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FINAL REPORT
FOR
A STUDY TO GUIDE RESEARCH AND DEVELOPMENT TOWARD AN OPERATIONAL METEOROLOGICAL SOUNDING ROCKET SYSTEM

(October 1966 - April 1967)

Contract No.: NASW-1522

Prepared for:

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PREFACE

The work represented by this report was initiated in October,1966, under a NASA six-month study contract, NASW-1522.

It is the intent of the study to take a systems point of view in establishing research and development guidelines and design criteria for future meteorological rockets. No attempt is made to design a rocket or to provide a detailed design specification.

The ideas contained in the report are inductively and deductively based on personal experiences and both data and opinions presented by others in the published literature, technical conferences, and private discussions. It would be impossible to acknowledge, by individual mention, all of the contributors to this study; however, a bibliography is included to credit direct statements and to refer the reader to more comprehensive treatments of some subjects.

ABSTRACT

This report describes the results of a study conducted to derive a set of guidelines for future research and development toward an operational meteorological rocket system. Primary emphasis is placed on the rocket vehicle.

The desirable attributes of a meteorological rocket vehicle are based on functional, operational, and economic considerations. These attributes are enumerated and a state-of-the-art survey is included to determine their achievability.

Existing classes of rocket vehicles are discussed together with gun probes, which compete economically in certain altitude regions. Current rocket-vehicle improvement attempts are also discussed.

The conclusions of the study are stated in the form of recommended criteria for the design of a meteorological rocket vehicle.

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Section 1. INTRODUCTION

1.1 Definition of the Study Problem

The process of developing new tools for high-altitude meteorological research has three major facets: (1) that of developing the means to measure previously unobservable quantities, (2) that of improving presently obtained measurements in altitude, accuracy, frequency, and spatial resolution, and (3) that of decreasing the cost of presently feasible techniques to a level which permits their synoptic application.

This process is currently being carried out by a large number of people under sponsorship of several government agencies. Development work is being done on sensing devices, telemetering circuits, parachutes, tracking stations, rocket vehicles - in short, on all of the important elements of the high-altitude meteorological data acquisition system. It is the purpose of this study to approach the development of one of these components, the rocket vehicle, from a system-engineering point of view. An attempt is made to look at the meteorological rocket as an element or subsystem of the larger meteorological data acquisition system, and then, from this viewpoint, to develop design criteria for the ideal rocket.

1.2 Method of Approach

The fundamental design goal for any system, subsystem, or component is to maximize its value.[1] Since it is the object of this study to establish design criteria for a meteorological rocket, the first question that needs to be asked is: What constitutes value in a meteorological rocket? As was previously pointed out, the rocket vehicle is a subsystem in the larger meteorological data acquisition system. The object of this larger system is to provide the data necessary to eventually perfect man's understanding of the atmosphere. As an element of the data acquisition system, the rocket vehicle has value proportional to its contribution to this goal.

When we think about designing a rocket vehicle, however, we become concerned with much smaller and more specific goals. The actual design of the rocket is based on criteria established by answering several questions:

How much weight will the rocket need to carry?
What diameter will the payload be?
How high should it go?
How much acceleration can the payload stand?
What handling characteristics should the rocket have?
How large can the impact dispersion circle be?
What safety features are necessary?
How reliable must it be?
What environmental conditions must it withstand?
How much can it cost?

The answers to these questions constitute a set of criteria for the rocket vehicle subsystem design.

Before a rocket vehicle is finally designed, a set of even more detailed questions must be answered, such as:

What materials will be used for the various parts?
How shall it be propelled?
How long will it be?
How heavy?
What diameter?
How many stages?

The answers to the questions on this level of detail constitute the actual design of the rocket.

It is often a tendency of engineers to move too rapidly to the level of greatest detail. To get down to the real design work as rapidly as possible, the design criteria are often set in an artificial or arbitrary manner. This is exemplified by the idea, "Let's design one that will do everything model X will do; only let's have it cheaper and more reliable." Worthwhile advances are certainly made using this approach; however, minimizing the negative value is only part of the task of maximizing the net value of a system.

Intense consideration of only a few of the design factors while neglecting others is called suboptimization; it leads to incomplete, therefore unsatisfactory, solutions. To avoid suboptimization, it is necessary to develop the design criteria logically from the overall system requirements, always keeping the maximum-value goal in mind.

The first part of this study is a determination and enumeration of the desirable attributes of a meteorological rocket. Since the most fundamental of these attributes is the capability of carrying payloads that can make the most useful meteorological measurements, a determination of the high altitude meteorological measurement requirements is necessary in the very beginning. To determine these requirements, the needs of both operating meteorologists and research scientists are considered and an overall look is taken at the present meteorological data acquisition system to determine the most effective role for the meteorological rocket. Other worthwhile attributes of meteorological rocket vehicles are discussed based on operational considerations, including safety, and economic considerations.

At this point, the desirable attributes of the vehicle subsystem are determined; however, the task of establishing design criteria is not complete. It is obvious that many useful features can never be incorporated in a system design. Some are too expensive, some may be incompatible with other more useful requirements, and some may be unachievable at the present state of technology.

The second is to determine the state of the art in meteorological rockets, measurement techniques, and related equipment. This knowledge is needed to determine what is and what is not technologically feasible. It is also necessary for the purpose of fitting the rocket in with the other components of the system. Before a rocket is designed, one should know how large and how heavy its payload will be. This is partly a function of the measurement requirement, but also a function of the present state of the electronic miniaturization art.

The final task is to take the desirable attributes of the meteorological rocket subsystem, combine them with the state-of-the-art knowledge, and synthesize a set of design criteria for future research and development.

Section 2. ATMOSPHERIC MEASUREMENTS AND THE METEOROLOGICAL ROCKET REGIME

2.1 Purposes of Atmospheric Measurements

There are basically two purposes for which atmospheric measurements are made. The first is to obtain data which can be used with existing models of atmospheric processes to forecast their effects, and the second is to obtain the data necessary to formulate an understanding of the physical processes that govern the behavior of the atmosphere. The ultimate goal is to obtain an understanding of the atmosphere sufficient to make long-term predictions of its behavior.

There are two large scientific groups involved in making atmospheric measurements. One group, the meteorologists, is mainly concerned with prediction of weather, although there is a large faction of this group, called research meteorologists, that is concerned with the improvement of atmospheric models and the explanation of currently incompletely understood phenomena. The aeronomers, who comprise the second group, are research scientists primarily interested in the upper atmosphere, above 60 kilometers.

At the present time, there is increasing interest among meteorologists in the region above 60 kilometers and, conversely, increasing interest on the part of aeronomers in the lower regions. This recent merging of interests has several causes, a few of which are:

(1) The techniques of the meteorologist are being called upon to forecast conditions encountered in the flight of manned and unmanned spacecraft.

(2) Aeronomers are recognizing a continuity of mechanical energy propagation by wave motion through the stratosphere into the mesosphere and higher.[2]

(3) Ionospheric phenomena, e.g. sporadic-E layers, are recognized to be influenced by meteorological factors (wind shear),[3] and hope of forecasting their occurrence may depend on meteorological techniques.

(4) Models of the stratospheric circulation system include the mesosphere.[4]

The above are only examples of factors that are now leading to a merger of the interests of atmospheric investigators. A consensus is now emerging which states, in essence, that for genuine understanding of physical processes in any part of the atmosphere, knowledge must be available of the state of the atmosphere at every level. To obtain a complete atmospheric model, vertical as well as horizontal synopticity is necessary.

2.2 Present Meteorological Measurements

As it now stands, the meteorological observation system is very large and complex. At ground level, atmospheric temperature, barometric pressure, relative humidity, wind speed, wind direction, and cloud cover are observed on a more or less continuous basis. These observations are made from a very large number of stations spread over most of the earth's land masses, and from a few stations on buoys and ships at sea.

Above the ground, several methods are used to gather meteorological data, including airplanes making direct observations and releasing dropsondes, balloon-borne radiosondes, constant-level balloons, earth satellites, gun probes, meteorological rocketsondes, and high-altitude rocket probes.

An extensive network of stations exists for launching and monitoring balloon-borne radiosondes. These sondes are capable of measuring humidity to approximately 7 kilometers and pressure, temperature, and wind to about 30 kilometers where the balloons burst. Because of their low cost and ability to gather important structural data in the troposphere and lower stratosphere, these sondes are a very important part of the total meteorological data system. Approximately 300,000 radisondes are deployed each year by the various agencies of the United States Government.

Currently under development by the National Center for Atmospheric Research is a promising system for studying tropospheric global circulation patterns by means of constant-level, horizontally drifting balloons.[5] Each balloon is equipped with a miniature radio transmitter powered by sun cells to telemeter solar elevation angle, from which the balloon's position can be calculated. Like satellites, balloons of this type can circle the earth many times in their lifetime. Unlike satellites, however, they are carried by the prevailing winds and their very position provides useful atmospheric data. This system is called Global Horizontal Sounding Technique or GHOST.

Another efficient tool for the synoptic acquisition of meteorological data on a global basis is the artificial earth satellite. It is possible, using instruments on board a satellite, not only to monitor the characteristics of the tenuous atmosphere through which the satellite is traveling, but also to observe the troposphere and the earth itself from a distance. Meteorological satellites, making infrared and visible photographs of the earth and its cloud cover, have collected a substantial amount of useful information on global circulation patterns, cyclonic storm behavior, earth-atmosphere heat exchange, and other parameters essential to the understanding of the atmosphere. In addition to their contributions to atmospheric research, the meteorological satellites have also been useful as operational tools in weather forecasting.

The satellites that have thus far been flown have been capable of measuring several parameters over very wide horizontal distributions but only at selected altitudes. At the present time, remote sensing instruments are being developed for obtaining vertical distributions of temperature, water vapor, and density. The infrared interferometer spectrometer developed by Goddard Space Flight Center and the University of Michigan has been demonstrated on balloon flights and found capable of accurate temperature measurements from cloud-top altitude to approximately 30 kilometers.[6]

In addition to their usefulness as instrument platforms for data acquisition, the satellites can serve as relays in a global communication link for meteorological data. Meteorological balloon sites, constant-level balloons, meteorological rocket sites, automatic surface weather stations, and oceanographic buoys can all communicate their information to orbiting satellites which can temporarily store it and re-transmit it on interrogation from a common data-handling facility. Such systems will eventaully allow coordinated reduction of all the various types of meteorological data. It is generally agreed that coordinated data handling on a global basis is necessary for better understanding of atmospheric processes and for accurate long-term weather forecasting.

The large network of radiosonde balloons, the constant-level GHOST balloons, and the meteorological satellites together provide the means for economical acquisition of synoptic data in the troposphere and lower stratosphere. Additionally, the satellites acquire much useful in-situ data on density, composition, and electrical properties of the atmosphere above 200 kilometers. There remains, however, a very extensive region of atmosphere that cannot be reached by either balloons or satellites. In this region, extending from 30 to 200 kilometers, it is necessary to use probes boosted aloft by either guns or rockets.

2.3 Desirable Measurements for Meteorological Rockets

Between the altitudes of 30 and 200 kilometers, the measurements that are necessary to describe the state of the atmosphere and its influencing factors fall into four categories. These are neutral structure, composition, radiation, and charged particles. Of these four groups, only the first three are of major meteorological interest, and synoptic observations of them for meteorological purposes are most significant below 100 kilometers. Charged-particle measurements are made above 60 kilometers (bottom of the ionospheric D region); and whether or not these measurements have meteorological significance, synoptic observations would be beneficial for purposes of modeling radio communication conditions.

The quantities comprising the structure of the atmosphere are temperature, pressure, density, and wind. Below about 90 kilometers, where mixing is prevalent and the mean molecular weight is essentially constant, temperature, pressure, and density are precisely related by the hydrostatic equation and the general gas law so that knowledge of one of these quantities, together with altitude, permits calculation of the other two. For the purpose of determining structure below 90 kilometers, the requirement is to measure temperature, or pressure, or density, and wind. At higher altitudes, where diffusive separation of gases occurs, it is necessary, additionally, to determine the mean molecular weight or to measure the partial pressure of a single gas constituent.

Below 90 kilometers, composition measurements are relatively unimportant except for the minor constituent, ozone. Although the maximum ozone concentration in the region above 30 kilometers is very low, this gas has considerable meteorological importance. As a strong absorber of ultraviolet radiation from the sun, ozone is responsible for the negative lapse rate of temperature in the stratosphere and for the temperature peak at 50 kilometers.[7] It also plays an important role in the photochemistry of the ionosphere. Until recently, detailed profiles of ozone in the stratosphere have not been available; however, new rocket-borne instruments are now being developed.[8,9] Ability to carry an ozone measurement payload is a very desirable attribute of a future meteorological rocket system.

