The origins and antecedents of the *Ghauri* missile – An assessment

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The launch of the Ghauri missile by Pakistan in April 1998 opens up new security concerns in South Asia. An analysis of the data put out in the Pakistani press coupled with published information reveals that the Ghauri is the North Korean Nodong missile supplied on a turnkey basis to Pakistan. The range of the Ghauri with a possible nuclear warhead weighing between 700 kg and 1 tonne would be between 950 and 1100 km.

Background

The launch of the *Ghauri* missile on 6 April 1998, by Pakistan has kindled widespread speculation on its origins and capabilities. The preliminary reports indicated a major enhancement of capabilities as compared to earlier assessments[1]. In this article, we look at the available evidence and try to make some inferences about the origins and capabilities of the most recent missile to enter the arsenal of Pakistan. This analysis uses as a baseline:

(i) The reports on the performance of the missile as put out in the Pakistani Press[2,3] and images of the missile reproduced in various newspapers and magazines[4,5].
(ii) Available open information on sizes, ranges, and payloads of missiles developed by various countries[6–8] as well as reports on the exports of such missiles.
(iii) A simplified range and trajectory model with approximate corrections for atmospheric drag and gravity effects.
(iv) Empirical engineering data based on discussions with experts and published information in the technical literature.

Ghauri performance and Pakistani press reports

Table 1 gives the details of the flight as reported in the Pakistani Press. One source gave the total flight time of the missile as 9 min and 58 sec with the missile going up to 350 km. From these data, the path of the missile appears to have been almost due west. Figure 1 shows the ground trace of the missile path based on the published data. The range appears to be about 705 km. The typical trajectory of a missile involves:

(i) The powered phase which involves a vertical lift-off and a programmed turn to achieve the required velocity and angle for injection.
(ii) The ballistic phase in which the missile is subjected only to the forces from the earth's gravity field.
(iii) The re-entry phase.

The ballistic phase can be modelled fairly accurately for the calculation of the range[9]. The powered phase and the re-entry phase are more difficult to model and are to some extent vehicle-specific. The powered phase involves a vertical lift-off, a range of powered burn times and a programmed turn to achieve the optimum injection angle. These can be approximated reasonably well to get some idea of the range achieved during the powered phase[10]. For medium range missiles like the *Ghauri*, the injection altitude would be between say 25 and 50 km. The range for the re-entry phase can also be similarly approximated[11]. Since most of the range is achieved during the ballistic phase of the flight, these approximations (based on the velocity achieved by the rocket at ignition cut-off) do not cause any major errors in the calculation of the range. The other factors that we have to correct for are the velocity losses due to atmospheric drag and also losses due to the influence of the earth's gravity field. The drag forces are generally between 5% and 10% of the final velocity achieved. The gravity losses are dependent on the time of the powered flight. High drag losses generally mean low gravity field losses and vice versa. In our analysis, we have assumed a combined velocity loss of 1 km per sec from both these effects[12,13]. The available data and images

Table 1. Flight details reported by the Pakistani press

Lift-off weight of the *Ghauri*	16 tonnes
Propellant weight	13–14 tonnes
Payload	700 kg
Place of launch	Malute near Jhelum
Place of impact	near Quetta
Lift-off time	7.23 A.M. (7.25 A.M.)
Impact time	7.33 A.M.

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suggest that the *Ghauri* is a single-stage liquid fuelled rocket. This was the starting point of the analysis. If the calculated and achieved performance do not match the achieved results, we could always come back and take a look at this assumption again though the visual evidence for a single-stage missile is fairly strong. Expert opinion also favours a single-stage liquid rocket as the most likely configuration[14].

If the rocket is liquid-fuelled, there are several propellant combinations to chose from. The specific impulse is a measure of the ability of the rocket fuel to impart velocity to the rocket. A higher specific impulse involves a higher velocity. It also generally means a higher level of technology. To take care of these, range calculations, at least initially, are based on two values of the specific impulse, 250 sec and 235 sec. These are typical sea level specific impulse values achieved by the fuel oxidizer combinations[15,16].

