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Potential Benefits of Magnetic Suspension and Balance Systems

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INTRODUCTION

The concept of using feedback controlled magnetic fields to support models in wind tunnels dates back at least to the early 1950's when work began in France at ONERA. The first experimental results from ONERA were reported in 1957, reference 1. An annotated bibliography of magnetic suspension and balance systems (MSBSs) is provided in reference 2 and serves as a synopsis of existing work in this field. Systems which have been constructed and operated for aerodynamic research have been excerpted from reference 2 and are listed in chronological order in Table 1. A common feature is their small size, a feature that has, with a few exceptions, prevented their use for serious aerodynamic research.

The development of the magnetic suspension and balance system concept has been supported by the Langley Research Center, both through in-house research and through contracts and grants, since the late 1950's with varying degrees of vigor as priorities permitted. In 1971 work on MSBS at NASA Langley prompted the suggestion that operating the relatively small wind tunnels then fitted with MSBS at cryogenic temperatures would be the best way to increase the test Reynolds number, thus overcoming to some extent, the limitations on serious aerodynamic research imposed by the small physical size of the facilities.

The results of theoretical analysis of the cryogenic tunnel concept, and experience in building and operating a low-speed cryogenic tunnel, were so promising that all efforts toward MSBS were redirected towards the development of transonic cryogenic tunnels as a solution to the problem of inadequate Reynolds number capability at transonic speeds. This effort culminated in two new wind tunnel facilities at Langley; the 0.3-m Transonic Cryogenic Tunnel, and the U.S. National Transonic Facility. The progress in cryogenic tunnels to date is summarized in references 3,4,5 and 6.

Following the successful development and demonstration of cryogenic tunnels, research activities in MSBS at Langley were resumed in 1977. It soon became obvious that the emergence of new technology in superconductivity, large magnet construction, computers, control techniques, and innovation in MSBS systems made the application of MSBS to large tunnels, not only feasible, but very attractive. References 7, 8, and 9 deal with the system aspects of integrating MSBS into large transonic tunnels and reference 10 updates the status of MSBS research. The use of MSBS's to upgrade existing facilities was strongly endorsed at a recent testing conference, reference 11. Also, several papers seeking to define the optimum wind tunnel for various speeds have called for inclusion of an MSBS, references 12, 13, and 14.

It is the intent of this paper to outline the potential of a large MSBS to solve existing problems related to support interference in wind tunnels as well as to speculate on the potential for unique new aeronautical research. An additional section is included on possible spinoff to technologies other than wind tunnels. The overall tone of this paper is intended to be optimistic, predictive, speculative, and imaginative.

IMPROVEMENTS TO CONVENTIONAL WIND TUNNEL TESTING TECHNIQUE

Static Aerodynamic Coefficients

The most obvious and straightforward improvement MSBS offers in the determination of static aerodynamic coefficients is the complete elimination of support interference error due to flow distortion. Figure 1 (taken from reference 15) presents a simple example of this problem where the configuration has a large squared-off base area and the primary error due to the model support is in the base pressure coefficient. Even in this simple case there are secondary error sources due to distortion of the wake flow. Also, when this configuration is at a high angle of attack, thus exposing the support to the flow, the error becomes larger due to increasing tunnel blockage.

Much larger errors can occur in cases where there are large areas of separation with some coherent structure. Two examples of such flows are transverse cylinder flow and the flow over swept delta wings. The structure in the first case is the coherently oscillating Karman vortex street, and, in the second case, the stationary vortex over the wing. Intrusion into either of these flow fields by the model support system may cause gross error in the static aerodynamic coefficients.

An example of a cylinder-like flow field occurs when a missile is at high angle of attack, as shown in figure 2 (taken from reference 16). The coefficient in this case is shown to differ by as much as 40 percent depending on support location. Figure 3 contains a comparison of three schemes of supporting a sharp-edged delta wing configuration with differences in rolling moment coefficient as a function of sideslip angle as large as 400 percent depending on the support scheme (data taken from reference 17).

