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A History of India's Heavy Water Production

In the 1960s India embarked on a nuclear power program employing reactors based on the design of Canada's heavy water moderated CANDU reactors.[2] Most of the other power reactors in the world use light (ordinary) water as the moderator but these reactors use large pressure vessels which would have been difficult to manufacture in India. Also heavy water moderated reactors can use natural uranium as fuel and as a result India would not have to import enriched uranium from the United States, allowing India to keep the reactors outside of the International Atomic Energy Agency's (IAEA) safeguards system. Therefore they could be and have been used to support India's nuclear weapon program.

However, to make this scheme work, India would need to provide the heavy water for its reactors. It is generally known that India's heavy water production efforts in the 1970s and 1980s performed rather poorly and as a result India faced serious heavy water shortages. It is also generally known that since the 1990s India has not only been able to meet all of its heavy water needs but India also exports heavy water. India is now the largest heavy water producer in the world.

While this general outline of India's heavy water program is known, producing a more specific history is difficult. India's Department of Atomic Energy (DAE) and its associated Heavy Water Board (HWB) have not provided aggregate annual heavy water production figures, let alone production figures for specific plants, for over forty years. Nor have they provided accurate cost data even to the Indian government.

More serious than the lack of published production figures are the numerous misleading and false statements made by the DAE about the heavy water production program. While the ostensible reason given by the DAE for these statements is the strategic nature of its heavy water program, it appears these statements are at least partially designed to deflect internal criticism of the program.

As will be discussed in this paper, one of the more striking examples is India's Talcher heavy water plant. This plant was purchased from a West German consortium and was supposed to start operation in 1976. The construction was seriously delayed and the plant was not physically completed until 1979 and the potassium amide catalyst needed to produce heavy water was not introduced into the plant until 1981. The plant contained serious design flaws and was never able to produce any nuclear-grade heavy water. Nevertheless the HWB's website currently states that the plant was commissioned in 1978 (when it was still under construction) and operated until 1994 when it was forced to stop production only due to problems with the

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[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation and a faculty member of the Pardee RAND Graduate School, this paper is not related to any RAND project or the Pardee RAND Graduate School and therefore these organizations should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] For an explanation of what heavy water is, see Appendix 1.

associated fertilizer plant that provided hydrogen to Talcher.[3] This plant is still listed on the HWB's website as not being shut down.[4]

However, over time some revealing details have emerged regarding India's heavy water production program. One key source is the Indian scientists themselves. Proud that they have slowly overcome the many problems that faced them, they needed to explain what the problems were in order to describe how they solved them.

I have constructed an account of India's heavy water production effort using key details that have emerged over the past thirty years. Given the lack of specific production information and economic data, this account, of necessity, must be broad brush. Nevertheless, a number of important conclusions can be drawn.

My account helps confirm and reinforce analysis from the 1980s which showed that India could not have provided the heavy water needed for the Madras 1 and Madras 2 nuclear power reactors and the Dhruva plutonium production reactor. India must have acquired this heavy water (amounting to roughly 350 metric tons) from some illicit source or sources.

The paper helps confirm and reinforce economic analysis showing that the cost of the heavy water production in India must have been and is heavily subsidized, which in turn represents a major subsidy for the entire Indian nuclear program.

Finally the paper shows that India's current success in producing heavy water has a serious downside, namely overproduction. India has accumulated a heavy water stockpile of over 4,000 metric tons which will grow to over 5,000 metric tons by 2020. The carrying charge on this expensive material must be substantial and could increase the cost of the heavy water by 50% to 100%.

This paper will first place India's heavy water production problems in context by describing two general problems faced by India. The paper will then provide a history of India's heavy water production effort, followed by conclusions. Appendix 1 provides technical information on what heavy water is and the various means for producing heavy water. Appendix 2 provides a detailed history of each of India's eight heavy water plants.

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[3] This is a common DAE tactic to blame problems on organizations outside of the DAE. See: Heavy Water Board, Department of Atomic Energy, Government of India. Link

[4] Similar DAE behavior is found in India's nuclear power program. The Rajasthan 1 reactor has been shut down for over two decades. In 1993 the reactor was officially taken over by the government so that the Indian Nuclear Power Corporation would not have to keep taking the financial losses associated with this reactor. Yet the reactor is still on India's list of nuclear power reactors.

Two General Heavy Water Production Problems Facing India

The history of India's heavy water production is driven by two general problems that confronted India that were not specific to any particular heavy water production process. First, India needed to try to produce the heavy water as needed, having neither too much capacity nor too little. This is a problem facing any country wanting to build heavy water power reactors. It is serious enough to call into question the economic viability of any nuclear power program based on heavy water. Second, the equilibrium time of heavy water production processes is long compared to other industrial processes and there is a need for long periods of uninterrupted operation. This was a particular problem for India in the 1970s and 1980s.

Matching Heavy Water Production to Demand

Heavy water is an expensive commodity and as best as is possible, the production should be matched to the demand. However, this is difficult since for any reactor most of the demand for heavy water occurs only once. When a heavy water reactor starts operation, a large amount of heavy water must be supplied to provide the water needed for both the reactor's moderator and coolant. After the reactor has started it only needs enough heavy water to make up for the amount lost during the reactor's operation which is only about one to three percent of the reactor's heavy water inventory per year. For example, for the small 200 MWe nuclear power plants that India built in the 1980s, 1990s and 2000s, each reactor required an initial heavy water inventory of 250 metric tons. Yet only 3 to 8 metric tons of heavy water per year would be needed by the reactor once it started operation.

Assume that two percent of the heavy water is lost each year. If one wants to build a heavy water plant to supply a single heavy water moderated nuclear power reactor, how large should the annual heavy water production be? To match the long-term heavy water demand, the heavy water production plant should only produce two percent of the reactor's total inventory each year. However, at this production rate, to provide the heavy water needed for the reactor's startup, the heavy water plant would need to start producing heavy water 50 years before the reactor started operation. It would be very difficult to plan that far in advance. Further, building a heavy water production plant with a small annual output would lack economies of scale. Instead, plants with a much larger heavy water production capacity are built. If one built a production plant that produced about 20% of the reactor's inventory each year, then the plant would only have to start operation five years in advance of the reactor. But then once the reactor started operation, the plant would be producing ten times too much heavy water.

The way that nuclear planners expected to avoid this problem was to continue building new reactors. Continuing large-scale heavy water production would be needed to supply the initial heavy water inventory for each new reactor. However, Canada's experience shows how difficult it can be in practice to match supply and demand.

Canada's first attempt to build a heavy water plant in the 1960s was a total failure. It used the dual temperature water-hydrogen sulfide exchange process that the U.S. had developed and used in its plant at Savannah River, South Carolina. However, when Canada attempted to build a similar plant at Glace Bay, Nova Scotia, which is a coastal site, the design did not sufficiently compensate for the corrosive properties of salt water. The plant had to be torn down and completely rebuilt. Canada's second attempt at Port Hawkesbury got off to a slow start as there was difficulty scaling up and optimizing the U.S. heavy water production technology.[5] Only the fact that the U.S. had surplus supplies of heavy water to export prevented Canadian reactors from sitting idle from lack of heavy water.

In the 1970s there were very large overestimates of the demand for nuclear power. This combined with the fact that its heavy water production plants initially performed poorly, led Canada to plan to build a total of nine heavy water production plants with a combined nominal capacity of about 6,400 metric tons per year. Only four plants with an annual capacity of about 2,400 metric tons per year were actually built.[6] Two additional plants started construction but were never completed as it became apparent that the demand for nuclear power and thereby heavy water was far less than anticipated. These two plants, which were 70% and 40% completed, were instead torn down.[7] Even the production of four plants was far too much and Canada accumulated large inventories of heavy water. In the mid-1980s Canada shut down three of these four plants and in 1997 the last of these four plants was shut down. Each of the four plants operated for less than twenty years.[8] Canada, which at one time was the largest heavy water producer in the world, now no longer produces heavy water.

Argentina had a similar experience but on a smaller scale. It began building the Arroyito heavy water production plant in the 1980s. It is based on the mono-thermal ammonia-hydrogen exchange process and has an annual capacity of 200 metric tons per year. It was built to provide the 600 metric tons of heavy water required to start the Atucha II nuclear power reactor as well as additional planned heavy water power reactors. Argentina planned to start operation of Atucha II in the mid-1980s but in fact it did not start operation until 2014. No other heavy water reactors have been built in Argentina. The Arroyito plant only started operation in 1994. It has generally operated only intermittently and at reduced capacity, to produce the small amounts of make-up heavy water needed for Argentina's other two operating heavy water power reactors, as well as small amounts for export.

