ASSESSING THE COMPARABILITY OF DUAL-USE TECHNOLOGIES FOR BALLISTIC MISSILE DEVELOPMENT

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EXECUTIVE SUMMARY

Statement of the Problem

As the number of states with nuclear weapons or with the apparent potential to deploy nuclear weapons increases, the development and proliferation of delivery systems become increasingly important. There are a number of delivery systems which can be considered, including aircraft, cruise missiles, and ballistic missiles. While particular requirements and available choice vary, for some countries, solid-fueled ballistic missiles can provide the optimum combination of invulnerability, accuracy, and relative economic and technical feasibility. The purpose of this study is to assess the foreign availability of criticial components necessary for the indigenous assembly of intermediate or short-range ballistic missiles, and to compare those components which are available with those which are manufactured in the U.S.

Tasks

To these ends, the study is broken down into the following tasks:

-- 1. Countries and country-groups of interest are discussed and categorized on the basis of their capabilities to develop and produce complex and technologically advanced weapons systems. For the purpose of assessing indigenous capabilities to develop ballistic missile systems, two broad categories are defined. The first includes those states which have demonstrated the capability to produce advanced weapons, such as India, Brazil, Israel, Taiwan, and South Africa. The second group includes states with a somewhat lesser capability, such as Argentina, Pakistan, Indonesia, and

Egypt. In addition, the key parameters of interest in the assessment of ballistic missile performance, such as payload, range, accuracy of delivery, and reliability, are delineated and minimum criteria for the development of an operational ballistic missile are established.

-- 2. The resources required for the development of ballistic missiles are examined. The major tasks necessary for such an effort are broken down, and the resources required to meet the performance criteria are discussed in terms of personnel, facilities, and materials. On this basis, resources which are available indigenously are distinguished from those which must be acquired abroad with respect to each of the country categories. (Table 1) In particular, guidance and propulsion systems are identified as essential components likely to be procured externally by even the more advanced group of countries.

-- 3. As guidance and propulsion systems emerge as the primary components which are likely to be procured externally by both categories of states, the foreign availability of these systems is examined in detail. In each case, following a general discussion of the types of applicable systems, those which are manufactured and are potentially available are identified. In addition, problems of adaptability and modifications which are required on systems for use in ballistic missiles are discussed. This is followed by an examination of the significant parameters which can be used to compare and evaluate the relative performance of "off-the-shelf" guidance and propulsion systems in the context of ballistic missile development.

-- 4. Various propulsion systems are then compared using a specific trajectory model. A variety of single- and two-stage systems is run through the model of the trajectory to yield ranges for payloads between 250 to 1500 kilograms. This allows for the comparison of the performance of systems including components manufactured in the United States with the performance of those for which U.S. suppliers have been excluded. (Table 4)

Findings

-- 1. The development and production of solid-fueled ballistic missiles with ranges between 1000 and 2000 kilometers is technically within the capabilities of states with experience in the production of advanced weapons systems, and military aircraft in particular. This group of states includes India, Brazil, Israel, Taiwan, and South Africa. States with lesser capabilities in this area, such as Argentina, Pakistan, and Egypt will require greater external assistance.

-- 2. Efforts by both groups of states are likely to be dependent on externally procured guidance and propulsion systems. Potentially applicable guidance systems are manufactured in a number of states, including the United Kingdom, France, and the United States. Detailed assessment of the comparability of these systems is not possible as many of the key performance parameters are not available in catalogues or from ordinary contacts and discussions with suppliers. They can only be obtained by actual measurements and testing of samples, and perhaps by detailed discussions with suppliers in which the suppliers assume a real sale will result. In particular, the unclassified available data does not allow for the meaningful, quantitative comparison of the performance of ballistic missiles which include inertial navigation systems (INS) supplied by U.S. manufacturers with the performance of those from which U.S. suppliers have been excluded. However, a limited assessment of the relative capabilities of various guidance systems can be made which includes a qualitative classification of potentially useful, adaptable and available systems. On the basis of this assessment, we conclude that there are approximately 15 "dual-use" INS systems manufactured by Western European firms which are potentially applicable to ballistic missile development.

-- 3. Detailed data for the evaluation of solid propulsion systems is generally available. Using this data of the model discussed above, we conclude that there are ten single-stage rockets which can carry a 500 kilogram payload at least 1000 kilometers. Of these, six are manufactured in the U.S., two in France, and two in Italy (the Ariane Booster and the Alfa). There is also a variety of foreign-manufactured two-stage systems with ranges from 200 to 930 kilometers (with 500 kilogram payloads). In addition, combinations of U.S. and foreign manufactured stages could potentially yield similar range-payload combinations.

General Conclusions

Assessments of the foreign availability and comparability of weapons components such as guidance systems are hampered by two factors.

-- 1. The actual availability of components is not clear in the absence of an effort to purchase them. While some systems may be advertised or listed in catalogues, they may not be available to all purchasers. At the same time, systems which are not listed in catalogues may be made available to real or prospective customers.

-- 2. In some cases, the performances of potentially available components are environmentally dependent and the necessary data is not published nor readily obtained. In the case of guidance systems, performance in a ballistic missile is substantially different from performance in an aircraft and the evaluation of particular systems requires a test program to determine the necessary coefficients.

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I. INTRODUCTION

Problem and Scope

As the number of states with nuclear weapons or with the apparent potential to develop nuclear weapons increases, the assessment of the capabilities of these states to deliver these weapons becomes an increasingly salient arms control issue. In the past, United States policy has focused on controlling weapons proliferation. In the light of recent developments it must also now consider the prospects and avenues for controlling the proliferation of delivery systems.

The delivery vehicles potentially available to a Third World state or less developed country (LDC) include manned aircraft, cruise missiles, and surface-to-surface ballistic missiles. The particular choice of delivery system for each state will depend on the objectives and capabilities of that state. For a nation seeking a small number of relatively unsophisticated nuclear weapons, manned aircraft provide the simplest, most direct method of delivering nuclear weapons. Civilian and military aircraft of many different types are widely available, and in the absence of air defense, can be highly accurate. The countries of interest all have a cadre of trained pilots and maintenance personnel. Whatever aircraft modification might be required should be well within the technical capabilities of most of these countries. Organizing and structuring a delivery capability using aircraft would be least visible and can be accomplished with the least likelihood of arousing suspicion (assuming that this is a concern) and therefore external political pressure.

On the other hand, aircraft are slow and easily tracked and may have to penetrate air defenses. Also, since most aircraft can only be "launched" from airfields, they are more vulnerable on the ground than small cruise missiles or ballistic missiles. As a result, alternative delivery systems are likely to be sought.

Cruise missiles, which are frequently cited as possible nuclear delivery vehicles, are also relatively slow vehicles, but in a terrain-hugging flight path are less vulnerable to defensive measures than larger manned aircraft. Vulnerability to air defenses would still be a concern, however, if only a few cruise missiles were to be deployed.

The simplest type of cruise missile would be an aircraft modified for unmanned operation using inertial or radio guidance. However, an all-inertial system would provide relatively poor accuracy of delivery (on the order of one percent of the range) and any radio link would be subject to jamming.

A cruise missile of the type now being developed in the U.S. is far too complex for an industrializing country to manufacture. It requires an advanced, sophisticated engine and a terrain contour guidance system (with accurate contour maps) both of which would tax the capabilities of even advanced industrialized states. Simpler cruise missiles can be designed but they would be larger and more observable to an air defense system. In addition, it is our judgment that the development of cruise missiles of sufficient sophistication to provide an advantage over other systems would be beyond the capabilities of many of the countries we are considering in this study. Development would perhaps be facilitated if the major components (engine, guidance, etc.) were available from foreign suppliers, but they are not. In addition, if cruise missiles were designed to operate in an environment which includes effective defense systems, a significant force would include a large number of systems.

Ballistic missiles, on the other hand, can provide rapid and potentially reliable delivery vehicles against which defensive measures are essentially non-existent. A ballistic missile is more readily "hardened" in a protective enclosure than an aircraft, and does not require a runway for launching. In this sense, it is less vulnerable to a first strike. Its relatively short flight time, measured in terms of minutes, allows for a much more rapid response than would be available from aircraft or cruise missiles. Thus, militarily, there are a number of advantages to a ballistic missile force relative to other delivery vehicles.

There are also a number of potential disadvantages associated with a ballistic missile force. In the first place, nuclear warheads for ballistic missiles require greater sophistication than weapons designed for aircraft delivery. As a result, if the number of nuclear tests is limited, the reliability of a ballistic missile warhead may be relatively less than a weapon designed for aircraft delivery. In addition, fixed ballistic missiles which are not protected in a hardened silo may be more vulnerable than maneuverable aircraft in some circumstances.

After weighing these potential advantages and disadvantages, a state with a very small number of nuclear weapons which can develop a sophisticated nuclear "package" and seeks to maximize the probability that the target will be reached, either to increase the credibility of its deterrent or to use in a war, may be particularly attracted to a ballistic missile force. Furthermore, as we shall demonstrate below, the development of intermediate-range ballistic missiles (IRBMs) can be assisted, to a significant degree, by imported "dual-use" technologies.

Dual-Use Technologies

There are a number of paths by which an industrializing state could potentially obtain ballistic missiles. In the first place, weapons systems are often available for purchase. Combat aircraft, tanks, and a variety of small missiles are routinely made available to such users by a variety of producers.

In addition, weapons systems can, at least in theory, be developed indigenously, using some components which are manufactured locally, perhaps under license, and some which are purchased abroad.[1] The ratio of imported and locally manufactured components depends, in part, on the availability of systems or the resources for internal production. Weapons systems, such as nuclear weapons, which are not available for purchase must be manufactured internally. In addition, even though a system may be available for purchase, states which have the resources for internal production of weapons systems may find economic and political reasons to engage in such production. This alternative allows states to maintain secrecy, develop an indigenous technology, minimize the expenditure of hard currency, and avoid the political and technological dependence which results from reliance on foreign suppliers. Thus, India and Israel, for example, produce and design most of the components for military aircraft, and manufacture other components, such as engines, under license. Weapons system parts which are manufactured indigenously are readily replaced, maintained, and upgraded, which also contributes to the attractiveness of this method.[2]

Intermediate-range ballistic missiles (1000 to 2000 kilometers) are generally not available for purchase. No such systems are manufactured for commercial export (although in some special cases [Polaris/Poseidon] ballistic missiles have been sold to close allies). A large number of components for such a development program, however, can be procured externally, including such critical components as guidance and propulsion systems. These systems were not specifically developed and manufactured for use in ballistic missiles, but were developed for uses in other military and civilian systems. For example, guidance systems developed for use in military as well as in civilian aircraft may well be useful in ballistic missiles.

Such systems fall broadly in the category of "dual-use" technologies. Included in this category are systems and components which, while ostensibly designed for non-military purposes, can be adapted to military uses. Civilian radios are readily turned into military radios, and aircraft designed for civilian uses can be converted into bombers with relative ease. "Dual-use" technologies are found in a variety of other areas, including aircraft production, tank and armored personnel carrier manufacture, and nuclear weapons development. Computers designed for truck manufacture have reportedly been used by the Soviet Union for the production of troop carriers,[3] and the military implications and potential of "civilian" nuclear power facilities have been studied at great length.

In the area of ballistic missile development, however, many essential components are not readily applicable to clearly civilian or other military programs. For example, the uses of rocket engines large enough for a ballistic missile are very limited, and include only satellite launch vehicles and atmospheric sounding rockets designed to carry scientific payloads into the upper atmosphere.[4]

In this sense, however, the "dual-use" nature of rocket propulsion systems is apparent. The U.S. and Soviet Union have both used ICBMs as boosters in their space programs. The Atlas and Titan rockets which placed U.S. satellites and astronauts into orbit were designed as delivery vehicles for nuclear weapons. According to reports, the Soviet Union also replaced the nuclear warheads on top of SS-5 and SS-6 ICBMs with satellites and these military missiles became space boosters.[5] Similarly, the systems used in India to place a satellite into orbit and those under development in Brazil for the same purpose are "dual-use" systems, in that they can also be used, wholly or as components, as ballistic missiles.

Whether the objectives and motivations for the Indian and Brazilian space efforts are primarily military or civilian, both states are devoting scarce resources to these efforts. Other states may seek to develop similar capabilities, but either lack or are unwilling to devote similar resources. Instead of a large-scale indigenous development effort, such states may seek to purchase "dual-use" components for such a ballistic missile system abroad.

In this study we will endeavor to identify, assess the availability, and compare critical dual-use technologies applicable to ballistic missile development. To these ends, the study is broken down into the following sections and tasks:

-- In Section II (Task I), countries and country-groups of interest are discussed and categorized on the basis of their capabilities to develop and produce complex and technologically advanced weapons systems. This discussion, which is based on the experience of one of the authors (Yaron), provides a basis for the evaluation of the relative capabilities of these states to develop and produce intermediate-range ballistic missiles. This section also delineates the key parameters of interest in the assessment of ballistic missile performance, such as payload, range, accuracy of delivery, and reliability, and minimum criteria in these areas are established.

-- Section III consists of a general discussion of the resources required for the development of ballistic missiles (Task II). The major tasks necessary for such an effort are broken down, and the resources required to meet the performance criteria established in Section II are discussed in terms of personnel, facilities, and materials. On this basis, resources which are available indigenously are distinguished from those which must be acquired abroad with respect to each of the country categories established in Section II. In particular, guidance and propulsion systems are identified as essential components likely to be procured externally.