Above 90 kilometers, the atmosphere is reasonably non-turbulent, and diffusive separation of the various gases begins to occur.[7] Additionally, because of the relatively little prior absorption of solar radiation, dissociation and ionization of the gas molecules takes place in the daytime and recombination takes place at night. This region is therefore variable and uncertain in its composition. Measurements of composition in this region are necessary to an understanding of the processes that take place. Because several different chemicals exist in varying quantities, these composition measurements are usually made using mass spectrometers.

Throughout the stratosphere and mesosphere, radiation from the sun is an important factor influencing the atmosphere. Radiations from other sources are also of interest to meteorologists and aeronomers as indicators of atmospheric processes; therefore, many radiometers are flown on rockets. Radiometers are flown to measure air density by solar absorption,[10] ozone concentration by UV absorption,[11] airglow,[12] and other quantities.

The D region of the ionosphere, extending from 60 to 90 kilometers, overlaps much of the altitude range where meteorological measurements are desired. In this region, charged particles consisting of positive ions, negative ions, and electrons exist together with the neutrals. These particles, although their number densities are down 16 orders of magnitude or more from those of the neutrals, are thought to have an appreciable effect on the physics of the region. Furthermore, layers of these charged particles are important in low-frequency radio communication. For meteorological purposes, synoptic measurements of such quantities as positive ion density, negative ion density, electron density, and electron temperature are needed for a physical understanding of this region. Since the meteorological rocket will traverse the same altitude range, it should be utilized for D-region investigations.

Section 3. DESIRABLE ATTRIBUTES OF METEOROLOGICAL ROCKET VEHICLES

The fundamental purpose of a meteorological rocket is to make one or more of the measurements discussed in the previous section. Design of the rocket should, therefore, be directed toward this end; however, in addition to the functional task, there are operational and economic considerations that must be taken into account.

3.1 Operational Considerations

Safety, ease of launch preparation, minimization of support functions, logistic simplicity, and maintainability are the primary operational attributes of a meteorological rocket vehicle. Together with performance and economic constraints, these operational considerations should weigh heavily in the vehicle design.

Because of the high energy density of propellents, rocket motors are regarded as being hazardous and they are, therefore, shipped, stored, and handled with a great deal of caution. For maximum safety, the rocket motor should be insensitive to shock, sparks, and even open flame, making it possible to handle and store the rocket with no more elaborate precautions than those accorded to any flammable materials. Packaged-liquid motors have their fuel and oxidizer separately packaged; and, with the solid propellent gas generators removed, they have the desired non-hazardous handling properties. This propulsion method should therefore be considered along with methods of reducing the handling hazards of conventional solid-propellent motors.

At many launching sites, it is necessary to conduct rocket launch preparation activity in the radiation field of high-power radars. Although the probability of accidentally firing an electro-explosive device by an r-f source is very small, several precautions must be taken to further reduce this probability. Replacement of these electrically-initiated pyrotechnics with percussion-initiated devices, which could be mechanically locked until ready for use, would be one method of reducing the hazards in handling a meteorological rocket.

A meteorological rocket system intended for synoptic use will be widely dispersed to launch sites both close to and remote from population centers. For operation near cities, the controlled impact areas are necessarily small and provisions must be made in the rocket vehicle design for minimizing the falling mass hazard. This means that all of the material leaving the launcher as part of the rocket vehicle or its payload must reliably be consumed, fall into a controlled area, fall slowly, or be broken into particles whose fall energies will be too small to inflict damage on people or property. To design a meteorological rocket whose operation is not severely limited by the falling mass problem, a combination of the above methods should be considered. The non-hazardous design may be more expensive than its predecessors; however, the additional expense should be largely or completely negated by the value of the more complete meteorological data.

Another economic benefit resulting from falling-mass-hazard elimination is reduction of the number of people necessary to support the launch operation. Measuring low-altitude wind profiles, calculating launcher settings to compensate for these winds, and predicting impact points often requires as many people as the rest of the launch operation. By designing a vehicle with extremely low dispersion or with the falling mass hazard otherwise reduced, this operation can be simplified or eliminated.

The personnel requirement for meteorological rocket launch operations should be held to a minimum. Ideally, it would be desirable for the entire operation, consisting of removal from storage, vehicle preparation, payload installation, pre-launch checkout, rocket launch, and data recording, to be accomplished by two people. This is feasible, however, only if the entire system is designed for simple assembly and operation. Payloads, rockets, and other components of the system should be completely assembled, calibrated, and checked out at the factory and only dismantled to the minimum extent necessary for shipment to the field. Modular design is desirable since field installation then consists mainly of component emplacement and interconnection.

Maximum use should be made of remote-control features. Rocket arming and disarming, payload status control, and launcher control should be capable of being performed from the launch control center. Since the number of functions to be performed in a given time is by far the greatest during the last few minutes preceding launch, activities requiring long periods of time must be minimized in order to limit the number of operators required. For the sake of safety, rocket arming should not be accomplished until just prior to launching,and battery limitations require waiting until the last minute to utilize internal power for on-board instrumentation. Both of these functions are performed at the same time the tracking, data collecting, and launching stations are being activated; therefore, if the functions required at the pad can be performed remotely, the maximum utilization of operators is achieved.

For maximum system effectiveness and for most efficient maintainability, it is desirable to stock a well selected inventory of spare parts. These parts should be small and rugged so that they can be easily shipped, stored, and used without damage. At most launch sites, protected storage will be limited; so even though components are small and rugged, they should be packaged in containers geometrically configured for dense storage.

Simple and efficient maintainability should be a part of the rocket vehicle design. This requires consideration of the environment to which the system will be exposed while in storage and use, establishing rates of component failure, determining probability statistics and failure modes through testing, developing component life expectancy data, and establishing a frequency of inspection. Design based on these considerations will reduce maintenance costs for a given level of reliability. Logistic support requirements are also minimized when the components and subsystems are designed for maximum reliability with a minimum of maintenance over the useful life of the system.

3.2 Economic Considerations

In reality, every consideration taken into account in a system design is an "economic consideration." Each of the performance attributes of a system has some positive economic value which must be traded against its cost. The ability to assign dollar values to these attributes as conveniently as costs are determined would reduce much of the decision making in system design to the level of simple arithmetic.

Unfortunately, such positive value estimation is usually very difficult. It may be possible to arrive at a rough estimate of the long-term economic value of a given percentage improvement in weather forecasting accuracy; but when the uncertainty in this estimate is compounded with an even greater uncertainty in estimating the effect of a given improvement in meteorological rocketry on the eventual ability to make forecasts, the resulting uncertainty in evaluating the positive, dollar values of the rocket improvement becomes astronomical.

The value of making measurements of the types listed in section 2 of this report has already been judged and found to be sufficient to justify considerable funding. There is little doubt that these performance requirements for meteorological rockets should be somehow satisfied. Consideration of economic factors in determining meteorological rocket design criteria must, therefore, turn to negative value or cost.

Most of the operational factors that were previously discussed offer potential savings in cost of labor for rocket launching. To the agency sponsoring rocket development and manufacture, these cost considerations are often considered secondary; however, from the system point of view, they are equal in importance to the costs of the vehicles themselves.

Traditionally, meteorological measurements have been acquired and analyzed synoptically for the understanding of large-scale weather patterns and for weather forecasting. It would be desirable for rocket-acquired high-altitude data to receive this same kind of synoptic treatment; however, unless the meteorological rocket can be very inexpensive to build and operate, the cost of such a program is prohibitive.

Just as the large-quantity requirement is the factor that dictates inexpensive design, it is correspondingly the factor that makes low-cost production possible. When large quantities are to be produced, extra engineering effort can be applied to the tasks of creating a low-cost design, expensive but efficient automatic tooling can be used for production, and manual functions can benefit from progress along the learning curve. If the costs of engineering, tooling, and start-up learning can be amortized over large numbers of production units, then unit cost will reflect the savings due to improved efficiency with only a small contribution from initial expense.

In designing for low cost, particular attention should be given to the problem of producibility. Shapes and materials should be selected for minimal machining, and manufacturing tolerances should not be unnecessarily restrictive. Interchangeability of parts is unquestionably a desirable feature; so mating parts must be held to tight tolerances. Other tolerances should be relaxed as much as possible.

Section 4. CURRENT STATE OF THE ART

4.1 Measurement Techniques

Figure 1 is a chart showing a comparison of the techniques that are currently in use for making structural measurements between 30 and 100 kilometers. For easy comparison, the approximate errors in all the temperature, pressure, or density measurements are shown in terms of measured or calculated temperature. Some of these techniques are routinely used for synoptic soundings. The others, because of their expense, are used for more specialized research at higher altitudes. By value-engineering, it is possible that some of these latter techniques may be sufficiently reduced in cost that they may become practical for extended-altitude synoptic use. Each of these techniques will be described in this section and discussed in terms of its possible application to high altitude synoptic use.

The most frequently used rocket-borne temperature measurement system uses a 10-mil bead thermistor as the primary transducer. In this system the resistance-versus-temperature characteristic of the thermistor frequency modulates a blocking oscillator, which in turn amplitude modulates a telemetry transmitter. The instrument package is carried to an altitude of 60 or 70 kilometers by a sounding rocket, then is ejected and allowed to descend by parachute.

The errors of this system have been analyzed by several investigators on the basis of mathematical models that take into account the effects of radiation, lead conduction, internal electrical heating and time lag.[13, 14] On the basis of these analyses, it is generally agreed that the bead thermistor is a reasonably good sensor having error less than ± 5°C or so below 55 kilometers. Above 55 kilometers, the accuracy of this sensor deteriorates rapidly.

The density of the atmosphere decreases exponentially with altitude and the mean free path of molecules increases exponentially. In the region between 30 and 100 kilometers, the average scale height (altitude interval over which density or mean free path changes by a factor of ϵ, the natural

Measured Parameter	Technique	Useful Altitude Range	Approximate Measurement Error
Temperature	Bead Thermistor Thin-Film Thermistor Grenade	20 - 60 km 20 - 75 km (est.) 30 - 90 km	± 2°C to ± 5°C ± 2°C to ± 5°C ± 2°C to ± 20°C
Pressure	Pitot-Static	30 - 100 km	Pressure ± 5% ± 5°C to ± 10°C for derived temperatures
Density	Accelerometer Sphere Inflated Sphere	30 - 115 km 20 - 120 km	± 5°C to ± 10°C for derived temperatures Comparable to the accelerometer sphere with high-quality radar
Wind	Parachute Chaff Inflated Sphere Grenade Chemical Trails	20 - 60 km 30 - 80 km 30 - 70 km 30 - 90 km 80 - 160 km	± 5 m/sec ± 10 m/sec ± 5 m/sec ± 3 m/sec to ± 30 m/sec ± 3 m/sec

Figure 1. Atmospheric Structure Measurement Techniques used between 30 and 100 kilometers

log base) is approximately 6.5 kilometers.[15] At 60 kilometers, the molecular mean free path is 0.26 millimeter which is approximately equal to the diameter of the bead. In this increasingly tenuous atmosphere, the air-to-sensor heat transfer process becomes very inefficient, and the competing processes of radiation and conduction cause appreciable errors. The measurement is further degraded by a slower sensor time constant and higher parachute fall rate, also caused by the low air density.

As a result of these factors, the system errors reach such a magnitude above 60 kilometers that the method is no longer useful. Either better accuracy at a given altitude or increased maximum altitude for useful measurements would constitute improvement to this system. These can be achieved by lowering the descent rate of the instrument, decreasing the time constant of the sensor, and minimizing heat-transfer mechanisms that compete with the desired atmospheric communication. Much work has been done pertaining to each of these means of improvement; and by combining such currently achievable components as a microminiature payload, a Stoke's-flow parachute, a thin-film thermistor, and a radiation shield, it should be possible to obtain useful direct temperature measurements to about 75 kilometers.

The speed of sound is a secondary structural parameter in the atmosphere. It is determined by the equation:

$$V = \sqrt{\frac{\gamma RT}{M}} ,$$

where V is the speed of sound, γ is the ratio of specific heats for air, R is the universal gas constant, T is the air temperature, and M is the mean molecular weight. The air temperature can be determined by measuring the speed of sound in the atmosphere and solving the above equation for T. In practice, this method is hampered by the same factors that limit the maximum altitude of the direct measurements. It is difficult to couple enough acoustic energy to the low-density atmosphere so that a large enough signal can be obtained at the receiver to determine the speed of sound.