As will be discussed below, at the beginning of India's nuclear program the poor performance of its heavy water production plants meant that it did not have enough heavy water to supply its new nuclear reactors. India could have imported heavy water but this would have required placing the reactors under IAEA safeguards. Instead the reactors sat idle. In the 1990s India began to produce a surplus of heavy water. It managed to export some heavy water, but India has acquired a great excess inventory of heavy water. This inventory will grow over at least the next several years again showing the difficulty of matching heavy water supply and demand. Realistically, the DAE should shut down several of its heavy water plants to curtail the excess production but in the past it has proved reluctant to take this step. Instead, the DAE has not only kept its current heavy water production plants operating but has also proposed restarting heavy water production at one of its plants (Tuticorin).

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[5] M.R. Galley and A.R. Bancroft, "Canadian Heavy Water Production-1970 to 1980," AECL-7429, Atomic Energy of Canada Limited, October 1981.
[6] Glace Bay, Port Hawkesbury, Bruce A and Bruce B.
[7] Bruce D and LaPrade respectively.
[8] Glace Bay operated for only nine years, Bruce A eleven years, Port Hawkesbury fifteen years and Bruce B eighteen years.

Need for Uninterrupted Power Supplies

A 1980 report makes clear the need for uninterrupted electrical and steam supplies for heavy water production plants.[9] It said:

> Reliability of steam and electrical energy supplies is another very important consideration. The in-process inventory in a heavy water plant relative to the production rate is large compared to most other chemical process industries. As a result, heavy water plants are particularly slow to come to equilibrium following a perturbation which causes departure from an equilibrium or steady-state operation. Even brief interruptions in steam or electricity supply can result in disproportionately large reductions in productivity.

The equilibrium time for the plants in India is on the order of a week to a month. In the 1970s and 1980s India's electrical grid could not reliably provide power for this length of time, which was a major reason for the poor performance of its early heavy water plants. This problem is only exacerbated for heavy water plants which rely on hydrogen produced by an associated fertilizer plant. Any disruption of the operation of the fertilizer plant disrupts the operation of the heavy water plant. Only when India took steps to deal with the unreliable electrical grid and the supply of hydrogen from fertilizer plants did its heavy water production plants operate much more efficiently.

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[9] *Fuel and Heavy Water Availability*, International Nuclear Fuel Cycle Evaluation, International Atomic Energy Agency, Vienna, 1980, pp. 206-207.

History of India's Heavy Water Production and Demand

India has had eight heavy water production plants. They are listed in Table 1. Detailed descriptions of the plants and their operating histories are provided in Appendix 2.

India first needed large amounts of heavy water for the Canadian provided research/plutonium production reactor CIRUS. This reactor started operation in 1960 and required about 20 metric tons of heavy water for its moderator. The U.S. provided the heavy water for this reactor and as of the end of 1963 had provided over 32 metric tons of heavy water to India.[10] This heavy water was provided to India under the condition that it would be used for peaceful uses only. India violated this pledge in 1974 when it used plutonium from CIRUS to conduct a nuclear weapon test.

In the late 1950s, India purchased a heavy water production plant (Nangal) from a U.S. company. The plant used a West German provided hydrogen distillation process and began sustained production in 1962. It had an annual production rate of 14 metric tons per year and apparently produced at close to its capacity into the 1970s.

In 1964, Canada agreed to build the Rajasthan 1 reactor. It had a design similar to that of the CANDU prototype being built in Canada (Douglas Point). The reactor had a net power output of 200 MWe. The 250 metric tons of heavy water needed to start this reactor was provided by Canada. However, due to the failure of the Canadian heavy water plant at Glace Bay and the slow start of its Port Hawkesbury plant, much of this heavy water actually originated in the U.S.

In 1967 the Rajasthan project was expanded to a second reactor and India also planned to build four more reactors of the Douglas Point design, two near Madras (MAPP 1 & 2) and two at Narora using indigenous resources. In the late 1960s and early 1970s, India decided to build four heavy water production plants to provide the heavy water for these reactors. India chose three different heavy water production technologies.

At that time the only proven process for producing large amounts of heavy water was dual temperature water-hydrogen sulfide exchange. This process was first developed and deployed in the U.S. Canada was building several large heavy water plants that would use this process. The DAE had studied the published information on this process for many years and conducted its own experiments. The DAE decided to build its own heavy water plant (Kota) based on this process. India would provide the engineering, design details and perform the construction. To take advantage of excess steam produced by the Rajasthan 1 nuclear power plant, the plant was located adjacent to this reactor.[11] Kota was designed to produce 100 metric tons per year.

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[10] W. P. Bebbington, J. F. Proctor, W. C. Scotten and V. R. Thayer, "Production of heavy water in the United States," *Proceeding of the Third International Conference on the Peaceful Uses of Atomic Energy,* Held in Geneva, Switzerland, August 31 to September 9, 1964. Volume 12, Nuclear Fuels-III, Raw Materials, United Nations, New York, 1965, p. 335.

[11] S. Fareeduddin, "Production of Heavy Water in India," Bhabha Atomic Research Centre, 1973.

Table 1

Indian Heavy Water Plants

Name	Process	Design Capacity Metric Tons per Year	Actual Capacity Metric Tons per Year	Year Started Production	Currently Producing Heavy Water	Permanently Shutdown
Nangal	Hydrogen Distillation	14	14 declining to 7	1962	No	Yes
Tuticorin	M/T* Ammonia-Hydrogen Exchange	71	49	1978	No	No, in Long-Term Preservation
Baroda	M/T Ammonia-Hydrogen Exchange	67	45	1980	No	No
Kota	D/T Water-Hydrogen Sulfide Exchange	100	80	1987	Yes	No
Talcher	D/T Ammonia-Hydrogen Exchange	63	0	Never	No	No, Producing Solvents
Thal	M/T Ammonia-Hydrogen Exchange	110	78	1987	Yes	No
Manuguru	D/T Water-Hydrogen Sulfide Exchange	185	200	1991	Yes	No
Hazira	D/T Ammonia-Hydrogen Sulfide Exchange	110	80	1991	Yes	No

*M/T = mono-thermal, D/T = dual temperature.

The other three plants would be provided by foreign vendors. The M-S Gelpa European consortium would provide two plants using French mono-thermal ammonia-hydrogen exchange technology. The Baroda plant would have an annual production capacity of 67 metric tons and the Tuticorin plant would have an annual production capacity of 71 metric tons. The West German company Friedrich Uhde GmbH would build a plant at Talcher using the dual temperature ammonia-hydrogen exchange process. Its annual production capacity would be 63 metric tons per year. These four plants were scheduled to start operation between 1973 and 1976. Their production, combined with that from Nangal, would give India a nominal annual heavy water production capacity of 315 metric tons per year. This would be more than enough heavy water to start one reactor a year if need be.

The heavy water program based on these five plants initially performed very poorly. Only one of the four new plants, Tuticorin, would start operation in the 1970s. Initially its production rate was only 10% to 20% of its design capacity. Further, the plant at Nangal which started operation in 1962, no longer had access to the electrolytic hydrogen provided at no cost by the associated fertilizer plant. Based on economics the plant should have been shut down. However, India's need for heavy water was so great that India continued to provide some electricity for electrolysis. However, the heavy water that Nangal produced was now very expensive as the cost of production increased by a factor of approximately 25. Nangal's production dropped to an average of 7 metric ton per year. Therefore, in the late 1970s, India was producing no more than 14 to 21 metric tons of heavy water per year. India had hoped to provide the initial heavy water supply for the Rajasthan 2 reactor but by 1980 had to purchase heavy water from the Soviet Union. As a result the reactor had to be placed under IAEA safeguards.

In the early 1980s Indian heavy water production was still quite low. Of the three remaining new plants, only Baroda started operation. This plant's production was no better than that of Tuticorin. India's heavy water production was no more than 15 to 35 metric tons per year. In the face of this low production, India decided to build two more plants which it termed "second generation plants." A plant at Thal, based on the mono-thermal ammonia-hydrogen exchange process, would have a production capacity of 110 metric tons per year. A plant at Manuguru, based on the dual temperature water-hydrogen sulfide exchange process, would have a production capacity of 185 metric tons per year. This would nominally add 295 metric tons of production per year to what should have already been 315 metric tons per year of capacity. These two plants were scheduled to start operation in 1987 and 1988 respectively.