An additional source of error due to flow distortion may occur in the transonic flow regime. An example of this problem is shown in figure 4, taken from reference 18. Since there is no support free data with which to compare, the problem is shown in terms of the difference in axial force coefficient for several support configurations. As can be seen, as the Mach number is increased through the transonic range, the errors are not only large, but they reverse direction. Although magnetic suspension may not offer the same propulsion airflow as available for this type of experiment, the use of magnetic suspension has great potential in the evaluation of errors due to support interference. Additional information on support interference problems amenable to solution by the use of a MSBS is available in reference 19.

Eliminate Error Due to Geometry Distortion

Figure 5 serves to illustrate the distortion to the model geometry necessary to allow wind tunnel testing of the Shuttle-747 combination using a conventional sting support system. Since one of the concerns of this coupling was the effect of the blunt base space vehicle on the vertical stabilizer performance of the transport, it would have been desirable not to have altered the empennage and reduced the size of the vertical tail.

Remove Restrictions On Static Testing Due to Supports

A common restriction of conventional sting support systems occurs in static testing at high angle of attack, and the common solution is to use bent or "dogleg" stings. This is usually necessary to keep the model away from the test section ceiling. However, even with bent stings, large angles of pitch or yaw frequently require the use of an additional, smaller model in order to test with reasonable levels of tunnel blockage. With a MSBS the mechanical support mechanism is eliminated, and the model can be freely positioned in the center of the test section with no blockage or support interference, due to the sting.

A more complex restriction occurs in testing a configuration in ground effect, either during takeoff, landing, or hover. Figure 6 is a photograph taken during tests of the Shuttle Orbiter in a landing attitude. To obtain the necessary data it was necessary to construct an artificial ground plane in a large tunnel and then use a small model. Note the slot cut through the ground plane for the sting. A later phase in the testing required additional slots to be cut in order to obtain data for cross-wind conditions+. A MSBS would have required none of these artifices to assist in acquiring the data, and the cross-wind testing could have been conducted over a continuous sweep of yaw angles rather than at a few discrete angles.

Dynamic Stability

One of the major advantages of MSBS, and the advantage that led directly to the work on MSBS at NASA Langley, is the ability of a magnetic suspension and balance system to provide more accurate dynamic stability data from wind tunnels.

Provide Concurrent, Improved, Dynamic Stability Data

In the typical small-amplitude forced-oscillation method of dynamic stability testing, the model must be considerably distorted to allow even the small amplitude (typically 1 or 2 degrees) oscillations on the fixed sting support. Further, the typical small amplitude forced oscillation mechanism severely limits the location of the center of oscillation, a fact which has in the past limited the usefulness of test results on configurations such as the Mercury and Gemini Capsules and the Apollo Command Module.

In contrast, by using a MSBS, there is no distortion of the model to accommodate the support system. Further, with a MSBS the oscillation center of the model being tested can be varied at will, a very desirable feature for configurations where the center of gravity has not been fixed or for a configuration envisioned to have a large shift in center of gravity over its flight envelope.

Multiaxis Capability

An additional advantage of MSBS for the classical method of extracting dynamic stability information is the ability it provides for simultaneous oscillations of the model, either forced or free, about any of the six degrees of freedom of the suspended model. This capability can be used, for example, to provide a suitably combined pitching and plunging oscillation in order to achieve a pure angle of attack oscillation, thus providing the ability to separate the effects of Cm(alpha) from the effects of Cm(qdot).

Parameter Identification Techniques

Although the interest at NASA Langley in MSBS was prompted in large part by the desire to find a better way to do small-amplitude forced-oscillation testing in transonic wind tunnels, the need for such a capability may have been eliminated by the emergence in recent years of parameter identification techniques to determine the dynamic characteristics of physical systems.