-- Sections IV and V examine the foreign availability of guidance and propulsion systems in detail (Tasks III and IV). In each case, following a general discussion of the types of applicable systems, available systems are identified. In addition, problems of adaptability and modifications which are required on systems for use in ballistic missiles are discussed. This is followed by examinations of the significant parameters which can be used to compare and evaluate the relative performance of "off-the-shelf" guidance and propulsion systems in the context of ballistic missile development.

-- Various propulsion systems are then compared using a specific trajectory model. A variety of two-stage systems is run through the model of the trajectory to yield range-payload combinations. This allows for the comparison of the performance of systems including components manufactured in the U.S. with the performance of those from which U.S. suppliers have been excluded (Task V).

Such comparison and relative assessment will, however, be shown to be far more difficult in the case of guidance systems. Many of the key performance parameters of guidance systems are not available in catalogues or from ordinary contacts and discussions with suppliers. They can only be obtained by actual measurements and testing of samples, and perhaps by detailed discussions with suppliers in which the suppliers assume a real sale will result. In particular, the unclassified available data does not allow for the meaningful, quantitative comparison of the performance of ballistic missiles which include INS systems supplied by U.S. manufacturers with the performance of those from which U.S. suppliers have been excluded. However, a limited assessment of the relative capabilities of various guidance systems can be made which includes a qualitative classification of potentially useful, adaptable, and available systems.

II. CATEGORIES OF STATES AND KEY PARAMETERS

The design and manufacture of a ballistic missile, whether largely indigenous or based on imported components, requires resources and personnel which are frequently found in the manufacture of other advanced weapons systems. As will be discussed in detail below, local aircraft industries can provide a technical foundation and skilled personnel for a ballistic missile development program. Thus, the nature and level of sophistication of the national aircraft and other weapons industries can serve as key criteria in the evaluation and categorization of the capabilities of industrializing (non-Organization for Economic Cooperation and Development) and less developed countries (LDCs) to develop and manufacture ballistic missiles.

On this basis, two large groups of countries can be discerned. The first group includes those states which have demonstrated capabilities to produce technologically advanced weapons systems, and aircraft in particular. India, Brazil, Israel, Taiwan, and South Africa produce various types of aircraft. While many components, including, in many cases, engines, are manufactured under license, or, in some cases, imported, other components, specifically air frames, are of local design. Although South Korea has not produced aircraft, it does have a military shipbuilding industry which produces ships of local design as well as under license.[6] In addition, a contract which calls for coproduction and assembly of Northrop F-5s in South Korea, has recently been concluded.[7]

States in this first category have demonstrated an advanced technological capability and infrastructure necessary to design and develop technically complex and sophisticated military systems. Two of these states, India and Brazil, have announced ongoing rocket development programs. India has developed and successfully launched a booster which has placed a satellite into orbit, and Brazil is well advanced in this process. These space boosters will also be able to serve as a basis for the production of ballistic missile delivery vehicles.

A second group of states, including such countries as Argentina, Pakistan, Egypt, and perhaps Indonesia, possesses a somewhat less-advanced technological base, but still demonstrates some interest and capability in this area. Such countries may have some aircraft assembly facilities, but do not manufacture advanced aircraft or complex weapons systems. Similarly, a few individuals may be found to be doing research in the areas of propulsion and guidance, but these are relatively sparse when compared to states in other categories. While, as will be seen, these countries may be capable of developing a ballistic missile from available dual-use components, they will be faced with more obstacles than the states with broader technological bases.

The nature of ongoing research and the development of experience and expertise in the areas of guidance and propulsion are reflected, to some degree, in research publications in these areas. In a search of three large data bases,[8] 41 papers by Indian authors were found dealing with solid propellants and there were 11 in the area of gyroscopes, guidance, inertial systems, and accelerometers. Israeli authors have published 14 papers on guidance-related topics and two on solid propellants. In addition, individual papers on solid propulsion have been published in Taiwan and Argentina and on inertial navigation in Argentina, Pakistan, and South Africa. (The South

African articles are in the context of mining operations, but many of the techniques described, such as the use of gyrocompassing to determine azimuth, are applicable to ballistic missile development.) While these publications indicate ongoing research and the development of expertise in countries like Israel, Argentina, and Taiwan, the lack of entries for Brazil and South Korea should not be taken as evidence that research and development in the areas of propulsion and guidance is not taking place, but rather may reflect publication policies in these countries.

Choice of Key Parameters for Evaluation

In the evaluation of the capabilities of any potential delivery vehicle for nuclear weapons, the key parameters are payload, range, accuracy, and reliability.

Payload

In order to serve as a delivery vehicle for relatively crude and unsophisticated nuclear weapons, we will assume a minimum payload of 500 kilograms.[9] This figure represents a rough estimate of the size of a 10 kiloton weapon which has undergone limited testing and is based on the evolution of nuclear weapons in the U.S. While smaller weapons could conceivably be developed, their reliability is likely to be relatively more uncertain in the absence of an extensive testing program. In order to evaluate the impact of different sized warheads, however, ranges are also computed for warheads of 250 kilograms, 750 kilograms, 1000 kilograms, and 1500 kilograms.

Range

Given a specific payload weight, the range of a missile can be computed. While ranges vary from a few kilometers for small tactical missiles to thousands of kilometers for large strategic missiles, we are primarily interested in missiles of intermediate range. Although short-range missiles could inflict great damage if wheeled up to the border and fired, one can assume that nuclear-armed missiles would be launched from secure sites well within national boundaries. Thus, ranges from such possible launch sites in the interior to potential targets are of interest. In examining potential launch sites and targets, it is clear that such intermediate "strategic" distances range from 400 to 2000 kilometers, depending on the particular regions of interest. In many cases, however, optimal distances are at least 1000 kilometers. Thus, the most important militarily significant ballistic missiles include those with ranges of from 1000 to 2000 kilometers. Systems with smaller ranges are not as useful, while, as will be seen below, those with greater ranges are significantly more difficult to assemble from available "dual-use" technologies.

Accuracy

The accuracy necessary for a ballistic missile delivery system is, to a large degree, a function of the purpose of that system. If the major motivation of such a program is political and symbolic, designed to increase national status and prestige, poor accuracy and a circular error probability (CEP) measured in terms of kilometers may be sufficient. On the other hand, if the primary purpose is to develop an operational system, the accuracy becomes more critical. As a "countervalue" system or deterrent, designed to be aimed at "soft" targets, such as cities, a ballistic missile with a nuclear warhead requires an accuracy of a few kilometers. However, in a system designed for use against specific targets, such as military bases or installations, or against opposing nuclear delivery vehicles, accuracy of a few hundred meters or less would be necessary, particularly with respect to "hard" targets.

Reliablity

The reliability required of a ballistic missile system varies, like the accuracy, with the purpose of that system. As a political symbol, a single success, as in the case of the Indian nuclear test and satellite, may be sufficient. On the other hand, for an effective weapons system, higher reliability is necessary. A system that is perceived as unreliable and not likely to be operational in times of crisis would not be a very effective military instrument.

The reliability of particular systems may vary greatly and design criteria in this area are to some degree contingent on the available resources and production costs. In some cases, a larger quantity of less expensive and less reliable systems may be more cost effective than fewer but more reliable systems.

III. DISCUSSION OF RESOURCES REQUIRED FOR DEVELOPMENT OF BALLISTIC MISSILES

For the purposes of analysis, a program to develop a ballistic missile is similar to other engineering projects involving advanced technology. In the case of missile development, the basic structural requirements include project management, systems analysis and integration, structure and static testing, propulsion, guidance and control, and flight testing.

The particular structure of the development program will depend, to some degree, on the speed with which a final product is required. A crash program will clearly have requirements which are different from a more leisurely research and development program. In the latter case, less experienced and qualified personnel may take the time to gain experience, but in a crash program this time is unavailable.

Personnel, Facilities, and Materials Required

Project Management

The overall coordination and management of a project with the complexity of ballistic missile development requires personnel with similar experience in comparable programs. This group is responsible for assigning personnel and resources, directing the manufacture of components (see below), and purchasing compatible subassemblies abroad.

Managers of aircraft factories and production facilities for other technologically advanced military vehicles would be most likely to possess the skills and experience necessary for the integration of the large number of individual tasks involved in missile development. Five to ten professionals with both the necessary managerial and technological competence and experience are necessary for the management of the project.*

Systems Analysis and Integration

These groups are responsible for choosing the basic configuration of the missile, determining its specifications, such as range and accuracy, and integrating the various components. On the basis of the specifications, systems analysts are responsible for making fundamental design decisions, such as the designation of a particular mode of control for the system (see below).

Fifty to one hundred professionals, including academics and engineers with experience in missiles and rocket propulsion, are necessary for these groups. Within this group, particular expertise in the areas of flight dynamics control and instrumentation, computers, vibration analysis, and terminal ballistics and tracking is required for design and for the analysis of the performance of subassemblies and the completed system. While most of these individuals are available in aircraft industries, terminal ballistics experts are likely to be found in ordinary manufacturing. These functions will also require computational facilities, such as an IBM 370 or a CDC 6000 Series system, which is not likely to be found in the aircraft industry, but can be provided by other sectors.

Structure and Static Testing

The structural components essentially link the various systems together, both physically and operationally. The two stages of the rocket must be connected, generally through an interstage which includes pyrotechnic devices

*The number of personnel required as specified in this and other sections is based on the experience of one of us (Yaron).

and other equipment, and the warhead must be attached. This requires the manufacture and testing of interstage structures which are compatible and able to meet stringent requirements for balance and stability. For this purpose, assembly fixtures and jigs, which allow for precision mounting and manipulation of components for machining and assembly, must be manufactured.

In order to insure the proper distribution of stress along the missile and to enhance structural integrity, a series of static tests must be performed on the structure. This requires such test equipment as static load frames, beams and stands, strain gauges, proportional amplifiers, environmental test facilities, and vibration tests. On the basis of these tests, the strength of the missile structure and subassemblies can be verified, and, if necessary, design changes introduced. Finally, a rocket test stand to test the propulsion unit, and accompanying high temperature gauges, and photographic equipment is required.

The manufacture of the various structural and static test equipment and the execution of these tasks requires from 60 to 100 experienced mechanical engineers, structural metal workers, and skilled fitters and assemblers. Particular expertise in the areas of stress analysis (in order to simulate the flight profile on the test stand), strain gauge attachment, and the computer software necessary for data reduction, is required. This expertise can generally be found in aircraft production and perhaps in the shipbuilding and machine tool industries. Most of the design and assembly of test facilities, however, can be undertaken by personnel from the areas of bridgemaking, and crane and lifting machine manufacture.

Guidance and Control

Guidance and control systems are highly complex and difficult to design, develop, and manufacture. Thus, these components, including an inertial monitoring unit (IMU), flight computer, auto pilot, and input/output units, are likely to be sought abroad (see Section IV). The guidance and control group is responsible for the analysis of the adaptability of the available inertial navigation systems to the overall system. As will be discussed in detail in Section IV, each system must be analyzed in terms of its stability, resistance to acceleration and shocks, adaptability to the forces encountered in the trajectory of a missile, and the control system (hydraulic or electromechanical). This task requires from 20 to 30 highly qualified personnel with experience in control systems and precision instruments. Ten to twelve such people are required to test the IMU itself. Any system which is chosen is likely to have a significant rate of deviation from the advertised specifications, so that each system must be tested and retested. The training and experience necessary for this task can be developed in aircraft manufacturing and maintenance programs. The facilities which are required for this task include a three-axis test table with readout and computing equipment which will permit the evaluation of the performance of navigation equipment, and test stands for accelerometers and standard geodetic reference devices. In addition, this group is generally responsible for the electrical systems in the missile. Both single-shot batteries and stabilized power supplies (thermal batteries, high voltage, and discharge units) which are adaptable to the acceleration profiles of missile flights are necessary. Due to high load requirements of missile systems, aircraft power supplies are not readily adaptable.

Propulsion

As will be discussed in greater detail below, solid-propulsion systems are more likely to provide the basis of a ballistic missile developed from imported technology. In a project using externally procured solid rockets, the propulsion group is concerned primarily with the selection and purchase of motors -- including igniter, nozzle, and fuel -- with pyrotechnics, and with the testing of these systems. In addition to investigating and analyzing available propulsion and pyrotechnic systems, this group must also adapt and integrate these systems into the rest of the structure. In the event that the motors which have been selected do not include a steering system, such a system must be designed and developed (see Section V). Finally, the group must participate in the testing of the rocket motors to generate thrust-time, pressure-time, and stress temperature curves. Such testing will require a pyrotechnic handling facility (a protected bunker), and measuring and computation equipment. A total of 20 to 30 professionals is required for this group.

Flight Tests

These tests require 30 to 35 people for short periods of time. Twenty technicians are necessary for operating the radar facilities at the test range and can usually be provided by the Air Force. An additional 15 people are required to operate high-speed cameras, photo-theodolytes, and other range equipment.

In summary, the design, development, and production of a ballistic missile will require a minimum of 200 to 300 skilled and highly trained personnel, and a significant supporting infrastructure of personnel and facilities. Many of these can be supplied by an aircraft industry (see Table 1). In addition, individual specialized components, including batteries, a guidance system, pyrotechnics, telemetry, and propulsion units are necessary. Having established these requirements, we can now proceed to analyze the potential sources for their provision, both indigenous and imported, and, in particular, to identify those areas in which external assistance is most important.