The shortage of heavy water had serious consequences for India's nuclear power program. In 1982 the MAPP 1 reactor was completed but India could not provide the 250 metric tons of heavy water needed to start the reactor. India could have imported the needed heavy water but this would have required placing the reactor under IAEA safeguards. Instead India kept the reactor, which represented a substantial capital investment, idle for 16 months until it acquired heavy water from other sources. In the mid-1980s the MAPP 2 power reactor and India's plutonium production reactor Dhruva came on line. Together these two reactors would have required around 330 metric tons of heavy water, far more than India could have provided. The key question is where did India acquire the heavy water required for these three reactors?

This question was raised by Milhollin in 1986.[12] He has reasonably suggested that India acquired the required heavy water illicitly from the Soviet Union, China or by diversion from the Rajasthan 1 reactor which had been shut down due to a serious construction flaw. In this way India kept MAPP 1, MAPP 2 and Dhruva outside of IAEA safeguards so that they could be used in India's nuclear weapons program.

My analysis has confirmed that Indian sources could not have provided the heavy water required by these three reactors. Indeed it is now clear that the heavy water shortfall was even larger than Milhollin suggested as his analysis was deliberately conservative. The heavy water production at Nangal in the 1970s and 1980s was significantly less than Mulhollin assumed. In addition, it is unclear how much of Tuticorin's production before 1985 was nuclear-grade heavy water. A 1988 Indian government audit has stated that between 1978 and 1986, India produced a total of only 190 metric tons.[13] Probably only about 150 metric tons of this material was produced before 1985 and not all of it may have been nuclear-grade. Yet MAPP 1, MAPP 2 and Dhruva would have required nearly 600 metric tons of heavy water. Before 1978 India may have accumulated a stock of around 100 metric tons of heavy water from the operation of Nangal. These numbers would imply that India acquired roughly 350 metric tons of heavy water by illicit means. Today, the source of this illicit heavy water is still unknown.

One possible source for this illicit heavy water would have been diversion from the safeguarded Rajasthan reactors. It is now clear how this diversion might have taken place. These reactors, especially Rajasthan 1, leaked a substantial amount of heavy water that was apparently downgraded to a concentration of only 2% to 3%. India used the water distillation section of the Kota plant to upgrade this material back to reactor-grade (see Appendix 2). India may have declared the downgraded heavy water as lost and then kept the reconcentrated heavy water outside of safeguards.

By the mid-1980s, the production from Tuticorin and Baroda had gradually improved though the two plants would each have their annual production capacity derated by over 30%. By this time it was apparent that Talcher had such serious design flaws that it would never operate. Kota, seriously delayed by damage incurred during a commissioning attempt in 1982, was still not operating. India authorized the construction of yet another plant, Hazira. It was based on the mono-thermal ammonia-hydrogen exchange process and had a design capacity of 110 metric tons of heavy water per year. India considered building three additional heavy water plants but they were not started as India's heavy water production began to be sufficient for its nuclear program.

In 1987, the second generation plant Thal began operation, as did the long-delayed Kota plant. Apparently neither plant could produce at its designed capacity. Thal would eventually be derated from 110 metric tons per year to 78 metric tons per year and Kota would be derated from 100 metric tons per year to 80 metric tons per year. Nevertheless, combined with the production from Tuticorin, Baroda and Nangal, India was probably producing between 100 to 200 metric tons of heavy water per year. In 1989 and 1991 India was able to provide the heavy water

[12] Gary Milhollin, "Dateline New Delhi: India's Nuclear Cover-Up," *Foreign Policy*, Fall, 1986.
[13] K.S. Jayaraman, "India offers to sell surplus heavy water," IANS India Private Limited, Yahoo News.

needed to start up the Narora 1 and Narora 2 reactors. At this point India's heavy water supply was more or less in balance.

A key turning point in India's heavy water production program occurred in 1991. That year, the Hazira plant started operation, though like most other Indian plants, it apparently could not produce its design capacity and was eventually derated from 110 metric tons per year to 80 metric tons per year. The delayed Manuguru plant also started in 1991. Unlike many of the other plants, Manuguru has been a great success. It is the only Indian heavy water plant not to have its production capacity derated. Instead, it has actually produced about 200 metric tons per year compared to its design capacity of 185 metric tons per year. Combined with the output of the other plants, in the 1990s India was producing about 450 to 500 metric tons of heavy water per year (nominal full capacity was 539 metric tons per year) and India began accumulating large amounts of excess heavy water.

From 1993 through 2000 India would start up six more reactors (Kakrapar 1, Kakrapar 2, Kaiga 1, Kaiga 2, Rajasthan 3 and Rajasthan 4) which required a total of about 1,500 metric tons of heavy water. India's requirement for make-up heavy water during this interval was likely less than 300 metric tons.[14] India also exported somewhat less than 200 metric tons of heavy water during this period for a total of around 2,000 metric tons. Yet during this interval, India probably produced around 3,000 metric tons of heavy water,[15] giving it a surplus of about 1,000 metric tons of heavy water.

From 2000 until today India has started six more heavy water power reactors (Tarapur 3, Tarapur 4, Kaiga 3, Rajasthan 5, Rajasthan 6, and Kaiga 4) which would have required about 2,000 metric tons of heavy water. During this interval, the demand for make-up heavy water was around 1,300 metric tons. India's exports of heavy water during this period were probably less than 200 metric tons for a total of roughly 3,500 metric tons.

In the meantime, Baroda was shut down from 1998 to 2005 as it could no longer obtain hydrogen from the adjacent fertilizer plant. In 2002, Nangal was permanently shut down. In 2005 Baroda restarted, using a pilot facility to transfer deuterium from water to ammonia though it is not clear how much heavy water it produced. In 2007 Tuticorin was shut down and placed in long-term preservation. In 2011 Baroda was shut down, though the site has not been closed.

From 2000 until today, India's four other heavy water plants (Manuguru, Kota, Thal and Hazira) have continued production. Their total production capacity is 438 metric tons of heavy water per year. India's production of heavy water from 2000 until today would have been roughly 7,000 metric tons. Therefore India produced a surplus of roughly 3,500 metric tons of heavy water during this period. Combined with its surplus from the 1990s, India would have a surplus of over 4,000 metric tons of heavy water.

Four new heavy water power reactors were to have started up in 2015 and 2016 (Kakrapar 3, Kakrapar 4, Rajasthan 7 and Rajasthan 8) which would have required about 2,000 metric tons of

[14] This estimate assumes the loss of 2% of each operating power reactor's inventory each year.
[15] If India produced 3,000 metric tons over seven years, this would represent an average production rate of 429 metric tons per year.

heavy water. However, funding to finish construction of these reactors has been delayed and it is unclear if these reactors will be finished even by 2020.[16] Meanwhile India is continuing to gain a net of about 300 metric tons of heavy water per year (400 metric tons per year production minus about 100 metric tons per year of make-up heavy water). By 2020, India's heavy water surplus could be more than 5,000 metric tons. Logically the DAE should be moving to curtail its heavy water production but has instead proposed restarting Tuticorin.

Though India has never provided any production figures, reading between the lines of the DAE annual reports, it appears that the two plants which use dual temperature water-hydrogen sulfide exchange technology, Manuguru and Kota, perform better than Thal and Hazira, the two plants which use mono-thermal ammonia-hydrogen exchange technology. Kota is the only first generation plant to still be operating.

This outcome is in accord with general worldwide experience, where most heavy water has been produced using dual temperature water-hydrogen sulfide exchange technology. Virtually all of the heavy water produced in the U.S. and Canada used this technology and currently both Pakistan and Iran use this technology to produce heavy water.

The Indian plants using mono-thermal ammonia-hydrogen exchange technology have been hampered by their need to draw hydrogen from linked fertilizer plants. Any interruption in the fertilizer plant's operation adversely affects heavy water production. Also the steam reforming of hydrocarbons process used to produce hydrogen in the fertilizer plants produces hydrogen depleted in deuterium (typically only about 105 ppm). This low deuterium concentration reduces the amount of heavy water that can be produced.

India significantly improved its heavy water plants using mono-thermal ammonia-hydrogen exchange technology by adding a water distillation backend. The benefits of this addition were demonstrated at Tuticorin in the mid-1980s. Baroda, Thal and Hazira also received water distillation backends though it is not clear why the DAE waited until the early 1990s to so improve these plants.

Implications for Economics

India's DAE has never provided reliable cost figures regarding the production of heavy water. In 2007 Ramana examined this issue in detail.[17] He stated that the DAE has not provided cost data to the Indian government so that even those who are supposedly in charge of the DAE do not know the costs associated with the production of heavy water. Nevertheless Ramana has provided cogent arguments to support his conclusion that the costs of heavy water are understated and therefore the cost of heavy water production is being subsidized by the Indian government at large.