One successful technique uses explosive grenades detonated at regular altitude intervals.[16] At the instant of grenade explosion, a pulse is radioed to a ground station and the length of time is measured for the sound of the explosion to reach a microphone array on the ground. This method gives the temperature profile through an approximate altitude interval of 30 to 90 kilometers. The microphone array used with the grenade system consists of at least five microphones placed on crossed baselines, each about 800 meters long. By comparing times of arrival of the acoustic wavefront at the various microphones, it is possible to determine direction of arrival and compute the wind-versus-altitude profile.

As presently configured, the experiment is flown on a Nike-Cajun rocket with a payload 56 inches long weighing 60 pounds. Nineteen grenades are expelled at altitude intervals of 3 to 5 kilometers. A tracking system is necessary to pinpoint the position in space of each grenade burst. The single-station and multiple-station DOVAP systems are currently used.

The grenade technique has been a very successful workhorse in obtaining atmospheric structure above 60 kilometers; however, for synoptic use, it has several drawbacks. The ground equipment required is expensive. Compared with other techniques, the payload is dangerous to handle. The payload is necessarily large and an expensive rocket is required to boost it. Although good average temperatures are obtained between grenade bursts, the technique offers little potential for obtaining fine structure.

The pitot-static probe, as the name implies, makes measurements of ram and static pressure as a rocket payload ascends.[17] From these measurements, the ambient pressure, density, and temperature are calculated over an altitude range of approximately 30 to 100 kilometers. The pressures measured over this altitude range vary from approximately 10 to 10^{-3} mm Hg, and rather sophisticated pressure gages are needed to cover the range. In addition to the pressure measurements, the angle of attack and velocity of the payload must be known.

In its present form, the pitot-static probe flies on a Nike-Apache rocket. The payload contains a pair of radioactive ionization gauges for pressure, a magnetometer and optical aspect cell for angle of attack, a DOVAP transponder, and a telemetering system.

Work is currently being done to reduce the complexity of the instrument and package it for a Boosted-Arcas vehicle.[18] It is doubtful that the expense of this experiment can ever be brought down to equal that of the thermistor method; however, it has a much higher altitude capability and is therefore a contender for high-altitude synoptic use.

Another method of obtaining air density to 100 kilometers and above is the falling-sphere technique. There are several variations on this theme, all having in common the principle of determining air density by measuring the drag deceleration of a falling sphere. In some cases, the deceleration is measured by an internal accelerometer.[19] In other cases, it is obtained by differentiation of radar position or velocity data.[20, 21] Both acceleration-measurement methods yield about the same accuracy in density or derived temperatures; however, the radar-tracked inflated spheres also provide data for wind profiles.

The principal advantage of the accelerometer sphere is that an expensive tracking radar is not required to determine atmospheric density. Its disadvantages are payload complexity and cost. For maximum accuracy, the sphere should have a large diameter-to-weight ratio. Present spheres of this type are rigid, have a diameter of 7 inches, and weigh approximately 9 pounds. They are flown on Nike-Cajun, Nike-Apache, Nike-Iroquois, and Nike-Tomahawk rockets.

To adapt this technique to synoptic use, the sphere must be made less expensive, more compact, and lighter so that a cheaper vehicle can be used to launch it. All of these improvements are within the realm of feasibility and a synoptic falling sphere experiment is therefore possible.

The inflated passive spheres make extremely simple payloads and have already been flown on low-cost vehicles such as the Arcas. Their principal disadvantage is that, in order to obtain good density or wind data, the launch site must be equipped with an excellent radar, preferably one having a doppler velocity-measuring capability.

A possible improvement to the passive sphere, that would make it more attractive for widespread synoptic use, would be the addition of a microminiature transponder so that it could be tracked with a less expensive radar. The transponder would have to be carefully designed for minimum weight and installed in such a manner that it would not distrub the ballistic properties of the sphere.

Three of the five wind techniques shown in Figure 1 are by-products of temperature or density methods already discussed. The chaff and chemical trail methods, however, deserve individual mention.

The chaff wind measurements are made by expelling a bundle of small metal or metallized plastic pieces at high altitudes, allowing them to fall and separate to form a chaff cloud, then tracking the motion of the cloud with a radar.[22] The chaff particles are usually cut as dipoles to a length appropriate to the tracking radar.

The most that can be said for chaff is that it is a very inexpensive wind technique. The payloads are simple and cheap and the vehicle requirements are not severe. Although an altitude range of 30 to 80 kilometers is shown in the chart, this range cannot be covered in a single shot. At high altitudes and in turbulent situations, the chaff diffuses very rapidly to a large-diameter cloud, irregular in shape and of uneven cross section. Tracking error and thus wind measurement error are therefore functions of altitude, time after release, and radar quality.

Chaff payloads have been flown on several vehicles, among which are the Loki-Dart, the Cajun-Dart, and gun probes. Chaff is a useful synoptic technique where other parameters are not required or are provided by a separate probe.

Several types of luminescent chemical trails are flown for the measurement of wind.[23] The method consists of releasing a gas or vapor trail from a rocket payload or a gun-launched projectile and photographing it at intervals from a geometrically spaced array of cameras. Trigonometric correlation of the data on film permits rather accurate calculation of winds. The technique is primarily useful at higher altitudes than 100 kilometers; however, some useful measurements can be made as low as 80 kilometers. A disadvantage of chemical trails is that they can only be used under ideal visibility conditions. Shots must be made at twilight or in total darkness and the sky must be locally free of clouds.

4.2 Payload Miniaturization

Minimization of meteorological payload weight and volume is important for several reasons. From the vehicle design point of view, it is a simple matter of economics. If the payload is small and light, a smaller, lighter, and therefore less expensive vehicle is necessary to lift it to a given altitude.

In equilibrium measurements such as the temperature and wind measurements currently being made, the maximum measurement altitude is limited by the descent velocity of the retarded payload and the response speed of the sensor. It is possible to decrease the descent rate of a payload by increasing the drag of the descent device or by decreasing the weight of the payload. In a volume-limited payload, both of these methods require miniaturization of the measurement circuits and components.

When new miniaturized devices are first introduced, they are usually more costly than their full-sized counterparts; however, in the long run, miniaturization is not necessarily accompanied by increased cost. As a matter of fact, the miniature components end up being cheaper than their predecessors; for example, etched circuits are now cheaper than hand-wired circuits, transistors and solid-state diodes are cheaper than equivalent vacuum tubes, and standard integrated circuits such as differential amplifiers and flip flops are cheaper than similarly-performing discrete-component versions. Miniaturization of meteorological payloads will be costly in the initial phases, but, especially for instruments that are finally selected for synoptic application, it will save many dollars in the long run.

Since the inception of the electronic art, components and circuits have grown continually smaller. At any stage in this process, the word miniaturization has a new meaning. In this discussion we will consider, as miniaturization techniques, any methods that might be used to make a new meteorological rocket payload significantly lighter or smaller than those currently in use. Thus the use of solid-state devices to replace tubes will be considered a miniaturization technique, although in many cases, such replacements are made for reasons other than miniaturization. Similarly, the replacement of hand-wired circuits with printed or etched circuits is considered a miniaturization technique if it makes the circuit smaller or lighter.

Except for some developmental models, the telemetering payloads used with the 30 to 60 kilometer low-cost meteorological rockets employ a cavity-tuned vacuum triode to generate the UHF carrier signal.[24] In most cases, the low-frequency circuits use transistors as active elements. In these low-frequency circuits, the replacement of vacuum tubes with transistors has been a simple matter. At the carrier frequency of 1680 MHz, however, such replacement has only recently been made feasible. Until the overlay transistor was introduced by RCA in 1964, it was necessary to generate a fundamental signal at approximately 100 MHz or below, amplify it in several stages to a level of 4 watts or greater, then multiply the frequency by means of varactor diodes. The overlay transistor permitted a higher fundamental frequency, higher power level, and, consequently, greater power conversion efficiency. At the present time, solid-state power sources suitable for meteorological rocket use are produced by RCA, Motorola, Western Microwave, Texas Instruments, and others.

The principal advantage of a solid-state power source is not in circuit miniaturization, but in overall payload weight reduction due to a smaller stored energy requirement. The cavity-tuned triode currently in use is of comparable size to the solid-state sources. In typical operation, however, it requires approximately 1 watt from the filament supply and 2 watts from the plate supply for each 100 milliwatts radiated. This gives it a typical power conversion efficiency of 4.3% when 300 milliwatts are radiated. This low power-conversion efficiency, coupled with the need for separate low and high-voltage batteries for the filament and plate, makes it necessary to carry a heavy and bulky battery pack. Typical of the present day solid-state power sources is the RCA model S170 which requires only a single voltage source and converts d-c to UHF with a nominal efficiency of 26% and a minimum efficiency of 10%. Since the low-frequency signal-conversion circuits consume very little power, a payload using this source would require less than half the battery weight of one using a vacuum-tube source.

In recent years, the field of electronic packaging has been revolutionized by the advent of monolithic, silicon integrated circuits. These circuits are produced in the same manner as diffused junction transistors except that several different circuit elements, including resistors, capacitors, diodes, and transistors are simultaneously diffused in a single semiconductor slice.[25] Conducting leads between these elements are formed by selective etching of a vacuum-deposited aluminum film on the surface of the slice.

Integrated circuits can be custom designed for specific applications or general-purpose integrated circuit modules, such as flip-flops, gates, differential amplifiers, and operational amplifiers, can be used to replace conventional circuits. Using these circuits, volume and weight reduction of 100 times can be attained in certain applications.

Many conventional circuits, including some of those now used in meteorological rocket payloads, cannot be replaced by integrated circuits. Such circuit elements as large capacitors, inductors, power resistors, and stable precision resistors cannot be constructed by ordinary integrated circuit techniques. To solve these problems, other methods have evolved for miniaturizing these difficult, passive components. Thin and thick-film resistors, metal-oxide-semiconductor capacitors, and film capacitors are examples.

Conventional tuned circuits and filters use inductors to obtain their frequency-dependent characteristics. Since only very small inductors can be produced by microcircuit techniques, other means have evolved to obtain high-Q tuned circuits. These include active R-C filters, negative impedance converters, miniature acoustic resonators, digital filters, and semiconductor delay lines.

Very seldom is it possible to reduce an entire electronic system, such as a telemetering package, or even a transmitter, into a single integrated circuit. As was previously pointed out, many components cannot be microminiaturized at all. Furthermore, a degree of isolation is often necessary between individual circuits to prevent undesired capacitive, inductive, or thermal coupling. In practice, several microcircuits, individually encapsulated, together with some conventional discrete components, are wired and packaged together to form an operating system.

In order not to defeat the original purpose of the microcircuits, the system packaging should also be viewed from the point of view of volume and weight reduction. A minimum of high density material is used. Plugs, sockets, and other types of connectors are omitted, and components are soldered or welded directly into the circuit. Individual component packages are dovetailed or otherwise closely spaced. Intercomponent connections are made using etched or printed circuit boards. These are typical techniques of high-density packaging.

Where weight, but not volume, is of primary importance, microcircuit components are still used, but high-density packaging is not necessary. The important thing here is to use light-weight structural material and leave empty space where material is not needed.

At the present time, none of the payloads used on rockets for meteorological measurements make extensive use of the microminiaturization techniques that have been discussed. All of them can be miniaturized to some degree and in most cases miniaturization could be accomplished with an attendant long-term cost reduction. The possible results of miniaturizing one of these payloads, the standard thermistor-parachute rocketsonde with a receiver for use with the AN/GMD-2 tracking system, are estimated and shown in Figure 2.

With the light-weight descent package achieved using these miniaturization techniques, descent rates equal to those of the Arcas package can be obtained with a much smaller parachute. The descent rate of a parachute and its load is directly proportional to the square root of the total descent weight and inversely proportional to the flying diameter of the parachute. The Arcas parachute is 15 feet in diameter, weighs about 4 pounds, and carries a 4.5-pound load. The reduced-weight payload would descend at the same rate with a 7-foot diameter parachute of the Arcas type, weighing approximately 12 ounces.