Distinction Between Indigenously Available Resources and Those Which Must Be Acquired Abroad

Personnel

As noted, the design and development of a ballistic missile, taking maximum advantage of externally acquired "dual-use" technology, will require from 200 to 300 skilled and highly trained personnel, from project managers to stress analysts and computer programmers. Most of the required expertise can be found in a country with an aircraft manufacturing facility. Thus, countries like Israel, India, and Brazil can be expected to have the necessary personnel to staff a dual-technology ballistic missile development program. States with less extensive aircraft manufacturing capabilities, such as Taiwan, South Africa, and South Korea, may also be able to gather together the requisite number of qualified engineers and managerial and other specialized personnel, but at a greater cost.

The third tier of states with limited aircraft-related industries, such as Pakistan and Argentina, will find it difficult to locate indigenous and experienced guidance, propulsion, test, software, and management personnel to supply indigenous expertise. However, these states may seek to "import" experts from abroad, particularly in the area of guidance and propulsion. In this sense, the nuclear industry may again provide an analogy. In this area, technicians and engineers have been recruited across international boundaries for a variety of both civilian and "dual-use" projects. In the case of ballistic missile technology, foreign expertise is likely to come from the U.S. and Europe. In some cases, countries selling individual components may provide some skilled personnel on a contractual basis. In the nuclear power industry, for example, technicians are often provided to maintain facilities which are exported to other countries.[10]

Individuals with particular skills may also make themselves available for work on national ballistic missile development programs. The volatility of the aerospace industry has, at times, made a large pool of experienced engineers from the U.S. space and ballistic missile programs available and there is evidence that they are being actively recruited by other states.[11] Individuals with technical backgrounds are highly mobile and may be attracted by high salaries and fringe benefits available in other states.

A second source of personnel is the Western European space and ballistic missile development programs. While the number of experienced personnel which are available is much smaller than in the case of the U.S., some may be recruited by states for work on the development of ballistic missiles. For example, there are approximately 240 personnel involved in the effort by a non-governmental group (OTRAG) from West Germany to develop "commercial" satellite launch facilities. While they began their work in Zaire, they were expelled in response to West German pressure and are now reported to be operating in Libya.[12]

Components

Given the complexity of a ballistic missile development program and the cost of a totally indigenous effort, most states which seek such a capability are likely, as noted above, to depend on imported technology for the most complex and costly components, and support equipment when available. Thus, only those components which are not readily available abroad or are relatively simple are likely to be manufactured indigenously.

Those items which are likely to be procured externally are summarized in the accompanying table. Most of these systems, subassemblies, and components are available from a variety of sources and should not pose a particular procurement problem. However, certain components necessary for ballistic missile development, such as single-shot batteries, tracking radar and equipment, pyrotechnics, guidance systems, and propulsion units are not widely available. There are three manufacturers of single-shot batteries outside the U.S. -- one in the U.K., one in France, and one in West Germany.[13] Pyrotechnics, while found in many industrial catalogues, are not always sold to any purchasers, although experience has shown that at a sufficient price, such items are available. Finally, and most importantly, there are a relatively small number of sources of guidance and propulsion systems which are adaptable to ballistic missile programs. As a result of the importance of these components to any such development effort, foreign availability of these systems will be discussed in detail in the following chapters.

TABLE 1
COMPARISON OF RESOURCES REQUIRED FOR MISSILE DEVELOPMENT WITH THOSE AVAILABLE FROM AIRCRAFT INDUSTRIES

	AVAILABILITY IN AIRCRAFT INDUSTRY			
RESOURCES REQUIRED FOR MISSILE DEVELOPMENT	ASSEMBLY ONLY	LICENSED PRODUCTION	DESIGN & PRODUCTION	AVAILABLE FROM AIR FORCE
1. Management				
5 to 10 Individuals	*	*	*	
2. Systems Analysis & Integration				
Specialists:				
Flight Dynamics			*	
Control & Precision Instruments and Programmers	*	If produced in aircraft	*	
Computer Aided Design	*	*	*	
Vibration	*	*	*	
Tracking		*	*	If well equipped
Terminal Ballistics	--------------Ordinance Engineering-----------			
Computers	--------Must come from computer industry------			
3. Structure and Static Testing				
Photo Equipment				
Jigs	*	*	*	
Static Load Frames & Stands	*	*	*	
Strain Gauges	*	*	*	
Environmental Test Facilities		*	*	
Vibration Test Facilities		*	*	
Assembly Fixtures	*	*	*	

Note: * = Capability available in sector.

RESOURCES REQUIRED FOR MISSILE DEVELOPMENT	AVAILABILITY IN AIRCRAFT INDUSTRY ASSEMBLY ONLY	LICENSED PRODUCTION	DESIGN & PRODUCTION	AVAILABLE FROM AIR FORCE
Mechanical Engineers:				
Structural Metal Workers		*	*	
Skilled Fitters & Assemblers	*	*	*	
Stress Analysts			*	
Computer Programmers & CAD			*	
4. <u>Guidance & Control</u>				
20 Professionals in Control System & Precision Instruments	----Must come from control systems industry----			
12 Professionals to Test IMU	-----Instrument technicians (from Air Force)------ --can be trained by the manufacturer of the IMU--			
3 Axis Test Tables			?	
Single-shot batteries	----------Torpedo manufacturing facility--------------			
Stabilized power supply	------Electronics industry-----------			
5. <u>Propulsion</u>				
20 to 30 Specialists				
Pyrotechnic Handling Facility				Army
6. <u>Flight Tests</u>				
Radar Technicians				*
Radar Equipment				
Test Range				
High-Speed Cameras		*	*	
Photo-Theodolites		*	*	
15 Specialists		*	*	*

Note: * = Capability available in sector.

IV. ASSESSING FOREIGN GUIDANCE AND CONTROL SYSTEMS

General Discussion of the Problem and Types of Applicable Systems

The guidance system serves as the brain and central nervous system of the missile. Without such a system, the missile would go off in random directions and would be incapable of performing any task other than threatening to hit any point within its range, including the launch site. Similarly, the better the guidance system, the greater the accuracy and reliability of the system.

Given the complexity of the guidance task, this system is likely to be imported. In this context, three types of guidance system can be distinguished: external command systems, flight programmers, and inertial navigation systems (INS).

External guidance systems rely on radio signals transmitted from the ground, while the other two systems are self-contained. External systems, however, including "beam riders" are subject to deliberate electronic interference. Electronic flight programmers carry a predetermined "most probable" trajectory and an automatic sequencer which issues instructions on the basis of this trajectory. Such devices do not measure the instantaneous position, velocity of acceleration of the missile, and, as a result, are imprecise and unreliable. They can be used in the testing stage of missile development instead of an expensive and potentially scarce inertial measuring unit (IMU), but are half to one third less precise than an IMU. An inertial guidance system is based on an IMU consisting of gyroscopes and accelerometers mounted on a platform, and an associated flight computer. The IMU measures instantaneous accelerations and angles in three dimensions during the powered flight. (More advanced missiles also use the IMU for terminal guidance.) These six measurements are transmitted to the flight computer to calculate the missile's position, which is then compared with the programmed trajectory. The difference, in the form of an error signal, is used to control the missile, usually through an automatic pilot which manipulates the aerodynamic or thrust vector controls of the missile.

Prior to launch, the trajectory must be fed into the memory of the flight computer and the platform (which serves as a reference system for the IMU) must be aligned in the plane of the trajectory. This alignment can be performed optically or by using the gyroscopic capacity of the IMU as a gyrocompass. The former system relies on geodetic measurement of the direction of the desired flight plane. A collimator is used to compare this direction with the direction of the inner mounting platform in the missile, which is then redirected by remote control in line with the flight plan. A gyrocompass alignment uses the north-south precession of the gyros in the platform to determine the geographical north. This is compared with the direction of the flight plane via the computer, and the difference in the form of an error signal is used to reposition the inner mounting of the platform. In contrast to optical alignment, gyrocompassing is entirely internal to the inertial system and requires no additional equipment. It should be noted, however, that not all IMUs can be operated as gyrocompasses.

Availability

In choosing a guidance system from among those manufactured abroad, an LDC must first consider the question of availability. While many systems are produced in a number of countries, and are advertised in catalogues, not all such systems are available for purchase, and of those which are available, not all are readily adaptable to missiles.

Programmable guidance units must be specifically designed and manufactured for particular projects, including missile development. Although sequencers are available in theory, they require such a great degree of adaptation and individual reworking as to be considered as components which require special development. The process of development is iterative, relying on numerous flight tests for gradual improvement, and is therefore costly, time consuming, and far from the "off-the-shelf" design philosophy which is likely to be pursued by an LDC.

In contrast, INS units can be purchased for use in missile development programs as "off-the-shelf" items. Such units are usually available as spares or replacement parts for exported aircraft, both civilian and military. For the purposes of this study, such systems can be considered as available for purchase. It should be noted, however, that availability may vary with the particular customer. A variety of political and economic factors may influence decisions to sell items to one customer or to withhold items from another.

Adaptability

Most internal navigation units which are available as "off-the-shelf" components were designed for use in aircraft. As a result, not all can be used in ballistic missile programs, and those that are useful must be adapted. There are a number of factors which limit the adaptability of aircraft INS systems to ballistic missiles, including hardware limitations, significant differences in the flight profile which affect performance, and the different alignment procedures for the INS in a ballistic missile system.

Hardware Integrity

All INS systems occupy a certain physical space and have a defined weight, volume, and configuration which are not readily altered. In some cases, these specifications may be incompatible with the missile: the weight may be too great, or the surface area greater than that of the missile structure. In addition, in aircraft INS systems, the direction of the sensors is generally unimportant (except that they be mounted orthogonally), but in ballistic missiles, there are preferred orientations selected to minimize the acceleration dependent errors.[14] Therefore, given a specific missile structure, an INS system which can be so oriented must be chosen.

Furthermore, while the acceleration of most aircraft is relatively low and constant, ballistic missiles are subject to high acceleration (20 g's or more) and sudden changes of acceleration at staging. This subjects the components, including INS, to greater forces and torques which may weaken their structure and affect performance. An INS system must be chosen which can withstand these forces.

Finally, the INS performance may be a function of the physical environment in which it is placed. In a ballistic missile trajectory, an INS is subjected to greater temperature extremes than in a conventional aircraft environment, so that the system chosen must be capable of adequate temperature control or operation across a wide range of temperatures. More importantly, pressures vary from one atmosphere to near zero (vacuum) in a very short period and many

INS systems which are sensitive to such pressure changes will be severely degraded. In particular, those which are lubricated by some type of oil or other liquid or are housed in a gaseous container must be artificially pressurized.

Impact of Flight Profile on Performance

Although the physical structure of an INS may be able to withstand the differences between the high acceleration rates of a missile flight profile and that of an aircraft, this difference also affects performance of INS systems. In an aircraft, these error sources (particularly those which are proportional to g^2 and g^4) are relatively insignificant. In the case of a ballistic missile, however, these terms are far more important. A system which is highly accurate in an aircraft may be very inaccurate in a missile, so that an INS must be chosen in which these contributions to the error are minimized.

In addition, the difference between the flight profile of a missile and aircraft introduces other variables which must be considered. An aircraft flies relatively close to the surface of the earth, and, as a result, aircraft can use a barometer or radar altimeter to get altitude data, obviating the need for one of the three gyroscopes in the INS. In a ballistic missile, however, this vertical channel must be mechanized. Similarly, INS systems designed for aircraft rely on torquing to maintain an earth-referenced orientation. To maintain such an orientation in a ballistic missile trajectory, torquing commands which are far more complex are required. In some cases, the torquing motor and electronics are not adequate for this task.[15]

Alignment

The alignment of an INS in an aircraft is relatively simple and autonomous, requiring only the input of the initial position, and initial errors are readily corrected by the pilot. The alignment of a ballistic missile is more complex, particularly with respect to the azimuth. As noted, this alignment may be accomplished internally through gyrocompassing, or via an external reference system. However, many "off the shelf" INS systems are not readily aligned by either system.

INS systems developed for aircraft are not designed for the emplacement of a collimator mirror necessary for external optical alignment. Even if a mirror can be adapted, the external structure of the missile may interfere with the alignment process in a particular INS system and may leave critical components in this process inaccessible. Similarly, alignment based on gyrocompassing requires a compatible flight computer capable of executing a gyrocompass computing subroutine. In particular, the interface between the computer and the platform servo must allow for the introduction of the trajectory data without influencing the accuracy of the platform position measurement. Thus, for a missile system, an INS must be chosen which can be aligned in the context of this system or which can be readily adapted for alignment in this system.

In summary, the assessment of the adaptability of foreign guidance and control systems to ballistic missile development involves a number of factors. More importantly, as will be discussed below, it is very difficult to assess the adaptability of individual systems without physical testing. Specifications and published data do not allow for assessing structural compatibility, impact of high acceleration, and staging alignment. On the basis of these criteria, however, some systems, such as those with only two accelerometers, can be eliminated a priori.

Limitations on Quantitative Assessment and Comparison of Systems

General Discussion of Error Sources

The accuracy of a ballistic missile and the deviation from the target, both cross-range and down-range, are determined by a number of factors. Errors in the cutoff signal, non-instantaneous cutoff, atmospheric effects during reentry, unanticipated gravitational anomalies, and inaccuracies in the guidance system all contribute to these errors

Guidance System Errors

Most of the error sources listed above can be made relatively small by careful design and testing of the system (see below). The most significant source of error is likely to be attributable to the guidance system. Guidance and control errors result from the three basic components of the Inertial Measurement System (the gyroscopes, accelerometers, and platform) and from the flight computer.

