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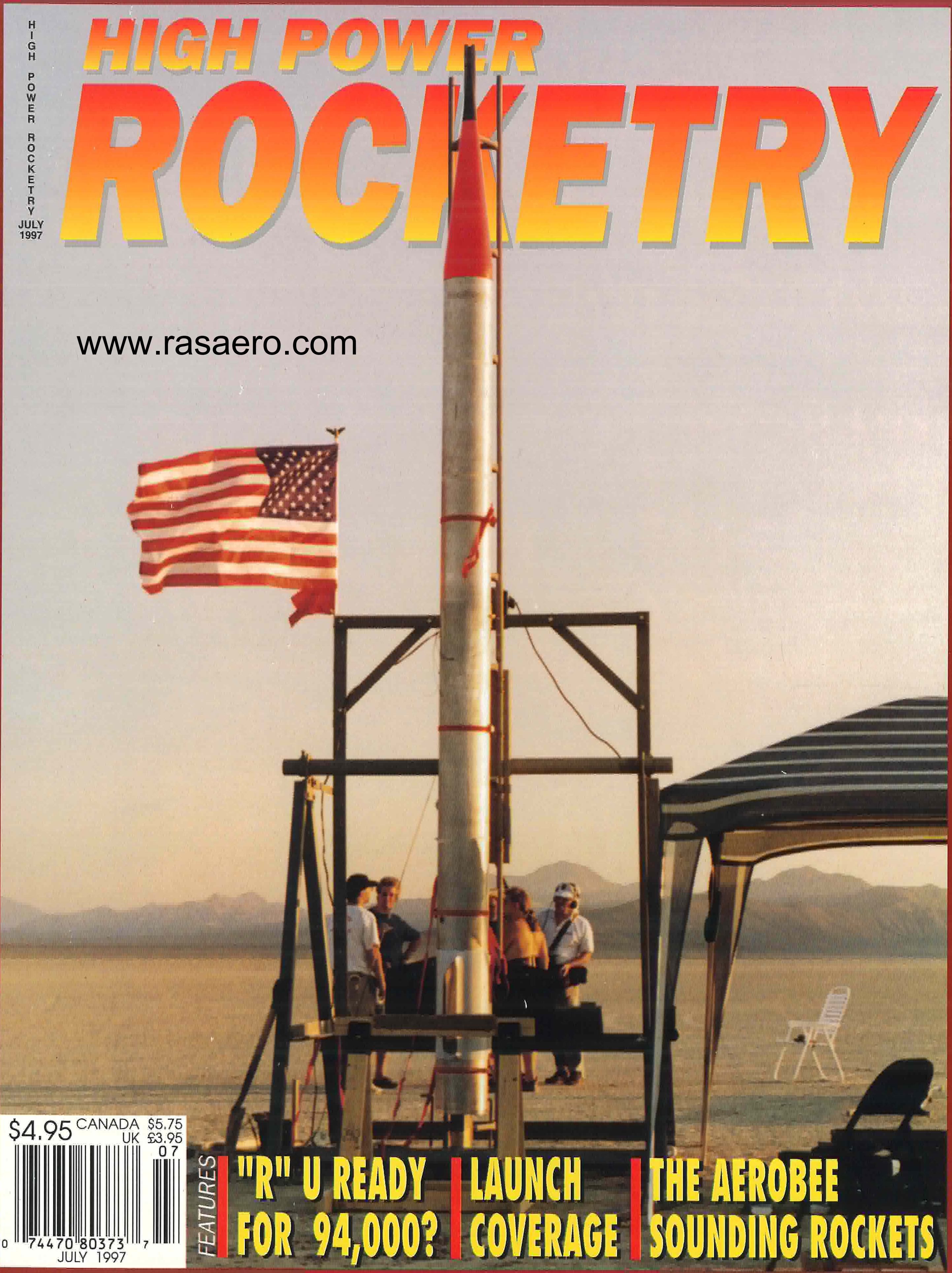

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FEATURES

"R" U READY FOR 94,000?

LAUNCH COVERAGE

THE AEROBEE SOUNDING ROCKETS

OuR Project

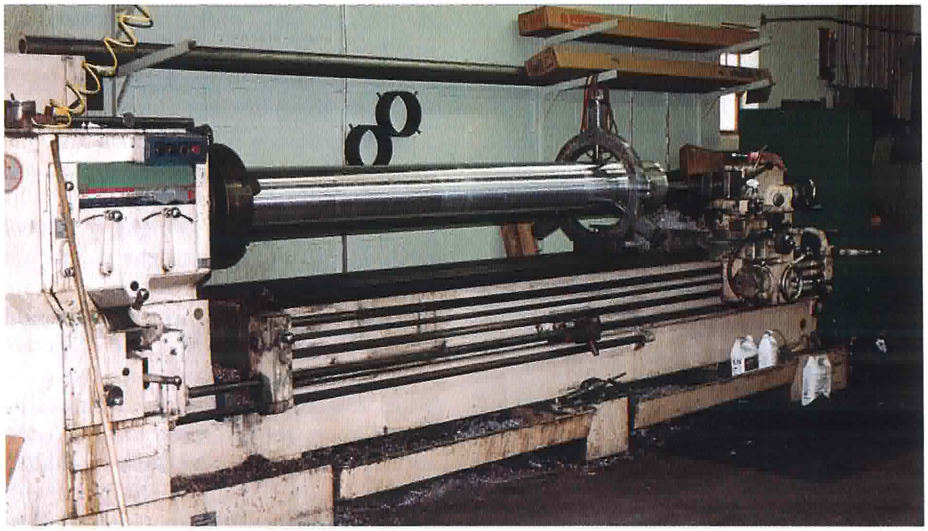
by Phil Prior, M.D. #2949

Photos for both articles (see page 52) by Dario Brisighella, Earl Cagle, Mark Clark, Phil Prior, Paul Robinson, and Jim Rosson.

It was Danville '94 and I found myself tipping a few cold ones with a couple guys guaranteed to be a bad influence. Both serious rocketeers, Paul Robinson is a general contractor from New Hampshire and Jim Rosson is an electrical engineer who develops new technologies at Delco Electronics. They were discussing the possibility of a 10-inch motor. Paul had discovered some seamless 10-inch aluminum tubes and was bent on building a large rocket motor. His preliminary calculations came out to about an R270,000! Apparently he had already contacted Frank Kosdon and received a tentative offer of assistance.

Being a newbie at the time, I was listening intently. I was sufficiently ignorant to believe that this would be relatively simple, so I volunteered to contribute to the effort. Little did I know that, given the task ahead, I might just as well have volunteered to help Sisyphus in Hades - but this looked like a good team. I had known Jim for awhile and Paul seemed like a straightforward, resourceful guy. Dr. Kosdon needs no introduction, and I myself had some experience in mechanics and machining as well as copious newbie enthusiasm. Thus the team was formed.

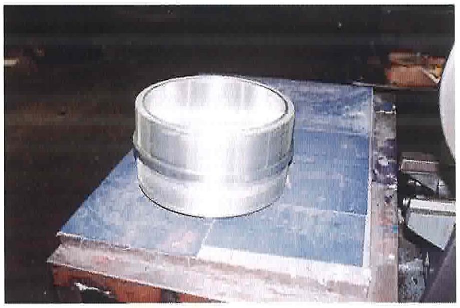
We rested comfortably for a couple of months, almost forgetting the conversation until Paul called our bluff by buying the tubes. Considering that there are "no refunds/no exchanges" on 10-inch tubes, there was no turning back. As we began to lay specific plans the enormity of the



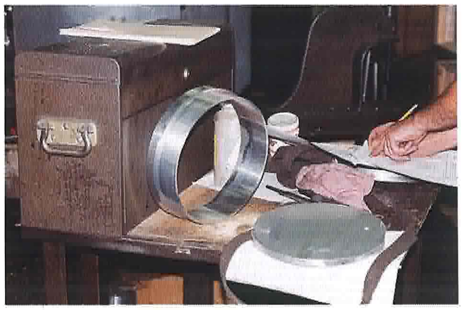
We took our time and did this project right. The top photo shows a 150 pound block of graphite waiting to become a nozzle. The second photo shows the motor casing on the lathe. ***(Rosson, Robinson)***

We recycle! Plenty of aluminum shavings from this project.

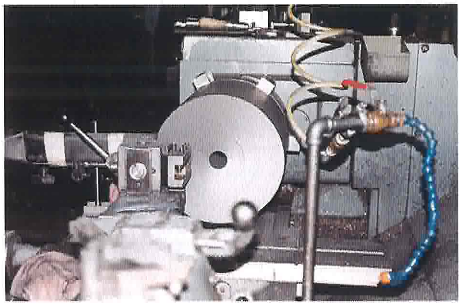
Test fit of the forward closure.



Completed bulkhead/coupler.



Completed aft closure.



The graphite block being turned into a nozzle. *(Robinson)*

task ahead started becoming apparent. We remained implausibly undaunted.

From that point forward it took awhile to get focused as a group. Everyone had ideas on everything and there were multiple tasks ahead. It became apparent that the project would take forever if every component was debated as a group. Consequently, the individual components of the project were divided into categories and assigned to individuals on the basis of skill and experience. Jim was the primary designer and would oversee the electronics development. Paul would be responsible for the motor, airframe, machine work, and precision mechanical parts. I would provide the tower and assist wherever needed. Frank and Jim would do the actual propellant casting using one of Frank's formulations. We would rely on Frank's basic motor design which would be modified as needed during motor development. Shortly after the tubes were acquired the propellant grains were cast. Jim had already completed the design drawings of the vehicle and forwarded them to Paul.

Shortly after the final dimensions of the grains were known, Paul modified the dimensions of the airframe and motor casing working closely with the machine shop and Jim. Having both interior and exterior machining done on 10-inch tubing requires some serious machinery and skills. This rocket was to be a Kosdon "minimum diameter" and needed to stand up to some major-league impulse. Paul had his hands busy dealing with O-ring grooves, thread specs, flexural loads, total weight, burst strength, recovery system anchors, nozzle dimensions... well, you get the picture.

Having been assigned the tower, I also had some serious thinking to do. The basic design was based on antenna tri-tower, but erecting and stabilizing a 660-pound rocket mandated some attention to the sheer weight involved. Pushing this vehicle upright would not be an option. I opted for an A-frame with the pivot at the apices which would be placed near the CG of the rocket to reduce the sheer work necessary to bring the vehicle upright. Removable motor prep stands were built in and additional brackets were added to hold a 12-volt winch. It was also equipped with an integral blast shield to avoid the possibility of the massive exhaust undermining the tower on liftoff. And then there were the electronics...

Early on, Jim Rosson had been in contact with Bob Rau and John Dunbar. John is a ham operator with a keen interest in amateur TV and Bob is commercially involved with on-board video and GPS systems. Between the three of them, they would develop the recovery electronics and on-board video/GPS. The "OuR" rocket would be equipped with downlink video, GPS with overlay on video, and one accelerometer with a "Hail Mary" timer as the ultimate fail safe. Jim designed and roughed out the laminate nosecone which would elegantly house the electronic components and massive battery power necessary to power the them. Paul completed the exterior machining on the laminate structure and produced a metal tip necessary for the electronics. In the back yard, pyrotechnic charges were developed which provided a vigorous ejection of the nosecone to an apogee of around 50 feet out of the body tube.

Originally our goal had been a launch date during BALLS 005, but as the date drew near there were many "i's" undotted and "t's" to be crossed. We believed that we could be ready, but acknowledging that 'haste makes waste' we reluctantly decided to postpone the flight. As it turned out, had we flown the motor as designed at that time failure was inevitable. Sometimes even a dark cloud has a silver lining.

We wouldn't fly our big rocket, but BALLS 005 was both a training exercise and an educational experience. Due to a shortage of hotel rooms we ended up attending as a group, sharing limited space while working feverishly on a number of last minute projects. Paul concentrated on an M-powered scaled-down version of OuR project which captured the third highest altitude of the BALLS 005 launch. Jim and I tower-launched an M-to-K two-stage which unfortunately was not tracked. We all certified Level 2. More importantly, we proved the ability of the team to work long and hard together in close proximity with minimal friction.

The biggest lesson from BALLS 005 came from the large motor attempts. Rocket after rocket over-pressurized and catoed. It became apparent that simply upscaling smaller designs wouldn't work. After BALLS 005 we had an entire year to work out a solution. We consulted every professional source we could find. Consensus among the propulsion engineers that would work with us was that the lowest grain was likely collapsing into the nozzle throat under thrust and choking, or over-pressurizing, the motor. Case bonding the grains would take care of that, but with a full year to prepare we decided to thoroughly model our motor. Static firing a full R was certainly not an option.

Fortunately Frank had cast some smaller grains simultaneously with the R grains. This would allow static firing of smaller motors with the same propellant. Paul contacted John Johnston and Rick Loehr who graciously volunteered to run some thrust curves on their test stand. Armed with this data our consultants were able to make further recommendations regarding nozzle/throat configuration and configuration of the lower grains. We were also told that our original paper liners would likely burn through, which would jeopardize the motor. We modified the motor components to new specifications. Once again, Paul was living at the machine shop.

Eventually it came time to assemble all the components and actually build and erect the rocket. Paul and I met in Buffalo, New York to transfer the airframe components to our farm for preliminary assembly. For months beforehand components were criss-crossing the country for various modifications. I spent time making final adjustments on the tower. The UPS man verbally abuses me one day after unloading a 150-pound piece of graphite off his truck. Soon, all parts are here in one place. We wanted to be prepared as a team for final assembly on the desert. To get there and discover that some phase of assembly didn't work would be disastrous. We also wanted to be efficient to avoid any launch delays and meet our goal of launching at 0900 PST 8-16-96. We had promised the launch organizers a specific time to maximize safety.