[16] The Nuclear Power Corporation of India Limited's website lists the expected date of commercial operation of these four reactors as being "under review." Strangely, in 2017 India approved the construction of ten more heavy water power plants even though it has not fully funded the four plants it currently has under construction.
[17] M. V. Ramana, "Heavy Subsidies in Heavy Water: Economics of Nuclear Power in India," *Economics and Political Weekly*, August 25, 2007.

My findings only reinforce Ramana's analysis. Five out of eight of India's heavy water plants have been derated by 20% to 33% which would produce a corresponding 25% to 50% increase in the cost of the heavy water produced at these plants.[18] The heavy water produced at Nangal between 1978 and 1990 was very expensive as the production costs increased by approximately a factor of 25 (see Appendix 2). The Talcher plant was a total write-off, apparently never producing any nuclear-grade heavy water. India has held thousands of tons of heavy water unused for many years and is only continuing to add to its heavy water surplus. Given the high cost of this material, the carrying charges on this heavy water stockpile must be substantial and could increase the cost of the heavy water by 50% to 100%.[19] Part of India's solution to the problem of unreliable electricity supplies was to build dedicated coal/oil power plants at the heavy water production plants. However, this supply of electricity would have been rather expensive. Due to their small size, these plants would not have been economical.

Conclusions

India selected natural uranium fueled, heavy water moderated power reactors because it could more easily master their technology as compared to light water reactors which require enriched uranium fuel and massive reactor vessels that would have been difficult to manufacture in India. Heavy water reactor technology also had the advantage that it could be developed outside of IAEA safeguards and could help support a nuclear weapon program. Indeed, in 2006 India designated eight of its heavy water power reactors as military and has continued to keep them outside of IAEA safeguards.[20]

The selection of heavy water moderated power reactors required India to produce large amounts of heavy water (on the order of hundreds of metric tons per year). But two general issues posed serious problems for the Indian program, which initially led to heavy water shortages and caused the heavy water that India did produce to be very expensive.

The first of these issues applies to any nuclear program. Heavy water is a costly commodity and ideally one would only want to produce as much as is needed. It turns out that this is a very difficult problem as most of the heavy water demand occurs only once, at the start of a heavy water reactor's operation. India's early heavy water production problems meant that it did not have sufficient heavy water to start several of its reactors. As a result, power reactors, representing a substantial capital investment, sat idle.

Canada built a large number of heavy water production plants to ensure its supply of heavy water. However, this led to a large overcapacity, and some plants were only partially built before being torn down. Other plants operated for far less than their design lives before being shut down. By 1997 Canada had shut down the last of its heavy water plants. India is the largest heavy water producer today only by default, as Canada has removed itself from this very unprofitable business.

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[18] Tuticorin, Baroda, Kota, Thal and Hazira.

[19] Assuming a government cost of funds of 5%, holding heavy water unused for eight years increases its cost by about 50% and holding it unused for fourteen years increases its cost by 100%. India has maintained a stockpile of excess heavy water since the 1990s and has not started any new heavy water moderated power reactors since 2012.

[20] These eight reactors are: Madras 1, Madras 2, Kaiga 1, Kaiga 2, Kaiga 3, Kaiga 4, Tarapur 3 and Tarapur 4.

The second general problem is that heavy water production plants have large in-process inventories and therefore long equilibrium times. As a result, the plants need to operate for long uninterrupted periods. However, India in the 1970s and 1980s was poorly suited to produce heavy water as the supply of electricity was unreliable, which led to substantial production losses. Part of India's solution to this problem was to build dedicated coal/oil power plants at the heavy water production plants to ensure the supply of electricity. However, this supply of electricity would have been rather expensive since these small plants would not have been economical. Uninterrupted operation is even more difficult for heavy water plants which rely on hydrogen produced by an associated fertilizer plant, since any disruption of the operation of the fertilizer plant disrupts the operation of the heavy water plant.

The findings in this paper confirm and reinforce Milhollin's 1980s work showing that up to 1987 India faced severe heavy water shortages. Indeed, Milhollin's calculations were deliberately conservative and it is now clear that the heavy water shortages were larger than Milhollin had shown. The question that Milhollin posed in the 1980s remains: where did India obtain the illicit heavy water needed to run its reactors? This illicit heavy water was a significant aid to India's nuclear weapon program since it allowed India to keep three reactors outside of IAEA safeguards, including a dedicated plutonium production reactor.

Since the 1990s India has shifted into a situation of significant oversupply. Though India has been able to export some heavy water (mainly to South Korea), India holds very large stocks of this expensive substance. In 2000 its surplus stocks were likely around 1,000 metric tons. Today they are probably more than 4,000 metric tons and still growing at the rate of around 300 metric tons per year. Logically India should be moving to curtail its heavy water production but the DAE has instead proposed restarting its plant at Tuticorin.

Ramana has argued that the economics of India's heavy water production are poor and the findings of this paper only reinforce this conclusion. Five out of eight of India's heavy water plants were derated by 20% to 33% leading to a corresponding 25% to 50% increase in the cost of the heavy water produced at these plants. The heavy water produced at Nangal between 1978 and 1990 was very expensive as the costs of production increased by approximately a factor of 25. The Talcher plant was a total write-off, apparently never producing any nuclear-grade heavy water. India has apparently held thousands of tons of heavy water unused for many years and is only continuing to add to its heavy water surplus. Given the high cost of this material, the carrying charges on this heavy water stockpile must be substantial and could increase the cost of the heavy water by 50% to 100%.

Appendix 1

Heavy Water and the Processes That Produce It

All elements consist of different types of atoms called isotopes. The isotopes of any particular elements contain the same number of protons but different numbers of neutrons. The various isotopes are generally referred to by the total number of protons and neutrons contained in the nucleus. Thus, the two most common isotopes of uranium are referred to as U-235 (92 protons and 143 neutrons) and U-238 (92 protons and 146 neutrons).

Hydrogen contains two stable isotopes H-1 (a single proton) and H-2 (a proton and a neutron). Hydrogen is unique among the elements in that its isotopes have been given specific names. The term hydrogen often refers to just H-1 whereas H-2 is called deuterium.[21]

Natural uranium consists mainly of 0.7% U-235 and 99.3% U-238. Pure uranium that contains less than about 5% to 6% U-235 (is less than 5%to 6% enriched) cannot sustain a nuclear chain reaction. However, uranium with a lower enrichment can sustain a nuclear chain reaction if it is interspersed with a light element (moderator) which slows down the neutrons produced by the fissioning of uranium. However the moderator must not absorb too many neutrons.

Ordinary water is an excellent moderator. However, though oxygen absorbs very few neutrons, the hydrogen in water absorbs a significant number of neutrons. As a result natural uranium cannot sustain a chain reaction using water as a moderator and enriched uranium (generally in the range of 2% to 5%) must be used in reactors that use ordinary water as the moderator.

Deuterium absorbs only about one thousandth as many neutrons as does hydrogen and water composed of deuterium instead of hydrogen can easily sustain a chain reaction using natural uranium as fuel. Water composed of deuterium is termed heavy water.[22] In practice it is very difficult to produce water that is 100% deuterium and nuclear-grade heavy water is 99.8% deuterium. Even the 0.2% of ordinary hydrogen in nuclear-grade heavy water doubles the number of neutrons absorbed.

Graphite is the only other readily available moderator that can use natural uranium as fuel. However, the nuclear properties of graphite are inferior to that of heavy water and natural uranium fueled nuclear power reactors using graphite as the moderator cannot compete economically with power reactors that use heavy water.

There are two main sources of hydrogen, either water or hydrocarbons. The concentration of deuterium is only about 140 to 150 ppm in ordinary water and only about 125 ppm in hydrocarbons. This low natural concentration means that any heavy water production method must process very large amounts of raw material and will necessarily be a substantial undertaking.

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[21] Hydrogen also has one radioactive isotope, H-3, which is called tritium. Tritium has one proton and two neutrons.
[22] Heavy water is only about 10% heavier than ordinary water.

There are a variety of methods to separate hydrogen and deuterium.[23] They depend either on the difference in the chemical bond in various hydrogen containing substances or the actual physical weight difference between hydrogen and deuterium. The main processes involve electrolysis, distillation or chemical exchange.

