Q11 15 marks	Related question in the same paper: Explain the key challenges for India's energy security. What measures do you suggest for ensuring energy security along with economic growth and sustainability ?	Energy security as a whole.	Q6 supplies one measure in depth: the second stage.

Also related, verbatim: 2022, GS III Q12 (15 marks): "Do you think India will meet 50 percent of its energy needs from renewable energy by 2030 ? Justify your answer. How will the shift of subsidies from fossil fuels to renewables help achieve the above objective ? Explain."

CARRY THIS METHOD TO ANY "DISTINGUISH, EXPLAIN, IMPLICATIONS" QUESTION

1. **Compare** in a table, basis by basis.
2. **Define** the term exactly, then anchor it in the named event.
3. **Say what the event proves**, and what it does not yet prove.
4. **Give implications** through their mechanisms.
5. **End with** the conditions that decide the outcome.

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2.3 What to prepare next

INSTITUTIONS AND FACILITIES

IGCAR	Indira Gandhi Centre for Atomic Research, Kalpakkam: designs India's fast reactors; runs the Fast Breeder Test Reactor.
BHAVINI	Bharatiya Nabhikiya Vidyut Nigam Ltd, a DAE public sector undertaking: builds and commissions the PFBR.
AERB	India's nuclear and radiation safety regulator, set up in 1983 by government order; the SHANTI Act, 2025 provides for its statutory recognition.
Fast Reactor Fuel Cycle Facility	Under construction at Kalpakkam to reprocess FBR fuel and recover bred plutonium.

IDEAS

Breeding	Producing more fissile material than is consumed.
Closed fuel cycle	Reprocessing spent fuel to recycle plutonium and uranium, rather than treating it all as waste.
Small Modular Reactors	Factory-built reactors of smaller size; the focus of the Nuclear Energy Mission.
Baseload	Steady, round-the-clock supply that complements variable solar and wind.

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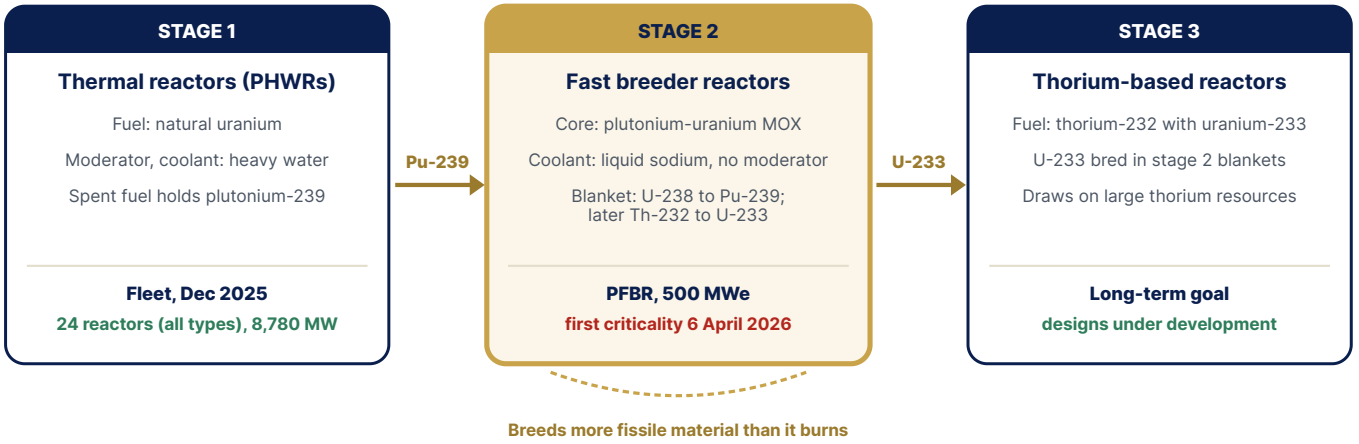
3 Additional information

Everything needed to answer this question well. Tier 1 holds what the demand needs; Tier 2 places it within the wider debate on nuclear power and clean energy.