4.3 Existing Meteorological Rockets

For many years, the only regular probing of the atmosphere was with instruments carried aloft by balloons to an altitude of approximately 30 kilometers. After 1957, the artificial satellite provided atmospheric scientists with great quantities of data above 200 kilometers. This, however, with the exception of some rocket grenade experiments measuring temperature and wind, left the region of the atmosphere between 30 and 200 kilometers essentially unprobed. Consequently, about this time,

Name of Part	Miniaturization Method	Resulting Weight	Volume
Transmitter	Solid-State Circuit	2.5 oz.	1 in^3
Receiver	Hybrid Microcircuit	1.5 oz.	1 in^3
Modulation Circuits	Integrated Circuits	1.5 oz.	2 in^3
Battery Pack	Silver-Zinc Rechargeable	1.3 oz.	1.5 in^3
Temperature Sensor	Shielded Film Thermistor	0	1 in^3
Structure	Foam-Potted Plastic Frame	4.0 oz.	8 in^3
Total		10.8 oz.	14.5 in^3

Figure 2. Potential Miniaturization of Thermistor Payload

observational studies above the 30 kilometer region were initiated with the use of rocket systems.

The first vehicle intended for regular soundings between balloon and satellite altitudes was a modified Loki anti-aircraft rocket designed to be fired from a gun.[4] The modified version was designated Loki I and carried 2 pounds of chaff to approximately 35 kilometers. Shortly thereafter, another version of the Loki, designated Loki II, was developed which had the capability of transporting the 2-pound chaff payload to approximately 60 kilometers. In 1958 - 1959, the Arcas was developed as an interagency project to provide a vehicle with a larger payload capacity for measuring atmospheric conditions at altitudes up to 60 kilometers.

Since that time, numerous versions of meteorological rockets have been developed or proposed. These include Hasp, Roksonde 200, SSR-1, Sirocco, Ute, Tempest, Wasp, Loki-Dart, Judi-Dart, Deacon-Arrow, Owl, AG-32, Aeolus, Raven, and others. Several meteorological rocket systems, manufactured outside the United States, are currently being manufactured, or are in development. These include the Skua family of vehicles of the United Kingdom, Kappa II from Japan, Aeolus and Hat from Australia, Belier from France, Dornier from Germany, and Meteo I from Italy.

All of the vehicles listed above essentially fall into two general classes epitomized by the Arcas single-stage rocket and the Judi-Dart. These two vehicle types will be described in detail.

4.3.1 The Arcas and Its Variations

The Arcas is a 4.5 inch diameter, single-stage solid-propellant, end-burning rocket vehicle. Its propulsion system contains 42 pounds of propellant with axially oriented silver wire imbedded in the grain to increase the burning rate. A star-shaped indentation in the aft end of the grain provides a burning surface until cones around the wires are fully formed. The grain is cast in one piece, and the circumferential surface is impregnated with an epoxy-resin to inhibit burning. The cast grain is held in the motor tube by bonding the forward end to an aluminum headplate. The motor tube is deep drawn from annealed SAE 4130 steel, .040-inch thick, and 59.3 inches long.[26]

Ignition of the motor is by an electrically activated squib-igniter which is inserted in the motor nozzle prior to launch. The igniter leads are connected to a bulkhead connector on the inner side of the launcher breech plate. Final arming is performed by connecting the firing lines to the bulkhead connector on the outside of the launcher breech plate.

The vehicle is stabilized by four cast aluminum fins which are bonded and bolted to the aft end of the case.[27] Vehicle weight at launch, less payload, is 68 pounds; and its rated capability is to deliver a 7-pound net payload, 4.5 inches in diameter, to 64 kilometers when launched from sea level. (See Figure 3.)

The Arcas vehicle is launched from a closed-breech launcher, which comprises a 20-foot long tube to guide the rocket during initial acceleration, a free-volume cylinder to trap and retain the rocket exhaust gases, and an azimuth table assembly to permit training of the launcher through 360 degrees in a horizontal plane and 180 degrees in a vertical plane.[28] An auxiliary gas generator can be attached to the launcher to generate additional pressure in the free-volume cylinder and thus increase the initial launch acceleration. The launcher is held in place by bolting the azimuth table to a concrete launch pad. At launch, the free-volume cylinder traps the ignited motor gases and builds up a pressure which forces a piston, attached to the motor nozzle, up the tube. The rocket is centered and supported in the tube by four styrofoam spacers which fall away with the piston when the rocket leaves the launcher.

Payload separation occurs near vehicle apogee. A steel tube, inserted in the propellant grain, leads to the separation device contained in the headplate. At thrust termination, heat conducted through the steel tube ignites a pyrotechnic delay train which burns for approximately 100 seconds, and in turn ignites a gas generator, which generates pressure to shear pins holding the payload.

The standard Arcas payload has a volume of 170 cubic inches. An alternate payload volume of 240 cubic inches can be made available by the addition of an extension ring. Three types of atmospheric measurement packages, which are considered standard, are carried in government inventory. These, when incorporated with the Arcas vehicle, are designated PWN/6A, PWN/6B, and PWN/7A meteorological probes.

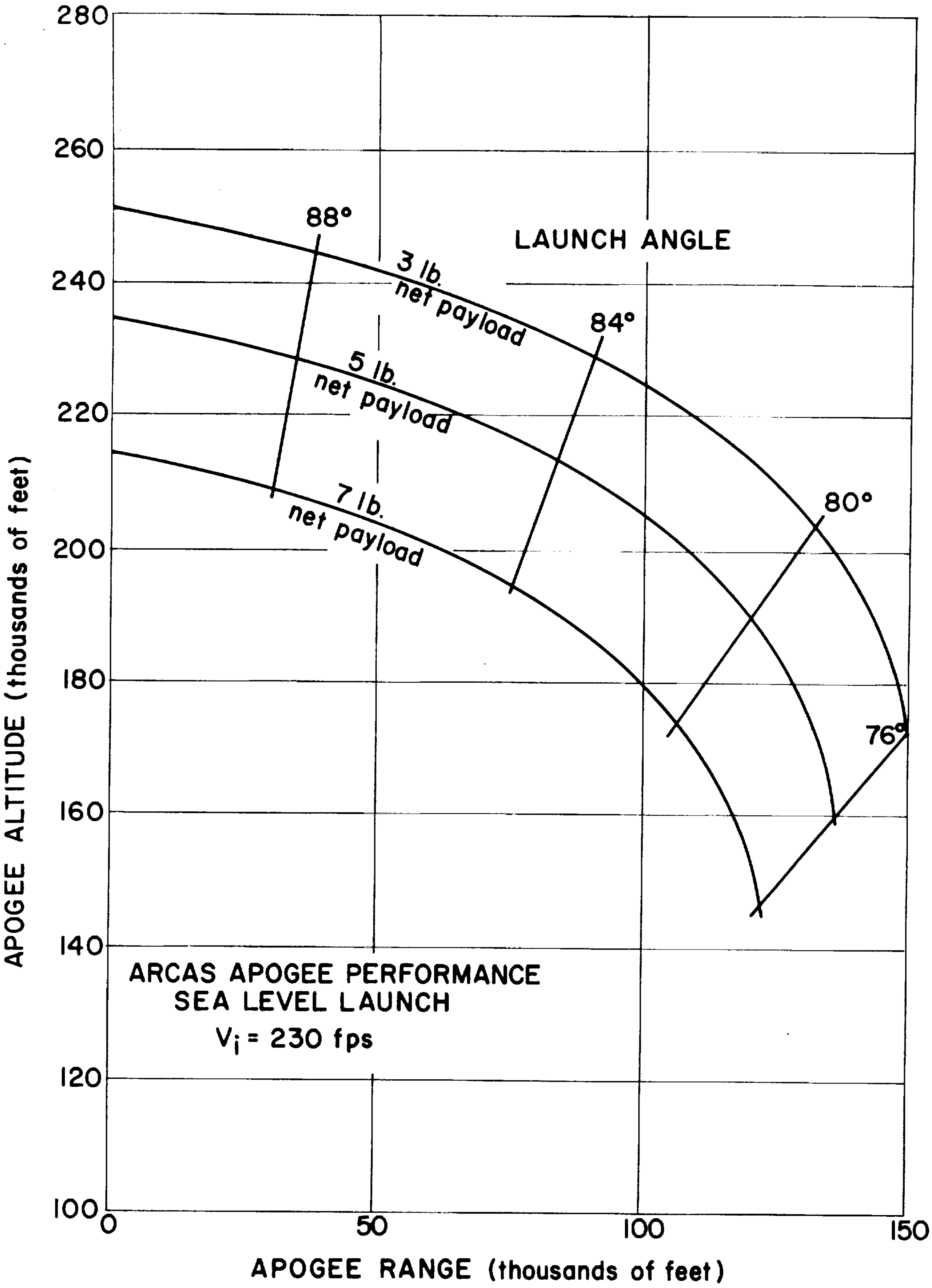


FIGURE 3

DATA ACQUIRED FROM ATLANTIC RESEARCH TECHNICAL DATA SHEET

The PWN/6A payload is called Arcasonde 1A and is a telemetry package, temperature sensor, and 15-foot diameter silk parachute. The payload is separated from the vehicle near apogee and the parachute is hauled from its container. The entire package falls freely until sufficient dynamic pressure has built up to inflate the parachute. The telemetry package is suspended on the parachute and transmits temperature information during its descent. The parachute is tracked by ground-based radar, and the lateral motion is assumed to be the average wind between two altitudes coincident in time with the lateral space positions used in computing lateral rate. The instrument package weighs about 3.5 pounds and operates on a frequency of 1680 MHz which is compatible with the AN/GMD-1 tracker.

The PWN/6B payload contains an AN/DMQ-9 transponder-telemetry package and parachute. This transponder package is somewhat heavier than the Arcasonde 1A and operates on a receiving frequency of 403 MHz and a transmitting frequency of 1680 MHz. These frequencies are compatible with the AN/GMD-2 tracker, which differs from the AN/GMD-1 in that the slant range to the airborne package is obtainable. The main advantage of this system is that a skin-tracking radar is not required.

The PWN/7A payload contains a mylar sphere, called Robin, which is either metallized or houses a radar corner reflector. The Robin is ejected near vehicle apogee and tracked with a precision radar. By knowing the sphere weight and drag characteristics and by computing the sphere's fall rate from radar data, atmospheric density and lateral winds can be calculated.

Soundings higher than 64 kilometers are possible with the Arcas by incorporating a booster. Several boosted-Arcas vehicles have been developed including Boosted-Arcas I, Boosted-Arcas II, Sidewinder-HV-Arcas, and Sparrow-HV-Arcas. These vehicles have gross payload capabilities of 10 to 30 pounds to altitudes of 84 to 174 kilometers.[29]

4.3.2 Boosted Dart Variations

The Loki-Dart and Judi-Dart vehicles, as well as numerous other commercial competitors, are essentially identical. The Loki-Dart and Judi-Dart both have been used extensively in collecting wind and temperature data from 55 kilometers down. Although several versions of both the

Loki-Dart and Judi-Dart have been used, the Judi I rocket, manufactured by Rocket Power Incorporated, and its dart are discussed here as being typical of this class of vehicles.