Running an electrical current through water can break the water apart into hydrogen and oxygen. This process is known as electrolysis. The chemical bond between deuterium and oxygen is stronger than that of hydrogen and oxygen and as a result deuterium is concentrated in the remaining water as the electrolysis proceeds. If electrolytic cells are placed in a cascade where the residual water is further concentrated in deuterium in each step, it is possible to produce nuclear-grade heavy water. It would be very expensive to produce electrolytic hydrogen for just heavy water production. Instead, heavy water was produced only at places where electrolytic hydrogen was already being produced for some other reason (usually for the production of ammonia for fertilizer). In this way the cost of producing the hydrogen was borne by the fertilizer plant and not the heavy water plant. Norway operated the first plant that produced metric ton quantities of heavy water. This plant used electrolysis. However, there are now other less expensive methods for producing hydrogen (usually steam reforming of hydrocarbons) and therefore electrolysis is no longer used to produce heavy water. Electrolysis is still sometimes used to upgrade heavy water that has become partially diluted during use.

Since deuterium is heavier than hydrogen, simple distillation processes can be used to concentrate deuterium to produce heavy water. The distillation of hydrogen is the most effective distillation process. The main problem with hydrogen distillation is that hydrogen's boiling point occurs at a very low temperature (-250^{o} C or -420^{o} F). Not only is hydrogen difficult to handle at such low temperatures but it must be very pure since any impurity would freeze out in the plant and clog the process lines. Hydrogen produced by electrolysis is an excellent feed for this process but as was discussed in the last paragraph, electrolysis is no longer used to produce hydrogen. In the 1950s and 1960s hydrogen distillation was seriously considered as a means to produce heavy water but it is no longer seen as a competitor to the chemical exchange processes that are used to produce heavy water.

Water distillation is a simple process to produce heavy water. However, since most of the weight of water is from the oxygen, the difference in weight between ordinary water and water that contains deuterium is rather slight. The Manhattan Project produced heavy water by water distillation but the plants were large and energy intensive. Water distillation is no longer seen as an effective primary process for the production of heavy water.

However, since most of the separative work in any isotope separation process is performed in the stages where the desired isotope is least concentrated, once the deuterium reaches a concentration of 1% to 10%, the ease and simplicity of water distillation become advantageous. Therefore water distillation is often used as the finishing step for more complicated heavy water production processes. Also water distillation is a common method for upgrading heavy water that has become diluted during use or in an accident.

[23] For more on heavy water production processes see: Manson Benedict, Thomas H. Pigford and Hans Wolfgang Levi, *Nuclear Chemical Engineering*, 2nd Edition, McGraw-Hill Book Company, New York, 1981 and Stelio Villani, *Isotope Separation*, American Nuclear Society, 1976.

In the prototype ammonia-hydrogen chemical exchange process developed in France, the deuterium was concentrated in liquid ammonia and ammonia distillation was used as the finishing step. Ammonia distillation is no more effective than water distillation and this process has not been used at any other heavy water production plant.

Chemical exchange processes are the dominant means of producing heavy water today. When two hydrogen containing substances are brought into contact with each other, the deuterium often concentrates in one of the substances. The degree of concentration depends on the temperature. If one of the substances is a gas and the other a liquid, then by using an exchange tower where the gas flows up through the liquid that is flowing down, a substantial concentration of deuterium can take place. The process and equipment are similar to those used in industrial distillation processes such as are used in the oil industry.[24]

Unlike a distillation process where the gas can be condensed into a liquid and the liquid boiled into a gas, a chemical exchange process must either chemically transform one substance into the other while operating at one temperature (mono-thermal exchange) or have two exchange towers operating at different temperatures (dual temperature exchange). The three chemical exchange processes that have been used are water (liquid)-hydrogen (gas), ammonia (liquid)-hydrogen (gas) and water (liquid)-hydrogen sulfide (gas).

When electrolysis was being used as a primary method to produce heavy water, the latter stages in the cascade were generating hydrogen that was enriched in deuterium. Burning the hydrogen to recover the deuterium was too expensive, so instead the hydrogen was reacted with water using a platinum catalyst to recover some of the deuterium. Since electrolysis is no longer used to produce hydrogen, neither is the water-hydrogen chemical exchange process.

Ammonia-hydrogen chemical exchange is used in a number of plants today. The heavy water plants using this process are generally co-located with fertilizer plants that produce hydrogen by steam reforming of hydrocarbons, since it would be very expensive to produce hydrogen just to produce heavy water. In this way the cost of producing the hydrogen is borne by the fertilizer plant and not the heavy water plant. The hydrogen is mixed with nitrogen in the ratio of three moles of hydrogen to one mole of nitrogen. This is the proportion needed to produce ammonia (NH_3) and is called syngas (synthesis gas). The syngas is first run through the heavy water production plant to extract the deuterium before being used to produce the ammonia product.[25]

The ammonia-hydrogen exchange process is most commonly used as a mono-thermal process. It is fairly easy to thermally disassociate the ammonia into syngas and to chemically convert the syngas into ammonia. Note that the heavy water plant only produces enough ammonia to replace the ammonia destroyed by disassociation, so that there is no net ammonia production in the heavy water plant even though the adjacent fertilizer plant produces large amounts of ammonia. Since the deuterium is most concentrated in the ammonia at low temperatures, a mono-thermal plant generally operates between 0^o C and -25^0 C. The reaction rate between the ammonia and

[24] Strictly speaking, since there is countercurrent flow, the process is called rectification instead of distillation.
[25] The nitrogen in the syngas is chemically inert in a heavy water plant using ammonia-hydrogen chemical exchange.

hydrogen is slow, requiring the use of a potassium amide catalyst dissolved in the ammonia. Though the process is an effective means of producing heavy water, the amount produced is generally no larger than that of the hydrogen production rate of the fertilizer plant which limits the economies of scale. Furthermore, the heavy water plant is dependent on the uninterrupted operation of the fertilizer plant.

It is also possible to have a free-standing ammonia-hydrogen exchange heavy water plant by using water as the feed and using a water-ammonia chemical exchange step to replenish the deuterium-depleted ammonia. Though this process has been used in Argentina and experimentally in India, it does not appear to be competitive.

It is also possible to have a dual temperature ammonia-hydrogen exchange heavy water plant co-located with a fertilizer plant. One such plant was built in India but it contained serious design flaws and there has been no interest in building any additional plants.

Most of the heavy water that has been produced world-wide has used the water-hydrogen sulfide exchange process. It would be very expensive to chemically transfer deuterium from hydrogen sulfide to water and therefore mono-thermal chemical exchange is not practical.[26] Instead, all water-hydrogen sulfide exchange plants are dual temperature. It would be possible to produce nuclear-grade heavy water in just one stage but the equilibrium time would be on the order of one year. Instead, the water-hydrogen sulfide chemical exchange process is broken into several stages to reduce the equilibrium time. The process is generally used to produce water that is about 10% to 30% deuterium. Water distillation sometimes supplemented by electrolysis is then used to produce nuclear-grade heavy water.

Since water is directly used as feed, the plants do not need to be linked to a fertilizer plant and can be as large as desired, which provides economies of scale. Another advantage of this process is that the reaction between the water and the hydrogen sulfide occurs rapidly and no catalyst is needed. A disadvantage of this process is that it is energy intensive. Another disadvantage is that any plant requires a large inventory of highly toxic hydrogen sulfide.

The U.S. initially developed the water-hydrogen sulfide chemical exchange process and built two large plants but they were both shut down by 1981. As was discussed in the text, Canada built four large plants which used this process and produced up to 2,400 metric tons of heavy water per year. All four plants were shut down by 1997. Today there are at least four plants using this process in operation: two in India and one each in Pakistan and Iran. Additional plants could be operating in Russia or China.

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[26] Manson Benedict, Thomas H. Pigford and Hans Wolfgang Levi, *Nuclear Chemical Engineering*, 2nd Edition, McGraw-Hill Book Company, New York, 1981, pp. 765-767.

Appendix 2

Histories of Individual Indian Heavy Water Plants

Nangal

In the early 1960s India completed a large hydroelectric dam at Bhakra. Such was the state of India's economy at the time that there was not a sufficient demand for this electricity. A significant portion of this power (164 MW) was used to produce hydrogen by electrolysis. The hydrogen was used to manufacture ammonia which was used to produce fertilizer.

The Nangal heavy water plant was built co-located with this fertilizer plant. By arranging the electrolytic cells in a cascade it was possible to have one-fifth of the total hydrogen produced with a deuterium content about 2.5 times normal. The high purity hydrogen produced by electrolysis is ideal as feed to a hydrogen distillation heavy water production plant, allowing the deuterium to be extracted from the hydrogen before it is used in the fertilizer plant. India purchased such a plant from a U.S. company, Vitro Engineering Division, which subcontracted the hydrogen distillation plant construction to a West German company, Gesellschaft Linde. Using the portion of the hydrogen that was enriched in deuterium, it was possible for Nangal to produce 42 kilograms of heavy water per day. Assuming 8,000 hours of operation per year (91% capacity factor), Nangal would produce about 14 metric tons of heavy water per year. Nangal was India's first heavy water production plant and had the largest output of any hydrogen distillation plant worldwide. It was also the last hydrogen distillation plant ever to be built worldwide.