The gyroscopes, which in a conventional system are rapidly spinning wheels mounted on a platform, sense the acceleration of the missile through their angular displacement with respect to the gyro case. Such displacement results in an error signal which then realigns the gyro case and is transformed by the flight computer into a command to the rocket motor. The major sources of error in the gyroscope are the "gyro bias drift rate," "gyro unbalance drift," and "gyro compliance drift."

These error sources are attributable to the construction of the gyroscope itself and are caused by extraneous torques on the system, deviation of the center of mass from a precise axis, and mechanical properties of the wheel bearings and structural elements of the gyro. Errors from the accelerometers, which sense the spatial (non-angular) position and velocity of the missile, result from extraneous forces ("accelerometer bias"), improper calibration ("scale-factor error"), non-linearity, and initial misalignment. Similar factors are attributable to the stable platform for the gyros and accelerometers, which can be misaligned and suffer structural deformation, also resulting in error terms.

Finally, the computational process contributes an additional source of errors. Early digital computers would create errors by rounding off, simplifications, and time lags between sensing, commands, and execution. The flight computers which are currently available (and are often included with INS packages -- see below), minimize these errors.

The relative and absolute contribution of each factor in a particular system is a function of the particular IMU and associated gyroscopes, accelerometers, and platforms. Each component and error factor is associated with a specific set of error coefficients for a given system. The contribution of each factor to the overall error is then determined by the particular flight path and profile of a specific ballistic missile system. Acceleration sensitive terms, for example, vary with g or g^2, so that the gyro acceleration sensitive drift would be greater in systems which experience a higher acceleration than those with a "flatter" profile. Similarly, the gyro bias drift varies with burn time, so that short burn times lead to small errors (see Table 2).

Errors in Cutoff Signal

At the end of powered flight, the guidance and control system must steer the missile and control the rocket so that at cutoff the system will be in position and possess the velocity necessary to deliver the warhead to its target. As cutoff cannot be instantaneous, the INS and autopilot must determine the moment of cutoff slightly prior to that time and signal the various systems accordingly, taking into account the delay between the moment the signal is sent and thrust termination. However, the design of the control loop and thrust vector control system can minimize the effects of the sensor signaling and computation processes "to arbitrarily low and trivial levels."[16]

Variations in the actual termination and staging process may also impart residual forces to the missile, but this source of error can be readily minimized in a solid-fueled booster. The rapid opening of portholes in the forward end of the motor reduces the thrust very quickly.[17] In addition, as Hoag notes, if this procedure occurs simultaneously with the separation of the warhead, the rocket will fall back and leave the warhead free, preventing tumble.

Gravitation Field Anomalies and Targeting Errors

Unevenness in the earth's gravitational field resulting from local variations in the mass of the earth's surface results in deviations in the flight path of the rocket. These deviations can be limited by accounting for gravitational anomalies in the computation of the trajectory. Furthermore, compared to other factors, this error source is rather small.[18] Similarly, uncertainty in the location of the target contributes a small factor to the overall inaccuracy (less than 100 meters over a 3000 kilometer range) and in the case of a first generation ballistic missile program, such an error is not very significant.

Reentry Errors

In the course of reentry through the earth's atmosphere, a ballistic warhead is subjected to a variety of aerodynamic forces. While these forces can be anticipated and compensated for in the powered phase of the flight, this compensation is less than perfect and wind and atmospheric variations during reentry contribute to the net inaccuracy. These factors are accentuated by the high-drag blunt warheads designed to minimize heat transfer to the payload. As a result of this shape, an undesired lift is produced and the dwell time in the atmosphere is increased, allowing for greater variations from the planned trajectory. Sophisticated reentry vehicles, which are spin stabilized about a symmetrical axis, allow for the damping of deflecting forces resulting from structure asymmetries in the payload. The net contribution of these reentry errors is also relatively small.

Categories of Available Systems

Guidance and control systems can be procured as complete units or in the form of individual components, including the accelerometer, gyroscope, platform, and computer, which are then assembled. Given the complexity inherent in the assembly of guidance components and the problems of compatibility, however, a ballistic missile development program which relies, to a great extent, on imported components is likely to rely on complete guidance systems (except, perhaps, for the computer) rather than subassemblies.

Inertial guidance systems are manufactured in the U.S., U.K., France, West Germany, Italy, Japan, Sweden, Israel, the Netherlands, and Canada.[19] In addition, components are available from companies in Australia, Ireland, and Switzerland. There are a variety of different types of inertial systems, which can be classified by the type of gyroscope accelerometers and reference system. Conventional gyroscope systems may have either two or three gyros (see Table 2), and may be mechanical gyros or may involve new technology in the form of lasers. Conventional platforms usually consist of three or four platforms mounted on gimbals, while advanced "strapdown" gyros allow for the removal of the accelerometers from the inertial platform. The latter are, in general, more adaptable to a ballistic missile, as the accelerometers can be mounted directly on the vehicle, allowing for greater reliability, and the transformation from the sensor frame to the inertial frame is computed rather than mechanized.

While, as will become clear, the detailed information necessary to evaluate the adaptability of inertial systems to ballistic missiles is often not readily available, some systems can be eliminated from consideration. In particular, two-gyro systems, such as the Sperry Rand (U.K.) MRG-2 Twin Gyro Platform, is not useful for ballistic missile development.

Evaluation

The most important factor in the evaluation of INS systems is the accuracy which the system can provide. As can be seen from Table 2, the various sources of drift and error are generally not published by the manufacturers and are not readily available, except, perhaps, to potential customers.

Furthermore, data that is published (often in the form of a cumulative drift rate) is highly uncertain, varying with particular units. To attain the advertised drift rate, a purchaser may have to go through a number of units, testing each one carefully.

In addition, the cumulative drift rates which are listed in catalogues or other sources are based on the assumption that the guidance system is employed in an aircraft. As noted above, however, the flight profiles of ballistic missiles differ from those of aircraft by a major degree. In an aircraft, acceleration rates are relatively low and constant and errors which vary with g or g^2 are relatively less important than other factors. In a missile, however, accelerations are much higher (see Section V) throughout the powered flight. Thus, the g and g^2 factors are relatively more important in a ballistic missile system than in an aircraft, and, as noted above, without the explicit knowledge of the value of the error terms for a specific INS system and the flight profile of the rocket, it is not possible to calculate the contribution of these terms to the net guidance error.

Despite these problems, however, one could still compare the relative accuracies of various guidance systems and discuss their qualitative merits if the relative magnitude of the error terms were consistent across different systems in a given flight profile. In other words, if the contribution to the total error from the initial azimuth error in one system is greater than the contribution of that factor in a second system, one could evaluate the relative accuracy of two systems even if only one error term were known in both systems. Examinations of systems in which sufficient data is available, however, reveal that this relationship is not consistent.[20] A smaller initial azimuth error (or any other term) does not consistently indicate a better overall system. Thus, in the evaluation of data on the eight major error factors in a given inertial system, it is difficult to compare systems with any degree of accuracy on the basis of catalogue data.

In this context, some analysts have raised the problem of "gimbal lock" which can occur in certain three-gimbal guidance systems under particular trajectories. This condition results from the near parallel alignment of two of the three gimbal axes and would cause the loss of one degree of freedom for the system. To insure against "gimbal lock," guidance systems would generally be restricted to those with four axes which are not susceptible to gimbal lock. However, trajectories which cause gimbal lock are not generally associated with first-generation ballistic missiles and this potential limitation is not of particular importance to this study.

As a result, first-order qualitative comparison of systems must be based on more general properties of the systems. In particular, some types of gyro systems are clearly more useful than others for adaptation in a ballistic missile program. For example, "strapdown" systems, which are attached directly to the missile structure and are not mounted on a gimbaled platform eliminate much of the complex mechanical structure generally associated with other inertial navigation systems. In addition, these systems are less sensitive to environmental variations, more readily maintained and more easily adapted to ballistic missile trajectories than conventional INS components.[21] On the other hand, strapdown systems require a highly sophisticated on-board computer to replace the physical inertial platform and are more difficult to align than a conventional INS. Thus, there are certain advantages to this form of INS, but the requirements for normal operation are more stringent. Such qualitative distinctions are noted, where available, in Table 3.

TABLE 2
BALLISTIC MISSILE ERROR SYNOPSIS

1. INERTIAL SENSING	1.1 ACCELEROMETERS	
	1.1.1 Bias	
	1.1.2 Scale Factor	
	1.1.3 Non-Linearity of second order (g/g^2)	
	of third order (g/g^3)	
	1.1.4 Cross-Axis Sensitivity	
	1.1.4.1 Bias	(g/cross g)
	1.1.4.2 Scale	(g/g/cross g)
	1.2 GYROSCOPES	
	1.2.1 Fixed drift	deg/hr
	1.2.2 Mass Unbalance Drift	deg/h/g
	1.2.3 Compliance Drift (Anisoelasticity)	$deg/h/g^2$
	1.3 INERTIAL PLATFORM (Assembled)	
	1.3.1 Initial Misalignment	arc-sec
	1.3.2 Servo Error	arc-sec
	1.3.3 Deformation	arc-sec/g
2. INITIAL CONDITIONS	2.1.1 Launcher Position Error	
	2.1.2 Initial Velocity Error Due to Earth Rotation	
	2.1.3 Vertical Alignment Error	
	2.1.4 Azimuth Alignment Error	
3. GUIDANCE FORMULATION & COMPUTATION	3.1 Flight Computer Algorithm Compliance	
	3.2 Flight Computer Architecture Adaptability to Real Time Trajectory Computing	
4. THRUST TERMINATION	4.1 Incorrect Cutoff Timing	
	4.2 Dispersion of Cutoff Duration	
5. INFLIGHT GRAVITY ANOMALIES	Incomplete Knowledge of Gravity Coefficient Distribution Along the Trajectory	
6. TARGETING	Incomplete Knowledge of Target Coordinates (Geodetic Data Precision Level)	
7. REENTRY	Lack of Control of Ablation Effects on the RV (Appearance of Parasitic Lift and Side Forces Due to Inhomogeneous Ablation of RVs Thermal Protection)	

Sources: Pittman, G.R., Inertial Guidance.
Hoag, D.G., "Ballistic Missile Guidance."

TABLE 3a
U.S. - MANUFACTURED I.N.S. SYSTEMS
GENERALLY AVAILABLE AND APPARENTLY ADAPTABLE

INERTIAL SYSTEM	APPLICATION	INSTRUMENTS	ACCURACY SPECIFICATIONS (IN DESIGN MODE)	PHYSICAL CHARACTERISTICS	COMMENTS
LN33 (LITTON INERTIAL SYSTEMS)	WEST GERMAN NAVAL AIR SERVICES BREGUET ATLANTIC MARITIME SURVEILLANCE AND ASW FLEET	2 NON-FLOATED G-1200 GYROS, 3 NON-FLOATED A-1000 ACCELEROMETERS	1 NM/HR, 3 FT/SEC (1-), 3 MIN (1-)-HEADING	(13x13x8.5)IN, 39 LBS	DEVELOPMENT BEGAN IN 1965 AND WAS COMPLETED IN 1971, CALCULATED MTBF = 1568 HR, ALIGN TIME - 10 MIN AT 0 F, RAPID ALIGN - 3 MIN AT -20 F
LN -33 INERTIAL NAV-ATTACK SYSTEM (L.I.S.)	F-4E AIRCRAFT	2 NON-FLOATED G-1200 GYROS, 3 NON-FLOATED A-1000 ACCELEROMETERS	1 NM/HR, 3 FT/SEC (1-) 7 MIN (1-) - HEADING (ANALOG)	(13x10x9)IN, 30 LBS	MATURE MTBF = 350 HR, USES P-1000 INERTIAL PLATFORM MTBF = 2000 HR)
AN/ASN -130 (L.I.S.)	U.S. NAVY F-18 AIRCRAFT	2 NON-FLOATED G-1200 GYROS, 3 NON-FLOATED A-1000 ACCELEROMETERS	1 NM/HR, 3 FT/SEC (1-), 4 MIN (1-) - HEADING	38 LBS. 0.7 CUBIC FT VOLUME	PREDICTED MTBF = 1400 HR, ALIGN TIME - 6 MIN FROM 0 F
AN/AJQ-25 (L.I.S.) (LW-33B) NAV-ATTACK SYSTEM - P-1000 INERTIAL PLATFORM	F-4E, MIRAGE, F-104 AIRCRAFT	2 NON-FLOATED G-1200 GYROS, 3 NON FLOATED ACCELEROMETERS	1 NM/HR, 3 FT/SEC (1-) 7 MIN (1-) HEADING (ANALOG), 6 MIN (1-)-PITCH/ROLL (ANALOG)	(13x10x9)IN 30 LBS 1.8 CUBIC FT	USES LC-4516 COMPUTER
SKN-2416 SINGER KEARFOTT INERTIAL SYSTEMS	F-16 AIRCRAFT	2 TWO-DEGREE-OF FREEDOM GYROFLEX GYROS (NON-FLOATED DISPLACEMENT), 3 SINGLE-AXIS SUB-MINIATURE, PENDULOUS LINEAR ACCELEROMETERS	1 NM/HR	(15x8x8)IN, 33 LBS	TESTED IN 1976-77, RAPID ALIGN - 9 MIN AT 0 F

SOURCE: THE ANALYTIC SCIENCES CORP. REPORT, "PERFORMANCE ANALYSIS OF WESTERN-MANUFACTURED NAVIGATION AND GUIDANCE SYSTEMS (TR-3034-1)