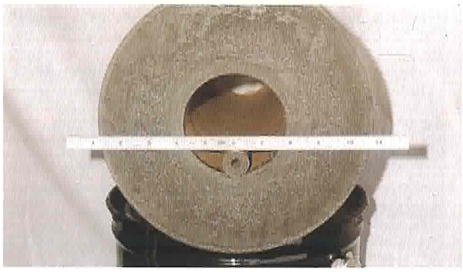
Several weeks before the projected launch, we came together from all parts of the country for final assembly of the motor and practice erection of the rocket and tower assembly. Jim and I went through some preliminaries the weekend before and then the whole group arrived the following week for final assembly. Extra personnel in the form of Ken Mizoi and Ray Forster provided invaluable help finishing the fin can and erecting the rocket. The weekend went well and we prepared for shipment on Ross Dunton's Magnum truck. He picked up our project and took it home to pack his own stuff for BALLS. Then came the phone call...

Ross had stopped at a weigh station and was 1200 pounds overweight. Sheer panic set in. At that time I could not imagine any way to remove that much weight from the truck and keep the project intact. I left early the next morning with a mental inventory of every duplicate or unnecessary nut, bolt, tool, or component. The obvious went first - Ross's magazine, shelves, and poor Teddy. Jim's Level 3 M project also got the boot, much to his chagrin. We went back to the weigh station with fingers crossed. Darn! Still 700 pounds over. Back to the drawing board. Ross waited patiently and weighed each object as I tossed out item after item. Finally we achieved the goal. Ross would get through the weigh station... as long as he had less than ½-tank of gas!

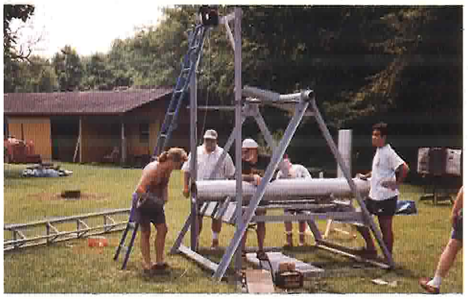
Paul and Ken Mizoi had arrived a day earlier at Blackrock and located the GPS coordinates provided us by LTR. Earl Cagle arrived to provide documentation of the project. We spent the night of the 14th fine-tuning the electronics. The GPS system is having a hard time obtaining satellite lock. Early on the morning of the 15th we set out for the desert with a full day's prep ahead. The tower went up smoothly and the dreaded transfer of the heavy booster section onto the prep stands also was without a glitch thanks to a little ingenuity from Ross. Then it came time to slide the fin can on. It slid halfway down the motor smoothly until the metal galled under the can. The same unit that had slid freely in Ohio was now firmly stuck four feet from its shoulder. The heat and sun were challenging our machining tolerances. To make a very long story short, a couple of three-pound sledges, lots of sand paper, and the loan of a grinder later, the fin can was seated on its shoulder.

Disaster #2 successfully averted, it was time for payload prep. This was largely Jim's area and he proceeded methodically. We were utilizing the cable-cutter technique described by Dave Crisalli in *HPR*. The initial ejection charge will blow the nosecone and drogue, with pyro cable cutters releasing the restrained main 'chute at 20,000 feet. Bob Stroud had designed and built a Kevlar drogue ribbon 'chute and reinforced main 'chute capable of surviving deployment at trans-Mach speeds. These 'chutes attached to two 7/8-inch forged eye bolts on the motor's forward closure. Bob is a great guy and unmatched in his field.

While visually tracking a vehicle at


Very large propellant grains. Note the familiar 29mm in the core.


Paul roughs up the core with a pipe brush.


It's time to test-fit the nozzle.


Ken Mizoi adds a smooth fillet to the welded fin can.


Paul and Jim case-bond the propellant grains into phenolic liners. ***(Rosson)***

A view of the electronics payload. *(Rosson)*

We appreciate the Trivak welding crew for their support. ***(Rosson)***

100,000 feet is virtually impossible, we couldn't resist packing in five pounds of fluorescent orange pigment so bright that Paul had it packed in a container marked "Agent Orange." If anything would be visible, this stuff would. Just a small amount could make a tremendous tracking cloud. With light fading, we approached the last critical step in assembly - winching the rocked/rail assembly up in place to be bolted to the tower. The winch groaned under its 660-pound load. We knew it could handle the load, but just barely. I feared that the desert heat might reduce its power. Fortunately my fears were unfounded and the rocket went up in place. Once bolted to the pivot plate, manipulation of the rocket was easy. It would pivot easily, allowing us to leave it horizontal overnight and swing to vertical in the morning when time would be precious. From this point forward we could function without power tools. Launch was inevitable, and all of a sudden the anxiety increased exponentially; we were really going to fly this thing!

Phil, Paul, and Jim take a break after erecting the tower.

Our rocket rested overnight, essentially ready to go. We put up the "No Smoking" sign and headed into Gerlach for the night with the exception of Jim who returned to camp out with his sweetheart - the rocket. The handheld GPS once again came in handy for nocturnal navigation.

We are up early again the following morning and what little prep that remained was completed. The rocket stands erect, ignitor in place, pointed a few degrees away from Gerlach and the spectator area. Film crews from BBC/ Discovery Channel are present. Jim Hart handles crowd control and hustles everyone on the playa to the designated spectator area. The main area is 1.5 miles away and the launch controller is at 1200 feet, well out of shrapnel range. At 0905 PST after a 15-count Jim pushes the button on the MasterBlaster. The 'balloon' igniter developed by Jim does its job perfectly. There is no lag - just what appears to be almost an explosion under the rocket. The fireball grows rapidly and there is a loud boom as the rocket shoots off the pad. This is the first launch I have seen with a blast deflector. Instead of mixing with the dirt the initial motor blast is deflected out and up around the rocket. I am convinced for a split second that the motor has blown the nozzle. These fears are short lived as the rocket comes out of the flash and dust cloud trailing the anticipated 30-foot flame. Jim and Paul watch silently, but I cannot contain my glee as the motor burns and burns and burns on a perfectly straight trajectory.

Our computer models had predicted the highest altitude coming from a longer burn time. Anticipated to burn about 11 seconds, the motor burns for a full 15 - not long enough to reduce efficiency but right at the edge of maximal efficiency. More importantly, it did not explode. The rocket was out of sight on a safe trajectory with a long coast ahead. After another minute John Dunbar, who had been watching his video screen, began to shout that he was seeing terrain and the curvature of the earth on his downlink video. Now we are all ecstatic... but where are those 'chutes?

We had hoped to catch a glimpse of the parachutes on the side-looking video. Another minute plus goes by and we hear a loud boom. I initially think I heard the impact, but the sound has a vaguely reminiscent characteristic to it. In my youth, back when military aircraft were allowed to exceed to it. In my youth, back when military aircraft were allowed to exceed the speed of sound over the continental U.S., it was a common phenomenon - a sonic boom. The rocket had returned but we didn't know where. Fortunately someone had seen a dust cloud and located the impact site. We drove over and the speedometer and GPS indicated 4.72 miles from the launch site. There was no discrete hole but rather an area 20-feet across appeared to have been fragmented and lifted by underground shock waves. A crowd gathers, and Frank produces his legendary shovel. We have plenty of digging volunteers and about four feet down we discover a small piece of the leading edge of the airframe. A small piece of parachute and some burnt Nomex are also located, indicating that a deployment charge did in fact fire, but the nosecone was not ejected for reasons unknown. The kind folks attending BALLS 005 wanted the rocket recovered and collectively donated over $400 to rent a backhoe for excavation. Paul later rented a backhoe and dug down approximately ten feet. He was still unable to touch the wreckage with a 8' long probe. At least we had the on-board footage. Ross wouldn't have to worry about weigh stations on the way home and we didn't have to clean the reload case (it was reloadable) although I doubt we would have bickered over that job!

Speculations regarding the cause of deployment failure are myriad. The GPS failed to regain lock, consequently one of four systems failed. However, there is no explanation for the accelerometer's failure. It is possible that under the conditions at apogee the ejection charges were not adequate. Just considering the temperature extremes of going from the heat of Mach speed to the extreme cold of space can generate some interesting theories. The nosecone may have welded to the airframe. Replacing the air in the payload section with near vacuum could also present some problems. Your guess is as good as OuR's.

We have multiple people to thank, but will do this privately. The altitude data can be found on pages 52-58 in this issue. The raw data is available on Earl Cagle's tape which includes the on-board flight footage. □

The stuff dreams are made of... It doesn't get any better than this... Any cliché fits this photo. WOW! ***(Brisighella)***

Team members, left to right: Frank Kosdon, Paul Robinson, Ken Mizoi, Jim Rosson, and Phil Prior. Quote of the year: "Let's dig this puppy out!" ***(Brisighella)***

Postflight Analysis of the OuR Project R Rocket Flight

by Charles E. Rogers

One of the most significant accomplishments in the history of high power and experimental rocketry occurred at the Black Rock dry lake on August 16, 1996 with the successful flight of the OuR Project R Rocket to an altitude of nearly 100,000 ft. To provide an independent assessment of the altitude achieved by the rocket the author was asked by the OuR Project team to perform the postflight analysis which follows in this article. The author gives special thanks to Jim Rosson, Paul Robinson, Frank Kosdon, and Phil Prior, the OuR Project team members who provided the data on the rocket which was used for the analysis. Technical data on the OuR Project R Rocket is included in two articles in this issue of *High Power Rocketry* (References 1 and 2), and specific technical data will be repeated herein as required to support specific aspects of the postflight analysis. The author feels that it's important for major rocket projects like the OuR Project R Rocket to be extensively documented to provide technical assistance and lessons learned for rocketeers developing similar projects, and to document the flight performance of the rocket to allow flight simulation software developers to further refine their drag and altitude prediction models. Combined with the information in References 1 and 2 this technical article should complete the full documentation of the OuR Project R Rocket.

The two primary sources of data from the R Rocket flight were the time to apogee measured from an onboard video camera which telemetered an outside view to the ground, and the downrange distance from the launch site where the rocket impacted. Normally techniques for using time to apogee for backing out the altitude of a rocket have limited applicability for high altitude high power and experimental rockets flying over 10,000 ft due to the difficulty in seeing the apogee of the flight. Additionally, for flights over 10,000 ft unless the person viewing the flight has some offset from the launch site, i.e. is not viewing the flight from directly under the apogee point, it's very difficult to ascertain the exact time of apogee and the viewer may time a false early, or late apogee based on misinterpretation of the rocket smoke trail. On the R Rocket, by using an onboard video system, a direct measurement of the time to apogee was possible. By telemetering the video data of the view out the rocket to the ground the data could still be gathered despite the destruction of the rocket on impact due to failure of the recovery system to deploy. Time to apogee analysis techniques also don't take into account trajectory effects, which can be important for many rockets, especially rockets in this class flying to nearly 100,000 ft. While unfortunate for the rocket, and further, a safety hazard, the rocket traveling downrange from apogee and impacting the ground in the same aerodynamic configuration (i.e., a whole body impact) as during ascent provided an additional data point (downrange distance) which allowed an assessment of the trajectory effects on the flight.

To perform the postflight analysis of the R Rocket flight numerous simulations were run on a pre-release version of the Rogers Aeroscience ORBIT trajectory simulation software to back out the apogee altitude from the time to apogee and the downrange distance. While backing out the apogee altitude from the time to apogee and downrange distance an opportunity also arose to compare the author's subsonic DATCOM, supersonic DATCOM, and supersonic curve fit CD models with the flight data. The author has previously published in Reference 3 comparisons of altitude predictions using these methods with flight data for the Frank Kosdon Full Metal Jacket series of rockets which reached Mach 2.2-2.4, and flew to altitudes of 30,000 to 40,000 ft. Analysis of the R Rocket flight data allowed comparison of these methods with flight data for a rocket reaching Mach 2.7 and flying to nearly 100,000 ft.

The weight and geometry data for the OuR Project R Rocket used in the trajectory simulations and the CD prediction runs is presented in Table 1. The author refers the reader to References 1 and 2 for additional geometry data, drawings, and photographs of the R Rocket and the R motor. The basic thrust curve of the R Rocket motor was provided to the author by the R Rocket team based on firings of sub-scale motors using identical propellant and scaled grain geometry. An issue arose on the contribution of the motor delay to the total impulse of the motor. The R motor had a 4.9 inch long, 21.0 lb full column delay using modified Kosdon TRM Dirty Harry propellant. Depending on how fast this delay was burning some portion of it would be consumed during the burn of the motor, contributing to the motor total impulse, and the rest would be consumed during the coast phase. It was determined that the most rea-

Table 1 - OuR Project R Rocket Weight and Geometry Data.

Liftoff Weight	660.0 lbs
Burnout Weight	354.5 lbs
Main Body Tube Diameter	10.5 in
Total Length	228.0 in
Nose Cone	
Shape	Conic
Length	52.5 in
Fin Canister Diameter	10.875 in
Fin Canister Shoulder Length	1.0 in
Nozzle Exit Diameter	5.82 in
Number of Fins	3
Root Chord	20.0 in
Tip Chord	15.0 in
Fin Span	15.0 in
Leading Edge Sweep	12.77 deg
Fin Thickness	0.375 in
Airfoil Type	Hexagonal
Distance Leading and Trailing Edges are Diamond Airfoiled (Perpendicular to Leading Edge)	2.5 in
T-Lugs:	
Number	2
Height	1.375 in
Width	1.0 in
Thickness	0.375 in
Diamond Airfoil Length	1.0 in

sonable burn rate to assume for the delay propellant at the motor operating chamber pressure was 0.15 in/sec, which meant 9.3219 lbs of the delay propellant was consumed at an assumed specific impulse of 150 sec, a typical delivered specific impulse for Dirty Harry propellant. To be conservative the remaining 11.6781 lbs of delay propellant was assumed to be consumed during the burn of the motor so that the burnout weight could be used from the beginning of coast, with no total impulse contribution from the remaining delay propellant. Table 2 summarizes the build up of the total impulse for the R motor, with the final total impulse used in the trajectory simulations of 260,576 Newton-seconds. Note that based on the actual propellant consumed during the burn of the motor the specific impulse was 199.4 seconds. By not carrying the weight of the remaining delay propellant during the coast, but not including any total impulse contribution when adding it to the main propellant, the delivered specific impulse of the motor based on initial weight minus burnout weight was lowered to 191.8 seconds. This insured that the trajectory simulation completed the burn with the correct burnout weight.