- unsymmetrical dimethylhydrazine (UDMH) and nitrogen tetroxide (N_2O_4)
- unsymmetrical dimethylhydrazine (UDMH) and red fuming nitric acid (RFNA).

There is a third possibility that the rocket uses a kerosene-based fuel called RP1 and RFNA. Such a combination would have a sea level specific impulse of about 225 sec. This is the combination used by the Russian *Scud* missiles[17].

Based on the data put out the following baseline was assumed as seen in Table 2. This is based on realizable hardware from the point of view of engineering. If the payload weight is reduced to 700 kg as reported in the Pakistani Press, then there would be some increase in range. Similarly, if the specific impulse is less than 235 sec the range will decrease. These two effects can be traded off against each other. The incremental velocity calculation based on these data for the two propellant combinations considered are:

- $\Delta V = 4.101$ km/sec for a specific impulse of 250 sec
- $\Delta V = 3.855$ km/sec for a specific impulse of 235 sec.

These are ideal values realized when there is no drag and no losses due to the earth's gravity. The combined losses from these two effects is assumed to be about 1 km/sec in our analysis. This is based on some empirical data available in the literature. After taking into account these losses, the incremental velocities that could be achieved are $\Delta V = 3.101$ km/sec for a specific impulse of 250 sec and $\Delta V = 2.855$ km/sec for a specific impulse of 235 sec. The ranges calculated for these two values for the ballistic phase of the flight alone are:

- Range (R) for the ballistic phase = 1072 km for a specific impulse of 250 sec
- Range (R) for the ballistic phase = 897 km for a specific impulse of 235 sec.

Since this does not include range from the lift-off and the re-entry phases, the actual range will be higher than that calculated here. Based on the reported missile characteristics this correction will be of the order of 50 km. Adding this correction the ranges for the assumed parameters of the *Ghauri* missile are: R for the case with specific impulse of 250 sec is 1120 km; R for the case with specific impulse of 235 sec is 950 km.

The actual distance travelled by the missile from the Press reports is 705 km. This is lower than the estimates we have obtained by calculation. This difference has to be reconciled in order to validate the data put out by the Pakistani Press. If we cannot do this then we have to assume that the data are incorrect or that our assumptions are invalid.

When one looks at the actual reported trajectory on a map (see Figure 1), one notices that the launch is due westward at a fairly low azimuth angle. Such a launch trajectory would mean that there will be an additional loss of velocity because of the earth's rotation. For the latitude of Jhelum this will mean a velocity loss of about 400 m/sec and since the launch is almost

Figure 1. Ground trace of the *Ghauri* launch.

Table 2. Some assumptions based on the data given

Lift-off weight	16 tonnes
Propellant loading	13 tonnes
Payload	1 tonne
Inert weight of the rocket (by subtraction)	2 tonnes

due west almost all of this loss has to be taken into account in our calculations. We can now re-compute the ranges for the two cases taking into account the earth's rotational effects. The incremental velocities for the two cases in such a situation are:

- $\Delta V = 2.701$ km/sec for the case with a specific impulse of 250 sec
- $\Delta V = 2.455$ km/sec for the case with a specific impulse of 235 sec.

The ranges for the two cases based on these incremental velocities are:

- 796 + 50 km = 846 km for the case with a specific impulse of 250 sec
- 651 + 50 km = 701 km for the case with a specific impulse of 235 sec.

The assumed parameters for the *Ghauri* based on the data put out by the Pakistani newspapers seem to be compatible with the case of a single-stage liquid fuelled missile with a specific impulse of around 235 sec. The inert weight to propellant weight for the stage (excluding the payload) is 0.1538, which is a reasonable realizable value for a missile of this kind[18]. The parameters given appear to be compatible with the reported performance. There is also a possibility that the *Ghauri* missile uses a propellant combination of RFNA and RP1 (kerosene). Such a combination would have a lower specific impulse of about 225 sec. This will also give the same range of about 700 km with a payload of 700 kg instead of the 1 tonne payload that we have assumed. This is also consistent with the observations.