TABLE [illegible]

INS SYSTEMS MANUFACTURED OUTSIDE U.S.
GENERALLY AVAILABLE AND APPARENTLY ADAPTABLE

MANUFACTURER/ COUNTRY	INERTIAL SYSTEM	APPLICATION	INSTRUMENTS	ACCURACY SPECIFICATIONS	PHYSICAL CHARACTERISTICS	COMMENTS
SPERRY/RAND LTD/UK	SLIC-7	TACTICAL SHORT-TO-MEDIUM RANGE MISSILES	THREE RING LASER GYROS	244 m/5 MIN (TEST) 1.5 NM/HR	DIAMETER = 6 IN LENGTH = 9 IN WEIGHT = 14 LBS	SLIC -15 STRAPDOWN VERSION ALSO EXISTS, ELECTRONICS BASED ON HYBRID MICROPROCESSOR
FERRANTI LTD/UK	NAVIGATION, HEADING, AND ATTITUDE REFERENCE SYSTEM (NAVHARS)	BAe SEA HARRIER	TWO 2-AXIS DRY OSCILLOGYROS (TYPE 142), ACCELEROMETERS		NAVIGATION PLATFORM-(13x8x8) IN 26.25 LBS	SELF-ALIGNING ATTITUDE REFERENCE PLATFORM, ON-LINE 8/30 F MINI-COMPUTER, INITIAL OPERATION CAPABILITY (IOC), DATE -1978-1979
FERRANTI LTD/UK	FIN 1060 INAS	AIRCRAFT	3 SINGLE-AXIS FLOATED RATE INTEGRATING GYROSCOPES, 3 SINGLE-AXIS VISCOUS-DAMPED FORCE FEEDBACK ACCELEROMETERS	AFTER NORMAL ALIGN-0.85 NM/HR, 2.5 KT (1-), AFTER RAPID ALIGN - 1.92 NM/HR 3.5 KT (1-)	INERTIAL NAVIGATION UNIT (10x12x17) IN	
FERRANTI LTD/UK	FIN 1010 DIGITAL INS (DINS)	PANAVIA TORNADO, JAPANESE FS-T2 AIRCRAFT	SINGLE-AXIS FLOATED RATE INTEGRATING GYROSCOPES (TYPE 122-011)			IOC DATE -1975-78
FERRANTI LTD/UK	541 INAS	BAe HARRIER, F-4M PHANTOM	K 25-19 GYROSCOPES	-2 NM/HR	5-BOX SYSTEM	IOC DATE -1966
FERRANTI LTD/UK	LASER INERTIAL NAVIGATION ATTACK SYSTEM (LINAS)	F-5, A-4 AIRCRAFT	RING LASER GYROS			3:1 WEIGHT AND PRICE REDUCTION COMPARED WITH CURRENTLY FITTED EQUIPMENT
FERRANTI LTD/UK	INERTIAL GUIDANCE SYSTEM	L3S ARIANE LAUNCHER	TYPE 125 GYROS			
MARCONI AVIONICS LTD/UK	NAVWASS (NAVIGATION AND WEAPON AIMING SUB-SYSTEM) E3R INERTIAL PLATFORM	SEPECAT JAGUAR	3 SINGLE-DEGREE-OF-FREEDOM GYROS, 3 ACCELEROMETERS	1 NM/HR, IF CAROUSELLED-0.01 NM/HR	PLATFORM (WITH MOUNTINGS)-(16 13x10) IN, 52 LBS	ROTATIONAL AVERAGING TECHNIQUE (CAROUSELLING) PROVIDES ADDED ACCURACY

SOURCE: THE ANALYTIC SCIENCES CORP. REPORT, "PERFORMANCE ANALYSIS OF WESTERN-MANUFACTURED NAVIGATION AND GUIDANCE SYSTEMS (TR-3034-1)

TABLE [illegible]

INS SYSTEMS MANUFACTURED OUTSIDE U.S.
GENERALLY AVAILABLE & APPARENTLY ADAPTABLE

MANUFACTURER/ (COUNTRY)	INERTIAL SYSTEM	APPLICATION	INSTRUMENTS	ACCURACY SPECIFICATIONS	PHYSICAL CHARACTERISTICS	COMMENTS
SAGEM (FRANCE)	UNI 40	SUPER ETENDARD, TACTICAL ATTACK AND FIGHTER BOMBER AIRCRAFT, LONG RANGE ASW PATROL AIRCRAFT, TACTICAL TRANSPORT AIRCRAFT	2 DYNAMICALLY TUNED DRY GYROS 3 DRY ACCELERO-METERS	1.2 NM/HR AFTER NORMAL ALIGN 3.0 NM/HR AFTER RAPID ALIGN; 3.5 FT/SEC (1σ) AFTER NORMAL ALIGN, 7.0 FT/SEC (1σ) AFTER RAPID ALIGN	(15x8x8) IN 33 LBS	OPERATING TEMP-ERATURE = -40 C to 55 C; NORMAL ALIGN TIME - 8 TO 10 MIN, RAPID ALIGN TIME = 1.5 TO 3.5 MIN; CONTAINED SELF GYROCOMPASS
SAGEM	SKN 2600	TACTICAL ATTACK AND FIGHTER BOMBER AIR-CRAFT, LONG-RANGE ASW PATROL AIRCRAFT	2 GYROFLEX GYROS, 3 DRY ACCELERO-METERS	1 NM/HR, 3 FT/SEC (1σ)	(13.5x8x8) IN 18.7 LBS	NORMAL ALIGNMENT TIME = 7 MIN, TEMPERATURE = -55 C TO 95 C, SINGER-KEARFOTT NAVIGATOR
SAGEM	ULISS (UNIVERSAL LIGHT INERTIAL SYSTEM SAGEM)	ULISS 52-MIRAGE 2000 AND 4000, ULISS 46-MIRAGE F.1, ULISS 45-FALCON 50, KC-135 TANKERS, ULISS 80-RETRO-FITTING FRENCH JAGUARS	2 TUNED ROTOR GYROS, 3 DRY ACCELEROMETERS	1 NM/HR FOR ALIGN TIME OF 10 MIN	33 LBS	80% OF SYSTEM IS STANDARD (PLATFORM, COMPUTER AND POWER SUPPLY) - INTERFACE VARIES ACCORDING TO AIRCRAFT TYPE AND MISSION
SFIM (FRANCE)	SIL 3 - STRAP-DOWN INERTIAL GUIDANCE SYSTEM	MISSILE GUIDANCE, HELICOPTERS	2 GAM 3 TUNED GYROS, 3 PEND-ULOUS PRECISION ACCELEROMETERS		(8.2x7.5x7.5) IN 15 LBS	CAN BE EXTENDED TO HYBRID SYSTEMS
SFIM	555, 255, AND 25M GYRO PLATFORMS	DASSAULT MILITARY AIRCRAFT	3 ACCELEROMETERS, 2 MINIATURE HIGH PERFORMANCE TUNED GYROS (GAM)	1.0 TO 1.5 NM/HR; ATTITUDES = ±0.1 VELOCITY = ±1 M/SEC		HIGHLY COMPETITIVE IN TERMS OF COST AND MAINTENANCE; EFFECTIVE IN LIGHT TACTICAL SUPPORT AIRCRAFT AND COMBAT HELICOPTERS
SFIM	26 SH STRAPDOWN SYSTEM		2 GAM 3 GYROS, 3 ACCELEROMETERS			
SY-2 CROUZET-SFENA (FRANCE)	SEXTAN	PUMA AND GAZELLE HELICOPTERS	3 LASER GYROS (CENTRALE D' ATTITUDE ET DE VITESSE-CAV)	1 NM/HR	66 LBS	INCLUDES DOPPLER RADAR UPDATE AND SOLID STATE MAGNETIC REFERENCE MAGNETOMETER. PRODUCTION [illegible], [illegible]-$60K

SOURCE: THE ANALYTIC SCIENCES CORP. REPORT, "PERFORMANCE ANALYSIS OF WESTERN-MANUFACTURED NAVIGATION AND GUIDANCE SYSTEMS (TR-3034-1)

TABLE 3c

U.S. - MANUFACTURED I.N.S. SYSTEMS PROVIDING INSUFFICIENT DATA TO ASSESS ADAPTABILITY

SYSTEM/ MANUFACTURER COUNTRY	APPLICATION	INVESTMENTS	ACCURACY SPECIFICATIONS	PHYSICAL CHARACTERISTICS	COMMENTS
LTN-72R LITTON INERTIAL SYSTEMS (U.S.)	NUMEROUS COMMERCIAL AIRCRAFT			(6x4x6) IN 75 LBS	THREE UNITS INSTALLED ON EACH AIRCRAFT WILL INTERFACE WITH TWO DIGITAL ARN-118 TACAN UNITS FOR UPDATES

SOURCE: THE ANALYTIC SCIENCES CORP. REPORT, "PERFORMANCE ANALYSIS OF WESTERN-MANUFACTURED NAVIGATION AND GUIDANCE SYSTEMS (TR-3034-1)

TABLE [illegible]

INS SYSTEMS MANUFACTURED OUTSIDE U.S.
INSUFFICIENT DATA FOR ASSESSMENT OF ADAPTABILITY

MANUFACTURER/ COUNTRY	INERTIAL SYSTEM	APPLICATION	INSTRUMENTS	ACCURACY	PHYSICAL	COMMENTS
FERRANTI LTD/UK	FIN 1065	SEPECAT JAGUAR (UPGRADE)				REPLACES MARCONI AVIONICS LTD. NAVWASS
MARCONI/UK	CINCH	GROUND ATTACK/ FIGHTER AIRCRAFT	GAS-BEARING 521 GYRO			FULLY SELF-CONTAINED DIGITAL INERTIAL NAV/ ATTACK SYSTEM, DESCENDED FROM NAVWASS, DIS-CONTINUED
SAGEM/ FRANCE	ETNA INTEGRATED NAV/ATTACK SYSTEM	DASSAULT-BREGUET SUPER ETENDARD		1 NM/HR		BASED ON LICENSE-BUILT SINGER-KEARFOTT SKN 2602 INERTIAL SYSTEM; ALIGNMENT CARRIED OUT VIA INFRARED DATA LINK DEVELOPED BY SOCIETE ANONYME DE TELECOMMUNICATIONS (SAT)
SFIM	550 PLATFORM AIRCRAFT	ALPHA JET OTHER	(FRANCE)			ATTITUDE PLATFORM OPERATES CORRECTLY IN ANY POSITION
SFIM	253 PLATFORM	F1 AIRCRAFT				DESIGNED FOR HIGH PERFORMANCE (ACCURATE VERTICAL, LOW HEADING DRIFT)
SFIM	CID 76 N.A.S.	SOME F1 AIRCRAFT		1.5 NM/HR		DOPPLER-INERTIAL SYSTEM

SOURCE: THE ANALYTIC SCIENCES CORP. REPORT, "PERFORMANCE ANALYSIS OF WESTERN-MANUFACTURED NAVIGATION AND GUIDANCE SYSTEMS (TR-3034-1)

TABLE 3c

US ADVANCED INERTIAL NAVIGATION SYSTEMS
(NOT WIDELY AVAILABLE)

INERTIAL SYSTEM	APPLICATION	INSTRUMENTS	ACCURACY SPECIFICATIONS	PHYSICAL CHARACTERISTICS	COMMENTS
DELCO ELECTRONICS CAROUSEL IV, IV-A	NUMEROUS COMMERCIAL AIRCRAFT, E-3A (AWACS), TITAN MISSILE	RATE-INTEGRATING SINGLE DEGREE OF FREEDOM GYRO (AC 651G), FORCE REBALANCE ACCELEROMETERS (AC 653A)	0.4 NM (1500 NM RANGE) 0.6 NM (4000 NM RANGE, 0.7 NM/HR (50%) 1.7 NM/HR (95%)	0.9 CUBIC FT. 53 LBS	PLATFORM ROTATES (CAROUSELS) RELATIVE TO LOCAL LEVEL - ALLOWS ENHANCED AZIMUTH ALIGNMENT, IV-A SYSTEM USES SLANT RANGE INFORMATION FROM DISTANCE MEASURING EQUIPMENT FOR AUTOMATIC IN-FLIGHT UPDATING
DELCO ELECTRONICS REDUNDANT CAROUSEL STRAPDOWN GUIDANCE SYSTEM	SPACE SHUTTLE INTERIM UPPER STAGE LAUNCHER	STRAPDOWN PLATFORM OF SIX DE 651 GYROS MAGNETICALLY SUSPENDED, GAS-BEARING, FLOATED, SINGLE DEGREE-OF -FREEDOM, SIX DE 653 ACCELEROMETERS (PULSE WIDTH MODULATED, SINGLE AXIS, FORCE- REBALANCED, FLUID DAMPED)			SIX GYROS AND ACCELERO- METERS COMBINED INTO THREE TWO-AXIS CLUSTERS
HONEYWELL H421 STRAPDOWN LASER INERTIAL NAVIGATION SYSTEMS (LINS)	BOEING 757 AND 767	RING LASER GYROS (GG1342)	1NM/HR, 4 FT/SEC (1σ) PER AXIS	(14x11x8) IN 48 LBS	MTBF = 2300 HR, IN PRODUCTION, FLIGHT-TESTED ON C-141 AIRCRAFT IN 1975
HONEYWELL AN/ASN-131 STANDARD PRECISION NAVIGATOR (SPN/GEANS)	MILITARY AIRCRAFT	TWO ELECTROSTATICALLY-SUPPORTED GYROS, THREE SINGLE AXIS ACCELERO-METERS	0.12 NM/HR VELOCITY = 2 FT/SEC 0.06 TO 0.08 NM/HR LONG TERM ACCURACY DEMONSTRATED	(18x16x18) IN 68 LBS	
HONEYWELL GEO-SPIN (EARTH RE-SOURCE RELATED-STANDARD PRECISION INERTIAL NAVIGATION) SURVEY SYSTEM	VERY ACCURATE NAVIGATION AND SURVEYING	ELECTRICALLY-SUSPENDED GYRO	0.05 TO 0.1 NM/HR		MTBF = 500 HR, MTTR = 20 MIN DERIVED FROM SPN/GEANS

SOURCE: THE ANALYTIC SCIENCES CORP. REPORT, "PERFORMANCE ANALYSIS OF WESTERN-MANUFACTURED NAVIGATION AND GUIDANCE SYSTEMS (TR-3034-1)

V. PROPULSION

Solid Versus Liquid Propulsion

Ballistic missiles and rockets can be fueled by either solid or liquid propellants, and before embarking on a development program, one of these two modes of propulsion must be chosen. Both forms of fuel pose particular advantages and disadvantages which are likely to be considered carefully before a choice is made. For a state which seeks to develop a missile which is simple and as readily maintained as possible, the simplicity of solid-fueled motors compared to liquid-fueled systems is likely to be a major consideration. Liquid-fueled motors require a great deal of complex plumbing, including pumps, valves, and many moving parts which are absent in a solid-fueled system. The simplicity of the latter renders it less subject to breakdown and failure. Liquid fuels also must be pressurized and the system must include sloshing control which contributes to the complexity. In addition, liquid fuels, which are more toxic and explosive, must be carefully loaded before launch, while solid-fueled systems which are less dangerous to handle do not face such requirements. Thus, solid-fueled systems inherently provide a greater state of readiness and can be stored for periods on the order of ten years.