TIER 1 · ESSENTIAL: THE COMPARISON, THE TERM AND THE IMPLICATIONS

Where the PFBR sits, and what criticality means

INDIA'S THREE-STAGE NUCLEAR POWER PROGRAMME: WHERE THE PFBR STANDS



WHAT "CRITICALITY" MEANS: THE EFFECTIVE MULTIPLICATION FACTOR, k-eff

k < 1 — Subcritical	k = 1 — Critical	k > 1 — Supercritical
Each generation of neutrons is smaller; the chain reaction dies away	Each neutron generation replaces the last; self-sustaining, steady, controlled	Neutron population grows; operators use it briefly to raise power, then return to 1

First criticality shows the core sustains the chain reaction; power raising, grid synchronisation and commercial operation come later

A teaching diagram. Stage 1 also includes India's light-water reactors at Tarapur and Kudankulam within the operating fleet; the fleet figure is from the Department of Atomic Energy (Rajya Sabha, 4 December 2025). The PFBR's blanket begins with uranium-238; DAE says it is designed eventually to use thorium-232. Sources: DAE Press Release No. 2/2026; AERB (July 2024).

Basis	Thermal reactor (conventional power reactors)	Fast Breeder Reactor (the Indian PFBR as the main example)
PART 1: THE DISTINCTION		
Neutron energy	Fission neutrons (born at about 2 MeV on average) are slowed to thermal energies, about 0.025 eV, where uranium-235 fissions most readily.	Neutrons stay **fast**; at high energy, plutonium-239 releases more neutrons per neutron absorbed, leaving a surplus for breeding.
Moderator	Needed: heavy water in PHWRs, light water in Kudankulam's VVERs.	**None**; a moderator would defeat the purpose.
Coolant	Heavy or light water, under high pressure.	The PFBR uses **liquid sodium**: excellent heat transfer, little moderation, and a high boiling point that allows near-atmospheric pressure. Sodium is the most common fast-reactor coolant but not the only one; other designs use lead, lead-bismuth or gas. The PFBR is a pool-type design: core, pumps

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

Basis	Thermal reactor (conventional power reactors)	Fast Breeder Reactor (the Indian PFBR as the main example)
		and heat exchangers sit in one main vessel holding about 1,150 tonnes of sodium.
Fuel	Natural uranium (PHWRs) or enriched uranium (light-water reactors).	**Plutonium-uranium mixed oxide (MOX)** in the PFBR core, with plutonium recovered from stage-1 spent fuel. Other fast reactors use metallic, carbide (as in India's FBTR) or nitride fuel.
Fissile balance	Conventional thermal power reactors, including India's PHWRs and light-water reactors, convert some U-238 to plutonium but are **net consumers of fissile material**. Thermal breeding is not physically impossible (for instance with thorium and U-233), but these reactors are not designed for it.	**Breeds**: a uranium-238 blanket becomes plutonium-239, so it **produces more fissile material than it consumes**.
Core and power	Larger, lower power density.	Compact core of high power density; demanding materials such as 316LN stainless steel, made in India for the PFBR.
Indian examples	PHWRs at Kakrapar, Rawatbhata, Kaiga; VVERs at Kudankulam; BWRs at Tarapur.	Fast Breeder Test Reactor (first criticality 18 October 1985; 40 MWt; mixed carbide fuel); **PFBR, 500 MWe**.
PART 2: CRITICALITY, AT KALPAKKAM		
The term	A reactor is **critical** when the effective neutron multiplication factor $\mathbf{k_{eff} = 1}$: the neutron population is maintained, on average, from one generation to the next (neutrons born in fission, less those absorbed without fission or leaking out, exactly replace the previous generation), so the chain reaction is **self-sustaining and steady**. At $k_{eff} < 1$ it is subcritical and dies away; at $k_{eff} > 1$ it is supercritical and grows. Control rods hold k_{eff} at 1. Criticality is a **state, not a power level**: a reactor can be critical at very low power.	
"First approach"	Fuel sub-assemblies are loaded in steps and control rods withdrawn slowly while neutron counts are watched, until the chain reaction sustains itself. AERB first permitted this stage in July 2024, and, after fuel-handling issues, issued fresh permission on 16 October 2025 for initial fuel loading, the first approach to criticality and low-power physics experiments.	
At the PFBR	**6 April 2026, 8:25 pm**: first criticality, after AERB clearance. Designed by IGCAR, built by BHAVINI; MOX core, uranium-238 blanket, liquid-sodium coolant; design life 40 years. More than 200 Indian industries, including MSMEs, contributed.	
What it proves	That the indigenous core design, fuel and control systems sustain a controlled chain reaction as designed. It does not yet prove power operation, breeding performance or economics: low-power experiments, power raising, grid connection and AERB approval for commercial operation follow.	
PART 3: IMPLICATIONS FOR THE CLEAN ENERGY FUTURE		
Fuel security	Breeding extracts far more energy from India's modest uranium; the PM said the reactor will help "obviate the need for nuclear fuel import".	
Gateway to thorium	A thorium-232 blanket can breed uranium-233 for the third stage. India's monazite was estimated in 2014 to hold about 1.07 million tonnes of thorium oxide (Atomic Minerals Directorate), among the largest thorium resources in the world. Thorium is not fissile by itself, so stage two must first build up fissile inventory.	
Low-carbon baseload	Nuclear plants generated 56,681 million units in 2024-25, about 3% of India's electricity. They supply low-carbon, round-the-clock power that complements solar and wind, while the Government targets 100 GW of nuclear **capacity** by 2047 and net zero emissions by 2070.	