The author received a predicted thrust curve for the R motor from the OuR Project team based on the sub-scale motor firing data, and ratioed the thrust curve to match the 260,576 Newton-seconds total impulse arrived at in Table 2. This thrust curve is presented in Figure 1, which based on the altitude at which the sub-scale motors were fired should be considered a sea level curve. The ORBIT v4.50 trajectory simulation software varies thrust with altitude, and the thrust at altitude of the R motor on a representative trajectory is also presented in Figure 1. The increase in thrust with altitude raises the total impulse of the motor approximately 3%. Note that the burnout altitude on a particular trajectory simulation is a function of the CD model used, the weight of the rocket assumed, etc., but the 21,000 ft burnout altitude shown in Figure 1 is representative of the majority of the trajectory runs.

To back out the apogee altitude of the OuR Project R Rocket flight from the time to apogee and the downrange distance the Rogers Aeroscience ORBIT v4.50 trajectory simulation software was run with various CD models, and those models were ratioed (the drag was increased) and the launch angle was adjusted until both the time to apogee and the downrange distance were matched. The Rogers Aeroscience CD v4.50 CD prediction software generates, and the ORBIT v4.50 trajectory simulation software uses two basic types of CD models, the File Entry model and the Direct Entry model. Figure 2 presents the predicted CD versus Mach number for the R Rocket using these two models. The File Entry model utilizes full subsonic and supersonic DATCOM methods to predict the CD of the rocket with Reynolds number and Mach number based on the actual shape and geometry of the rocket. The CD v4.50 software provides an output file of CD versus Mach number which can be used by the ORBIT software for the trajectory simulations. In the Direct Entry model a single overall representative subsonic CD is generated by the CD v4.50 software, or can be directly entered during the ORBIT trajectory simulation by the user. This single CD is the overall representative subsonic CD (CDr), and is the average of the CD values at Reynolds numbers of 1.0×10^6, and 1.0×10^7. The CD v4.50 software takes into account the actual geometry of the rocket and uses subsonic DATCOM methods to determine the CDr for the rocket, and then the CDr is used by the ORBIT software as an anchor point for subsonic CD curve fit equations based on Reynolds number, and transonic and supersonic CD curve fit equations based on Mach number. The particular transonic and supersonic CD curve fit equations used in the ORBIT software is known as the Rogers Aeroscience Mach 10 model. This model is documented in Reference 4 and is valid up to Mach 10. The model is based on data from conventional wind tunnel and ballistic free-flight wind tunnel tests of configurations typical of finned rockets.

As can be seen in Figure 2 the Direct Entry CD model tends to be conservative and predicts a higher CD for the R Rocket at all Mach numbers. As will be seen this conservatism in the model produces an altitude prediction for this rocket that is a closer match to the flight data, although it turns out both models substantially underpredicted the drag of the rocket. The drawback of the Direct Entry CD model is that at supersonic speeds it does not take into account the actual shape and geometry of the rocket. All rockets are modeled at supersonic speeds with the same generic CD

Table 2 - Rosson-Kosdon R Motor Total Impulse Build Up.

	Propellant Weight (lbs)	Specific Impulse (sec)	Total Impulse (Newton-sec)
Main Propellant Modified Kosdon TRM - Fast	284.50	201.0	254,356.7
Delay Consumed During Burn Modified Kosdon TRM Dirty Harry Assumes a 0.15 in/sec Burn Rate	9.3219	150.0	6,219.6
Delay Consumed During Coast Assume Mass Loss During Burn No Total Impulse Contribution	11.6781	0.0	0.0
Total Impulse			260,576
Specific Impulse			
Based on Actual Propellant Consumed		199.4	
Based on Initial Weight - Burnout Weight		191.8	

versus Mach curve, in this case a curve of the ratio of the supersonic CD divided by the subsonic CDr for a generic rocket. As illustrated in Figure 3, if the R Rocket had fins with a thickness to chord ratio of 3.5% with a leading edge sweep angle of 30°, and had a 4 to 1 tangent ogive nose cone, the configuration would be somewhat similar to the generic rocket configuration used to generate the Direct Entry curve fit equations, and hence the CD versus Mach number for the rocket would be similar to that which would be predicted using the Direct Entry model. The R Rocket design traded a lower fin sweep of 12.77° for a thinner fin of 2.1% thickness to chord ratio, and traded the increased weight of a 5 to 1 cone relative to a shorter ogive, all to reduce supersonic wave drag. These changes in the geometry of the rocket are taken into account with the supersonic DATCOM methods used by the CD v4.50 software, and as can be seen in Figure 3 the total drag of the rocket at supersonic speeds is reduced. As the R Rocket burned out at approximately Mach 2.7 it spent a considerable amount of time at supersonic speeds, and by using the CD v4.50 and ORBIT v4.50 software to analyze the effect of these design changes it turns out that they were good design decisions and increased the altitude of the rocket. On the other hand, using the Direct Entry methods these changes in the geometry of the rocket are not taken into account, and despite the reduction in wave drag from an improved aerodynamic configuration the Direct Entry method continues to model the rocket with the same supersonic CD versus Mach number curve. The File Entry CD method also modeled the subsonic Reynolds number effects more accurately than the Direct Entry method, producing the lower subsonic CD shown in Figures 2 and 3.

Figure 4 presents the graphical output from the CD v4.50 software for the R Rocket which includes both power-on and power-off CD, and the CD's for the different drag types for the various components of the rocket. The T-lugs were modeled using the protuberance drag option in CD

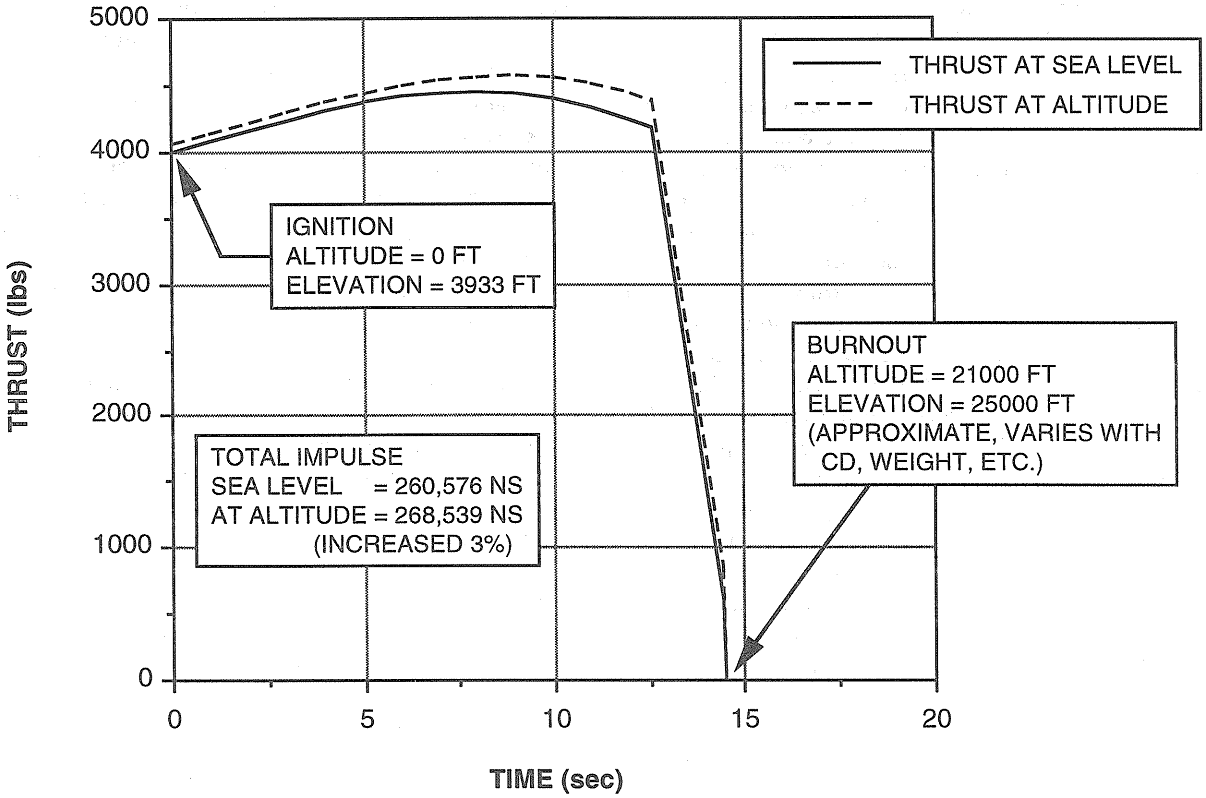


Figure 1 - Rosson-Kosdon R Motor Thrust Curve.

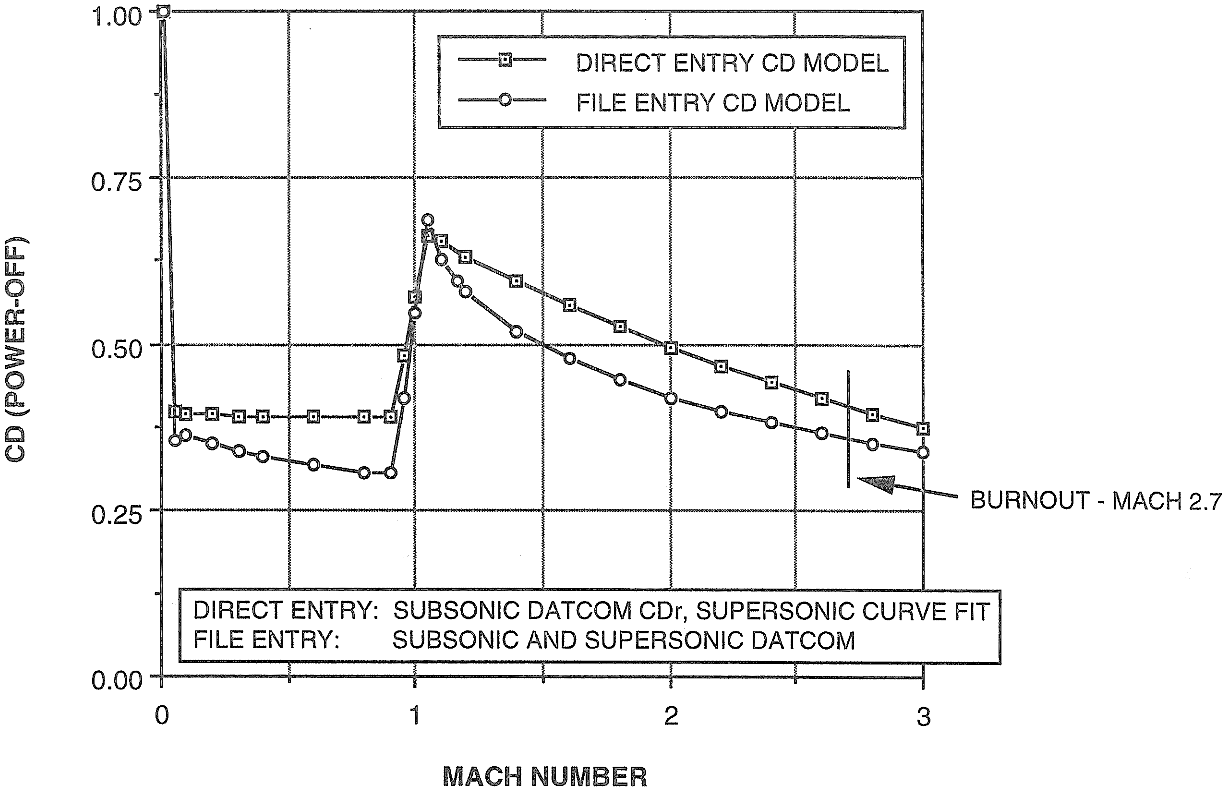


Figure 2 - Comparison of Direct Entry and File Entry CD Models for the R Rocket.