The Judi-Dart is a two-stage vehicle comprised of a propulsive first stage and an inert or non-propulsive second stage. The first-stage propulsion is a Judi I rocket motor designated 1.9KS 2100, which is 3.0 inches in diameter, 66 inches long, and contains 18.1 pounds of case-bonded composite propellant.[30] The grain is a cylindrical-perforate with a center diameter of 1.297 inches at the head end and 0.996 inches at the aft end. The motor thrusts nominally for 1.8 seconds and delivers a total impulse of 4000 pound-seconds. Temperature limits on this motor are -40°F to +140°F. The motor case is 2014-T6 aluminum and the nozzle expansion ratio is 5.44. [26]

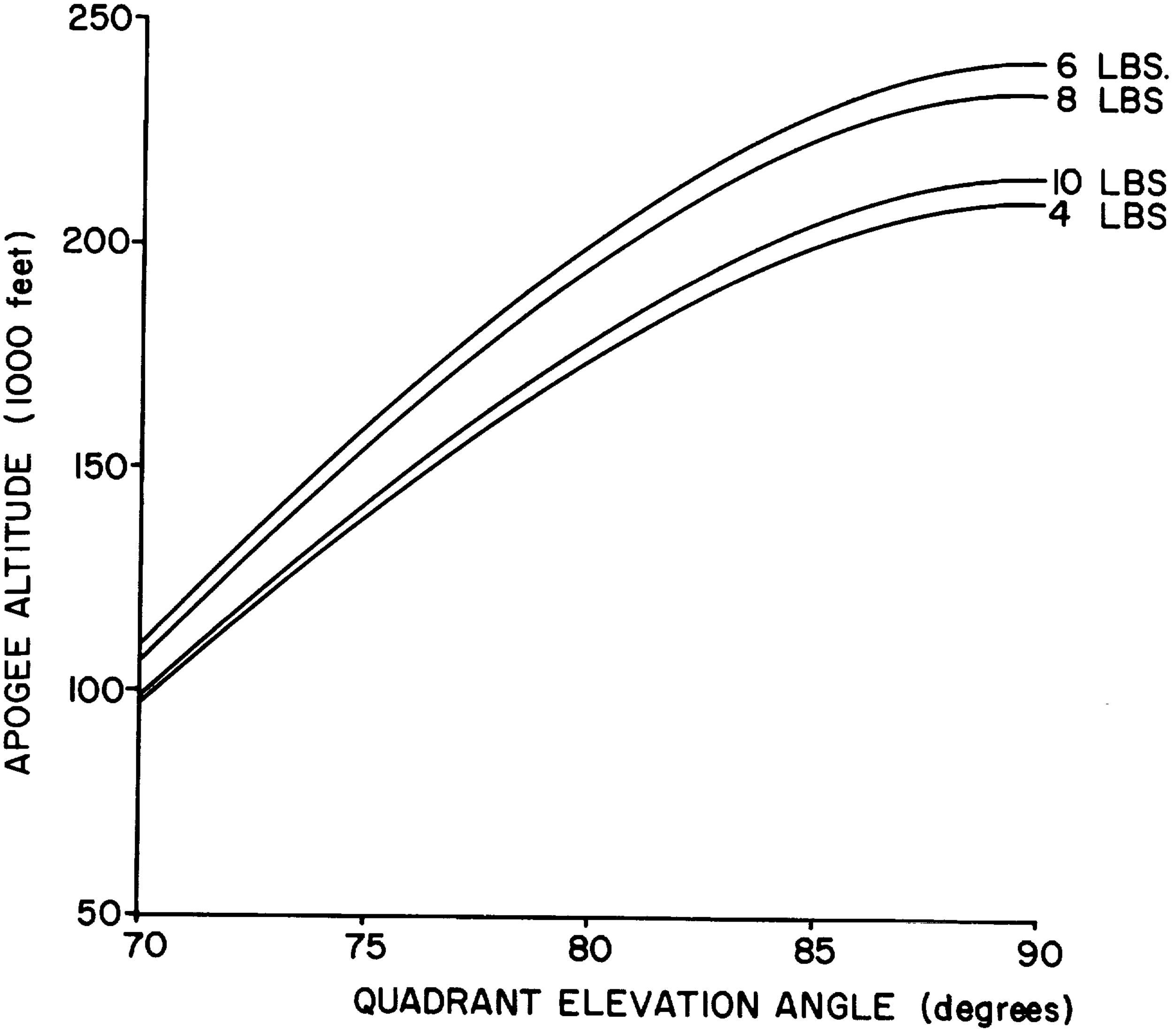
The motor is ignited by an electrically-activated, hot-particle igniter, which contains 25 grams of cupric oxide and aluminum powder. The igniter is inserted into the motor through the nozzle end. It is 30 inches long and has a pair of electrical conductors which protrude from the motor aft end and are attached to ground-power firing leads for igniter initiation.

The vehicle is stabilized by four clipped-delta fins which are welded to the aft end of the rocket motor case. Vehicle weight at launch, less dart and payload, is 24 pounds and its rated capability is to deliver a 6-pound gross, 1.375-inch diameter dart and payload to 60 kilometers when launched from sea-level as shown in Figure 4 . Experience has shown the apogee altitude to vary from 58 to 62 kilometers when launched at an 84° quadrant elevation angle.

The dart typically used has 1.375 inches outside diameter, is 40 inches long, and has an optimum weight of 6.5 pounds. A volume of 30 cubic inches is available for instrumentation.

At launch, an electrical power supply at the launch site is used to initiate the first stage propulsion unit. The vehicle then accelerates for 1.8 seconds to achieve a nominal velocity of 6000 feet per second. Maximum acceleration during this time is about 250 g's. A time-delay fuse, initiated either by ground power or by aerodynamic heating on the

FIGURE 4. JUDI — DART
APOGEE PERFORMANCE



nose tip, begins to burn at the time of launch. Upon thrust termination, the dart is separated from the booster by a differential drag load on the two bodies. The dart then coasts to its apogee altitude and the payload is ejected by a charge, fired by the time delay-fuse.

The Judi-Dart can be fired using a variety of launcher schemes. The most common launcher is an 8 1/2-foot tube which is mounted on an elevating mechanism. A spiral guide in the tube induces spin which is maintained in flight by canted fins.

In the past, the use of rocket-darts for meteorological data collecting has been restricted primarily to measurements made with chaff, falling spheres, and, more recently, with a single-channel telemetry-parachute payload. The Robin falling sphere, a 1-meter plastic balloon, is inflated upon ejection from the 1.5-inch inside diameter dart by means of a metered amount of isopentane encapsulated in the balloon. The balloon is then tracked by ground radar data. This technique has been used successfully several times.

A dartsonde, designated PWN/8A, has been developed by Air Force Cambridge Research Laboratories (AFCRL).[31] A temperature transducer, a single-channel telemetry circuit, and a parachute are contained in a 1.375-inch diameter dart. Additional efforts are currently being expended by AFCRL to improve the dartsonde package by incorporating a solid-state transponder to replace the transmitter. Temperature and wind measurements up to approximately 55 kilometers are currently being made by several organizations with systems of this type.

Another rocket-boosted dart which is in use today is the Cajun-Dart. This vehicle is being flown by Marshall Space Flight Center, Sandia Corporation, and others, for purposes of obtaining wind data in the 60-80 kilometer altitude region. The payload has a volume of 31 cubic inches and a diameter of 1.375-inches. Boost is provided by a TE-M-82-3, Cajun Mod III rocket motor, which provides a total impulse of 24,697 pound-seconds. Figure 5 presents a profile view of one version of this vehicle.

The Cajun-Dart provides a nominal payload apogee altitude of 93 kilometers when launched at a quadrant elevation of 80 degrees from

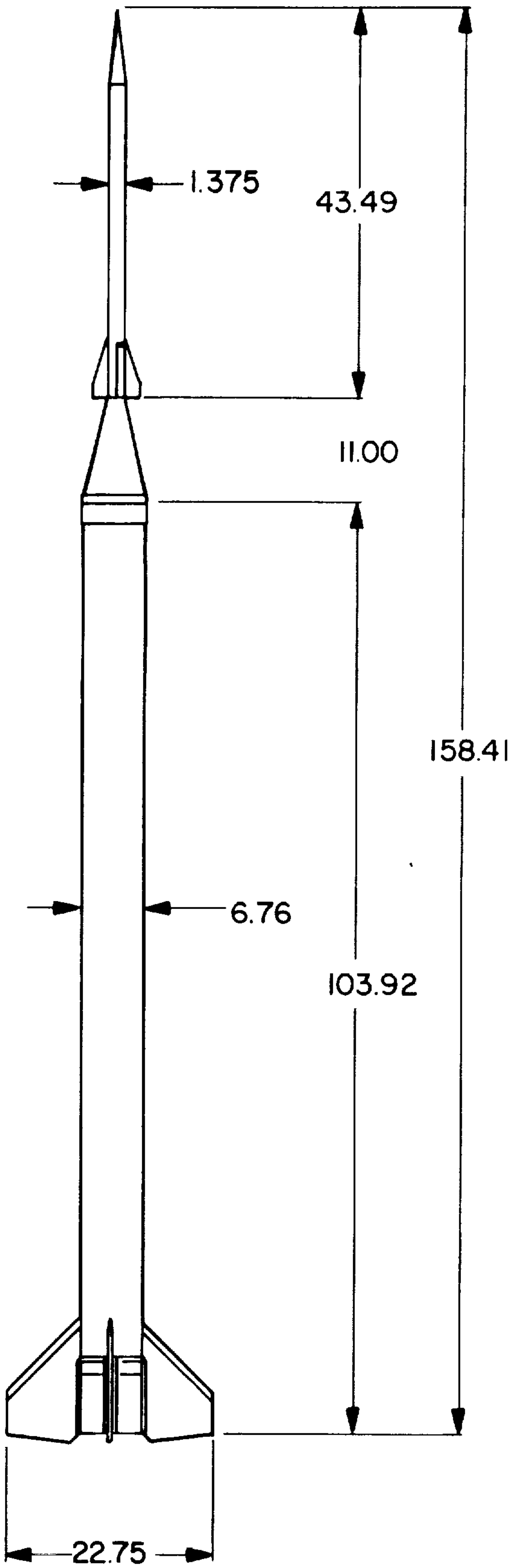


FIGURE 5. CAJUN BOOSTED DART

sea-level. Figure 6 shows the performance characteristics of this vehicle. As with all boosted-dart systems, the performance is significantly affected by variations in both drag and weight.

The dart carries approximately 1.33 pounds of chaff which has been cut to a length corresponding to 1/4 the wave length of the ground-based tracking radar signal. This chaff is deployed by an expulsion charge at apogee and tracked with a ground-based radar until the cloud has diffused to the point where the return signal is inadequate. Winds are then calculated from the lateral displacement of the chaff cloud as a function of time. It is generally agreed by users that the computed wind data are valid between the altitudes of 60 and 80 kilometers.

A boosted-dart vehicle capable of going to 140 kilometers is currently being developed by Air Force Cambridge Research Laboratories. This vehicle uses the currently-existing Viper motor to boost a 1.75-inch, 20-pound dart. The dart will have space for a 2- to 3-pound net payload.

Initial launch tests of this vehicle are scheduled at Eglin Air Proving Ground this summer. Initially the payload will be a passive inflatable falling sphere; however other payloads are planned for eventual use, including a spinning wire densimeter which will measure high-altitude air density by observing decay rate of the spinning wires.

4.4 Gun-Launched Probes

In addition to the various meteorological rocket probes which have been developed in recent years, a joint U.S. Army and Canadian venture called Project HARP (High Altitude Research Project), was established with the intent of providing "an economical and precise means for placing payloads in the earth's atmosphere by the use of gun-launched projectiles."[32]

Studies conducted at the Ballistic Research Laboratories in 1959 indicated that a 20-pound, fin-stabilized, atmospheric research probe would attain 76 kilometers altitude when launched from a 5-inch smooth-bore gun.[33] Initial development firings of the 5-inch gun were conducted in 1961. In 1963, a 7-inch gun was designed which included a new probe and substantial modification of the then existing barrels. In late 1961, McGill University in Montreal, Canada, began development of a 16-inch gun system. Significant progress has been made in the development of all three of these gun-probe systems and today guns are in use at White Sands Missile Range, New Mexico;