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Basis	Thermal reactor (conventional power reactors)	Fast Breeder Reactor (the Indian PFBR as the main example)
Closed fuel cycle	Reprocessing recovers reusable uranium and plutonium, improving fuel use and reducing the volume of high-level waste needing final disposal; DAE describes the three-stage programme as built on a closed fuel cycle. It does not eliminate waste: reprocessing produces streams that must be conditioned, stored securely and disposed of.	
Indigenous capability	The Government has approved pre-project activities for two further 500 MWe FBRs at Kalpakkam, replicating the PFBR design and using indigenous fuel.	
Conditions and challenges	Sodium burns in air and reacts violently with water, so leaks need strict design control; the originally sanctioned cost was ₹3,492 crore, against an estimated completion cost of ₹8,181 crore reported in 2026; criticality came about 16 years after the 2010 target; the fuel cycle facility is still under construction.	

Why fast neutrons breed. Plutonium-239 fissioned by fast neutrons releases more neutrons per neutron absorbed than with thermal neutrons. One neutron sustains the chain, some are lost, and the surplus converts U-238 in the blanket: U-238 + n → U-239 → Np-239 → Pu-239. With thorium: Th-232 + n → Th-233 → Pa-233 → U-233.

Criticality is not danger. In everyday speech "critical" sounds alarming; in reactor physics it is the normal operating state. Every power reactor runs at $k_{eff} = 1$. The danger lies in uncontrolled supercriticality, which control rods and inherent feedbacks are designed to prevent.

TIER 2 · EXTENDED UNDERSTANDING: THE WHOLE TOPIC AROUND IT

The case for the second stage

1. **Resource logic:** modest uranium, large thorium; breeders bridge them.
2. **Self-reliance:** design, components and fuel developed in India, partly under technology-denial regimes.
3. **Policy support:** Nuclear Energy Mission, SHANTI Act, 100 GW by 2047.
4. **Global standing:** the Government says India becomes the second country, after Russia, to run a commercial fast breeder once the PFBR is fully operational.

The cautions

1. **Sodium:** fires and sodium-water reactions; Japan's Monju was halted after a sodium leak in 1995.
2. **Time and cost:** about 16 years late; cost more than doubled.
3. **Fuel cycle:** breeding pays off only when bred plutonium is reprocessed and reused.
4. **Slow growth:** fast breeders add fissile stock gradually, so a thorium power fleet remains long-term. India has used U-233 at research scale: the 30 kWt KAMINI reactor at Kalpakkam (critical in 1996) runs on U-233 bred from thorium.

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Two debates worth knowing

Breeders, or more PHWRs, SMRs and renewables?

One view: proven PHWRs, Small Modular Reactors and cheaper solar with storage give faster, cheaper decarbonisation. The other: without breeders India's uranium supports only a limited fleet, and thorium stays out of reach. The balanced reading: **a portfolio**, in which breeders secure the long-term fuel base while PHWRs, SMRs and renewables meet near-term needs.

Private capital under the SHANTI Act: speed or risk?

Supporters say licensed private and joint-venture participation can mobilise the capital that 100 GW requires. Critics worry about liability, safety culture and regulatory capacity. The balanced reading: **scale with a strong, independent regulator**, while sensitive activities stay under Government control.

4 Pitfalls and variations

The mistakes that cost marks here, the claims never to make, and how the answer changes when the question changes.

4.1 Six pitfalls, each with its correction

Description, not distinction

~~A paragraph on each reactor.~~

A table: basis, thermal reactor, FBR.

"Thermal" misread

~~Thermal reactor means a coal power plant.~~

Thermal refers to slow neutrons, moderated by water or heavy water.

No k = 1

~~Criticality is when the reactor starts working.~~

k_{eff} = 1: successive neutron generations remain equal on average, sustaining a controlled chain reaction.

No Kalpakkam

~~A textbook definition only.~~

Name the PFBR, 500 MWe, first criticality on 6 April 2026, after AERB clearance.