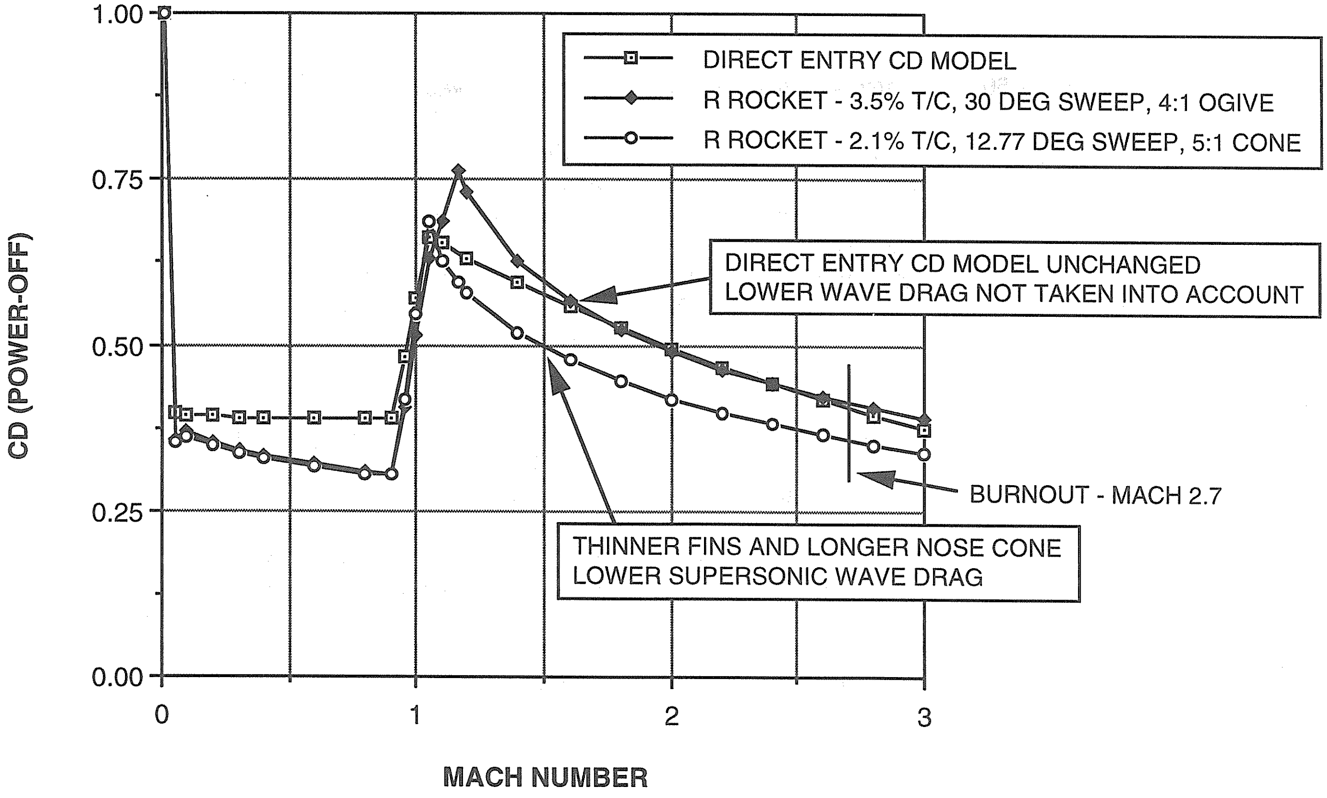


Figure 3 - Effect of Rocket Configuration on File Entry CD Model.

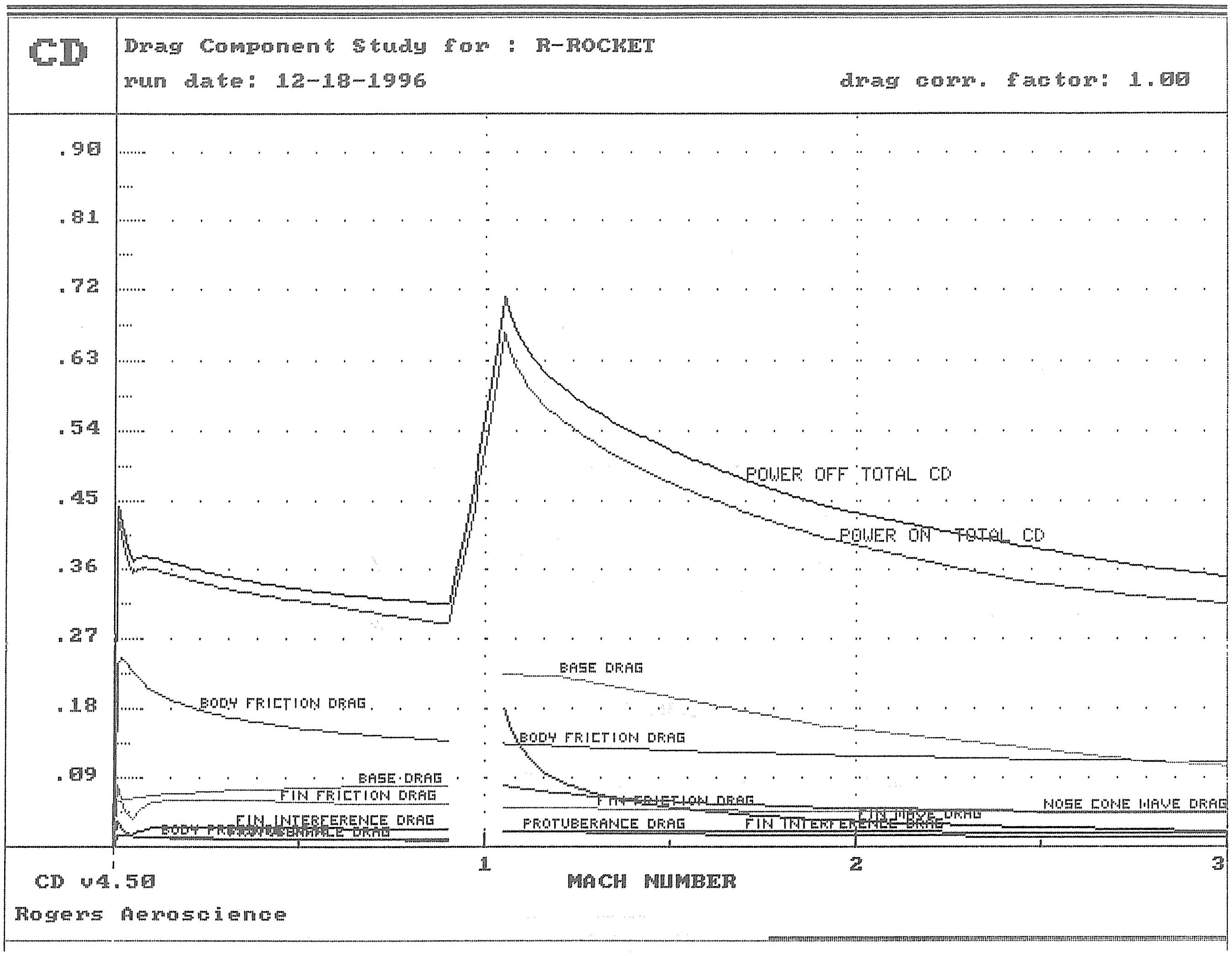


Figure 4 - CD v4.50 File Entry Method Predicted CD versus Mach Number for the R Rocket.

v4.50, and they increased the CD of the rocket body alone (not including the fins) by 4.5%. Additionally in Figure 4 the wave drag of the fin canister is included with the nose cone wave drag. As will be seen, Figure 4 is presented for reference only as both the File Entry and Direct Entry CD models substantially underpredicted the drag of the R Rocket.

The primary data from the flight of the R Rocket was the time to apogee measured from the onboard video, and the downrange distance of the impact point. Apogee was clearly evident from the onboard video, and occurred 80 seconds after lift off. The impact point of the R Rocket was 4.72 miles downrange from the launch point. Using the ORBIT v4.50 software trajectory simulations were run with the nominal Direct Entry and File Entry CD models for the R Rocket. Standard Black Rock launch site atmospheric conditions of 80° F at an elevation of 3,933 ft were used, and using a 20 ft launcher length the launch angle from vertical was iterated until the downrange distance was exactly equal to the actual distance of 4.72 miles. The results from these initial simulations are presented in Table 3, and it is apparent with both CD models that the time to apogee was substantially overpredicted. The likely reason was that the drag of the rocket was substantially underpredicted, so the CD of the rocket in both models was increased and new iterations were done on the launch angle for each new CD until both the time to apogee and the downrange distance were matched. The File Entry CD was increased by using a feature built into the ORBIT v4.50 software which allows the user to enter a CD correction factor that each CD at every Mach number will be multiplied by during the simulation. The Direct Entry CD was increased by simply entering a higher value for CDr, the subsonic CD which anchors the model.

Of interest in Table 3 is that after both drag models were increased the apogee altitude that was correlated from the time to apogee and the downrange distance came out essentially the same, approximately 94,000 ft. Towards the end of this article further data will be presented based on all of the trajectory simulations performed for the R Rocket that will show a clear trend of apogee altitude with time to apogee, and will provide further confirmation of the 94,000 ft apogee altitude for the R Rocket. To match the time to apogee, and hence the 94,000 ft altitude, both drag models had to be substantially increased. As expected based on the data in Figure 2 the Direct Entry model, which for this

Table 3 - Comparison of ORBIT v4.50 Trajectory Simulation Results with R Rocket Flight Data.

CD v4.50 Drag Prediction Method	Launch Angle [1] (deg)	Downrange Distance of Impact (miles)	Time to Apogee (sec)	Apogee Altitude (ft)	Altitude Error
Direct Entry of CD: CDr = 0.410 CDr Based on Subsonic DATCOM Using Actual Geometry of Rocket Subsonic: Reynolds Number Based CD Curve Fit Model Supersonic: Mach 10 CD Curve Fit Model	1.82	4.72	86.60	108,297	+15.2%
File Entry of CD: Subsonic DATCOM/Actual Geometry Supersonic DATCOM/Actual Geometry CD Correction Factor = 1.0	1.60	4.72	91.62	120,097	+27.8%
Direct Entry of CD: CDr = 0.495 (21% Increase in CDr) Subsonic: Reynolds Number Based CD Curve Fit Model Supersonic: Mach 10 CD Curve Fit Model	2.17	4.72	80.02	93,963	-0.04%
File Entry of CD: Subsonic DATCOM/Actual Geometry Supersonic DATCOM/Actual Geometry CD Correction Factor = 1.42 (42% Increase in CD at all Mach Numbers)	2.20	4.72	79.96	94,145	+0.15%

Estimated Apogee Altitude
94,000 ft
Matches Time to Apogee

Note 1: Launch Angle Measured from Vertical.

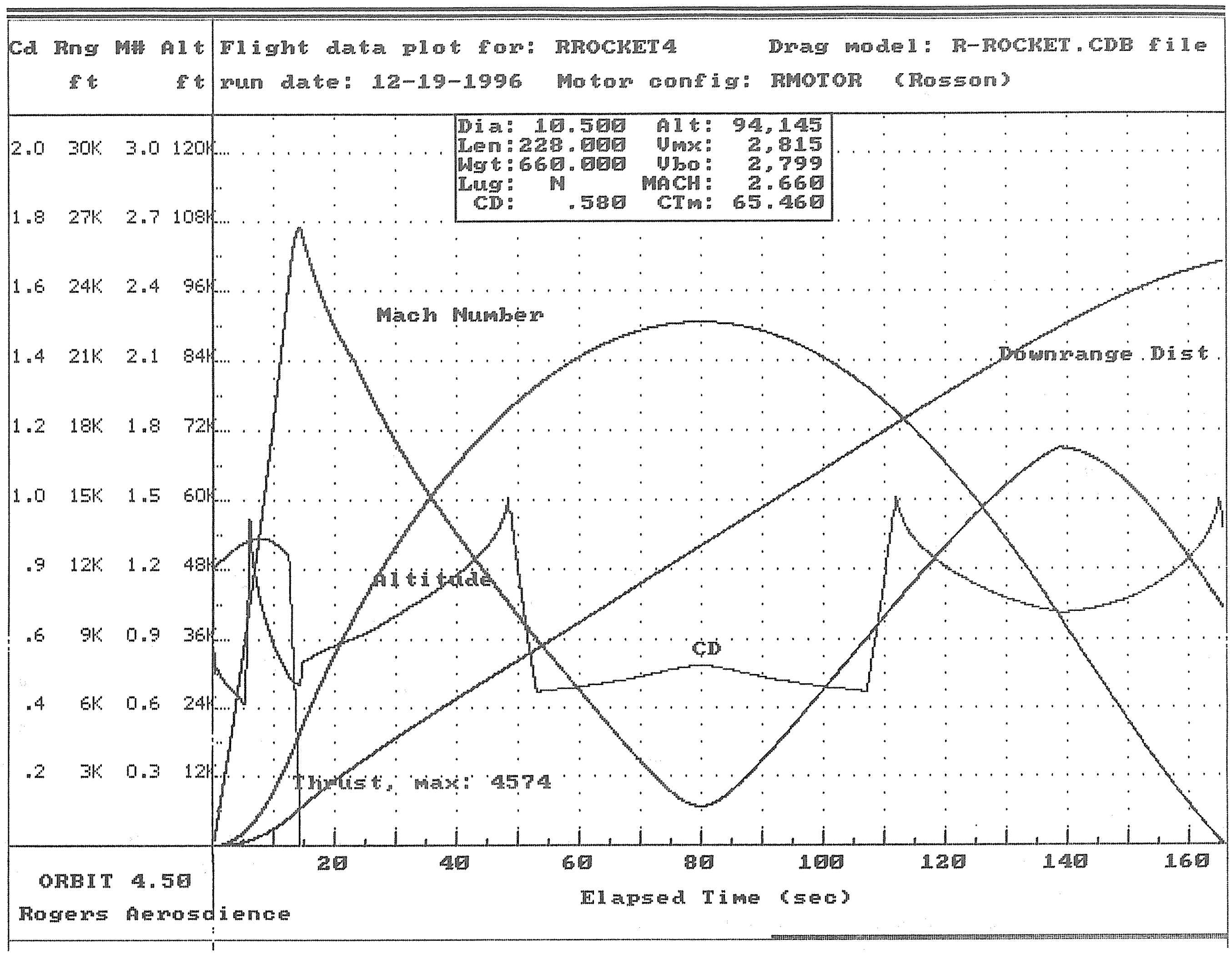
rocket was the more conservative drag model, produced a more conservative altitude prediction that was closer to the final altitude for the rocket. When compared to the 94,000 ft altitude backed out from the actual time to apogee the initial altitude prediction using the Direct Entry CD model was off by 15.2%, and the initial prediction based on the File Entry CD model was 27.8% off. To match the time to apogee the Direct Entry CD model drag had to be increased 21%, and the File Entry CD model drag had to be increased 42%, an extremely large increase in the predicted drag. Figure 5 presents the graphical output from the ORBIT v4.50 software which shows the results of the trajectory simulation for the R Rocket using the File Entry CD versus Mach number data presented in Figure 4, but with a drag correction factor of 1.42 (as can be seen in Figure 5, the actual CD values used in the trajectory simulation are the CD's from Figure 4 multiplied by 1.42) which matched the time to apogee and downrange distance flight data. Based on the trajectory simulation presented in Figure 5 after burnout at Mach 2.7 and coasting to apogee at 94,000 ft, on the downward leg of the trajectory the R Rocket reached Mach 1.7 at 41,000 ft, slowed down as it reached the denser lower atmosphere, and then impacted at Mach 1.03 (just barely supersonic), an impact speed of nearly 800 mph.