On the other hand, liquid-fueled systems are easier to control in flight, giving greater precision (see Section IV). Liquid-fueled systems also provide a higher impulse and can deliver larger payloads over greater distances than solid-fueled systems of comparable dimensions. Finally, liquid systems are more readily transported as the fuel and empty structure can be moved separately in contrast to solid-fueled systems. These benefits notwithstanding, many states with limited resources and capabilities are likely to choose a solid-propellant system in the development of ballistic missiles if both are available.

While not as complex as INS systems, the manufacture of a solid-fueled propulsion system for a ballistic missile requires a great deal of expertise, special materials, and specially constructed facilities. The mixing, casting, curing, machining, and finishing of a solid propellant and the lining and preparation of the motor case is a volatile process which necessitates precise and careful handling of the materials. Cracks, contaminants, and inhomogeneities in the propellant can have major effects on performance and can lead to the failure of the engine.

While these problems and obstacles have not prevented some states, such as India, from attempting to develop indigenous rocket propulsion systems, few countries have this capability. (It should be noted that the Indian program was apparently aided by French technology and technicians, although the extent of this involvement is not readily apparent.) In the effort to develop a ballistic missile, most countries are likely to seek propulsion systems from external sources. In this context, the "dual-use" nature of rockets can be examined.

In addition to providing the basis for ballistic missiles, rocket propulsion systems are useful for space-launch vehicles, meteorological rockets, sounding rockets, and surface-to-air missiles (SAMs). (Smaller systems are also used for other military purposes, such as antitank weapons and air-to-air missiles, but these are at least a factor of ten smaller than the systems under consideration in this study.) As such, the degree to which rocket propulsion units and solid-fueled systems, in particular, can be classified as "dual-use" technologies is limited. Other than as sounding rockets, there are currently no civilian, industrial, or commercial uses to which rockets motors could be put.

The restricted and primarily military utility of rocket motors and propulsion systems (which include the motor, fuel, ignition system, and thrust vector control) is reflected in the relatively limited number of propulsion units which are potentially available for purchase. In addition to those manufactured in the U.S., solid-fueled rockets are also manufactured in France, Great Britain, Italy, and Japan.[22] Most British rockets are relatively small and are not very useful in ballistic missile programs, but the Italian and French systems are more suitable (see Table 4). A number of larger propulsion units have been developed by France for use as nuclear delivery vehicles, but these units are not currently available for purchase or export. The remaining potentially available French and Italian solid-fueled propulsion systems which are large enough to be used in a short-range ballistic missile system are generally designed and classified as high-altitude meteorological research or sounding rockets and as various satellite and space launch vehicle related systems. These rockets are generally smaller than those designed for military payloads and, as will become clear below, result in a restricted payload and range combination when used as ballistic missiles.

Typical meteorological rockets are very simple, consisting of a solid propellant and a non-burnable structure (which takes up to 10% to 15% of the weight of the rocket). In addition, the ignition system is usually supplied with the rocket and can be used directly for ballistic missiles.

Adaptability

In general, all solid propellant rockets which are available can be adapted to a two-stage ballistic missile system. As these rockets were initially designed as single-stage high-altitude systems, however, the nozzle of the first stage must be adapted for use at low altitudes. By simply shortening the nozzle exit cone, this stage can be substantially improved.[23]

In addition, high-altitude rockets generally follow a vertical trajectory and do not generally include a thrust vector control system to allow for "steering" the rocket. Since such steering is necessary to place the missile in a ballistic trajectory, an aerodynamic or thrust vector control system must be added. The former involves the manufacture and installation of external control surfaces or fins, while the latter can be accomplished in a number of ways. The most likely methods of thrust vector control in a relatively simple ballistic missile design involve the insertion of controllable vanes within the nozzle or the addition of a controllable "jetavator" to the nozzle. Vanes are flat surfaces which alter the direction of the jet as it leaves the nozzle; a "jetavator" is a conical section which fits onto the nozzle and can be moved around by an externally placed axle, thus providing a deflection of the main rocket jet. Vanes are made from a heat-resistant metal, such as molybdenum or tungsten, while "jetavators" are made from steel rings covered by an insulating material and a molybdenum or tungsten surface. A series of small vernier engines may be used in a more complex system, as in the Indian space launch vehicle (SLV) system. Such small vernier engines are available from a variety of firms both in the U.S. and in Europe.

In addition to the steering required to put the rocket in the proper trajectory, an attitude control system is necesary to prevent destabilizing roll or pitch motions in the rocket. This system which is not inherent in many propulsion systems designed for satellite orbital insertion, for example, must include sensors and a steering system, such as the aerodynamic surfaces, movable nozzles, jet deflecting devices, or small thrusters mentioned above. While the sensors for this task may be included in the INS system (as in the case of the ULISS system manufactured by the French firm, SAGEM -- see Section IV), a separate system of "rate gyros" is usually required for attitude control. As in the case of "steering", the adaptation of an attitude control system is relatively straightforward, and while such "add-ons" may not be desirable, they are within the capabilities of most countries under consideration in this study.

Comparison of Suitably Modified Systems

Necessary Data

As noted above, the most critical factors in the comparative evaluation of ballistic missiles propulsion systems are the combination of possible payloads and ranges, as well as the reliability. For the purposes of this study, we will assume that the solid-fueled propulsion systems which are available for purchase are of a relatively similar reliability, and in our relative assessment, will focus on the range-payload combination.

Possible maximum ranges and payloads for a given rocket motor can be calculated on the basis of specifications such as total thrust, burn time, and propellant mass. This data is usually supplied in catalogues. In reality, most rockets do not burn at a constant rate and highly accurate calculations of range-payload combinations also require detailed knowledge of fluctuations in thrust as a function of time (thrust-time curves), but by assuming a constant mean thrust throughout the burn-time (a rectangular thrust-time curve), errors of only a few percent are incurred. Similarly, detailed calculations require knowledge of the "structural factor" of the rocket system. This is the part of the missile which is not consumed as fuel and includes external casing, INS, interstages, instrumentation, etc. While this is often available in catalogues, it includes, in general, approximately 20% of the rocket's mass, and this figure can be substituted when specific information is lacking.

In calculating maximum ranges for given payloads, certain assumptions regarding the flight profile must also be made. As in the case of evaluation of guidance and control systems, such factors as the impacts of the earth's atmosphere and the earth's rotation on the range are neglected (see Appendix I). These factors contribute very slightly to the range and, in an essentially comparative analysis, are not important as they are comparable in all systems.

The inability to throttle and control the thrust of relatively simple solid rocket motors places some limit on the ranges which can be obtained short of the maximum range. However, in targeting points less than the maximum range, missiles can be launched into non-optimal trajectories in which higher altitudes result in shorter horizontal distances. In addition, these trajectories may be designed to be deliberately short ("under-dimensioning"). To compensate for this shortfall, small solid "strap-on" rockets can be added and ignited at the end of the launch phase. These can then be jettisoned when the precise predetermined velocity is reached. While this procedure may be less than optimal, a state which only has access to available "dual-use" technologies may select this course.

Stages

As can be seen from Table 4, most single-stage systems which can be procured externally are not capable of carrying a 500 kilogram payload over a substantial distance. Thus, in order to reach targets at ranges of 1000 to 2000 kilometers, a multi-stage system is required. Similarly, while a two-stage system is structurally relatively easy to construct from the available components, a three-stage system which is assembled from the relatively limited available rocket motors is likely to be structurally unstable. As a result, for the purposes of analysis, we will focus on two-stage systems.

Structurally, the strongest systems based on imported technology are likely to be constructed from two identical stages. However, this combination is less than optimal. In an optimally designed multi-stage rocket, each stage imparts an equal increment of velocity to the system. Thus, each stage is somewhat smaller than the one directly below, and the ratio of propellant masses is determined by the nature of the propellant, exhaust velocity, structural factor, and warhead mass. Therefore, these optimal design criteria are unlikely to be met when a ballistic missile which is developed from externally procured rocket motors, and, in particular, from two identical stages. While different combinations of rockets could be used to increase the range and payload of the system, practical technical constraints and the small number of rockets which is available limit the number which are compatible. For example, a system in which the first stage is dimensionally smaller or substantially larger than the second stage may be structurally weak and may require major modifications to one or both stages. Other combined systems may require the addition of control devices in the form of aerodynamic vanes and altitude control rockets to assure flight dynamics compatibility.

The data base for this section was assembled by contacting the various producers and manufacturers of solid rockets, as listed in the Interavia ABC directory, the Index of Manufacturers, published by Aviation Week and Space Technology, and in Jane's Weapons's Systems and Aircraft volumes. In addition to data found in these sources, each manufacturer was contacted and data on potentially useful solid-fueled rockets was requested. While most responded, a few chose not to provide further information, and a few did not respond. Thus, the data, while representative, is not complete.

In addition, it should be noted that in some cases, data is listed as unavailable. While this data may not be readily provided to academics engaged in research, one can assume that potential customers may be provided with more information. For the purposes of this study the data was, in most cases, adequate for comparative evaluation.

Evaluation

As can be seen from Table 4, the number of either single- or two-stage missiles assembled from foreign components capable of carrying a 500 kilogram warhead to distances of 1000 kilometers is limited. Ten single-stage rockets could conceivably perform this task (Table 4a), four of which are manufactured outside the U.S. While two of these systems are integral components of the French strategic deterrent force, and are not thought to be currently available for export, two are Italian systems and may not be subject to restrictions. The Ariane Booster strap-on and the Alfa rocket can carry a 500 kilogram payload 1400 kilometers and 920 kilometers, respectively.

There are many more possible two-stage designs, including systems based on both identical and distinct rockets. (See preceding note on compatability and optimum design of two-stage systems.) Of the two-stage systems manufactured solely from non-U.S. rocket motors, only those which include the French IRBM stages or the Italian-made Ariane strap-on or Alfa motors can carry a 500 kilogram payload over 1000 kilometers. There are, however, many two-stage systems which include other rockets with ranges of 700 to 930 kilometers as calculated in our model for 500 kilogram payloads. For example, a system of two French Mammoth stages has a range of 800 kilometers. This engine is similar to those which the French government has licensed for manufacture in India and Pakistan.[24] The Polka, also manufactured by the French firm SNPE, is used as a booster for the Masurca surface-to-air missile. Two Polkas have a range of 660 kilometers with a 500 kilogram payload.

There are, in contrast, 12 two-stage systems composed of identical stages manufactured in the U.S. which can carry a payload of 500 kilograms to 1000 kilometers or more. While many of these rockets are clearly <u>not</u> dual-use technologies, such as the M-56 Minuteman I second-stage, a number were designed primarily as sounding rockets and satellite apogee motors. For example, the Star and Castor series of rockets stacked into a two-stage system can carry 500 kilogram payloads well over 1000 kilometers. In addition, the TX-526, TX-354, and XM-100 engines, which were developed for use in the Athena reentry test vehicle and Sergeant missile respectively, could be used in a ballistic missile program.

Similarly, there are a large number of two-stage systems that could be developed from non-identical stages (including U.S. and foreign motors in combination). Any of the larger motors discussed above, including the French P-16 and P-4, the Italian Alfa and Ariane and a variety of U.S. systems could serve as first stages. There are also many smaller units, as demonstrated in Table 4c, that could be potentially adapted as second stages. Some of these two-stage systems have already been combined, as in the case of the Nike-Hercules. While nominally an anti-aircraft missile, a Hercules first-stage (M-88) and a Nike (TX-30) second-stage could potentially carry 500 kilograms approximately 400 kilometers (according to our model -- see Appendix I) when configured as a ballistic missile.