Criticality as electricity

~~The PFBR now supplies 500 MW to the grid.~~

Power raising and grid connection follow first criticality.

Only celebration

~~Thorium will now power India.~~

Add the conditions: fuel cycle, sodium safety, cost and delay, fleet replication.

4.2 Never write these

- "FBRs need no fuel" or "create energy from nothing."
  They convert fertile U-238 into fissile Pu-239; the fuel is still consumed.
- "FBRs use thorium as fuel today."
  The PFBR core is MOX with a U-238 blanket; thorium blankets are a later design aim.

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- "Criticality means a nuclear accident."
  It is the normal, controlled state of an operating reactor.
- "The PFBR is cooled by water."
  It is cooled by liquid sodium; water would moderate the neutrons.
- "India's first fast reactor is the PFBR."
  The Fast Breeder Test Reactor reached criticality in 1985; the PFBR is the first prototype at power-plant scale.
- "Nuclear power is a large share of India's electricity."
  About 3% in 2024-25.

4.3 If the question changes

If it asks	The structure becomes	What must change
The **three-stage programme**	Resource logic; each stage's reactor, fuel and output; status	The flow becomes the spine.
Critically examine nuclear power for net zero	Merits; risks (safety, waste, cost); role in the mix; view	Balance, not one reactor.
The **SHANTI Act** or private participation	Old law; new provisions; benefits; concerns	Law and governance at the centre.
The same question for **15 marks**	Add the three-stage diagram and the breeding equation	Room for mechanism and debate.

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5

The model answer

One model answer, written to the 150-word limit, in the form this question calls for: a comparison table, two points on criticality anchored in the PFBR, and headed points on implications with their conditions. The introduction covers the whole question; the conclusion settles its demand.

Model answer ## Comparison table, then points

153 words

Kalpakkam's 500 MWe PFBR reached first criticality on 6 April 2026, opening stage two of India's thorium-oriented three-stage nuclear programme.

1. Thermal reactor versus FBR

Basis	Thermal	FBR (PFBR)
Neutrons	Moderated, slow	Fast, unmoderated
Coolant	Water or heavy water	Liquid sodium
Fuel	Natural or enriched uranium	Plutonium-uranium MOX
Fissile balance	Generally net consumer	Designed to breed surplus
Example	Kakrapar PHWRs	Kalpakkam PFBR

2. Criticality

- $k_{eff} = 1$: each neutron generation replaces the last, sustaining a controlled chain reaction.
- PFBR's AERB-cleared criticality validates its core, not grid supply or proven breeding.

3. Clean-energy implications

- **Fuel security:** U-238 breeds Pu-239, multiplying uranium utilisation.
- **Thorium bridge:** Th-232 blankets can later yield U-233.
- **Low-carbon baseload:** complements renewables towards 100 GW nuclear capacity by 2047.
- **Closed cycle:** reprocessing recovers fuel, though radioactive waste remains.
- **Constraints:** sodium safety, costs, reprocessing readiness, delays.

Criticality proves the concept; commercial operation, demonstrated breeding, reprocessing and follow-on FBRs will decide whether thorium-powered clean energy future materialises.

DEMAND
A basis-by-basis distinction, criticality defined through the PFBR, then implications through their mechanisms

HIDDEN DEMAND
First criticality proves the concept, not power; the promise depends on the fuel cycle, safety, cost and a fleet

STRUCTURE
About a third, a quarter, and two-fifths, with conditions inside Part 3

BALANCE
Introduction 20 words, conclusion 20 words; 153 words in all

Why it works: the introduction places the PFBR in the three-stage programme and names the milestone, so all three parts follow from it; the table distinguishes basis by basis; criticality is defined exactly ($k_{eff} = 1$) and tied to Kalpakkam, with what comes next; each implication names its mechanism; the challenges answer the hidden demand; the conclusion gives a view.

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

6 Other ways to write it

The model answer above remains the answer. These outlines show how a different, equally valid answer could be built, and when each choice works.

Approach	How it is built	When it works
Three-stage flow answer	Part 3 opens with a three-box flow (PHWR, FBR, thorium reactor) with the PFBR marked, then two lines of implications.	When you draw quickly and neatly.
k-strip for Part 2	A small strip: k < 1 subcritical, k = 1 critical, k > 1 supercritical, with the PFBR at k = 1.	When a visual saves words.
Open with the resource gap	Introduction: modest uranium, large thorium; the breeder is the bridge. Then the three parts.	When you want a purposeful start.
For 15 marks	Add the breeding equations, the SHANTI Act and the portfolio debate.	When there is room.