In searching for the source of this apparent larger than predicted drag one must first consider the limitations of this analysis approach where the drag of the rocket is backed out from time to apogee, or for that matter altitude. The disadvantage of this approach is that all errors between the predicted and actual performance are blamed on mispredicting the CD of the rocket. Therefore to reasonably assess the accuracy of the CD predictions one must carefully control the flight experiment, i.e., very accurate data on the rocket is required. Table 4 illustrates this by showing the performance sensitivities of the R Rocket and the apparent CD errors that they produce. To begin with the entire analysis of backing out the apogee altitude from the time to apogee and the downrange distance probably has a combined experiment/analysis accuracy of +/- 5%, which is equivalent to an apparent CD

Table 4 - Performance Sensitivities and Equivalent CD Errors for R Rocket Based on ORBIT v4.50 Trajectory Simulations.

	Change in Apogee Altitude	Equivalent CD Error
+/- 5% Error in Estimated Altitude	+/- 5.0%	+/- 8.7%
Variation of Thrust with Altitude	+7.8%	+13.6% [1]
Total Impulse Decreased 5%	-11.5%	+20.7%
Liftoff Weight Increased 5%	-10.8%	+19.5%

Performance Sensitivities are Relative to Initial 120K ft Altitude Est.
Note 1: CD Increase Required to Eliminate Increase in Altitude from Thrust with Altitude.



Flight data plot for: RROCKET4 Drag model: R-ROCKET.CDB file
run date: 12-19-1996 Motor config: RMOTOR (Rosson)

Dia: 10.500 Alt: 94,145
Len: 228.000 Vmx: 2,815
Wgt: 660.000 Vbo: 2,799
Lug: N MACH: 2.660
CD: .580 CTm: 65.460

Figure 5 - ORBIT v4.50 Trajectory Simulation Results for the R Rocket. File Entry Method - Drag Correction Factor = 1.42.

error of +/- 8.7%. In the author's opinion the weight of the R Rocket was accurately determined, and the total impulse of the motor based on subscale motor test data was also accurate. But as Table 4 shows, not being aware that the total impulse of the motor was 5% less than predicted, or that the rocket weighed 5% more than predicted, would produce apparent errors in CD of 20.7% and 19.5% respectively. Note that in comparison with a less accurate trajectory simulation program that does not take the variation of thrust with altitude into account, the error in the CD prediction would appear to be 13.6% greater. In this case having a less accurate trajectory simulation would make the CD prediction appear to be more accurate. The author feels that extreme care and precision was taken in putting together this project, but the fact remains that the entire 660 lb rocket could not be weighed in its entirety prior to launch, and due to cost concerns and the non-availability of a thrust stand capable of firing a motor in this class (over 4,000 lbs of thrust) the actual thrust curve from firing the full size motor was not available. Still the OuR Project team is to be commended for their effort, and in the author's opinion this flight experiment was as carefully controlled as possible and the data in this article and References 1 and 2 should be considered accurate. At most uncertainty in the data for the rocket would only explain an apparent CD misprediction of approximately 20%. With the CD misprediction approximately 40% it is clear that there is a large component of drag present that is not being modeled by the basic drag models in the CD v4.50 software.

It is clear from viewing the onboard video that the source of the greatly increased drag of the R Rocket was due to the rocket spinning during the flight. While the R Rocket was not intended to spin during flight, apparently the fins, or the leading edges of the fins, were slightly misaligned causing the rocket to spin. Additionally, the R Rocket was not only spinning, but it was also coning. In this dynamic situation the precessional angle, or coning angle subjects the rocket to an angle of attack. Simplifying the dynamic situation we can assume that the aerodynamic angle of attack that the rocket sees is exactly equal to the coning angle. Note that if the rocket was just randomly oscillating in several axes with an amplitude of +/- 4.0°, in terms of increasing the drag of the rocket this would be roughly equivalent to a constant 2.0° angle of attack. If on the other

Figure 6 - Total Coning Angle versus Flight Time. Aerobee 150 Flight 4.78 GS.

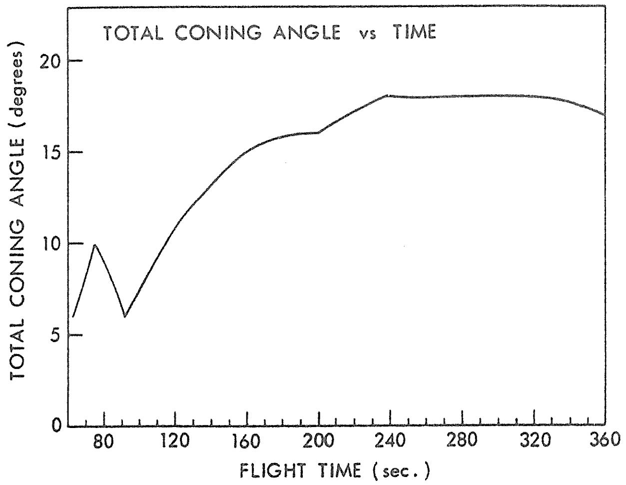


Table 5 - R Rocket Spin Rate Data Measured from Onboard Video.

	Time from Liftoff (sec)	Dynamic Pressure (psf)	Revolutions per Second
1 Revolution 6.80-10.61 sec	8.70	2396	0.26
1 Revolution 8.55-11.75 sec	10.15	3103	0.31
1 Revolution 10.61-13.31 sec	11.96	3970	0.37

Table 6 - R Rocket Coning Angle Data Measured from Onboard Video.

	Time from Liftoff (sec)	Dynamic Pressure (psf)	Coning Angle[1] (deg)
First Apparent Coning Angle	8.1	2119	Approx 3.5?
Additional Coning Angles During Flight	11.07	3554	3.5
	14.21	4199	3.5
	29.50	331	5.5
	36.00	134	7.0
	48.00	31	10.5
	65.14	3.6	17.0

Note 1: Actual Measurement was Max Horizon Angle during each Revolution from View out Side of Rocket. Coning Angle is Assumed to be Equal to the Max Horizon Angle.

hand the rocket were spinning and had a coning angle of 4.0°, this would be equivalent to a constant 4.0° angle of attack. This coning effect is a real effect for sounding rockets. To reduce trajectory dispersions many sounding rockets are spin stabilized. These spinning sounding rockets do exhibit coning, and there have been inflight measurements of the coning angles. Figure 6 presents flight data for the coning angles measured during the flight of an Aerobee 150 sounding rocket (Flight 4.78 GS, from Reference 5). For this particular Aerobee flight burnout of the Aerobee sustainer occurred at 53.0 sec, and at burnout the spin rate was 1.60 revolutions per second. At 80 seconds the flight conditions of the Aerobee were an altitude of 268,000 ft with a velocity of 4,950 ft/sec. At 200 seconds the Aerobee flight conditions were an altitude of 626,000 ft with a velocity of 1,750 ft/sec. At both flight conditions the dynamic pressure, a parameter which will be explained shortly, was less than 0.5 psf. As can be seen from Figure 6 spin stabilized sounding rockets can have large coning angles on the order of 10°-15° when they are flying at very low dynamic pressures after having essentially left the sensible atmosphere.

The spin rates and coning angles measured from the R Rocket onboard video are presented in Tables 5 and 6. The spin rates and coning angles in Tables 5 and 6 were measured from a tape of the onboard video using standard video equipment. Portions of the video are definitely fuzzy, and measurement of the data from the video is definitely subject to interpretation. The author would encourage others with a copy of the onboard video and access to digital video editing equipment to make further measurements and confirm and/or refine the data in Tables 5 and 6. The rotation rates were measured by timing each revolution of the rocket as either the southern or northern end of the Black Rock dry lake came into view. The video showed the characteristic left side of the horizon going down, and then the right side, and then the left side, etc., which is the view one would expect to see from a spinning rocket that is coning. The maximum angle of the horizon from horizontal during each complete revolution, or what appeared to be a complete revolution was measured from the video, and from the geometry of the rotation of the rocket it's an excellent assumption to assume that the maximum horizon angle is equal to the coning angle. Using the flight time from the video the trajectory simulation which was presented in Figure 5, which used File Entry with a drag correction factor of 1.42 and which matched the time to apogee, was used to obtain an estimated dynamic pressure to go with each of the rotation rate and coning angle data points.

To build a coning angle model based on the flight data the logical choice would be to make the coning angle a function of dynamic pressure. The drag, lift, moments, aerodynamic loads, and the aerodynamic force acting on the fins producing the spin are all directly proportional to the dynamic pressure. As an example, aerodynamic drag is defined as the product of the dynamic pressure multiplied by the CD and the rocket reference area S.

$$D = \overline{q}_{\infty} C_D S \qquad (1)$$

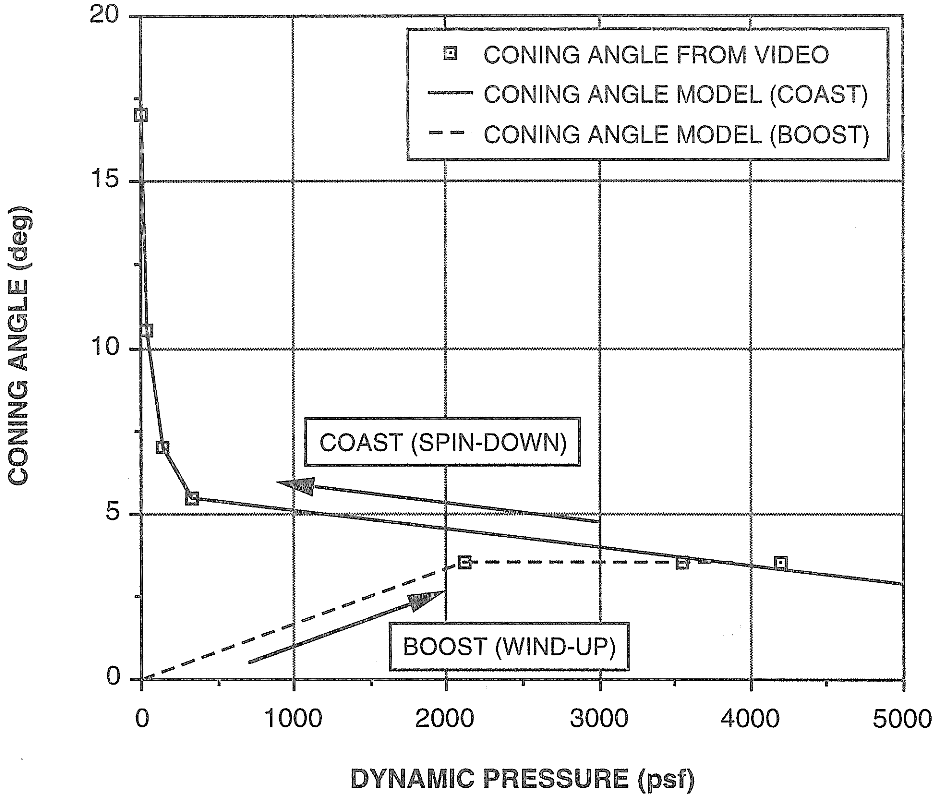


Figure 7 - R Rocket Coning Angle Model Based on Video Flight Data.

Where:

D = aerodynamic drag (lbs)

C_D = drag coefficient (dimensionless)

$\overline{q}_\infty$ = dynamic pressure (lbs/ft^2)

S = reference area (ft^2)

The dynamic pressure is defined as:

$$\overline{q}_\infty = \frac{1}{2} \rho_\infty V^2 \qquad (2)$$

Where:

V = velocity (ft/sec)

ρ_∞ = atmospheric density (slugs/ft^3)

Figure 7 presents the coning angle versus dynamic pressure model that was backed out from the video data in Tables 5 and 6, hereafter referred to as the R Rocket coning angle model. During boost as the spin rate builds up as the rocket goes through "spin-up" the coning angle would start at zero and then build up to some value. From the video data in Table 6 the first apparent coning angle was at 8.10 seconds at a dynamic pressure of 2,119 psf. As the exact coning angle at 8.10 seconds could not be determined from the video it was assumed that it was the same 3.5° coning angle measured at higher dynamic pressures later in the boost phase. Thus the rocket would follow the boost phase line up to the high dynamic pressure at burnout (approximately 4,050 psf), and then travel back down the coast phase line. After the rocket passed through apogee and began descending back towards the ground the rocket was modeled as going back up the coast phase line lowering the coning angle as the dynamic pressure built-up at lower altitudes prior to impact. Note that the R Rocket coning angle flight data during coast at low dynamic pressures showed large coning angles similar to the Aerobee 150 flight data in Figure 6.

The R Rocket coning angle model was added to the ORBIT trajectory simulation, and with the angle of attack of the rocket assumed to be equal to the coning angle the increase in the CD with angle of attack was calculated using a Rogers Aeroscience ΔCD with angle of attack model. As there was spin present during the flight of the R Rocket it was pretty obvious that the source of the spin was slightly misaligned fins. The increase in drag due to misaligned fins, or fin cant angle, was not added to the trajectory simulation for two reasons. The first reason was there was really no way to determine the angle that the fins were misaligned, or canted, as they had been intended to be perfectly aligned, and there was no observed obvious misalignment prior to flight. The only thing unusual concerning the fins prior to flight was when the fin canister was slid over the main body tube for final installation the fit was extremely tight. As the fin canister had to be forced on with considerable force the fins may have been warped slightly because

Table 7 - Drag Increase for the R Rocket with Representative Fin Cant Angles.