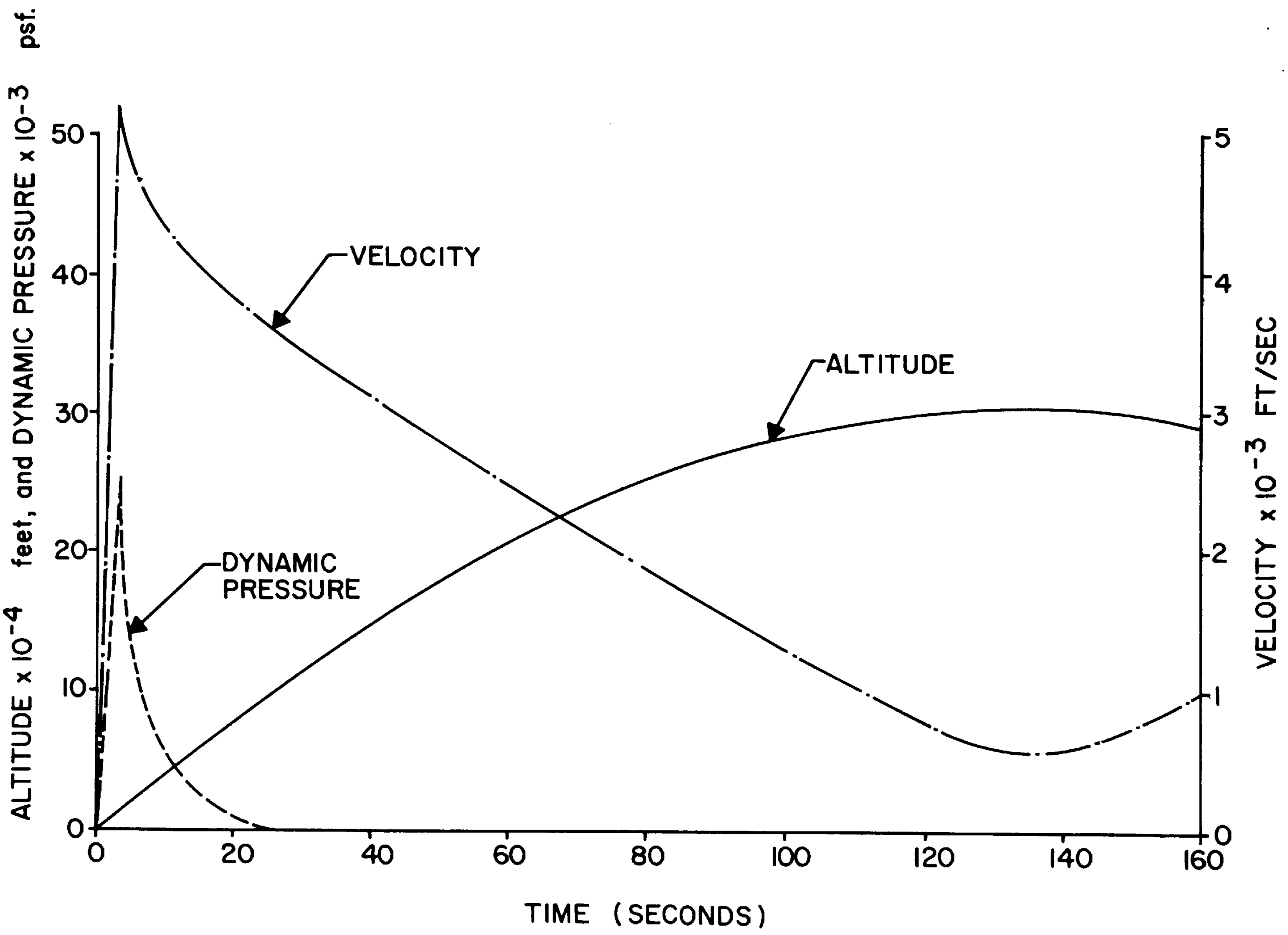


FIGURE 6. CAJUN-DART NOMINAL TRAJECTORY DATA (to apogee)

Wallops Island, Virginia; Yuma Proving Ground, Arizona; Barbados Island, West Indies; and Fort Greely, Alaska.

The 5-inch gun was the first version adapted to demonstrate feasibility of using a gun to make atmospheric soundings. The system consists of a 120 mm barrel extended to 32 feet and braced by a three-rod truss system to minimize flexure. Two hydraulic elevating pistons are attached to the barrel-to-mount adapter and the carriage. This gives the capability of elevation of this barrel and carriage combination of some 60^o, so the entire carriage is placed on an incline to permit the barrel quadrant elevation to reach firing positions near 90 degrees. Estimated costs to adapt a surplus barrel and mount is $15,000.[34]

Several 5-inch gun projectile configurations have been launched; however, a general purpose probe, which is typical of this system, is described here. The probe consists of a sub-caliber metal projectile, central-supporting sabot, plastic gas-sealing rings behind the sabot, and a payload. A powder charge is loaded into a 120 mm brass cartridge and an electrically-initiated extended-tube primer is threaded into the aft end of the cartridge. At ignition of the power charge, the pressure load is transmitted to the projectile which is forced out of the barrel. The sabot and gas-sealing parts fall away from the projectile as it leaves the barrel and the probe is then in free flight.

The payload compartment has a volume of about 20-cubic inches and can carry 1- to 2-pounds net. The gross probe weight is normally 20 pounds. To reach 60 kilometers a muzzle velocity of 5000 feet per second is necessary and the probe must withstand a peak acceleration of 50,000 to 60,000 g's for about 15 miliseconds.

Ambient temperature probes have undergone development firings from the 5-inch gun with varying degrees of success. About 5-cubic inches of the probe's volume is used for the temperature sensor and telemetry transmitter and the remainder is used for a 6-foot silk radar-reflective parachute. The transmitter is solid state and its components are imbedded in potting compound to protect them from the launch environment. Temperature is measured by a bead thermistor.

Five-inch guns located at White Sands Missile Range, Wallops Island, and Barbados are currently being used to place chaff and aluminized parachutes to 55-60 kilometers for wind measurements.

The 7-inch gun system was developed in 1963 with the intent of delivering 60-pounds to 65-pounds gross probe weight to 95 kilometers while retaining the mobility of the 5-inch gun system. The 7-inch gun, like the 5-inch, consists of a surplus barrel mounted to a field carriage. The barrel is extended to 55 feet, trussed to prevent droop, and mounted to a 175 mm, T76 field carriage. The gun mount is modified to achieve elevation angles up to 88 degrees without inclining the carriage. Adaptation of this configuration costs approximately $40,000, which Ballistic Research Laboratories feels could be reduced.

The powder charge for the 7-inch gun is inserted into the chamber in bags instead of being loaded into a brass case as in the 5-inch. This bagging technique is the same as used in the standard 175 mm cannon application. The powder is ignited by a plastic ignition tube filled with black powder and inserted through the main powder bags. An electric primer is used to fire the black powder in the ignition tube.

Four probe configurations have been launched. These contain usable volumes varying from approximately 35 to 100 cubic inches. The diameters vary between 3 and 5 inches and the fin spans are 7 inches.

Various powder charges are used with different projectiles; however in general, launch velocities range between 4000 and 6000 feet per second and launch accelerations vary between 25,000 and 50,000 g's.

Seven-inch guns are currently in operation at various sites, including White Sands Missile Range and Wallops Island. While there have been several launches from these guns, more experimental effort is needed on the powder charge and projectiles for general purpose applications. The launches that have taken place have carried both inert and active payloads including chaff, spheres, telemetry, and langmuir probes.

The 16-inch gun is a 50-caliber naval rifle, smooth bored to 16.4 inches. As with the 5-inch and 7-inch systems, an extension is added to the barrel. In this case, a 51-foot extension is used, making a total barrel length of 119 feet. The barrel is stiffened using 30 tons of

1.5-inch thick longitudinal steel gussets and 2-inch thick steel radial webs welded in place.[35] The barrel weight of the 16-inch gun is approximately 200 tons. Launch acceleration from this system approaches 20,000 g's.

Winds are being measured by chemilumeniscent trails at Barbados and Yuma Proving Ground, using the 16-inch gun. Additionally, various instrumented payloads have been launched with the 16-inch gun; however, because of the immense installation expense and logistics, it is very doubtful that this gun can be considered for multi-site use.

4.5 Critique of the Existing Vehicle Types

The Arcas vehicle was one of the pioneers in rocket meteorology and certainly has been a workhorse in gathering atmospheric data in the altitude region below 60 kilometers. This vehicle was developed in the late 1950's and, therefore, represents essentially 10-year-old technology. An evaluation of the Arcas, per se, would be of doubtful value; however, an evaluation of the concept of end-burning, and in general, single-stage meteorological rockets seems appropriate.

4.5.1 End-Burning Single-Stage Vehicles

Low-acceleration launch environments, inherent in end-burning rockets, have undoubtedly been a necessity in the past, since the instrumentation being transported evolved from that used for balloonsondes. The penalties of launch limitations due to wind, and relatively large impact dispersions, were tolerated in order to have the capability of carrying instrumentation for making direct measurements of meteorological parameters. However, technology in manufacturing components to withstand high acceleration environments has advanced to the point that the same measurements can now be made without the attendant disadvantages of a "soft launch." Telemetry transmitters, temperature transducers, Langmuir probes, sun-sensors, and accelerometers have been launched from guns with initial accelerations of several thousand g's. Certainly not all instruments envisioned for future meteorological measurements can withstand this type of environment; however, wind sensitivity and dispersion can be significantly reduced with initial accelerations of a few hundred g's, and instrumentation capable of surviving this level of acceleration is at hand.

A distinct advantage of end-burning rocket motors is the long duration of thrust, which results in the most efficient utilization of the rocket's energy in delivering a payload to a required altitude. With a long burn time, lower velocities are attained at a given altitude and the vehicle is at a much higher altitude when burnout occurs. Less energy is therefore lost to drag. Another factor contributing to the rocket's efficiency is that very little base drag (loss of energy due to a vacuum or low pressure region behind the rocket) is present during the long thrusting interval.

The Pyrotechnic delays used for initiation of payload separation, while relatively inexpensive, have some drawbacks. First, the end-burning motor has variations in burning time, which introduces an error in initiation of the pyrotechnic delay train. Secondly, the pyrotechnic delay time varies significantly with pre-launch ambient temperature variations. These variations, combined with different launch altitudes and launcher quadrant elevations, result in a large deviation in payload separation time and altitude. Separation near apogee is important because payload decelerating devices need adequate time to stabilize and allow the sensors to reach equilibrium with the atmosphere at as high an altitude as possible. An inexpensive timer which does not vary with the motor burn time and which could be simply and remotely set from the control center according to ambient temperature, launch altitude, and launcher QE, would be a worthwhile improvement.

4.5.2 Radial-Burning Single-Stage Vehicles

Radial-burning and combination end- and radial-burning rockets continue to be contenders for operational use. With present propellant burning-rate technology, radial-burning rocket motors thrust for a much shorter period of time than do end burners. As discussed above, this results in a less efficient utilization of the rocket's delivered impulse, because the drag losses are higher than those of a long burner. On the other hand, this type of grain configuration is more economical to manufacture than the end burner. A radial-burning grain can be cast directly into the case and case-bonded for support. A solid end-burning grain requires more elaborate techniques for supporting the grain.

Since the dynamic pressure loading on a vehicle increases sharply with decreasing burn time, short-duration radial burners present another area of concern. The heat flux attendant with high dynamic pressures requires special consideration in the case of a single-stage radial-burning rocket because of the long soak time during flight. This problem can be solved using structural and ablative materials developed for reentry and terminal defense missiles. The major disadvantage of the single-stage radial-burning vehicle is that of component cost. The entire vehicle airframe, including tail fins, must be capable of withstanding the severe heating and pressure-load environment. The motor case cannot be optimized purely as a pressure vessel, but must also be a good airframe. Another problem associated with high dynamic loadings is that of fin flutter. Prevention of flutter can become a major design factor which is not consistent with economy.

A final disadvantage of a single-stage rocket is the difficulty it presents in eliminating the falling mass hazard. A considerable amount of effort has been spent on the development of frangible and consumable rocket vehicles. Explosively fragmenting cases have been demonstrated; however, such cases can be hazardous to handle. The technology of consumable rocket motor cases is advancing in spite of such engineering problems as preventing auto-ignition of the case, finding a consumable material with adequate structural properties, and bonding head and nozzle closures to withstand peak operating pressures. In addition to the rocket motor case, the problem of reliably destroying the nozzle throat and payload housing has yet to be solved. Technology in non-explosive frangible materials, such as chemically stressed ceramics, is advancing to the point where these problems can be solved; however, large quantities of time and money will be required to solve these problems for the single-stage rocket and the result is apt to be more expensive than another vehicle system which is more amenable to reduction of the falling mass hazard.

4.5.3 Boosted-Dart Vehicles

As discussed in a previous section, both passive and active wind measurements, and equilibrium temperature measurements are routinely being made to approximately 55 kilometers using boosted-dart vehicles. The two major advantages of these vehicles are relatively small impact dispersion and inexpensive component costs.

Since the angular wind response during thrust of a fin-stabilized rocket is an inverse function of its velocity, the boosted-dart vehicles, with their large accelerations and short thrust times, are relatively insensitive to wind. Besides wind, dispersion is also caused by aerodynamic misalignments and thrust eccentricity. These misalignments cause trajectory angular displacements during thrust which result in large angular displacements at impact. The same misalignments have very little effect while the burned out vehicle is coasting. Shorter burn times, therefore, result in smaller trajectory angular errors.

Another desirable result of the short thrust time of the boosted-dart vehicle is that the booster motor need not be designed as an ideal aerodynamic structure. Although it is subjected to large dynamic pressures and high stagnation temperatures, it separates from the dart portion of the vehicle when these factors are at their maximum values. Eventual structural failures due to heat soak, fatigue, and even burn through are, therefore, of no consequence. Thus, it is possible to design the motor for minimum cost, ignoring aerodynamic sophistication.