Nangal started sustained operation on July 20, 1962. Published production information shows that from August 1962 to April 1964, the plant was producing at a rate of about 1.2 metric tons per month which was about 14 metric tons per year.[27] The plant is reported to have operated at near capacity for a number of years. However, Nangal was dependent on the provision of cheap electricity and as India's economy grew, electricity supplies became more expensive. In 1976, in answers to Parliament, the DAE reported that Nangal had an annual capacity of 10 metric tons.[28]

In November 1978, in the face of increasingly expensive electricity supplies, the fertilizer plant began to produce hydrogen by the steam reforming of hydrocarbons instead of using electrolysis.[29] This process used far less electricity than did electrolysis and was substantially less expensive. The hydrogen produced by this process was not pure enough to use in Nangal's hydrogen distillation plant, since due to the low temperatures involved, the impurities would freeze out in the plant. Therefore without a source of hydrogen, Nangal should have shutdown but instead India provided some power to continue electrolysis. However, since now the cost of

[27] D. C. Gami and A. S. Rapial, "Analysis of operating experience of a hydrogen distillation plant," *Proceeding of the Third International Conference on the Peaceful Uses of Atomic Energy,* Held in Geneva, Switzerland, August 31 to September 9, 1964. Volume 12, Nuclear Fuels-III, Raw Materials, United Nations, New York, 1965, p. 423.
[28] *Nuclear India*, April/May 1976, p. 5.
[29] O. N. Chhabra, "Replacement of Electrolysis Plant with Steam Naphtha Reformation Plant, Its Integration with Old Heavy Water Plant," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries,* February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

the electrolysis was borne by Nangal's hydrogen distillation plant and not the fertilizer plant, the resulting heavy water would have been very expensive. A rough estimate is that the cost of the heavy water produced at Nangal increased by a factor of 25.[30] India recognized that any electricity provided for electrolysis was highly wasteful. The average production rate was apparently about 7 metric tons per year.[31] However, the power was provided only intermittently. For example, it was reported that the plant was shut down for ten months between September 1982 and July 1983.[32] The DAE claimed that the reduction in Nangal's heavy water output was due to electricity shortages, when in fact the real problem was Nangal's inability to use the hydrogen that the fertilizer plant was producing. In 1987, in answers to Parliament, Nangal was said by the DAE to have an annual capacity of 14 metric tons, even though it was producing on average only about one half this amount.[33]

In March 1990, a new frontend was added to Nangal, which purified the hydrogen produced by the steam reforming of hydrocarbons at the associated fertilizer plant so that this hydrogen could be used in the hydrogen distillation plant.[34] In this way, India ended the wasteful use of electricity. However, while the electrolytic hydrogen was partially enriched to about 350 ppm of deuterium, the hydrogen produced by the steam reforming of hydrocarbons contained only 115 ppm deuterium. Though Nangal's hydrogen distillation plant increased the amount of hydrogen it processed by a factor of 1.8, Nangal's output was limited to producing only about 7 metric tons of heavy water per year.

In 2002 the fertilizer plant associated with Nangal, which had been owned by the government, was privatized. The government did not want to turn heavy water production technology over to the private sector. It was considered too difficult to move the hydrogen distillation plant to some other hydrogen producing site and as a result Nangal was shut down and decommissioned.

Talcher

In 1973 India contracted with the West German company Friedrich Uhde GmbH to build the Talcher heavy water production plant based on the dual temperature ammonia-hydrogen

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[30] Based on 1964 data the cost of electricity consumption at Nangal was about one-third of the total cost of the heavy water produced and Nangal used about 2.6 MW of electricity. After 1978 Nangal used 98 MW mainly for electrolysis to produce about one half as much heavy water. See: D. C. Gami and A. S. Rapial, "Analysis of operating experience of a hydrogen distillation plant," *Proceeding of the Third International Conference on the Peaceful Uses of Atomic Energy*, Held in Geneva, Switzerland, August 31 to September 9, 1964. Volume 12, Nuclear Fuels-III, Raw Materials, United Nations, New York, 1965, p. 427 and *Ibid.* It is unclear whether the DAE actually paid this increased cost or whether Nangal received heavily subsidized electricity. If the latter is the case, then the cost was paid by the electricity provider and India more broadly.

[31] O. N. Chhabra, "Replacement of Electrolysis Plant with Steam Naphtha Reformation Plant, Its Integration with Old Heavy Water Plant," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*, February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

[32] "Annual Report, 1983-1984," Department of Atomic Energy, Government of India, 1984.

[33] *Nuclear India*, Vol. 26, No. 3-4, 1988, p. 12.

[34] O. N. Chhabra, "Replacement of Electrolysis Plant with Steam Naphtha Reformation Plant, Its Integration with Old Heavy Water Plant," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

exchange process.[35] As the name implies, the process involves passing liquid ammonia and hydrogen gas through various exchange towers, some of which are operated at -30^{o} C and some at +65^{o} C. Since hydrogen is not very soluble in ammonia, the process must take place at high pressure. The reaction rate between the ammonia and hydrogen is very slow, especially at low temperatures. Therefore a catalyst, potassium amide, must be dissolved in the ammonia.

The production of hydrogen just for use in a heavy water plant would be very expensive. As a result Talcher was co-located with an ammonia production plant which produced hydrogen to manufacture fertilizer. The cost of producing hydrogen was borne by the fertilizer plant and not Talcher. However, the output of Talcher was limited by the quantity of hydrogen produced by the fertilizer plant.

Talcher was expected to have a heavy water output of 63 metric tons per year and to start operation in 1976. However construction was delayed in March 1975, when two exchange towers fell off of the ship transporting them from West Germany to India and replacement towers had to be procured. Talcher was physically completed in 1979.

Talcher was the first and only plant in the world to be built using this process. The plant as built contained a number of design flaws.[36] Talcher apparently never produced any nuclear-grade heavy water though it may have produced some small amounts of off-grade material. In particular, no other plant used the potassium amide catalyst at high temperature. In the hot towers the catalyst formed solid particles which clogged the towers. The tower temperatures had to be limited to only +50^{o} C to +55^{o} C which reduced the overall enrichment of deuterium. In addition, the plant consisted of three stages, each consisting of a hot and cold tower. Talcher was designed so that the ammonia flowed between all three stages. The separation process caused the catalyst concentration to drop to low levels by stage three, which again reduced the enrichment attainable in the plant. Further, each tower contained of a number of trays where the deuterium exchange occurred between the ammonia and hydrogen. As designed, the tray exchange efficiency was only 50% of its intended value. Finally the flow rate through the towers needed to be limited to just 65% to 70% of its design value to permit stable operation.

Initially, Talcher's operators did not know what was wrong with the plant and spent many years diagnosing the plant and proposing fixes. Ultimately, Talcher was not fixed and the DAE gave up the effort in 1994. It appears that Talcher was a total write-off. Surprisingly, Talcher was never closed. Instead, new equipment was installed to produce solvents which started operation in 1999. Talcher is still run by the HWB today.

The HWB has never been very forthright about Talcher problems. Today on its website, it claims that the lack of hydrogen from the fertilizer plant was the reason Talcher failed to produce

[35] E. Nitschki, H. Ilgner and S. Walter, "UHDE Process for the Recovery of Heavy Water from Synthesis Gas," *Separation of Hydrogen Isotopes*, Howard K. Rae, Editor, ACS Symposium Series, 68, American Chemical Society, Washington, D.C., 1978.

[36] T. K. Haldar, Manoj Kumar, and C.B. Ramamurty, "Operating Experience of Heavy Water Plant at Talcher Using Bithermal Ammonia-Hydrogen Exchange Process," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

heavy water,[37] even though the paper written by Haldar et al., clearly explained the plant's numerous design flaws. Today the HWB claims that Talcher was commissioned in March 1978. However Talcher was not physically completed until 1979 and the potassium amide catalyst needed to produce heavy water was not even introduced into the plant until 1981.[38] Talcher appears never to have produced any nuclear-grade heavy water. Talcher is one of the more extreme examples of the HWB's and the DAE's refusal to admit that there were serious problems with a plant and of their unwillingness to close an obviously failed facility.