Fin Cant Angle (All Fins with Same Cant Angle)	Increase in Total Rocket Drag from Fin Cant		
	Mach 1.05	Mach 2.0	Mach 3.0
0.5 deg	0.88%	0.56%	0.57%
1.0 deg	1.77%	1.12%	1.15%
2.0 deg	3.54%	2.24%	2.29%

of the binding of the fin canister during its installation. The second reason is that given the relatively low spin rates observed on the onboard video of 0.26-0.37 revolutions per second the fins were probably only slightly warped or misaligned, and the drag increase from low fin cant angles is quite low. Table 7 shows the predicted drag increase for the R Rocket at Mach 1.05, 2.0, and 3.0 for fin cant angles of 0.5°, 1.0°, and 2.0° (assuming all fins are canted at the same angle) based on a Rogers Aeroscience ΔCD with fin cant model. As can be seen from Table 7 the increase in drag from the fin cant is small, for a relatively large fin cant angle of 2.0° the drag of the R Rocket goes up only 2.0%-3.5%. The major increase in drag is due to the fin cant angle causing spin which causes the coning angle to develop, creating an increased angle of attack for the entire rocket.

The ORBIT v4.50 trajectory simulation results for the R Rocket using the coning angle model from Figure 7 is presented in Table 8. As can be seen the apogee altitude prediction is only 11.8% off from the flight data estimated altitude of 94,000 ft without the use of any drag correction factors. Adding an estimate for the fin cant drag would lower the predicted altitude further, and at this point the predicted altitude is close enough to the flight data estimated altitude that the effect of any uncertainties in the rocket total impulse, weight, etc., may begin to become significant. Thus in the author's opinion the major contributor to the underprediction of drag, and the overprediction of altitude for the R Rocket has been identified. The graphical output from the ORBIT v4.50 trajectory simulation of the R Rocket using the coning angle model is presented in Figure 8. To the author's knowledge the trajectory simulation presented in Figure 8 is the first time for model, high power, or experimental rockets where dynamic stability and angle of attack effects on the drag of a rocket have been taken into account in a flight simulation.

It can be argued that the 11.8% error in altitude from using the coning angle model is not much of an improvement over the 15.2% error from using the Direct Entry model. In reality the Direct Entry model did not take into account the thinner fins and longer nose cone of the R Rocket that decreased supersonic drag and increased altitude, nor did the Direct Entry model take into account that the rocket was spinning and coning which increased drag and decreased altitude. Simple supersonic CD models based on curve fit equations do not take into account the actual geometry of the rocket, spinning of the rocket, or angle of attack effects. Spinning or non-spinning, thick fins or thin fins, short nose or long nose, the Direct Entry model predicts almost exactly the same altitude for the rocket. For this reason, despite the conservative altitude predictions that are produced by Direct Entry type models (at least the specific CD curve fit equations developed by the author that are documented in Reference 4), the author believes that they are ultimately a dead end for CD prediction and altitude prediction. Only by modeling as many of the contributions to aerodynamic drag as possible can model, high power, and experimental rocketeers gain insight into the effect of rocket configuration and geometry, and angle of attack on aerodynamic drag, and ultimately improve the accuracy of flight simulations for model, high power, and experimental rockets.

With the fairly reasonable match of the altitude prediction for the R Rocket using the coning angle model the question arises of revisiting previous altitude prediction comparisons to assess the effect of this model on other rockets. In particular, if the R Rocket required this drag correction, why wasn't it required for previous flights? Of particular interest were the altitude predictions for the Kosdon Full Metal Jacket series of rockets, for which the original altitude predictions, without adding the coning angle model, are presented in Table 9 (from Reference 3). These rockets were rerun with the R Rocket coning angle model from Figure 7, and these new results are presented in Table 10. As can be seen the predicted altitudes are lowered by inclusion of the coning angle model by approximately 10%, but with the exception of the 23% underprediction of the LDRS XII Argonia Kansas flight the new altitude predictions still agree fairly well with the tracking data. The Full Metal Jacket LDRS XII flight was difficult to analyze as the fins had no leading edge airfoil (they had square leading and trailing edges), and in hindsight the blunt leading edge wave drag model used to predict the drag for the flight may have been too conservative. If the coning angles on the Full Metal Jacket flights were less than predicted by the coning angle model, but still nonzero, there would be improved agreement with the optically tracked altitude data.

In summary the addition of the coning angle model improves the accuracy of the altitude prediction for the R Rocket, and lowers the accuracy for the Full Metal Jacket series of rockets, though with the exception of the Full Metal Jacket LDRS XII flight the altitude predictions for all four rockets are essentially bracketed to nearly within +/- 10% when the coning angle model is included. Still, for the Full Metal Jacket series of rockets the altitude predictions are more accurate when the coning angle model is not included. The simple explanation for these results would appear to be that the R Rocket had spin and coned during flight, and the Full Metal Jacket rockets did not. Actually, while there is direct evidence from the onboard video that the R Rocket did spin and exhibited coning motion during flight, there is no evidence that any of the Full Metal Jacket rockets spun during flight. Of course there is no conclusive proof that they didn't spin either. The problem is that it is very difficult to see low or moderate spin rates on rockets like the Full Metal Jacket series that accelerate from zero to Mach 2.2-2.4 in 2.28 seconds in only 3,800 ft. Typically

Table 8 - Comparison of ORBIT v4.50 Trajectory Simulation Results with R Rocket Flight Data.

Drag Prediction Method	Launch Angle [1] (deg)	Downrange Distance of Impact (miles)	Time to Apogee (sec)	Apogee Altitude (ft)	Altitude Error
File Entry of CD: Subsonic DATCOM/Actual Geometry Supersonic DATCOM/Actual Geometry RAS[2] CD with Angle of Attack Drag Model R Rocket Coning Angle Model	1.95	4.72	84.24	105,132	+11.8%
			Flight Data 80.0	94,000 (est.)	

Notes:
1: Launch Angle Measured from Vertical.
2: Rogers AeroScience (RAS).

when a high power rocket is spinning at a high rate the smoke trail during boost and coast will show evidence of the spin, but none of the characteristic traits of a spinning rocket exhaust trail were present on any of the Full Metal Jacket flights. This still does not rule out a low spin rate of 0.30-0.40 revolutions per second as was experienced by the R Rocket.

The anecdotal evidence from witnessing model rocket and low end high power flights is that rockets with straight fins don't spin, and therefore do not undergo visible coning during flight. For the Full Metal Jacket series the presence of spinning is inconclusive. The data from the R Rocket flight shows that the rocket did spin and coning was present. Spin stabilized sounding rockets are designed to spin, and undergo coning after they have essentially left the atmosphere. The high coning angles at low dynamic pressures typical of sounding rockets were present during the long coast phase of the R Rocket as evidenced by the video data. Is it appropriate to take the coning angle model, or even just the assumption that the rocket is spinning and

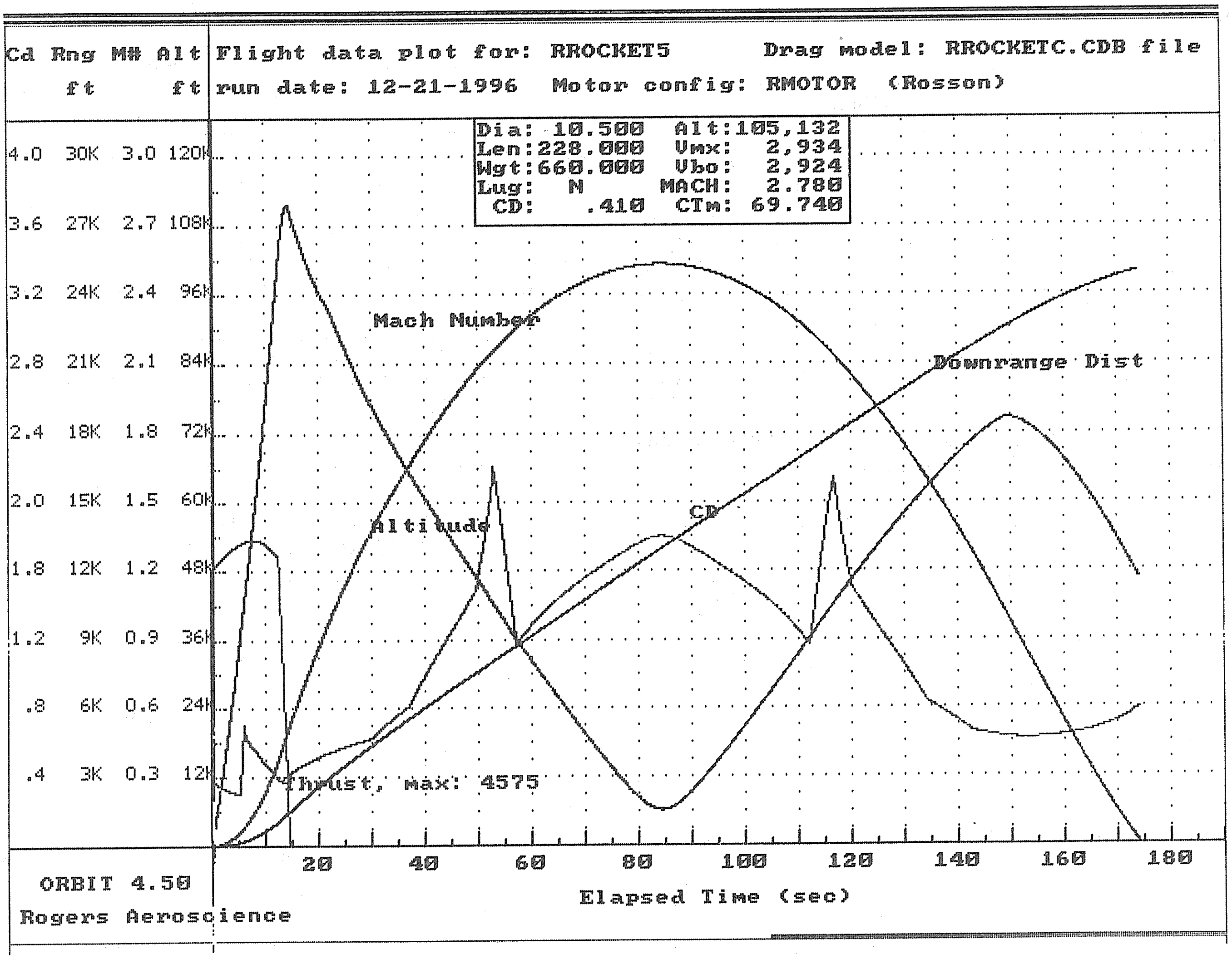


Figure 8 - ORBIT v4.50 Trajectory Simulation Results for the R Rocket Using R Rocket Coning Angle Model.

Table 9 - Rogers Aeroscience ORBIT v4.50/CD v4.50 Simulation Results for Kosdon Full Metal Jacket Rockets. Full Subsonic and Supersonic DATCOM Methods. No Spin - Zero Coning Angle.

Flight No.	Configuration	Predicted Max Mach Number	Tracked Altitude (ft)	Predicted Altitude (ft)	Percent Error
1 - LDRS XII	2:1 Bicone Fin Sweep = 0 deg Blunt Leading Edge Airfoil Liftoff Weight = 67.0 lb	2.36	35,407	31,285	-11.6%
2 - Black Rock 6	1.4375:1 Cone Fin Sweep = 62.63 deg Hexagonal Airfoil Liftoff Weight = 65.0 lb	2.43	30,038	32,216	+7.3%
3 - BALLS 005	4:1 Tangent Ogive Fin Sweep = 62.63 deg Hexagonal Airfoil Liftoff Weight = 70.0 lb	2.27	37,981	38,716	+1.9%

No Spin - Zero Coning Angle

Table 10 - Rogers Aeroscience ORBIT v4.50/CD v4.50 Simulation Results for Kosdon Full Metal Jacket Rockets. Full Subsonic and Supersonic DATCOM Methods. With Spin - R Rocket Coning Angle Model.

Flight No.	Configuration	Predicted Max Mach Number	Tracked Altitude (ft)	Predicted Altitude (ft)	Percent Error
1 - LDRS XII	2:1 Bicone Fin Sweep = 0 deg Blunt Leading Edge Airfoil Liftoff Weight = 67.0 lb	2.34	35,407	27,339	-22.8%
2 - Black Rock 6	1.4375:1 Cone Fin Sweep = 62.63 deg Hexagonal Airfoil Liftoff Weight = 65.0 lb	2.40	30,038	27,853	-7.3%
3 - BALLS 005	4:1 Tangent Ogive Fin Sweep = 62.63 deg Hexagonal Airfoil Liftoff Weight = 70.0 lb	2.25	37,981	33,370	-12.1%

With Spin - R Rocket Coning Angle Model

therefore coning during flight, and apply these results to all rockets on the basis of one flight where the fins on the rocket may very well have been warped due to binding of the fin can? The author believes that these methods should be applied to rockets that fly at high dynamic pressure, like the R Rocket which reached a dynamic pressure of 4,050 psf, and the Full Metal Jacket series which reached dynamic pressures of over 5,000 psf. For rockets flying at high dynamic pressure even the slightest fin misalignment, or misalignment of the fin leading edge will cause the rocket to spin, and to have coning motion present. Considering the 4,050 psf maximum dynamic pressure during the R Rocket flight it's almost amazing that the observed spin rate peaked at only approximately 0.40 revolutions per second. The fins of the R Rocket must have been only slightly warped. As for what qualifies as high dynamic pressure in terms of when to apply the coning angle model, the author proposes an admittedly arbitrary lower limit of 2,000 psf.