The component cost advantage of the boosted darts also stems from the fact that they are small vehicles which deliver relatively small amounts of energy. This, however, correctly implies that these vehicles have very limited payload transporting capability. The limitation in available payload volume must be viewed from two standpoints. If wind and temperature measurements up to 55 kilometers constitute the major usage, and if present measurement accuracies are acceptable, then certainly the Loki-Dart class of vehicle is adequate. However, if measurement altitudes are to be increased, accuracies improved, and parameters other than wind and temperature are to be measured, then the limited payload volume is a serious disadvantage of this vehicle.

Perhaps one of the most important points to be made in favor of the boosted dart is that the falling mass hazard can be reduced much more economically than with the single stage. The motor separates from the dart shortly after launch and becomes a high-drag body with severely limited range, even in case of malfunction. Only the small dart body or payload housing then remains to be destroyed. The complex problems of destroying motor case, nozzle, fins, etc. are avoided.

4.5.4 Gun-Boosted Probes

Atmospheric probes boosted by guns are a logical extension of the rocket boosted-dart technique. As such, the same pros and cons which apply to boosted-dart vehicles also apply to guns, except in a more extreme form.

In general, payload volumes are quite limited and launch environments are severe. Consequently, varieties of payloads which can now be launched by guns are limited. System reliability is presently lower than that of rocket-boosted probes. However, this is not necessarily inherent in the system and mainly reflects present state-of-the-art.

A major advantage of gun launched probes is the low impact dispersion. This results from the fact that the projectile is guided during its entire thrust phase and is in free-flight only during its coasting phase. As pointed out in the boosted-dart discussion, elimination of falling mass hazard from the probe and payload is much easier than destroying the propulsion unit. In the gun system, the propulsion unit remains on the ground.

A unique feature of the gun-boosted probe approach, is that the payload altitude can be easily varied by varying the powder charge placed in the gun. For example, the 7-inch gun probe, with larger payload volumes than the 5-inch, is intended primarily for the 90- to 100-kilometer altitude region. The same probes could be used for transporting payloads to the 60-kilometer altitude region.

4.6 Economic Comparisons

At a value-engineering symposium held at Fort Monmouth in 1965, the costs of the Arcas and Loki-Dart vehicles were examined and the possible effects of value engineering were determined.[36] The cost of the Arcas meteorological probe in lots of 1000 was put at approximately $2,100. Of this cost, approximately $250 applies to the net payload and $1,850 to the vehicle. Corresponding costs for the Loki-Dart in lots of 100 are $750 total, $250 for the net payload, and $500 for the vehicle.

It was estimated that extensive value engineering could reduce these costs considerably. For the Arcas, a vehicle cost reduction of $850 was anticipated to yield a future vehicle cost of $1000. A reduction of $90 in the Loki-Dart vehicle cost was estimated based on value engineering and increasing the procurement lot size to 1000 units. This would result in a future vehicle cost of $410.

An estimate of the costs of gun-launched probes was obtained through discussions with the cognizant personnel of the Ballistic Research Laboratories of Aberdeen Proving Ground.[34] In large quantities, the vehicle cost of the 5-inch gun probe is estimated to be $350 per round. Reboring of the gun at a cost of $1000 is required after 200 projectiles are fired making an additional amortized cost of $5 per round.

Since the three different classes of probes require vastly different ballistic coefficients, the probe tare weights and usable net payload weights also differ widely. Figure 7 attempts to normalize these differences by comparing usable net payload weight to ultimate achievable vehicle cost. Altitude has been eliminated as a parameter since all three are very nearly the same.

Vehicle Type	Net Payload Weight	Approximate Vehicle Cost	Ratio of Cost to Payload Weight
Arcas	7.0 pounds	$1000	$143/lb.
Loki-Dart	2.0 pounds	$ 410	$205/lb.
5" Gun-Probe	2.0 pounds	$350	$175/lb.

Figure 7. Ratio of Ultimate Vehicle Cost to Net Payload Weight

Considering the cost per pound of usable payload weight, the Arcas is the most economical method of transportation. If wind and temperature were measured using two of the seven payload pounds available in the Arcas, the other five pounds could be used to make three other measurements of equal value. Three additional gun launches or boosted darts would be required to collect the same data. However, if wind and temperature to 55 kilometers are the only necessary measurements then gun-launched probes are the most economical.

The 7-inch gun probe, although intended as a 100-kilometer capability probe, could easily be made to reach only 65 kilometers by using less powder in the gun. This probe has a payload capability of some 8 pounds and costs about $560 per launch. The ratio of cost to net payload weight for this probe is only $70 which is some 2.5 times more economical than any other method of making 55-kilometer measurements. However, again, since approximately 2 pounds is adequate to measure neutral structure to 55 kilometers, the 5-inch gun is the most economical for this application.

Several vehicles are currently being used for meteorological measurements in the 50- to 100-kilometer region. Cajun-Dart vehicles are presently being used by Marshall Space Flight Center and others to carry chaff to 90 kilometers for making high altitude wind measurements. The cost of this vehicle in lots of 100 is approximately $2,600 each. Substituting a booster like the Apache for the Cajun would increase the altitude and/or dart payload capability. Cost of the Apache-Dart in quantities of 100 would be approximately $3000 per vehicle. For about the same costs as in the dart configuration, the Cajun and Apache class of rockets can be used in single-stage form to carry multiple experiment payloads and instruments, not amenable to packaging in limited payload volumes, into the 60- to 100-kilometer region. Performance data for the Apache-Dart and single-stage Apache are given in Figure 8.

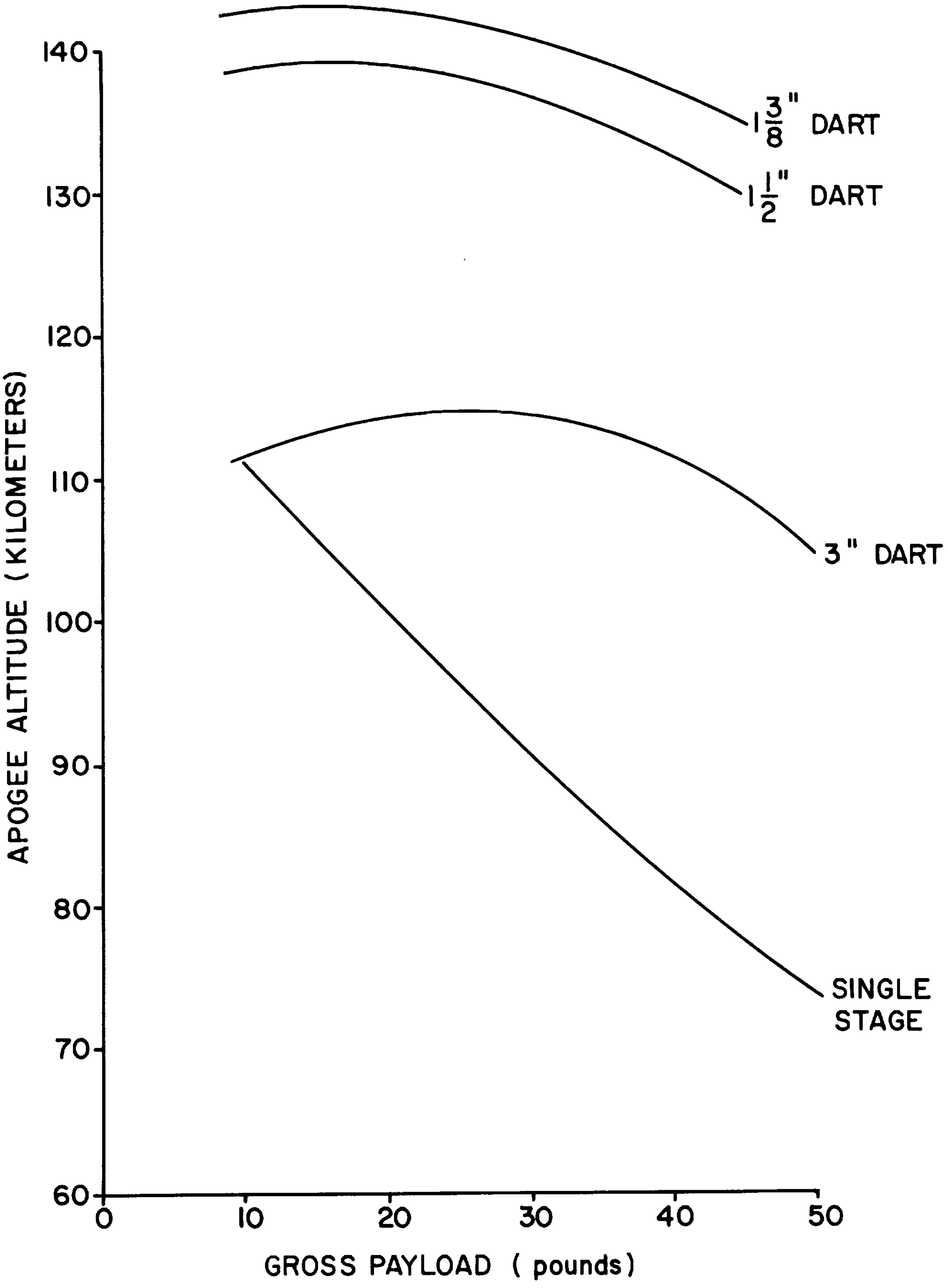
These costs are undoubtedly too high for extensive use of this class vehicle. However, since these costs represent several-year-old technology, it is felt that a 20% to 40% reduction could be achieved by value engineering. Assuming that the Apache vehicle could be reduced to 70% of its present cost, it would then cost about $2,100. If production quantities were increased to 1000 a year, then this cost would rapidly approach present Arcas cost.

High-altitude structural measurements requiring boosted Cajun- and Apache-class rockets are also being conducted. As discussed earlier, ram-pressure techniques for measuring density, falling spheres for density and wind, and grenade-acoustic techniques for winds and temperature are examples of such probes. A vehicle to perform this type of mission costs around $5000 each in lot sizes of about 25.

4.7 A Developmental Meteorological Rocket

The United States Army Missile Command has conducted investigations to determine: 1) future meteorological vehicle research, development, test, and evaluation (RDT&E) requirements through 1975; and 2) the

FIGURE 8.
100 KILOMETER ROCKET PERFORMANCE TYPIFIED BY THE APACHE CLASS OF PROPULSION.



adequacy of available meteorological rocket vehicles to satisfy these requirements.[37] They have concluded that the primary requirement is to transport atmospheric measurement payloads, in support of RDT&E programs, to altitudes of 61 to 76 kilometers. A secondary requirement is to transport payloads up to 152 kilometers.

Subsequent to the determination of requirements, a state-of-the-art survey was made to determine the availability of rocket vehicles for satisfying these requirements. It was concluded that no vehicles, either as presently configured or modified, would adequately fulfill their needs for RDT&E programs. In light of these findings, AMICOM has initiated efforts to develop a rocket vehicle for meteorological RDT&E use to 72 kilometers altitude. It is intended that this rocket vehicle will be used as the second stage of a two-stage vehicle to fulfill the secondary requirement for 152 kilometers.

For purposes of evaluating state-of-the-art improvement attempts, the defined requirements of this rocket vehicle are summarily described. The vehicle is to be capable of delivering a 7-pound net payload to a nominal altitude of 70 kilometers when launched from sea level with a launch quadrant elevation of 80 degrees. The reliability of the vehicle in accomplishing this objective is to be 95%. The rocket must be capable of being launched in winds up to 35 knots without requiring the use of complicated impact predicting equipment. The vehicle must be capable of being operated in any climate and at established test ranges, semi-permanent installations, or remote sites by five to ten operators. The payload will be separated near apogee and the expulsion device will be capable of easy deactivation for missions not requiring payload separation. Acceleration in the longitudinal axis will not exceed 100 g's, spin rate will not exceed 15 rps, and the internal payload temperature will not exceed 150°F. The target cost of the vehicle is $350 each (not including payload) in quantities of 2000-3000 per annum. A technique for eliminating the falling mass hazard is to be incorporated if feasible.

The vehicle being considered is a single-stage rocket which will remain with the payload to apogee. It will be launched from a 15-foot rail launcher, will be fin-stabilized, and will contain a case-bonded solid propellant. On the basis of preliminary conceptual information, the rocket motor case is to be 4130 steel, 0.036-inch thick, 4.8 inches in diameter, and 57.7 inches long. The grain being considered was PBAA, composite-type propellant, configured as a split cylinder core, to burn for 7.25 seconds. The motor is planned to have an average chamber pressure of about 1,300 psi, an average thrust of 1,640 pounds, a port-to-throat ratio of 1.5, and a propellant laoding fraction of 90%.