Tuticorin

In 1971 construction began on the Tuticorin heavy water plant which used the mono-thermal ammonia-hydrogen exchange process. Tuticorin was supplied by the French-Swiss consortium M-S Gelpra. In this process, hydrogen gas and liquid ammonia flow through exchange towers under high pressure. The towers are operated at temperatures between 0^{o} C and -25^{o} C. Since the rate of deuterium exchange between the hydrogen and the ammonia is slow, a potassium amide catalyst is dissolved in the ammonia. The production of hydrogen just for the extraction of deuterium would be very expensive and Tuticorin was co-located with a fertilizer plant which produced hydrogen to manufacture ammonia. In this way the cost of producing the hydrogen was borne by the fertilizer plant and not Tuticorin. The hydrogen was first sent to Tuticorin where the deuterium was extracted before being used in the fertilizer plant. The output of Tuticorin was limited by the amount of hydrogen produced by the fertilizer plant. Tuticorin was designed to produce 71 metric tons of heavy water per year.

In a mono-thermal process, in addition to the exchange towers, a portion of the hydrogen depleted in deuterium is converted into ammonia and part of the ammonia that is enriched in deuterium is heated to break it apart into hydrogen and nitrogen (cracked). In water the concentration of deuterium is about 140 to 150 ppm. However, the method used to produce hydrogen in fertilizer plants (reacting steam with hydrocarbons) results in hydrogen depleted in deuterium. Tuticorin was designed for hydrogen that was 125 ppm deuterium.

The French had built a plant based on this process at Mazingarbe. It began production in 1968 producing about 20 metric tons of heavy water per year. Mazingarbe used a single mono-thermal ammonia-hydrogen exchange stage to produce ammonia which was about two percent deuterium.[39] The ammonia was then distilled to produce ammonia that was 99.8% deuterium. The ammonia was then cracked and the resulting hydrogen burned to produce heavy water. Tuticorin was not designed to use ammonia distillation as a second stage but rather used a second mono-thermal ammonia-hydrogen exchange stage to produce ammonia that was 99.8% deuterium. The French plant at Mazingarbe suffered a major explosion in 1972 and was permanently shut down.

[37] Heavy Water Board, Department of Atomic Energy, Government of India. Link
[38] "Annual Report, 1981-1982," Department of Atomic Energy, Government of India, 1982.
[39] "Marzingarbe heavy water plant,' *Nuclear Engineering International,* Vol. 14, No. 158, July 1969.

Tuticorin was originally scheduled to start operation in 1975 but was actually commissioned in 1978. Initially Tuticorn performed rather poorly.[40] The plant reportedly had an equilibrium time of 14 days and suffered loss of production due to interruptions in the supply of hydrogen from the fertilizer plant and electrical power.[41] It was only in 1982 that the DAE stated that the viability of the mono-thermal ammonia-hydrogen exchange process had been demonstrated.[42]

Another problem was that the hydrogen supplied by the fertilizer plant contained only 105 ppm deuterium rather than the 125 ppm specified in Tuticorin's design. Efforts to change this only resulted in hydrogen that contained 108 ppm deuterium.[43] Using two ammonia-hydrogen exchange stages at Tuticorin rather than one exchange stage coupled with ammonia distillation, as at Mazingarbe, seems to have been a mistake as it appears that this setup could not reliably produce nuclear-grade heavy water.[44]

A major improvement in Tuticorin's operation occurred in 1984. To help deal with the frequent interruptions in operation, production at Tuticorin was limited to producing ammonia that contained just 40% to 60% deuterium.[45] A water distillation stage was added to increase the deuterium concentration to 99.8%.[46] It is reported that Tuticorin only began sustained production in 1984.[47] Indeed, the 1985-1986 DAE annual report touted the fact that Tuticorin was producing nuclear-grade heavy water which would seem to confirm that the plant had had difficulty doing so before then.[48] In 1987, the DAE revealed that Tuticorin had been derated to an annual capacity of only 49 metric tons per year—a 31% loss in capacity.[49] The HWB's website currently lists the same annual capacity for Tuticorin, showing that the derating was permanent.

From the late 1980s, Tuticorin apparently operated more or less satisfactorily until 2007, when the plant was shut down and placed in long- term preservation. The latest DAE annual report (2016-2017), raised the possibility of restarting Tuticorin. This would involve taking components from the heavy water plant at Baroda.

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[40] Milhollin, citing Indian sources, reports that Tuticorin produced 7 metric tons in 1979, 14 metric tons in 1980, 15 metric tons in 1981, 4 metric tons in 1982, and 23 metric tons in 1983. See: Gary Milhollin, "Dateline New Delhi: India's Nuclear Cover-up," *Foreign Policy*, Fall, 1986. However it is unclear how much of this production was nuclear-grade material.

[41] M. Periakaruppan, G. Arumugam, and P. Ayyanar, "Operating Experience at Heavy Water Plant, Tuticorin," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

[42] "Annual Report, 1982-1983," Department of Atomic Energy, Government of India, 1983.

[43] See: M. Periakaruppan, G. Arumugam, and P. Ayyanar, "Operating Experience at Heavy Water Plant, Tuticorin," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

[44] Before the addition of the water distillation backend in 1984, the plant's production of nuclear-grade heavy water was said to be "very low." *Ibid.*

[45] This change reduced the plant's in-process inventory of heavy water which reduced its equilibrium time and the amount of production lost when a plant stoppage occurred.

[46] M. Periakaruppan, G. Arumugam, and P. Ayyanar, "Operating Experience at Heavy Water Plant, Tuticorin," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.

[47] *Ibid.*

[48] *Nuclear India*, Vol. 24, Nos. 5-6, 1986

[49] *Nuclear India*, January-February, 1987, p. 11.

Baroda

Baroda was another mono-thermal ammonia-hydrogen exchange plant provide by the French-Swiss consortium M-S Gelpa. Baroda's design was similar to that of Tuticorin and the plant was to produce 67 metric tons of heavy water per year. India contracted for Baroda in the late 1960s and Baroda was actually the first of the two plants purchased from M-S Gelpa. Baroda was due to start operation in 1973 but actually started its commissioning in 1977, a year before Tuticorin. However, Baroda suffered a major explosion in its ammonia cracking unit and its commissioning was delayed until 1980.

Like Tuticorin, Baroda's initial production rate was poor and only slowly improved in the 1980s.[50] As at Tuticorin, the two-stage ammonia-hydrogen chemical exchange setup had difficulty producing nuclear-grade heavy water given the frequent interruptions in operation. In 1987, in answers to Parliament, the DAE revealed that Baroda had been derated to a production capacity of only 45 metric tons per year—a 33% loss of capacity.[51] As with Tuticorin, this was a permanent derating.

From the late 1980s through the 1990s Baroda slowly continued to improve. In 1993 the ammonia enrichment was limited to just 40% to 60% and a final water distillation backend started operation which significantly improved production. However, in 1998 the associated fertilizer plant that produced the hydrogen used in Baroda, greatly lowered its operating pressure.[52] Due to the low solubility of hydrogen in ammonia, the heavy water exchange process must take place at high pressure. The low pressure hydrogen from the fertilizer plant could not be used at Baroda and the plant was shut down in December 1998. Baroda resumed operation in September 2005, using a water-ammonia exchange frontend to provide deuterium feed, though it is not clear how much heavy water the plant was producing. On April 1, 2011, Baroda was shut down again. Recently the DAE has developed plans to remove components from Baroda to help prepare for a possible restart of Tuticorin. Based on these plans, it is likely that Baroda will never be restarted.

Kota

Kota is based on the dual temperature water-hydrogen sulfide exchange process. This process was first developed in the U.S. In the 1950s using this technology, the U.S. built the first two heavy water production plants that could produce hundreds of metric tons of heavy water per year. As was discussed in the text, Canada used this technology to build four large heavy water production plants.

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[50] Milhollin, citing Indian sources, reports that Baroda produced 12 metric tons in 1981, 5 metric tons in 1982, and 14 metric tons in 1983. See: Gary Milhollin, "Dateline New Delhi: India's Nuclear Cover-up," *Foreign Policy*, Fall, 1986.
[51] *Nuclear India*, January-February, 1987, p. 11.
[52] Heavy Water Plant Baroda, Heavy Water Board, Department of Atomic Energy, Government of India. Link

The DAE had studied the published information on this process for many years and conducted its own experiments.[53] In the late 1960s the DAE decided to build Kota. India would provide the engineering, detailed design and perform the construction. India would also procure the equipment though this would have "a fairly high import content."[54]

To take advantage of excess steam produced by the Rajasthan 1 nuclear power plant, Kota was located adjacent to this reactor.[55] Kota was designed to produce 100 metric tons per year. The plant uses three water-hydrogen sulfide exchange stages to produce water that is about 15% deuterium. Water distillation is used to increase the water to nuclear-grade (99.8% deuterium). Since this process uses ordinary water as feed, a production plant using this process does not need to be associated with a fertilizer plant and its production capacity is not limited by a fertilizer plant.