Finally, while technically difficult, it may be possible to stack three identical stages together to increase the range of these rockets. If such an effort were successful, ranges would increase significantly. In addition, smaller stages may be clustered horizontally. Both systems, however, are technically more complex than the two-stage stacking discussed above. Performance of individual stages is limited, more non-burnable structure is required, and, in the case of clustering, aerodynamic drag is increased due to the large cross-sections which are involved. In addition, altitude control is more demanding in that configurations and more sophisticated systems are required relative to two- or one-stage systems. As a result, these systems are not considered in detail in this study.

In summary, although the number of rocket motors made outside the U.S. which could potentially serve as first stages of ballistic missiles is limited, for the purposes of this analysis, these systems are essentially equivalent to a number of U.S. systems. If these large French and Italian motors are unavailable, the U.S. systems become the primary basis for ballistic missile development based on imported technology of components.

TABLE 4a

PERFORMANCE OF U.S. AND FOREIGN PROPULSION SYSTEMS

SINGLE-STAGE SYSTEMS

Engine	Country	Range(Km) (250 Kg payload)	Range(Km) (500 Kg payload)	Range(Km) (750 Kg payload)	Range(Km) (1000 Kg payload)	Range(Km) (1500 Kg payload)
M-56	USA	2890	2080	1570	1240	800
P-16	France	1740	1600	1470	1360	1170
Ariane* Strap-on	Italy	1660	1400	1210	1050	800
Castor 2	USA	1490	1140	900	740	540
TX-526	USA	1220	1060	940	840	680
P-4	France	1320	1000	790	640	440
Alfa	Italy	1130	920	760	640	480
Castor	USA	1140	870	690	560	390
TX-131-5	USA	1000	730	560	440	290
XM-100	USA	720	530	410	320	220

Notes: See Appendix I for discussion of model and computations.
See Appendix II for physical data on these rockets.

* Requires nozzle modification.

TABLE 4b

PERFORMANCE OF TWO-STAGE U.S. PROPULSION SYSTEMS

TWO IDENTICAL STAGES

Engine	Country	Range(Km) (250 Kg payload)	Range(Km) (500 Kg payload)	Range(Km) (750 Kg payload)	Range(Km) (1000 Kg payload)	VB** (m/sec)	Range(Km) (1500 Kg payload)
M-56	USA	4820	3510	2710	2170	5220	1500
Castor 2	USA	2640	2070	1680	1400	4180	1000
TX-526	USA	1900	1670	1500	1340	3810	1100
Castor	USA	2000	1570	1270	1050	3700	750
TX-39	USA	1960	1500	1200	990	3630	700
STAR 31 (TE-M-762)	USA	2390	1410	930	660	3530	370
TX-354	USA	1700-1620	1360-1300	1120-1080	940-900	3460-3400	700-650
TX-131-15	USA	1780	1330	1050	850	3440	600
M-57A-1	USA	2150	1310	890	630	3420	350
STAR 48 (TE-M-711-3)	USA	2080	1300	890	620	3400	600
STAR 37G (TE-M-364-11)	USA	1990	1100	700	470	3160	350
XM-100	USA	1280	980	780	630	2990	240
TX-261	USA	1360	820	570	420	2750	250
STAR 37S (TE-M-364-15)	USA	1180	550	270	150	2220	100
Talos	USA	600	450	360	290	2070	330
Astrobee F	USA	810	420	240	140	2000	100
M-88	USA	520	400	320	270	1950	190
Alcor-1B	USA	950	390	200	110	1920	100
M31	USA	430	300	220	170	1690	100
TX-30	USA	470	280	180	130	1640	100

** V_B = Burnout velocity with a 500 kg payload.

TABLE 4c

PERFORMANCE OF TWO-STAGE FOREIGN PROPULSION SYSTEMS

TWO IDENTICAL STAGES

Engine	Country	Range(Km) (250 Kg payload)	Range(Km) (500 Kg payload)	Range(Km) (750 Kg payload)	Range(Km) (1000 Kg payload)	Range(Km) (1500 Kg payload)
Ariane Strap-On*	Italy	2920	2500	2200	1940	1550
P-16(902)	France	2630	2420	2240	2070	1800
P-4 (Rita)	France	2160	1670	1340	1120	800
Alfa	Italy	1670	1380	1160	990	750
TOP-B	Italy	1690	930	560	360	160
800 Mammoth	France	1230	860	640	500	330
Mage 3	IT/FR/FRG	1620	810	480	300	150
TOP-A	Italy	1510	770	450	270	150
7392 Rance	France	1040	700	500	380	240
Polka	France	1200	660	430	300	170
Dropt	France	950	470	260	160	100
Mage 2	IT/FR/FRG	1020	430	220	120	150
7342 Vienne	France	640	380	250	180	150
Yonne	France	580	360	240	180	150
Mage	FR/IT/FRG	880	340	160	80	150
M-40	Japan	820	330	170	100	150
Stromboli	France	560	320	210	140	150

* Requires nozzle modification.

TABLE 4d

PERFORMANCE OF TWO-STAGE NON-IDENTICAL U.S. AND FOREIGN PROPULSION SYSTEMS[1]
(500 Kg)

2nd Stage(1)	1st Stage					
	Castor 2	TX-39	XM-100(2)	Rita	Mammouth	Alfa
Vienne (France)	1350	1050	800	1200	650	1300
Stromboli (France)	1300	1000	750	1150	600	1200
Polka (France)	1850	1450	1150	1650	950	1750
Dropt (France)	1600	1300	1000	1500	800	1550
Mage 1 (FR/IT/FRG)			850		700	
Mage 1S (FR/IT/FRG)		1300	1000		800	1550
Mage 2 (FR/IT/FRG)	1800	1400	1050	1600	850	1600
Mage 3 (FR/IT/FRG)	2050	1650	1300	1900	1100	2000
Alcor (USA)	1700	1350	1000	1600	850	
TX-30(3)(USA)	1100	900	650	1100	550	1100
STAR 37S(USA)	2050	1600	1200	1800	1050	1850
STAR 37G(USA)	2250	1850	1500	2050		2150
STAR 31(USA)	2400			2700		2350
STAR 48 (USA)	2200			2000		2150
M-40 (Japan)	1700	1300	900	1500	800	1300

(Notes are on page 61.)

TABLE 4e

PERFORMANCE OF TWO-STAGE PROPULSION SYSTEM
(500 Kg)

	1st Stage					
2nd Stage(1)	TX-526	Ariane	Alfa	M-56	Castor 2	Rita
Ariane	1400	1550				
Alfa	1000	1100	750			
M-56	1850	2000	1400	1500		
Castor 2	1400	1500	1000	950	1000	
Castor	1200	1300	850	950	850	750
TX-39	1150	1400	850	900	800	700
XM-100(2)	950	1000	650	750	650	550
Mammouth	950	1000	650	800		
Talos	800	900	530			
Rance	900	1000				

Notes for Tables 4d and 4e

1. In these arrays, an effort has been made to choose stages which are most compatible in terms of staging efficiency. Only combinations for which the booster provides 33% - 66% of the final velocity are provided.

2. This engine is from the Sergeant missile, which has been supplied to the FRG.

3. This engine is from the NIKE-Hercules SAM, supplied to Belgium, Denmark, Greece, Italy, Norway, Taiwan, and the FRG. The system is also produced under licence in Japan.

VI. CONCLUSIONS AND POLICY IMPLICATIONS

In this study, we have examined the capability of a variety of less developed countries (LDCs) and non-industrialized states to develop and produce intermediate-range ballistic missiles. We have noted that those states with advanced military aircraft production experience, such as India, Brazil, South Africa, and Israel, are likely to require less external assistance that those states without such experience, such as Argentina, Pakistan, and Egypt. Both groups, however, are likely to rely on externally procured guidance and rocket engines, and, in particular, inertial navigation systems and solid-fuel motors.

Foreign Availability

As a result of this finding, we have examined the foreign availability of these components, and of inertial navigation systems and solid fuel rockets in particular. The assessment of foreign availability is based on two components: analysis of those systems which are manufactured by various states (and are thus potentially available), and analysis of the degree to which these systems are actually available to foreign purchasers. While the first task is relatively straightforward and allows for an essentially complete listing of manufactured systems, the second is far more difficult. Some systems listed in catalogues may not, in fact, be available or may be available only to selected customers, and other items which are not listed in catalogues may be available for purchase. A complete assessment of the availability of systems can only be determined by customers prepared to "put cash on the table."

Comparability of Potentially Available Components

Inertial Navigation Systems

Although some catalogue data is available for the assessment of the performance of INS components, this data is not sufficient for the evaluation of their capabilities in ballistic missile systems. The assessment of the military usefulness of guidance systems requires detailed study of individual systems, the potential adaptability of specific guidance systems to ballistic missile development cannot always be judged on the basis of published specifications. While it may be possible to adapt particular systems in a ballistic missile application, assessment of this capability would generally require detailed design of the missile and procurement and testing of a sample INS for specific flight-profile sensitive parameters. Detailed discussions with the manufacturer may allow for some assessment but such information is often available only to genuine customers. Although MIT contacted a number of the major manufacturers, such detailed information was not made available. Similarly, quantitative assessments and comparison of different guidance systems to determine relative capabilities and accuracies in a ballistic missile program generally require detailed discussion with manufacturers and/or testing.

Solid-Fueled Motors

The performance of solid-fueled propulsion systems is not environmentally determined. As a result, we were able to establish specific criteria by which to determine military capabilities and to compare U.S. manufactured systems with those available abroad. Criteria such as range and payload were shown to be most important in determining the potential uses of solid rockets. By comparing different systems across range-payload combinations the relative capabilities of various systems was assessed.

Using a specific trajectory model, a variety of single- and two-stage systems is analyzed to yield ranges for payloads between 250 and 1500 kilograms. This allows for the comparison of the performance of systems including components manufactured in the U.S. with the performance of those from which U.S. suppliers have been excluded (Table 4). Of the ten single-stage rockets which can carry a 500 kilogram rocket 1000 kilometers, six are manufactured in the U.S., two in France, and two in Italy (the Ariane Booster and the Alfa). There is also a variety of foreign manufactured two-stage systems with ranges from 200 to 930 kilometers (with 500 kilogram payloads). In addition, combinations of U.S. and foreign manufactured stages could potentially yield similar range-payload combinations.

Implications for Export Policy

The foreign availability of comparable systems is one important factor in the determination of U.S. export policy, particularly in the area of dual-use technologies. Weapons delivery systems and their components are generally included under the provisions of the International Traffic in Arms Regulations (ITAR) as well as the Commodity Control List (CCL) established by the Export Administration Act (EAA). In the case of solid rocket motors and INS systems, however, these regulations are somewhat ambiguous. While the export of rockets, guided missiles, and missile and space vehicle power plants is included in the Munitions List of ITAR, meteorological sounding rockets are specifically excluded.[25] In addition, although inertial systems "inherently capable of yielding accuracies of better than 1 to 2 nautical miles per hour circular error of probability [sic]"[26] are included, this criterion, as noted above, is highly ambiguous.

As "dual-use" technologies, these components (particularly less accurate INS for commercial application) can also conceivably be included under the EAA and INS systems explicitly listed in the CCL. According to the provisions of the EAA, the question of foreign availability is an important criterion in determining the outcome of an export license application for items listed on the CCL. According to the legislation, export controls "for foreign policy or national security purposes" shall not be imposed on items which are "available without restriction from sources outside the United States in significant quantities and comparable in quality to those produced in the U.S."[27]

As these conclusions indicate, it is clear that the requirements established in the Export Administration Act of 1979 are not uniformly applicable to all commodities. While criteria are readily established and applied in the case of some products, such as solid rocket motors, other "dual-use" technologies, such as guidance systems, are subject to greater ambiguity.

This distinction is a result of the potential application of the product, the nature of the product itself, and, most importantly, the interaction of these factors. The performance of certain products, such as solid rocket motors, is essentially fixed and is not a function of the particular use to which they are put or the payload which they carry. The specifications and performance criteria of such systems do not vary significantly according to environment or mission. Thus, solid rocket motors provide the same thrust and range-payload curves whether used as sounding rockets, stages for space launched vehicles, or ballistic missiles. Once these are known for one application, they are known for other applications.

The performances of other components or products, in contrast, are very closely coupled to the application to which they are put. The quality of a particular guidance system, which is measured in terms of accuracy, depends to a very great extent, on the environment in which it is placed. Systems which are highly accurate in one environment, such as in passenger aircraft, may be highly inaccurate in other environments, such as ballistic missiles. Furthermore, the nature of a guidance system does not allow for the simple extrapolation of performance parameters across different environments. While enough data may exist to compare guidance systems in one particular application, this data, by itself, will not allow for quantitative comparisons with respect to other applications.

In conclusion, then, when products, by their nature, have different performance characteristics in different environments, and when these different characteristics cannot be extrapolated across environments, specific data on their performance in applications of interest is required. When, as in the case of guidance systems, this data is not published, detailed quantitative evaluation requires the actual testing of components.

LIST OF ABBREVIATIONS

ACDA	Arms Control and Disarmament Agency
ALCM	Air Launched Cruise Missile
CCL	Commodities Control List
CEP	Circular Error Probability
EAA	Export Administration Act
ICBM	Intercontinental Ballistic Missile
INS	Inertial Navigation System
IRBM	Intermediate-Range Ballistic Missile
ITAR	International Traffic in Arms Regulations
LDC	Less Developed Country
MCL	Munitions Control List
OECD	Organization for Economic Cooperation and Development
OTRAG	Orbital Transport-und-Raketen-Aktiengesellschaft (non-governmental West German commercial rocket group)

FOOTNOTES

[1]See SAI (Science Applications, Inc.), Considerations in Controlling Dual-Use Technology Products, prepared for U.S.A.C.D.A., September 1980.