7 Quick recall and Prelims crossover

Facts for rapid revision and Prelims.

1	PFBR first criticality: **6 April 2026**, 8:25 pm.	9	Criticality: $\mathbf{k_{eff} = 1}$; subcritical below, supercritical above.
2	PFBR: **500 MWe**; designed by **IGCAR**, built by **BHAVINI**.	10	Operating fleet: **24** reactors, **8,780 MW** (December 2025).
3	Core loading began: **4 March 2024**, in the PM's presence.	11	Nuclear share of electricity: about **3%** (2024-25).
4	AERB permission for first approach to criticality: **July 2024**; fresh permission **16 October 2025**.	12	Nuclear Energy Mission: **₹20,000 crore** for SMRs; **5** SMRs by **2033**.
5	Construction began **2004**; original target **2010**.	13	Nuclear capacity target: **100 GW** by **2047**.
6	Cost: **₹3,492 crore** originally sanctioned; **₹8,181 crore** estimated completion cost.	14	**SHANTI Act, 2025**: assent **20 December 2025**; provides for replacing the Atomic Energy Act, 1962 and CLNDA, 2010.
7	PFBR: **MOX** core, **U-238** blanket, **sodium** coolant, pool type.	15	Thorium: about **1.07 million tonnes** ThO_2 in monazite (AMD, 2014).
8	**FBTR**: first criticality **18 October 1985**; **40 MWt**; carbide fuel.	16	Projected capacity by **2031-32**: **22,480 MW** (DAE, December 2025; other DAE statements give 22,380 MW).

THE ONE SENTENCE TO CARRY OUT OF THIS DOCUMENT

Criticality at Kalpakkam is the moment a reactor first kept its own fire alight; the clean energy future depends on turning that steady flame into a fleet that breeds its own fuel.

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

8 Write it yourself

Write the answer in 150 words without looking back, then check it against each line below.

	Check	Yes / No
1	Does the introduction place the PFBR within the **three-stage programme**?	
2	Is the distinction a **comparison**, basis by basis, with Indian examples?	
3	Is criticality defined as **$k_{eff} = 1$**, a self-sustaining controlled chain reaction?	
4	Is the definition anchored in the **PFBR's first criticality** (6 April 2026), with what follows?	
5	Does each implication name its **mechanism** (breeding, thorium, baseload, fuel cycle)?	
6	Are the **conditions and challenges** named, and does the conclusion give a view at about the length of the introduction?	
7	Is it **150 words or a little over**, with no claim from section 4.2?	

Sources

- Department of Atomic Energy: Press Release No. 2/2026, first criticality of the 500 MWe PFBR (7 April 2026); Rajya Sabha Starred Question No. 52 and Unstarred Questions No. 482 (PFBR milestones, including AERB's permission of 16 October 2025) and No. 488 (4 December 2025); Lok Sabha Unstarred Question No. 795 (4 February 2026); Lok Sabha Unstarred Question No. 2830 on thorium (10 December 2014); parliamentary reply of July 2026 on PFBR commissioning and cost, as reported by News Karnataka (1 October 2026).
- Prime Minister's Office: PM witnesses commencement of core loading at Kalpakkam (4 March 2024).
- Atomic Energy Regulatory Board: initial permission for the First Approach to Criticality of the PFBR (statement of 27 July 2024, as reported by World Nuclear News, 1 August 2024); fresh permission of 16 October 2025, recorded in DAE's Rajya Sabha reply of 4 December 2025 and reported by The Federal (April 2026). Norton Rose Fulbright: summary of the SHANTI Act, 2025 (reserved activities).
- Press Information Bureau: Nuclear Energy Mission in the Union Budget 2025-26 (5 February 2025).
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- IGCAR: Fast Breeder Test Reactor, 40 years of first criticality (October 2025, as reported); KAMINI, the U-233 research reactor at Kalpakkam.
- Nuclear Engineering International: Criticality for India's PFBR (April 2026); American Nuclear Society, Nuclear Newswire (April 2026); International Panel on Fissile Materials blog (April 2026); DT Next (27 May 2026); Down To Earth (April 2026).
- UPSC Civil Services (Main): GS Paper I 2013; GS Paper III 2017, 2018, 2022, 2025 and 2026. Official question papers.

Distinguish between a Fast Breeder Reactor (FBR) and a thermal nuclear reactor. In the context of first indigenously developed prototype FBR at Kalpakkam, explain the term 'criticality'. What are its implications for clean energy future of our country ?

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3 Have the paper evaluated

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