Achievement of the technical and economic goals set for this program would result in a very good vehicle for transporting payloads to 70 kilometers. Since the AMICOM development program has bearing on the scope of this study, a few comments related to this effort are given. It should be noted, however, that the AMICOM program is presently in the exploratory development phase and new developments are undoubtedly occurring which could negate some of the comments.

While the Army's primary requirement is to measure wind, temperature, density, and pressure to 70 kilometers, the various reasons for making peaceful-purpose meteorological measurements require data to 100 kilometers. For this reason, a civilian counterpart of the Army 10-year plan for research and development efforts should focus on the entire 30- to 100-kilometer region.

With regard to the Army design approach, it is noted that the concept of a single-stage rocket that remains with the payload to apogee presents serious problems and requires costly solutions for eliminating the falling mass hazard created by the inert rocket components after the payload is expelled. Furthermore, the vehicle design parameters appear to be extremely optimistic and perhaps beyond the present state of the art. For example, the drag coefficients for vehicle-performance calculations seem to be between 10% and 30% lower than those experienced on current "low-drag" vehicles and this does not include launch lugs which must be used for a rail launch. The performance of a vehicle in this class will be significantly degraded unless the launch lugs are ejected immediately after launch.

The required Isp and burning-rate combination is beyond the state of the art for PBAA. Other propellants, polyurethane for example, can achieve the Isp and burning rate; however, they will not withstand low temperatures. Consequently, the Isp, burning rate, and environmental specifications combination appears to be optimistic.

Another possible area of difficulty is the motor port-to-throat ratio. Generally speaking, port-to-throat ratios of less than three result in erosive burning which cause larger-than-normal case pressures.[38] Since the motor case is fairly thin, difficulty may be encountered in containing these pressures.

In general, the design and cost goals set for this program appear to be somewhat optimistic. It is likely that many of them can ultimately be achieved; however, a long and expensive development program may be necessary for their realization.

Section 5. CONCLUSIONS AND RECOMMENDATIONS

In determining the measurement requirements for a meteorological rocket system, it was noted that the interests of the meteorologists are moving toward more complete horizontal coverage for synoptic low-altitude measurements, and toward greater peak altitudes for high-altitude measurements. Recently-popularized gravity-wave theory presents a model for energy coupling between the stratosphere and mesosphere and indeed into the thermosphere. Stratospheric and memospheric circulation patterns are receiving attention. Meteorological analysis methods are being applied to ionospheric problems. In short, the interests of meteorologists and aeronomers are beginning to merge. This philosophical point should be kept in mind as a key to operational needs of meteorological rockets to be developed, and plans should be made to obtain rocket and instrumentation capabilities for low-cost measurements at higher altitudes.

In the study of any physical process in the atmosphere, it is useful to have a complete data picture. This includes vertical and horizontal spatial variations and temporal variations of as many sensible parameters as relate to the process. To formulate such a complete data picture in high-altitude meteorological research, the rocket vehicles used should be capable of covering a large altitude range, should be designed for synoptic application, and should be able to carry payloads that make more than one or two measurements.

The height-range objective for a developmental met rocket is partly determined by the scientific interests discussed above and partly by the vacancy left by already-existing techniques. It was pointed out in the report that the region between 30 and 200 kilometers was entirely left to rockets and guns. For meteorological purposes, this region is further bounded by a natural ceiling in the neighborhood of 90-100 kilometers. At this level, diffusive separation of atmospheric constituents occurs and structural measurements give way in importance to composition and electrical measurements. This is also an approximate ceiling for low-to-moderate cost single-stage and dart vehicles; therefore, vehicle costs take a jump at about this level. Coincidentally, instrumentation costs also increase at about this point. It is concluded that the altitude range to be covered by meteorological rockets should be 30 to 100 kilometers.

There are several kinds of measurements that are of meteorological interest in the 30- to 100-kilometer regime and there are some others that should, at any rate, be made using the same rockets. Of primary importance are the 30- to 60-kilometer structural parameters. Because of their importance, a very large amount of effort in both instrumentation and rocketry is being applied to these quantities. The importance of higher-altitude structural measurements of greater-than-present quality is gaining increasing recognition. Also, it is considered that ozone measurements to 75 kilometers are of great value. The new meteorological rockets should be designed for versatility but should, particularly, be capable of carrying structure payloads to 100 kilometers and ozone payloads to 75 kilometers. Experiments to determine the behavior of charged particles in the ionospheric D region (60-90 kilometers) are needed, and the meteorological rocket should be designed to accept payloads for this purpose.

The state of the art in electronic circuit miniaturization permits considerable reduction in the telemetry and signal-conditioning circuits used in meteorological payloads. Reduction in the size of primary instruments is not necessarily so simple. Most of the currently-used techniques are somewhat reducible, however, and a few of them have promise for somewhat synoptic use. To satisfy the need for 100 kilometer structural measurements, the pitot-static experiment has promise together with the active inflatable falling sphere. It is estimated that the pitot-static payload could ultimately be reduced to about 12 pounds net and that an inflatable active sphere could have a net ascent package weighing perhaps 10 pounds and a descent package of less than 1 pound. The ozone payloads now weigh from 10 to 30 pounds (descent package, including parachute) and it is estimated that the 10-pound package, currently flown by Randhawa, is as light as this experiment can practically be constructed. Although the techniques discussed do not, by any means, exhaust the range of possibilities, it is believed that they are indicative of realistic payload weight requirements. A rocket to handle these payloads should be able to carry or boost approximately 10 pounds net to 100 kilometers. For simple structural measurements, the minimum diameter should be about 3 inches. For the ozone experiment, and for multiple-measurement payloads it should be about 5 inches.

Comparisons have been made of existing types of 55- to 70-kilometer meteorological rockets and gun probes. Correlation and extrapolation of the available information indicates that, in quantities of 1000, state-of-the-art, end-burning, single-stage vehicles should cost about $1000 each, boosted darts about $410, and gun probes about $350. Costs of carrying heavier payloads to higher altitudes have been calculated based on observing the costs of present rockets and using representative present material and production costs to estimate the costs of new vehicles. This information is plotted in Figure 9 .

Ratios of vehicle costs to pounds of net usable instrument weight show that the single-stage rocket, boosted-dart vehicle, and 5-inch gun probe are all competitive from a net-payload economics standpoint. However, gun-launched probes offer the most economical means of transporting instruments for making wind and temperature measurements only from 55 kilometers down.

Disadvantages inherent in the gun-boosted probe approach are severe launch environment and limited payload volume. Technology trends indicate that many atmospheric measurements can eventually be made with the gun-boosted probe; however, there will always exist a long lag time between innovations of new sensors and the ability to use them in a gun-boosted probe. A logical conclusion is that a companion arrangement between the gun-boosted probes for certain types of synoptic use and rocket-lofted payloads with larger volumes for quasi-synoptic higher altitude use, would be desirable.

The development of meteorological rockets for future use must carefully consider desirable operational attributes as well as vehicle cost. Operations on and around rocket motors and electro-explosive devices can be hazardous. To minimize the danger to field operations people, the use of percussion-initiated pyrotechnics and packaged liquid propellants should be investigated.

A meteorological rocket system will be used throughout a wide range of launch environments which affect the overall performance of a rocket. This dictates varying requirements for payload separation altitudes and times. Towards this end, the use of inexpensive, reliable, and field-adjustable timers should be investigated.

For the sake of operational economy, a meteorological rocket should not require the use of operators and equipment for measuring winds and

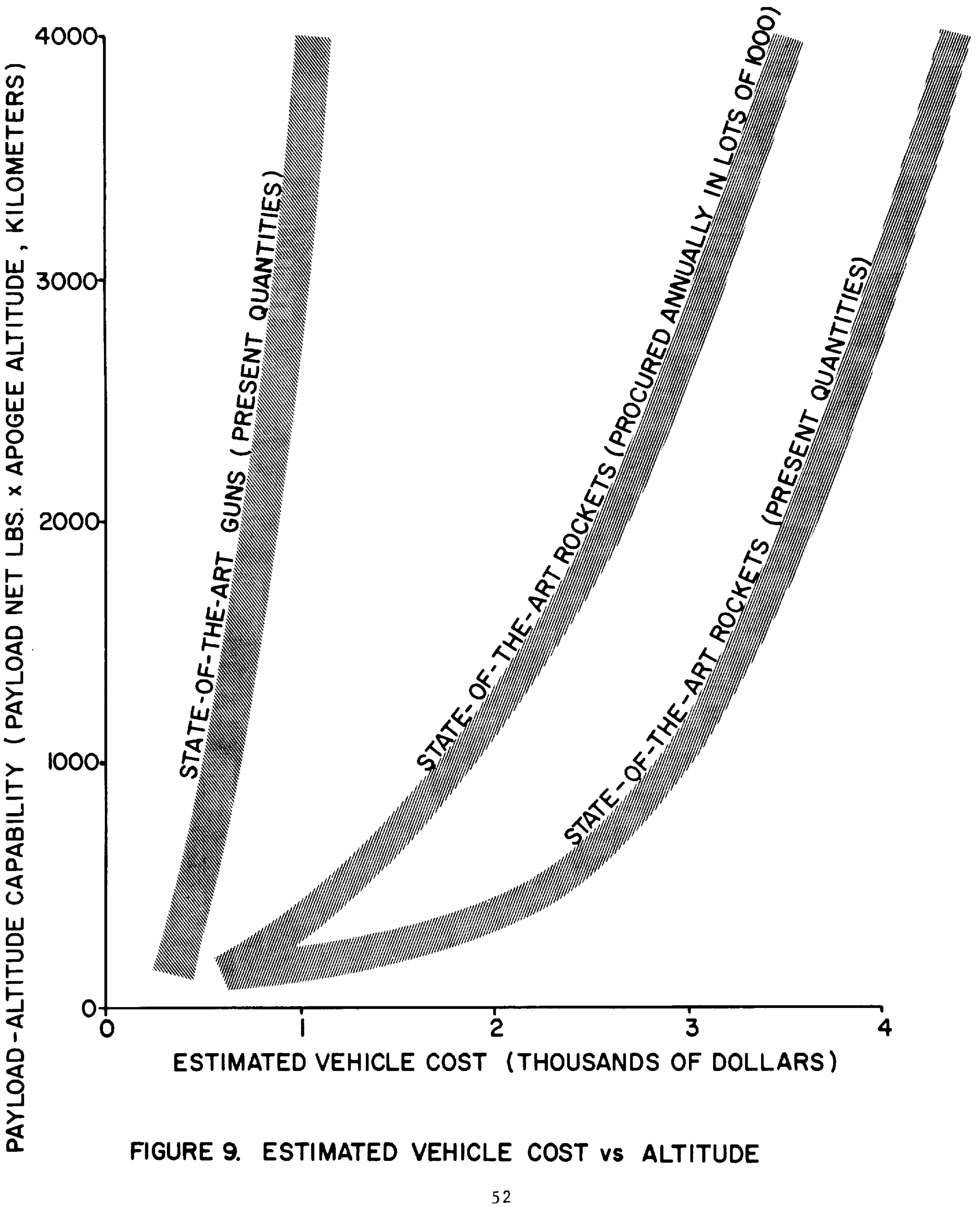


FIGURE 9. ESTIMATED VEHICLE COST vs ALTITUDE

calculating launcher settings to compensate for winds. This operation usually doubles the size of the field crew and greatly restricts the adaptability to changing conditions encountered in operational use. Additionally, the most careful and precise wind measurements and launcher setting calculations possible with present and near-future technology do not preclude the possibility of expended rocket parts falling in undesired areas. Consequently, a meteorological rocket system concept should be carefully weighed for its adaptability to eliminating, or at least greatly minimizing, falling mass hazards.

The conclusions just stated are recommended criteria for use in the design of a future meteorological rocket vehicle. It is apparent that more than one configuration can meet these criteria. In addition, it is quite unlikely that a single vehicle can cover the entire 30- to 100-kilometer region with optimum cost effectiveness. Since a great deal of work is being done on developing vehicles for simple measurements in the lower half of this region, it is suggested that NASA-sponsored effort be directed to the larger rockets needed for multiple experiments and for structural measurements in the upper half (65 to 100 kilometers).

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