[2]Gerald M. Steinberg, "The Evolution and Economic Impact of the Israeli Defense Industry," in Milton Leitenberg (ed.), The Role of Defense Industries in the Industrial Structures of Modern Nations (forthcoming).

[3]See Technology and East-West Trade, Office of Technology Assessment, U.S. Congress (Washington, D.C.: U.S. GPO, 1979).

[4]Despite the "dual-use" nature of sounding rockets, they are explicitly exempted from the Munitions Control List. See International Traffic In Arms Regulations, U.S. Department of State, February, 1976, p. 3.

[5]Soviet Space Programs, 1966-1970; Staff Report Prepared for the Use of the Committee on Aeronautical and Space Sciences, U.S. Senate by the Science Policy Research Division, Congressional Research Service, Library of Congress, Washington, D.C., 1971, p.131.

[6]Stockholm International Peace Research Institute, 1980 Yearbook, World Armaments and Disarmament, pp. 101-103.

[7]Aviation Week and Space Technology, November 24, 1980, p.27.

[8]Literature search from NTIS, Compendax (Corp. Engineering Index, Inc.) and IEE compilations.

[9]The first U.S. nuclear explosive weighed approximately 10,000 pounds. In contrast, current highly sophisticated U.S. weapons weigh less than 100 pounds. The estimate of 1,000 pounds (approximately 500 kilograms) for an LDC was based on the assumption that it could improve by an order of magnitude on the original U.S. design, but, in the absence of an extensive test series, would not be able to achieve the same order of magnitude as the most sophisticated U.S. designs.

[10]See, for example, Nucleonics Week, March 13, 1980, p. 11, and the Amsterdam Handelsblad, June 16, 1979.

[11]See exchange of letters in Physics Today, October 1980, pp. 92-100.

[12]Aviation Week and Space Technology, December 1, 1980, p. 18.

[13]India and Israel have also developed such batteries although the design specifications and source of components have not been published.

[14]TASC (The Analytic Sciences Corporation), Performance Analysis of Western-Manufactured Navigation and Guidance Systems (TR-3034-1), Report prepared for the Central Intelligence Agency, May 1980.

[15]Ibid., p. 2-2. Note that INS systems designed for ballistic missiles use inertial frames.

[16]D.G. Hoag, "Ballistic Missile Guidance," in B.T. Feld et al. (eds.), Impact of New Technologies on the Arms Race (Cambridge, Mass.: MIT Press, 1970), p. 65.

[17]George R. Pittman, Jr., Inertial Guidance (New York: John Wiley and Sons, 1962), p. 290.

[18]Hoag, p. 69.

[19]TASC, (The Analytic Sciences Corporation), Manual of Western-Manufactured Navigation and Guidance Components and Systems (Contract Number 79N-369200-000), May 1980.

[20]TASC, Performance Analysis of Western Manufactured Navigation and Guidance Systems (TR-3034-1), Report prepared for the Central Intelligence Agency, May 1980.

[21]Ibid.

[22]In addition, Japan produces Castor II engines under license and has an active space launch vehicle program directed by Tokyo University. So far as is known, these efforts are experimental in nature and do not include plans to export rocket engines.

[23]The fabrication of the nozzle itself is a highly complex process and most states are unlikely to produce their own nozzles.

[24]Science Policy Research Division, Congressional Research Service, Library of Congress, World Wide Space Activities, Report Prepared for the Subcommittee on Space Science and Applications of the Committee on Science and Technology, U.S. House of Representatives, 95th Congress, Washington, D.C.: U.S. GPO, September 1977.

[25]"International Traffic in Arms Regulations" (ITAR), Part 121-Arms, Ammunition, and Implements of War, U.S. Department of State, February 1976, p. 3.

[26]Ibid., p. 4.

[27]Export Administration Act of 1979, Section 4, Paragraph (C).

REFERENCES

1. Catalogue of Propulsion Motors for Spacecraft, European Space Research Organization, 1975 (ESRO-SP-96-ESTEC).

2. Hoag, D.G., "Ballistic Missile Guidance," in B.T. Feld, et al., (eds.), Impact of New Technologies on the Arms Race (Cambridge, Mass.: MIT Press, 1970).

3. Pittman, George R., Jr., Inertial Guidance (New York: John Wiley and Sons, 1962).

4. Science Policy Research Division, Congressional Research Service, Library of Congress, World Wide Space Activities, Report Prepared for the Subcommittee on Space Science and Applications of the Committee on Science and Technology, U.S. House of Representatives, 95th Congress, Washington, D.C.: U.S. GPO, September 1977.

5. TASC (The Analytic Sciences Corporation), Performance Analysis of Western-Manufactured Navigation and Guidance Systems (TR-3034-1), Report prepared for the Central Intelligence Agency, May 1980.

6. TASC (The Analytic Sciences Corporation), Manual of Western-Manufactured Navigation and Guidance Components and Systems (Contract No. 79N-369200-000), May 1980.

APPENDIX I

MODEL OF BALLISTIC MISSILE TRAJECTORY

The detailed calculation of the behavior and trajectory of a rocket is a complex task which generally requires numerous engineers, advanced computing facilities, and, most importantly, specific design and aerodynamic data.

For the purposes of comparison, however, a number of simplifying assumptions and approximations can be made, which, if applied consistently, do not affect relative performances and constitute relatively small perturbations at ranges of 1000 to 2000 kilometers. These assumptions and approximations include:

1) Neglecting the effect of atmospheric drag.

This would act to slow the rocket and lessen its range, particularly in the case of relatively small rockets, which fly entirely within the dense lower atmosphere. A rocket calculated to have a range of 200 kilometers may actually be limited to 100 kilometers due to the drag. Larger rockets which leave the lower atmosphere are less affected and the model is more accurate in such cases.

2) Assuming that the rocket follows a straight-line trajectory during powered flight.

In reality, the guidance system puts the rocket on a curved trajectory. Since the details of this trajectory are strongly dependent on structural and aerodynamic details, this simplification is adopted. This assumption allows

APPENDIX I: (continued)

for the relative accurate determination of burnout velocity, but does not allow for calculating distance traveled during powered flight. As a result, we do not calculate this contribution to the ground range. Since this contribution is on the order of the effect of aerodynamic drag at ranges of interest and is in the opposite direction, these effects tend to counterbalance each other.

3) A non-rotating earth (neglecting the Coriolis effect).

When a rocket is launched, it acquires the surface (tangential) velocity of its launch point. The impact of this varies with the launch point and target. Rockets traveling from west to east will gain approximately 10 kilometers for a 1000 kilometer nominal range, while they will lose approximately 30 kilometers in the opposite direction. While these effects are readily computed in specific cases, their magnitudes are of little significance.

4) Ideal propulsion cutoff.

Range errors due to thrust cutoff errors are very small (less than 1%).

With these assumptions, the equations for calculating the range follow from Kepler's and Newton's laws. These are included in A Model for Calculating Rocket Velocities and Ranges, a working paper available from the Center for International Studies, Massachusetts Institute of Technology (1981).

APPENDIX II

PROPULSION SYSTEMS -- PHYSICAL DATA

Engine	Country	Mfr.	(1) t_b (sec)	(2) ALPHA	Total Impulse/ Stage (kN-sec)	Chg. Wt. (Kg)	Use
P-16	FR	SNPE	76	.2	40993	16000	IRBM
P-4 Rita	FR	SNPE	55	.2	9709	4000	IRBM
Mammouth	FR	SNPE	18.2	.2	3607	1910	
Rance	FR	SEP	17.5	.2	2849	1565	
Yonne	FR	SEP	20	.2	1880	1250	
Dropt	FR	SEP	45	.2	1800	751	
Polka	FR	SNPE	4.6	.2	1569	690	Masurca SAM
Strom-boli	FR	SNPE	16.5	.2	1422	900	Dragon, Centaure Research Rocket
Vienne	FR	SEP	4.6	.2	1348	846	
Ariane Strap-on	IT	SNIA	27	.18	16900	7370	Ariane
Alfa	IT	SNIA	57	.143	13230	6920	Booster Upper Stage
TOP-B	IT	SNIA	76	.2	3680	1290	Satellite Orbital Insertion
TOP-A	IT	SNIA	70	.2	2927	1030	Same
Mage 3	IT/FR/ FRG	SNIA/SEP/ MAN	51	.2	2390	825	Same
Mage 2	IT/FR/ FRG	SNIA/SEP/ MAN	41	.2	1340	470	Same
Mage 1S	IT/FR/ FRG	SNIA/SEP/ MAN	42.5	.2	1180	410	Same

(Notes are on pp. 76-77.)

APPENDIX II (Cont.)

PROPULSION SYSTEMS -- PHYSICAL DATA (Cont.)

Engine	Country	Mfr.	(1) t_b (sec)	(2) ALPHA	Total Impulse/ Stage (kN-sec)	Chg Wt. (Kg)	Use
M-40	Japan	Nissan Motors	29(3)	.2	1027	380	
Mage 1	IT/FR/ FRG	SNIA/SEP/ MAN	47	.2	965	336	Same
TX-526	USA	Thiokol	55	.2	20534	9392	Research Rocket
M56A1	USA	Aerojet	60	.10	12436	4708	MMI 1st Stage
Castor 2	USA	Thiokol	38	.22	9730	3760	Scout SLV Sounding Rocket
TX-354	USA	Thiokol	39	.2	9048	4320-4410	Scout Strap-on
Castor	USA	Thiokol	40	.25	8359	3371	Sounding Rocket
TX-39	USA	Thiokol	30	.2	7295	3312	
TX-131-15(4)	USA	Thiokol	26.8	.19	6254	2982	Bomarc Booster
XM-100	USA	Thiokol	30	.27	5670	2678	Sargeant Tactical Missile
M-57A1	USA	Hercules	59	.18	4484	1660	MMI, 3rd Stage
Talos	USA		5.25	.62	2707	1272	Naval SAM
M-88(5) Quad	USA	Hercules	2.5	.61	2624	1360	1st Stage Nike-Hercules

(Notes are on pp. 76-77.)

APPENDIX II (Cont.)

U.S. PROPULSION SYSTEMS -- PHYSICAL DATA

Engine	Country	Mfr.	(1) t_b (sec)	(2) ALPHA	Total Impulse/ Stage (kN-sec)	Chg. Wt. (Kg)	Use
Astrobee	USA	Aerojet	64	.27	2442	992	Sounding Rocket
TX-261	USA	Thiokol	8.92	.2	2270	1054	Defense Research
TX-30	USA	Thiokol	26.6	.3	1680	985	Nike-Hercules Sustainer
M31A1	USA	Hercules	3.3	.73	1600	753	(Art'y.) Rocket) Honest John
Alcor 1B	USA	Aerojet	30	.15	1112	420	Sounding Rocket
(6) STAR 48 (TE-M-711-3)	USA	Thiokol	84	.2	5734	1994	Satellite Orbit Insertion
STAR 31 (TE-M-762)	USA	Thiokol	45	.2	3763	1292	"
STAR 37G (TE-M-364-11)	USA	Thiokol	45.5	.2	3025	1056	"

(Notes are on pp. 76-77.)

Notes on Preceding Table

The preceding table summarizes the performance of readily available rocket engines as calculated by the model described in Appendix I.

Only engines with ranges of interest are displayed. Many more were examined. In general, engines and sounding rockets produced in Britain and Germany are too small to be of interest, and so are not included.

1. t_b = Burn time; the duration of non-negligible thrust from the engine.
2. Alpha is a measure of the non-propellant portion of the rocket stage, including structural materials such as nozzle, casing, etc. Well-designed stages have values close to zero. Where this could not be calculated from available data, a typical value of .2 is assigned.
3. Burn time was not provided; this figure represents a minimum possible burn time calculated from supplied data.
4. This motor comes equipped with jetavator rings for thrust vector control.
5. This motor consists of four identical units in tandem.
6. These are three of a large family of motors, of which this is the largest. Propellant weight and thus total impulse can be adjusted downward over a considerable range at the buyer's discretion.

This data was compiled from data published in Jane's All the World's Aircraft and periodicals such as Aviation Week and Flight International, as well as from information supplied by the following manufacturers and organizations:

Aerojet General
Highway 50 S. Hazel Ave.
P.O. Box 13400
Sacramento, Calif. 95813

Atlantic Research Corp.
5390 Cherokee Ave.
Alexandria, Va. 22314

Chemical Propulsion Information Agency
Johns Hopkins University
Applied Physics Laboratory
Johns Hopkins Road
Laurel, Md. 20810

European Aerospace Corp. (A subsidary of Aerospatiale)
1101 15th St. NW, Suite 300
Washington, D.C. 20005

Hercules, Inc.
Hercules Tower
910 Market St.
Wilmington, Del. 19899

Societe Europeenne de Propulsion (SEP)
Tour Roussel Nobel
Cedex 3, F 920 80, Paris

Societe Nationale Poudres & Explosifs (SNPE)
12 quai Henri IV
Cedex 04, 75181, Paris

SNIA
Via Sicilia 162
00187 Rome

Space Vector Corp.
1963 Prairie St.
Northridge, Calif. 91324

Thiokol Corp.
P.O. Box 1000
Newtown, Penna. 18940