The DAE planned for Kota to go into operation in 1975 but the DAE vastly underestimated the difficulties involved. The water distillation part of Kota was not finished until 1980. In 1981, since the main part of Kota was still not in operation, this part of the plant started processing downgraded heavy water (2.5% to 3% deuterium concentration) from the Rajasthan reactors. In 1982 hydrogen sulfide was introduced into the main part of Kota and the DAE reported that Kota was "in the last stages of commissioning."[56] However, according to U.S. intelligence, Kota was seriously damaged during this commissioning attempt.[57] This incident was not reported by India or any unclassified source. This damage substantially delayed the startup of Kota.

Today India claims that Kota was commissioned in 1985 but this appears not to be true. In 1985 Kota was being tested at reduced pressures.[58] It was only in 1986 that all three sections of the primary enrichment stage were brought into operation.[59] It was not until the 1987-1988 DAE annual report that Kota was said to have commenced production.[60]

The initial production rate of Kota was poor, as it was reliant on the Rajasthan nuclear power plant for steam and electricity and the nuclear power plant's reliability was poor. It was only in the early 1990s, when a dedicated power plant was built at Kota, that its production improved. In 1987, Kota was reported to have been derated to a production rate of 85 metric tons per year[61] and today the HWB states that Kota's capacity is only 80 metric tons per year—a 20% loss of

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[53] P. G. Deshpande, D. C. Gami, and S. Nagaraja Rao, "Technical and economic considerations for producing 200 t/yr of heavy water in India," *Proceeding of the Third International Conference on the Peaceful Uses of Atomic Energy*, Held in Geneva, Switzerland, August 31 to September 9, 1964. Volume 12, Nuclear Fuels-III. Raw Materials, United Nations, New York, 1965.

[54] H. S. Kamath, "India's Heavy Water Production Programme," Press Information Bureau, Government of India, September 10, 2002.

[55] S. Fareeduddin, "Production of Heavy Water in India," Bhabha Atomic Research Centre, 1973.

[56] N. Srinivasan, "Heavy Water Production-A Frontier Technology," *Nuclear India*, September/October 1982, p. 8.

[57] "India's Heavy Water Shortages," National Security Agency, October 1982, formerly Top Secret, now declassified with redactions.

[58] *Nuclear India*, Vol. 24, No. 5-6, January/February 1986.

[59] *Nuclear India*, Vol. 25, No. 7-8, 1987, p. 5.

[60] *Nuclear India*, Vol. 26, No. 1-2, 1988.

[61] *Nuclear India*, January-February, 1987, p. 11.

capacity.[62] In recent years Kota has generally produced at close to its rated capacity except when some of its aging equipment has failed.

Thal

Thal is what the HWB calls a "second-generation" heavy water plant. Its construction started in the early 1980s when it became apparent that the heavy water plants that India had built were not performing as anticipated. Thal is based on the mono-thermal ammonia-hydrogen exchange process. Its design is generally the same as that of Baroda and Tuticorin but it was not built with foreign assistance. Thal incorporated some of the experience gained at Baroda and Tuticorin to improve performance. In particular, the associated fertilizer plant produces two separate streams of hydrogen so that the heavy water plant can continue production even if one hydrogen stream is down. Also, Thal was divided into two separate exchange sections, each designed to produce 55 metric tons of heavy water per year, resulting in a design capacity of 110 metric tons per year.

Otherwise, Thal suffered from some of the same problems as Tuticorin and Baroda. The concentration of deuterium in the feed was less than what the design anticipated. Thal also suffered from a loss of production due to interruptions in electricity supply. In 1994 a water distillation backend started operation at Thal which allowed the ammonia enrichment in the main plant to be limited to 40% to 60% and significantly improved operation.

Thal was planned for operation in 1987 and it was commissioned on schedule. Like most of India's heavy water plants, it got off to a slow start but gradually improved. However, it appears that Thal was never able to operate at its design capacity. Thal has been derated and currently the HWB states that the plant's capacity is only 78 metric tons per year.[63] This is a 29% loss of capacity.

Manuguru

Manuguru is what the HWB calls a "second-generation" heavy water plant. Its construction started in the early 1980s when it became apparent that the heavy water plants that India had built were not performing as anticipated. Manuguru is based on the dual temperature water-hydrogen sulfide exchange process. The plant uses three water-hydrogen sulfide exchange stages to produce water that is about 15% deuterium. Water distillation is used to increase the water to nuclear-grade (99.8% deuterium). Since this process uses ordinary water as feed, a plant using this process does not need to be associated with a fertilizer plant and its production capacity is not limited by a fertilizer plant. Manuguru consists of two identical production facilities, each approximate copies of the Kota heavy water plant. Manuguru's design production capacity is 185 metric tons of heavy water per year.

Though Manuguru started construction before Kota had started operation, several important changes were made in its design to improve the plant's output. Most importantly, Manuguru did not rely on outside sources for either power or steam. Rather, three dedicated coal-fired steam

[62] "Heavy Water Plant, Kota," Heavy Water Board, Department of Atomic Energy, Government of India. Link
[63] "Heavy Water Plant, Thal," Heavy Water Board, Department of Atomic Energy, Government of India. Link

boilers were built which each produced 30 MW_e as well as the steam needed for Manuguru.[64] In addition the plant separated the third exchange stage from the first two so as to reduce Manuguru's equilibrium time.[65]

Manuguru was scheduled to start operation in 1988 but the provider of the steam boilers went bankrupt which delayed the start of the plant until the end of 1991.[66] However, once Manuguru went into operation, its performance has been very good. The most recent annual report of the DAE (2016-2017), states that Manuguru has produced over 5,000 metric tons of heavy water over its lifetime, which is an average production rate of 200 metric tons per year.[67] This is higher than the plant's 185 metric ton per year design output. Manuguru is by far the most successful of the HWB's plants and is the only one not to have had its annual production capacity derated. Manuguru is currently the largest heavy water producer in the world. The success at Manuguru is the key reason why India went from a heavy water importer to a heavy water exporter.

Hazira

Hazira was the last of India's heavy water plants to be authorized and construction began in 1986. Hazira started operation on time in 1991. As with Thal, Hazira was not built with foreign assistance and is based on the mono-thermal ammonia-hydrogen exchange process. Hazira's design is very similar to Thal's with two separate exchange sections, each designed to produce 55 metric tons of heavy water per year, resulting in a design capacity of 110 metric tons per year. Similar to the setup at Thal, the associated fertilizer plant produces two separate streams of hydrogen so that Hazira can continue production even if one hydrogen stream is down.

Hazira suffered from similar problems to those at Thal. The plant was hampered by the deuterium concentration in the feed gas being only 103 ppm instead of the intended 115 ppm.[68] To reduce production losses due to power interruptions, in 1992 a water distillation backend started operation at Hazira which allowed the ammonia enrichment in the main plant to be limited to 40% to 60%.

Since Hazira started operation, it seems to have operated more or less satisfactorily. However, it appears that Hazira was never able to operate at its design capacity and it has been derated. Currently the HWB states that Hazira's capacity is only 80 metric tons per year.[69] This is a 27% loss of capacity.

[64] R. Bhatnagar, Ashok Sinha, A.C. Mohan Rao, "Commissioning and Maintenance Experience on Mechanical Equipments in Steam Generators of Captive Power Plant at H W P, Manuguru," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.
[65] Shri V.K. Khilnaney and R.R. Sonde, "Development of H_2S-H_2O Exchange Process Based Heavy Water Technology," IANCAS Bulletin, September, 2001, p. 29.
[66] *Nuclear India*, Vol. 25, No. 7-8, 1987, p. 6.
[67] "Annual Report 2016-2017,"Department of Atomic Energy, Government of India, p. 9. Link
[68] "Commissioning/Performance Activities of Heavy Water Plant (Hazira)," *National Symposium on Commissioning and Operating Experiences in Heavy Water Plants & Associated Chemical Industries*," February 27-28, 1992, Heavy Water Board, Department of Atomic Energy, Government of India.
[69] "Heavy Water Plant, Hazira," Heavy Water Board, Department of Atomic Energy, Government of India. Link