Origins and antecedents of the *Ghauri* missile

The next question to be addressed is whether there are any missiles developed by any other country that fit the profile of the *Ghauri*. This will enable one to make some inferences on the possible source of technology and maybe get a better handle on the performance of the missile. We can also re-examine the evidence based on such a comparison so as to validate both the source and performance. We have used data available in the public domain to make these comparisons[19–22]. The most likely sources for technology or procurement are China and North Korea. Iraq, Iran, Libya and Egypt are unlikely to be sources of supply based on geo-political considerations. A Russian source is also quite unlikely though not impossible. Based on these non-technical factors the most likely candidates are China and North Korea. Table 3 compares various missiles of China and North Korea with the *Ghauri*.

The length to diameter ratio or *L/D* ratio of the *Ghauri* missile as measured from photographs appearing in the Press range from 12 to 12.2 (ref. 23). From Table 3 missiles that have similar *L/D* ratios allowing for some measurement errors are:

(i) The North Korean *Scud-A*, *Scud-B* and *Scud-C* missiles;
(ii) The North Korean *Nodong-1* and *Nodong-2* missiles;
(iii) The Chinese DF2 single-stage missile; and
(iv) The Chinese 2 stage DF4 missile.

The *Scud-A*, *Scud-B* and *Scud-C* missiles can be ruled out on range considerations. It also makes no sense for

Table 3. Comparison of the *Ghauri* with missiles from China and North Korea

Missile	Length (*L*) m	Diameter (*D*) m	*L/D* ratio	Propellant combination	LOW tonne	Fuel tonne	Stage nos	*P/L* tonne	Range (km)	Country
*Ghauri***		12–12.2	Liquid (RFNA/?)	16	13	1	1		950–1120	Pakistan
CSS1(DF2)	20.6	1.652	12.47	Oxygen/alcohol	32	NA	1	1.5	1050–1250	China
CSS2(DF3/A)	24	2.25	10.66	RFNA/UDMH	64	60	1	2.15	2650–2800	China
CSS3(DF4)	28	2.25	12.44	RFNA/UDMH	80	NA	2	2.2	4750	China
CSS4(DF5)	32.6	3.35	9.73	RFNA/UDMH	183	NA	2	3–3.2	12–13000	China
CSST600 M9	9.1	1	9.1	Solid	6.2	NA	1	0.95	600	China
CSS6(DF21)	10.7	1.4	7.64	Solid	14.7	NA	2	0.6	1800	China
CSS-N3(JL1)	10.7	1.4	7.64	Solid	14.7	NA	2	0.6	1700	China
Scud-A	11.25	0.9	12.5	RP1/RFNA	6.3	4	1	1	300	N. Korea
Scud-B	11.25	0.9	12.5	RP1/RFNA	6.3	4	1	1	320	N. Korea
Scud-C	12.55	0.9	13.94	RP1/RFNA	7.3	5	1	0.5	550	N. Korea
*Nodong-1**	15.5	1.3	11.94	RP1/RFNA	19.5??	16??	1	1	1000	N. Korea
Nodong-2	15.5	1.3	11.94	RP1/RFNA	24??	20??	1	1	1500	N. Korea

*The *Nodong-1* missile is likely to have a lift-off weight (LOW) of 16 tonnes. This is based on a re-look at the figures given in the CDSS database. See ref. 5.
**The length and the diameter of the *Ghauri* should also be close to that of the *Nodong-1*.
RFNA, red fuming nitric acid; RP1 is a kerosene-based liquid fuel; UDMH, unsymmetrical dimethylhydrazine, a common liquid rocket fuel; LOW, lift-off weight; *P/L*, payload; tonne, metric tonne; *L/D* ratio, length to diameter ratio; NA, not available.

Pakistan to demonstrate a range capability it already has with the HATF/M9/M11 rockets it possesses. The DF2 can also be ruled out since it uses liquid oxygen and ethanol as oxidizer and fuel. Liquid oxygen is difficult to handle especially for a mobile missile. The DF4 is a two-stage missile with a far greater range and is not compatible with the available evidence that the *Ghauri* is a single-stage missile. The choice therefore narrows down to *Nodong-1*, *Nodong-2* or indigenous development.