With the modeling techniques presented in this article the author believes he has demonstrated practical methods for including coning angle and angle of attack effects for spinning model, high power, and experimental rockets, and that these modeling techniques should be applied to rockets flying at high dynamic pressures of 2,000-5,000 psf. For rockets that exceed a dynamic pressure of 2,000 psf at burnout, or prior to burnout, the author recommends using the R Rocket coning angle model presented in Figure 7, with an instantaneous transition from the boost model line to the coast model line at burnout. Whether to apply these methods to model and high power rockets that fly at dynamic pressures less than 2,000 psf opens up the broader question of when to model non-zero angle of attack effects in general. The basic subsonic and supersonic DATCOM methods used by the author assume that the rocket is flying at zero degrees angle of attack. The question is how good of an assumption this is for low dynamic pressure model and high power rockets. Because of the distribution of the area, and a good portion of the mass of the rocket along the body (body length to diameter ratios are often greater than 10:1) if the rocket is oscillating in angle of attack it may be prob-

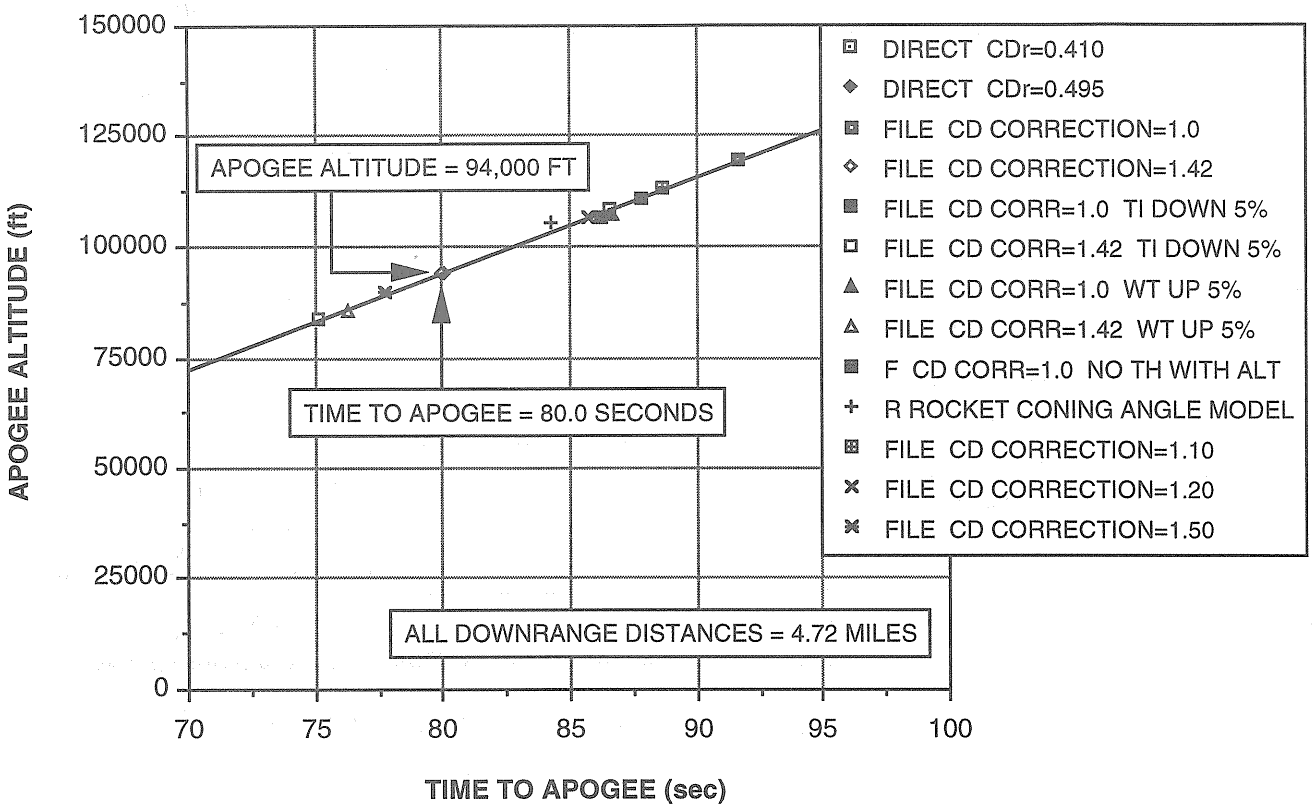


Figure 9 - Apogee Altitude versus Time to Apogee.
OuR Project R Rocket Trajectory Simulations.

able that these oscillations will coalesce into spinning and coning. Thus coning angle models may be the best method for modeling angle of attack effects for all rockets, even those that nominally would not be expected to be spinning. In the author's opinion it's not yet clear whether the coning angle model approach, or an approach based on random oscillations in angle of attack is the best approach for predicting the increase in drag from angle of attack for low dynamic pressure model and high power rockets. What is clear is that minor fin misalignments, etc., cannot be avoided and model, high power, and experimental rockets flying at high dynamic pressure over 2,000 psf will undoubtedly spin and undergo coning during flight, and coning angle models should be used for predicting the performance of these rockets.

A summary of the trajectory simulations for the OuR Project R Rocket used to back out the apogee altitude from the time to apogee is presented in Figure 9. The apogee altitude versus time to apogee is plotted for all of the trajectory simulations run for the R Rocket which were presented in this article, including: total impulse lowered by 5%, weight increased by 5%, no thrust with altitude, Direct Entry and File Entry CD models, drag increased 10%, 20%, 42%, and 50%, use of the R Rocket coning angle model, and various combinations of the above. As Figure 9 shows there is a clear trend of apogee altitude with time to apogee, and the simulation results are tightly grouped around the linear regression trend line. The data presented in Figure 9 thus confirms the analysis results presented earlier that based on the measured time to apogee of 80.0 seconds the OuR Project R Rocket achieved an altitude of approximately 94,000 ft.

References

1. Prior, Phil, OuR Project, *High Power Rocketry*, Vol. 12, No. 5 & 6, June/July 1997, pages 29-34.

2. Rosson, Jim, OuR Project: Data and Photo Chronology, *High Power Rocketry*, Vol. 12, No. 5 & 6, June/July 1997, pages 52-58.

3. Rogers, Charles E., The Aerodynamic Drag of Rockets - Overview of Drag Prediction Methods and Their Impact on Flight Simulation, *High Power Rocketry*, Vol. 10, No. 6, August 1995, pages 11-34.

4. Rogers, Charles E., Drag Coefficient Computer Program and Altitude Prediction Methods, proceedings from the 1984 Rocketcon conference, California Rocketry Publishing, 1984. Lecture notes also available direct from author.

5. Busse, Jon R., and Leffler, Merrill T., A Compendium of Aerobee Sounding Rocket Launchings from 1959 through 1963, *NASA TR R-226*, Goddard Space Flight Center, Greenbelt, Maryland, January 1966. (See pages 67-106 in this issue.)

OuR Project

Data and Photo Chronology

Introduction

No significant event is complete without the usual media circus. However, these guys from Great Britain were a class act. They were careful to keep out of the way and follow safety guidelines. *(Brisighella)*

It's been nine months since the project was flown. In hind sight we look back at the OuR Project and still go *WOW!* We put that rocket project together? The project started so innocent; lets build a simple, single stage large rocket that will hit 100,000 feet. Not something we need a crane to lift, but something four or five people could build and fly in year. Most of all, let's have some fun doing it.

Boy were we wrong! The project required many, many things we didn't consider. A few memorable ones include: over 2 years time, almost $20,000 (Yes, that's twenty thousand dollars! Over $10,000 in machining work combined with long distance phone bills of approximately $200 average per month for all of us), many weeks of post graduate level research (in areas of mechanics, chemistry, astrophysics, and electronics), 20-40 hours of OuR Project work per week by the principle team members, the list goes on and on.

In the end we asked ourselves at lot of questions. What did we really accomplish? What did we learn? Would we do anything different if we could have? What is the most important thing we should tell everyone about the project?

I will answer all these questions very simply. We proved a large diameter composite solid rocket motor could be successfully fired and flown. We learned how to work together. We learned that a team needs everything to be in writing to avoid misunderstandings. You must always define the limits of the project in money, time, and commitment for all members. Only people committed to the project will make it succeed (or maybe those that need to be committed!). Plan on going over budget or someone losing the ability to stay committed, it happens over time!

As far as things to do differently? There is *no one thing* we would do differently except maybe find a generous sponsor. The project was painful on all the team members financially, some more pained than others. Even many OuR Project contributors gave much more than originally planned. Thanks again Bob Stroud, Ross Dunton, our individual families, and all others we've forgotten to mention.

After reading these OuR Project articles, if you decide to do something like this, please remember a very important thing. It's only a hobby! NASA has set almost every altitude record there is. Don't get carried away in the thrill of success. Don't underestimate the requirements on anything, especially not your job, your spare time, your significant other, or the impact on your lifestyle. We paid very dearly for the OuR Project. We almost had one divorce, almost lost one team member's job, and had several unhappy ignored siblings. We kept it together, but just barely. Don't do what we did. Learn from OuR mistakes and do it better. That's why we publish these articles.

Lastly, we wish you well in your endeavors. All projects are important regardless of how large or how small. Enjoy!

From the OuR Project Team

The following pages give a photographic overview of the flight and recovery attempt. The drawing and data tables were submitted by team member Jim Rosson.

John Dunbar	**Electronics**
Dr. Franklin Kosdon	**Motor Design, Fabrication**
Phillip Prior	**Launch Tower, Logistics, Trial Assembly Facilities**
Robert Rau	**Electronics**
Paul Robinson	**Airframe Fabrication, Material Sourcing**
Jim Rosson	**Project Manager, Vehicle Engineering**

PROJECT MEMBERS

Ray Forster	Heavy Lifting
Earl Cagle	Video Documentation
Magnum Industries (Ross Dunton)	Transportation
Ken Mizoi	Fin Finishing, Heavy Lifting, GPS Programming
Bob Stroud	Custom Parachute System

SIGNIFICANT CONTRIBUTORS

Jim Rosson performs the final configuration check of the electronics while team members look on. Everyone is concerned about this payload. Recovery of the rocket depends on it. There is a lot to do with the launch just an hour away. Phil Prior (upper right) secures the rail, making sure the rocket is firmly mounted before lifting it to the launching position. *(Cagle)*

The example at right shows the center of pressure calculations for the rocket, essential for any flight.

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Type '?' at any prompt for help

Nose parameters
  Diameter at base of nose cone (d): 10.5
  Length of nose cone (Ln): 52.5
  Nose shape: Ogive Cone Parabola [O,C,P]: C

Computate a transition (default N): N

FIN parameters
  Number of fins: 3
  Diameter of bodytube at rear (R): 10.50
  Fin semispan (S): 15.00
  Fin midchord (Lf): 15.02
  Fin rootchord (Cr): 20.00
  Fin tipchord (Ct): 15.00
  Fin sweepback distance (Xr): 3.40
  Distance from tip of nose to fin leading edge (Xb): 196.5

Computate another set of fins (default N):

  ____________________________________________________________

Results
  0: magnitude of moment=2.00     acting at directed dist=34.97
  1: magnitude of moment=13.31    acting at directed dist=202.52

Tip of nose to Center-of-Pressure distance = 180.63
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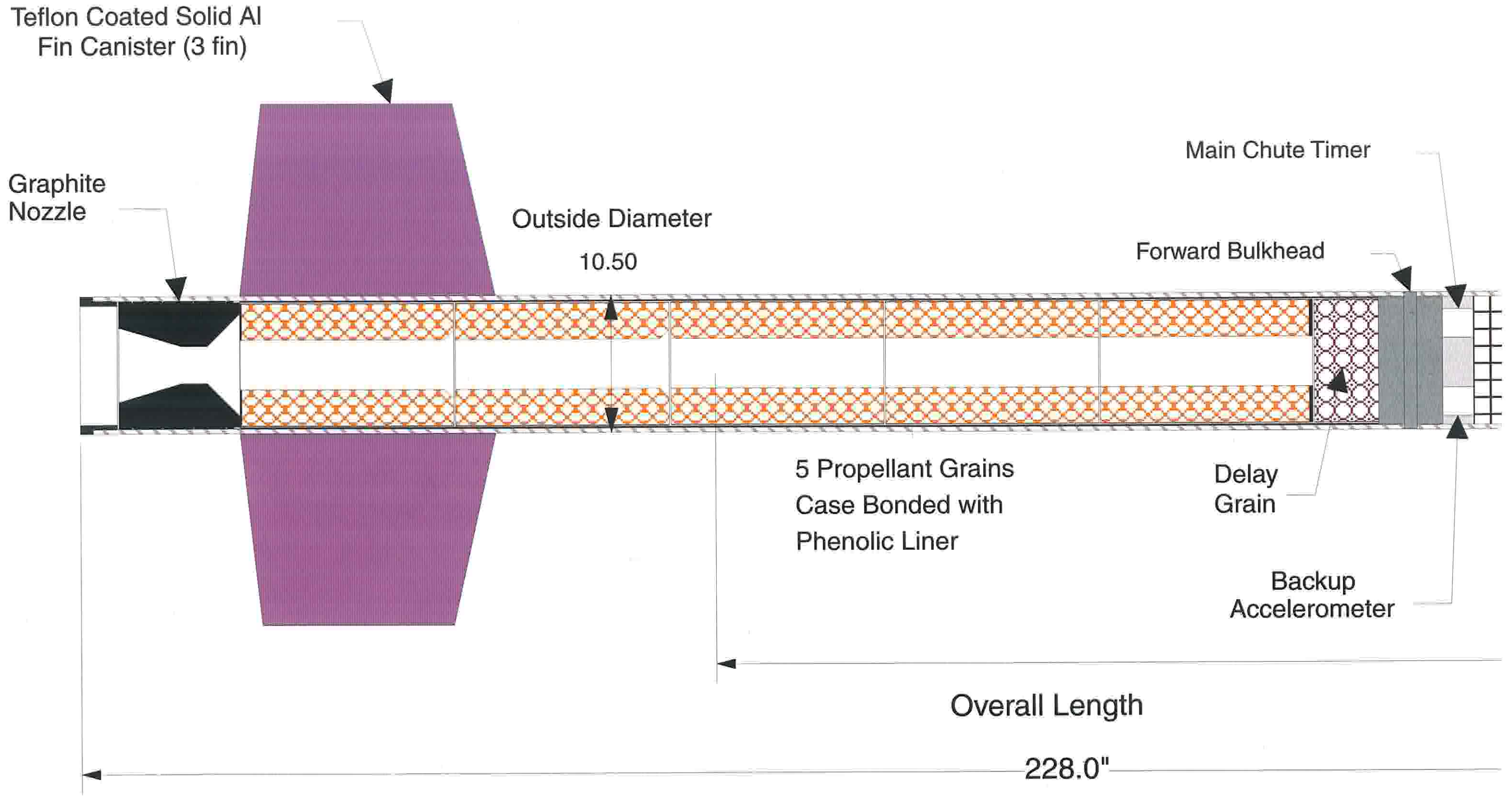
CENTER OF PRESSURE CALCULATOR - Version 1.2
(Copy of actual output from public domain software - CP Program Version 1.2 (MAC))