Available data (mainly from the CDSS) show that the *Nodong-1* developed and deployed by North Korea is made up of a cluster of 4 *Scud-B* engines. By increasing the diameter and the length of the stage a larger tank required to cater to the 4 engines is provided. Such a common tank would feed all the 4 engines and result in a significant improvement in performance over a missile that consists of only one *Scud* engine. The *Nodong-2* presumed to be under development is expected to further improve performance by reducing the inert weight of the stage. If the *Nodong* missile is a *Scud-B* derivative, it would most probably use RP 1 (kerosene) as fuel and inhibit red fuming nitric acid (IRFNA), as the oxidizer. The specific impulse of this combination would be about 225 sec.

Though the length to diameter (L/D) ratio of the *Nodong* matches that of the *Ghauri*, the weight of the propellant given for the *Nodong* (16 tonnes) in the CDSS database that we had consulted does not match the figure for the *Ghauri* (13 to 14 tonnes).

A comparison between the *Nodong-1* and the *Scud-B* using the CDSS database shows: an increase in the diameter of 0.4 m (0.9 m for the *Scud*, 1.3 m for *Nodong*); and an increase in length of 4.25 m (11.25 m for *Scud*, and 15.5 m for *Nodong-1*).

If all the increase in diameter and length of the *Nodong vis-à-vis* the *Scud* are translated into extra capacity of the tanks to carry fuel, then one can easily prove that the CDSS estimates are realistic. However in practice, while the increase in diameter directly translate into increased tank capacities, only a part of the increase in length contribute to increased tank capacities and more fuel. Some part of the length increase can be related to changes in the interfaces between the engine and the tanks and to changes in the interfaces coupling the tanks themselves. From empirical data derived from other rockets, only about 90% of the length increase directly contribute to increased tank capacity and hence more fuel. Using this correction factor, the estimate of the fuel capacity of the *Nodong-1* works to be about 14.4 tonnes. Some volume margins will also have to be provided for accommodating the vapours of the fuel and oxidizer termed ullage losses. This is typically 5–10% of the volume[24]. When these corrections are taken into account, the effective fuel loading of the *Nodong-1* would be about 13 tonnes. This is in agreement with the propellant weight figures put out by the Pakistani Press. This substantiates the earlier assessment that the *Ghauri* is indeed the North Korean *Nodong-1* missile.

Contacts between North Korea and the Makeyev Design Bureau of Russia apparently took place around 1989 (ref. 25). The Makeyev Bureau was involved in the design of the *Scud-B* in the late fifties and early sixties. This Bureau was also involved in clustering 4 *Scud* engines to build the SSN-4 (SARK) and SSN-5 (SERB) submarine launched ballistic missiles[26] which used RP1 as the fuel and a nitric acid/nitrogen tetroxide mixture as the oxidizer[27]. This mixture will give a marginally higher specific impulse than the traditional *Scud* fuel RP1 and RFNA. Help from the Chinese, who have also adopted a clustering approach and who use nitric acid and UDMH in many of their missiles, cannot be ruled out, though the *Ghauri* itself does not seem to have a Chinese pedigree. On balance, taking into account the complexity and development problems associated with the development of liquid rocket technology, it appears that the source of the *Ghauri* is North Korea. It also appears more than likely that the entire missile has been provided on a turnkey basis to Pakistan. This would mean outright procurement and maybe even setting up a production plant in Pakistan for catering to the larger numbers that may be required for deployment. A few months prior to the launch of the *Ghauri*, the US imposed sanctions against North Korea for violating the Missile Technology Control Regime (MTCR). It did not impose sanctions on the recipient country as is normally the case. The imposition of sanctions against Pakistan and North Korea in the first week of May immediately after newspaper reports[28] on the origins of the *Ghauri*, also seems to validate the North Korean connection[29]. Irrespective of the source, there is no doubt that the *Ghauri* represents a significant step forward for Pakistan. It could form the base for further upgrades to their missile capability.

One parameter that we have not been able to reconcile is the time of flight. The reports talk of a total flight time of 598 sec[30]. Assuming the ΔV that we have calculated, the flight in the ballistic phase would be around 380 sec. If a typical burning rate for a liquid rocket is assumed, the thrust time would be between 120 and 160 sec. The re-entry time at a velocity of about 2 to 2.5 km per sec would be about 30–40 sec. This still does not account for about 30 sec to 1 min of the reported trajectory time. When one looks at the image of the lift-off, it shows the time as 7.23 A.M.[31] Clearly the least error of the time measured is 1 min. This could account for the difference.

Figure 2 shows in pictorial form the likely range of the *Ghauri* missile from locations on the Indo-Pak border. This range calculation is based on a south or

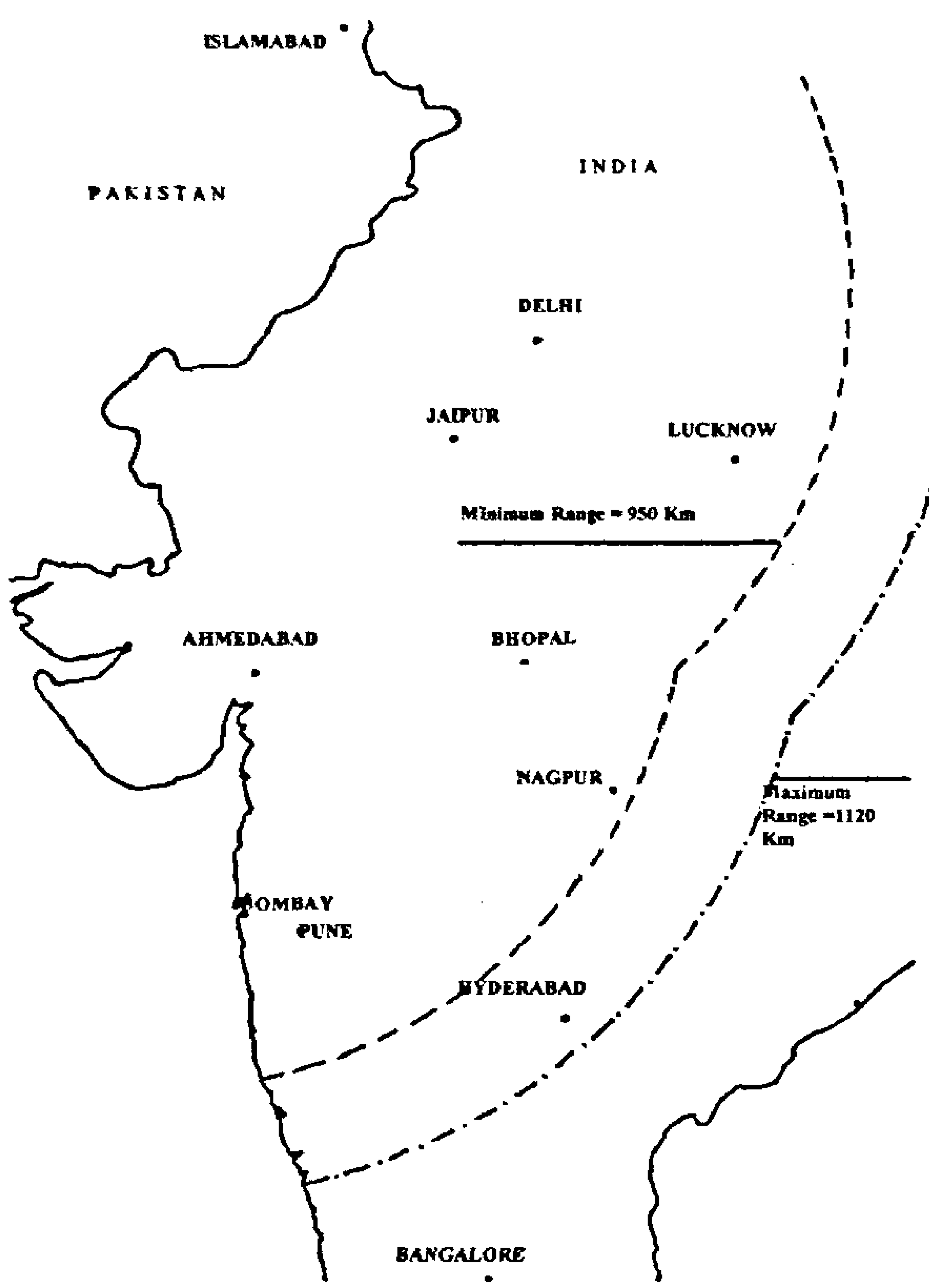

Figure 2. Range of the *Ghauri* missile.