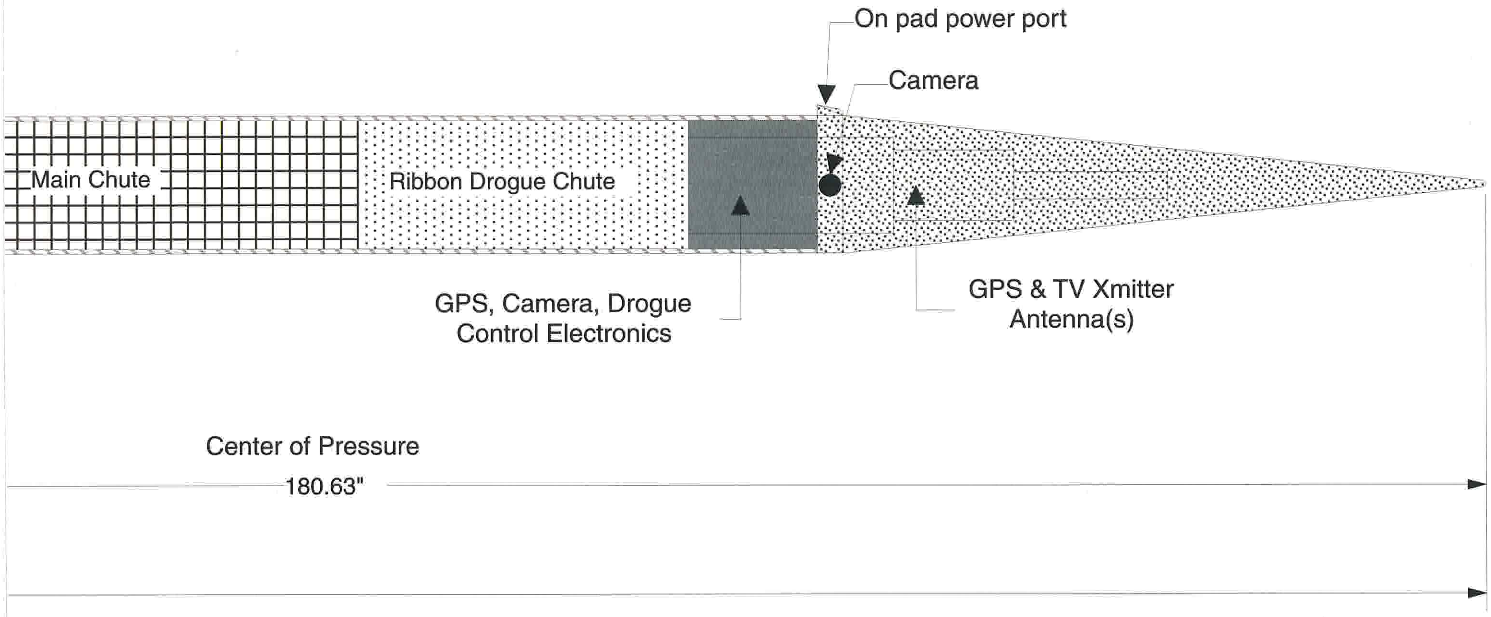
CENTER OF PRESSURE CALCULATION

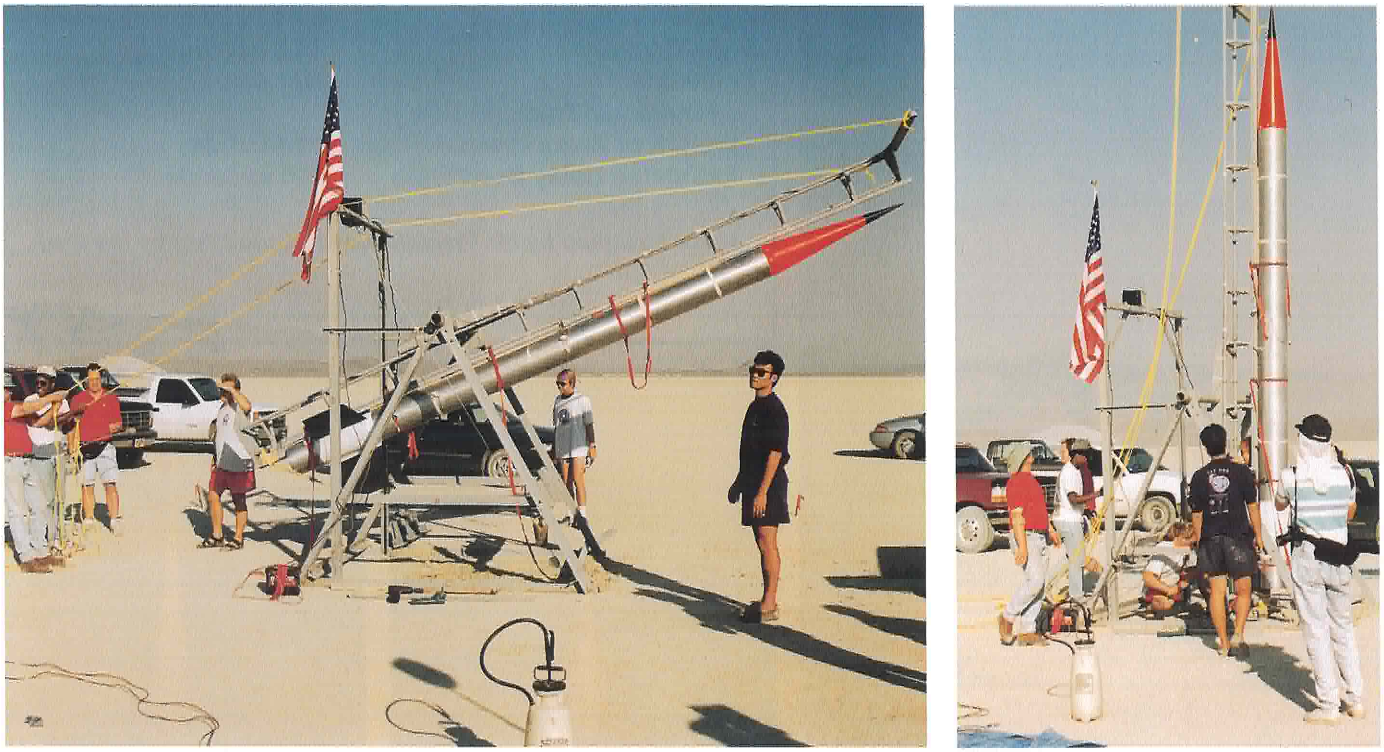
Ou"R" Project



The nose cone is positioned and later secured using the "shear pin" method described in *HPR,* October 1994, pages 10-11. Frank Kosdon discovers the core diameter has been modified. I wonder who got the privilege of explaining that?

(Cross Section View)





Rehearsals are now over; it is time for the moment of truth. The R-powered rocket is raised to the launching position. More work ensues. With the rocket locked into position, final checks are performed. It is time to move the crowd and arm the ignitor. ***(Clark)***

John Dunbar checks the antenna for reception on all channels. He is responsible for the successful real-time transmission of the video. The spectators and non-essential crew are relocated to a safe distance, below, before arming the ignition system. *(Clark)*

Component	Weight (lbs)	Momentum Center Distance (in)
Motor w/Prop	446	163
Payload Section	94	84
Recovery System	22	84
Nose Cone	30	30
Payload Electronics	28	30
Fin Canister	40	197
Total Weight	660	139.488[1]

[1] Estimated Center of Gravity

CENTER OF GRAVITY

~4 calipers of stability were achieved on paper. The rocket's total weight (660 pounds) made an accurate assembled check difficult. A quick check was made and the center of gravity was at least 30 inches ahead of the Cp, which was deemed sufficient.

And we have liftoff! All systems go... *(Brisighella)*

Weight of Propellant	284.5 pounds
Total Newtons	254,357 NS @ I_{sp}=201
Number of Bates Grains	5
Diameter of Grains	9.50 inches
Length of Grains	16.75
Core Diameter 1 (2 upper grain)	3.605 inches
Core Diameter 2 (3 lower grain)	3.875 inches
Nozzle Throat Diameter	3.15 inches
Expansion Ratio	3.41 (5.82 exit diameter)
Burn Time	14.5 seconds
Equivalent Rating	R17,542
Full Diameter Tracking Delay:	
Weight of Delay Grain	21 pounds
Estimated Delay Burn Time	110 seconds

Motor designed by Dr. Franklin Kosdon, modified by the team.

MOTOR SPECIFICATIONS

R17,542 254357 ns 14.5 sec 129.319 kg

Dia (in)	cd	L wt (lb)	mx alt (ft)	coast (sec)	CdA (in²)	BO wt (ft/s)	BO vel (ft/s)	BO alt (ft)	A_max (g)	tAmx (s)	max (sec)
10.5	0.45	570.0	101058	67.2	39.0	284.9	3132	22334	7.42	14.40	155.3
10.5	0.45	580.0	98854	66.4	39.0	294.9	3072	21895	7.26	14.40	153.3
10.5	0.45	590.0	96704	65.7	39.0	304.9	3014	21470	7.10	14.40	151.4
10.5	0.45	600.0	94595	65.0	39.0	314.9	2958	21058	6.96	14.40	149.6
10.5	0.45	610.0	92537	64.2	39.0	324.9	2903	20658	6.81	14.40	147.7
10.5	0.45	620.0	90527	63.5	39.0	334.9	2850	20271	6.68	14.40	145.9
10.5	0.45	630.0	88568	62.8	39.0	344.9	2798	19895	6.55	14.40	144.1
10.5	0.45	640.0	86653	62.1	39.0	354.9	2748	19529	6.43	14.40	142.4
10.5	0.45	650.0	84788	61.4	39.0	364.9	2700	19175	6.31	14.40	140.7
10.5	0.45	660.0	82966	60.7	39.0	374.9	2652	18830	6.19	14.40	139.0
10.5	0.45	670.0	81193	60.0	39.0	384.9	2606	18495	6.08	14.40	137.4
10.5	0.45	680.0	79462	59.3	39.0	394.9	2562	18170	5.98	14.40	135.7
10.5	0.45	690.0	77775	58.7	39.0	404.9	2518	17853	5.88	14.40	134.1

ORIGINAL ESTIMATED ALTITUDE

Estimated altitude was approximately 82,966 feet, based on final weight of 660 pounds, from line 10 above. Estimate is a SWAG based on Cd being held constant at subsonic, transonic, and supersonic speeds as well as constant thrust over the burn time and altitude.

The R-powered rocket reached well beyond the human eye's perception. Everyone looked for signs of recovery until the sonic boom was heard indicating rapid descent. The impact site was located over four miles away, but still within the confines of the launch area. Now the head scratching begins... "What are we going to do now?" Dario points the direction, sweat labor begins. ***(Clark, Prior)***

Parachute System - Stroud Safety Custom Built.

Two Stage Recovery, with all components staying attached;

Drogue was to be ejected at apogee via a GPS determined maximum altitude (primary system) and/or via apogee detect on an accelerometer backup (secondary system). Both systems used independent black powder charges (35 grams each) to separate the nose cone and eject the drogue.

Drogue Type: 6-foot Kevlar Ribbon 'chute, in a Stroud patented Nomex deployment bag designed for deployment speeds in excess of Mach 1, made from Kevlar ribbons to withstand extreme temperature variations. Main was to be released after a 110-second delay from drogue release (using primary system) or fixed time interval after apogee (using accelerometer backup system). The main was held in place via a retaining strap. The main was to be released by firing a pyrotechnic activated strap cutter. An additional black powder charge (70 grams) was to be fired with the backup system pyro cutter to ensure the nose cone had separated.

Parachute Type: 25-foot (approximate inflated size) Custom Stroud 'chute, in a Nomex deployment bag.

RECOVERY INFORMATION

The backhoe arrived late in the afternoon. When its limits were reached Ken Mizoi, who had the most energy, took over. After five hours enough pieces were found, right, to fill a garbage bag. *(Cagle)*

1) Modified Trimble GPS system for high altitude use.
2) Side looking video camera.
3) Flight telemetry downlinked to ground via a ATV (amateur TV) system, flight data (altitude, velocity, and location) superimposed and displayed on the ATV signal from the side looking camera.
4) Custom antenna and downlink receiver with TV and recording VCR.

The above items were built and supplied by Robert S. Rau of High Technology Flight, a division of RP industries, and John Dunbar.

5) Cambridge Accelerometer (backup system).
4) Backup RF transmitter locating beacons, one for nose cone and one for payload in case of separation.

PAYLOAD/ELECTRONICS INFORMATION

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