south-eastern launch from the Pakistan border. It also assumes a specific impulse of 235 sec and a payload of 1 tonne. As is obvious, the range with a 1 tonne payload is sufficient to hit Hyderabad. If the *Ghauri* uses IRFNA and RP1, a more realistic-specific impulse to use would be 225 sec. In such a case with a reduced payload of 700 kg the range would still be the same. In all probability the specific impulse of the *Ghauri* would be between these values.

More recently, the North Koreans have reportedly launched a satellite using a three-stage rocket[32]. The first stage of this rocket is the *Nodong-1* and the second stage is reportedly a *Scud*. A third small solid stage is reported to have put a small 13 kg satellite into orbit. US sources have, however, not confirmed a North Korean satellite in orbit and it is not clear whether this was a missile test that failed or a space launch that either failed or succeeded. The trajectory indicates that this was most probably a space launch that did not fully succeed. Reports also seem to suggest that both stages and even a third stage did fire successfully[33,34]. This means that the North Koreans do have the capability to be able to launch a 2-stage missile called the TAEPO DONG based on *Nodong-1* and *Scud* stages with a range of between 1900 and 2100 km and a 1 tonne payload. Such a missile if supplied to Pakistan could threaten all of India from locations well within Pakistan.

Conclusions

On balance the following conclusions seem warranted:

(i) The *Ghauri* is a single-stage liquid missile. The parameters for the missile put out in the Pakistani Press immediately after the flight seem to be compatible with the range reported.
(ii) The range *vis-à-vis* Indian targets with a 0.7 to 1 tonne payload is between 950 km and 1020 km.
(iii) The missile seems to have been bought from North Korea and is almost certainly the *Nodong* missile. A comparison of various parameters like range and the *L/D* ratio lends credibility to this inference. It is derived from the *Scud-B* missile of Russian origin by clustering. Its fuel delivers a specific impulse of between 225 and 235 sec with a specific impulse value of around 230 sec being the most likely possibility.
(iv) It represents a major step for Pakistan and provides a base for the development of even longer-range missiles if needed.

1. For an earlier assessment of Pakistan's development of the Hatf 1, 2 and Hatf 3 missiles see, Chandrashekar, S., ISRO internal report, January 1992.
2. Akhtar Hussain, *Dawn*, Internet Edition, 7 April 1998.
3. Iqbal Anwar, *News Pakistan* (Internet Edition), 7 April 1998.
4. Photograph published in *Outlook*, 20 April 1998, pp. 36–37.
5. Agencies report, *Times of India*, 7 April 1998.
6. Janne E. Nolan and Albert. D. Wheelon, *Sci. Am.*, August 1990.
7. The Federation of American Scientists website http://www.fas.org.
8. The Centre for Defence and International Strategic Studies (CDISS) website http://www.cdiss.org
9. Chandrashekar, S., *Peaceful and Non-peaceful uses of Space: Problems of Definition for the Prevention of an Arms Race* (ed. Bhupendra Jasani), Taylor and Francis, 1991, pp. 77–105.
10. See ref. 1.
11. Hubertus M. Feigl, *Peaceful and Non-peaceful uses of Space: Problems of Definition for the Prevention of an Arms Race* (ed. Bhupendra Jasani), Taylor and Francis, 1991, pp. 129–143.
12. George P. Sutton, *Rocket Propulsion Elements*, 6th edition, Wiley Interscience Publications, p. 126.
13. See ref. 1.
14. From the pictures of the *Ghauri* missile it appears that the *Ghauri* is a single-stage missile since there is no visible evidence of any interstages separating two stages. Experts involved in the design and development of rocket engines and stages for Indian space launchers agreed with this assessment. From the observed plume of the *Ghauri* missile, these experts were of the opinion that the missile was likely to be fuelled by liquid propellants. The plume characteristics of solid propellant and liquid propellant are different in the opinion of these experts.
15. George P. Sutton, *Rocket Propulsion Elements*, 6th edition, Wiley Interscience Publications, p. 194. This has been modified for actual conditions based on discussions with propulsion experts.

16. ISRO-SP-03-94, Liquid Propellant Rocket Engines, Library and Documentation Centre, Shar Centre, 1994.
17. Air & Cosmos no. 1421, Trente Ans de Missiles Balistiques Strategiques Rusees, 12–18 April 1993.
18. The inert weight to propellant weight ratio is governed by engineering considerations that include material and fabrication capabilities. Scale economies related to the size of the engine and stage also play a part in determining this ratio. For the *Ghauri* kind of engine and stage, expert opinion was sought to assess the veracity of the data put out in published sources after the *Ghauri* launch. Experts familiar with the design of similar liquid rocket stages and engines were of the opinion that the inert weight to propellant ratio of 0.1538 was realizable and realistic given the material and fabrication capabilities of countries like Pakistan or North Korea.
19. Robert. S. Norris *et al., Nuclear Weapons Databook*, vol. V, Westview Press.
20. See ref. 7.
21. See ref. 8.
22. See ref. 17.
23. The images used for the analysis are from refs 4 and 5.
24. George P. Sutton, *Rocket Propulsion Elements*, 6th edition, Wiley Interscience Publications, p. 217.
25. See Country briefings in the CDISS website http://www.cdiss.org.
26. See assessment by C.Vick in the Federation of American Scientists website at http://www.fas.org.
27. Air & Cosmos no.1421, Trente Ans de Missiles Balistiques Strategiques Rusees, 12–18 April 1993.
28. For e.g. a report on the North Korean link of the *Ghauri* was carried by *The Hindu* on 2 May 1998. Either by coincidence or by intent, the US imposed sanctions on a Pakistan laboratory almost immediately. *The Hindu*, 2 May 1998.
29. Chidanand Rajghatta, *Indian Express*, 5 May 1998.
30. See ref. 3.
31. See ref. 4.
32. See for e.g. Khergamvalla, F. J., *The Hindu*, 20 September 1998.
33. There is no confirmation from US official sources that a satellite was put into orbit. Other sources especially Russian believe that something was put into orbit. The most authentic source for tracking satellites put into orbit is the data put out by the North American Defence Command (NORAD). NORAD maintains an open web site, which lists current launchings and updates orbital elements for objects in orbit around the earth. The NORAD listings do not include a North Korean satellite as of 26 November 1998. The NORAD web site can be accessed at http://celestrak.com/NORAD/elements/index/html.
34. Jonathan McDowell from the Harvard Smithsonian Centre for Astrophysics runs a weekly service that reports on and provides updates on various launchings around the world. These reports are based not only on sources from NORAD but also other sources and contacts around the world. Weekly reports nos 371, 372 and 373 deal with the North Korean satellite/failed missile launching. Jonathan McDowell's weekly reports of space launchings can be accessed at http://hea-www.harvard.edu/~jcm/space/jsr/jsr.html.

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Induced responses, signal diversity and plant defense: Implications in insect phytophagy

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Damage to plant tissues due to insect feeding induces diverse biochemical and physiological processes generating at the feeding site, signals which move through the plant, eliciting induced responses. Both primary and secondary metabolites change following damage, resulting in changing profiles of allelochemicals. The damaged plant tissues respond in diverse ways, plant signal transduction involving communication within the plant of the concerned responses. Of particular relevance are the proteinase inhibitors which have the potential to contribute towards plant defense against insects, as also of a host of secondary chemicals which differ with different plants. Manipulation of induced plant defense in the regulation and stimulation of natural enemies involving characteristic volatiles emitted by infested plants is also discussed, besides the possible role of induced defenses in pest management.

CHANGES in plant function induced by insect feeding involve consideration of changes in resistance in terms of biochemical, physiological and morphological aspects which tend to alter plant growth, reproduction and storage, restricting, retarding or overcoming further damage essentially through eliciting diverse behavioural chemical stimuli resulting from induction. While constitutive defenses are always expressed in the plant, induced responses following insect damage enable a

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