Although not demonstrated, conceptually the use of parameter identification techniques is compatible with the requirement to determine the dynamic stability characteristics of models in a MSBS. The model would appear to be held rigidly in suspension. However, the dynamic characteristics would be extracted from the supporting coil currents as these currents changed in response to the demands of the model to be held fixed in space.

Improve Tunnel Productivity

Improvement in wind tunnel productivity is an area where MSBS has a particularly strong potential. Productivity is considered to be improved if:

1. the required data is obtained with less tunnel occupancy hours,

2. the data per hour is of higher quality,

3. fewer models are required,

4. less data reduction is required, and

5. previously unavailable, but desired, data is produced.

The following paragraphs will discuss a few examples to explain features of an MSBS which would provide these productivity improvements.

The drawings in figure 7 illustrate the 5 model/sting configurations that were necessary to obtain dynamic stability data for the crew escape module of an early version of the B-1 bomber. The tests were conducted in the Langley 8-ft Transonic Pressure Tunnel. Such relatively large tunnels are not only expensive to operate, but their time is valuable in the sense that they have more customers than they can serve. To obtain a sufficient data matrix to determine the dynamic stability characteristics of the model of the escape module, it was necessary to oscillate the model through 5 separate ranges of angle of attack in pitch, 4 ranges of yaw angle, and at 4 roll positions; a total of 80 conditions. Since each point in the matrix required the support to be changed, the test section had to be opened a total of 80 times. Note that the fifth configuration had to have a bulge in the underside to accommodate the balance for the highest pitch angle. This attempt to locate the balance oscillation axis on the proposed center of gravity position necessitated the construction of an additional model.

Had this facility been equipped with an MSBS, one less model would have been required, there would have been no distortion of model geometry, no supports would have been constructed, the data would have been improved due to the lack of support interference, the test section would never have had to be opened. The resultant testing time would have been reduced from many weeks to perhaps several days. Recourse to reference 20, which documents this test, reveals also that this was a sparse amount of data to acquire and that more points would have been desirable. Also unavailable are any mixed modes such as Dutch roll.

Figure 8, taken from reference 21, illustrates one method of evaluating support interference. In this example, the evaluation was necessary to allow extrapolation of wind tunnel results to flight. Figure 9 indicates the magnitude of the corrections determined and their nonlinearity with Mach number. For a typical cruise condition, these corrections are of the order of 10 percent of the total drag. This is a seizable correction and its application is absolutely necessary in configuration synthesis and performance prediction.

From a productivity point of view, these tests could have been eliminated with a MSBS resulting in savings in three areas: First, the family of large, expensive support hardware sketched in figure 8 would never have been built. Second, the additional tunnel time to test the different support configurations, as well as the test section entries required to make configuration changes, would have been unnecessary. Third, the extensive data analysis procedure documented in reference 21 would not have been necessary.

Two-body Aerodynamics

Figure 10 shows a model wind tunnel model of the Shuttle Orbiter attached to a ferry ship. It would be of prime engineering interest in this case to determine the aerodynamic coefficients of each vehicle in terms of the Orbiter attitude, axial location, and separation distance. The conventional method of obtaining this data is to test several values of each variable, requiring many different attachment points. The availability of an MSBS would allow the Orbiter to be "flown" to different locations, simultaneously measuring the forces on the carrier ship with a mechanical balance and on the Orbiter with the magnetic balance, to determine the sensitivity of the aerodynamic coefficients to location and attitude with one test installation. This procedure not only reduces tunnel time, test section entries, and extra time for model changes, but also has the potential to produce a better answer, thus improving productivity.

Stores Separation

One means of studying the problem of separating a store from a carrier aircraft is to separately support the model of the aircraft and the model of the store and equip each with a 6-component balance allowing simultaneous measurements of the aerodynamic forces. With a sophisticated drive for the support of the model of the store, it is possible to simulate the positions a store would take during a separation, and to determine the mutual interactions between store and aircraft. The practice of this art is summarized in reference 22. Figure 11, taken from reference 23, indicates the sophistication and complexity necessary in the drive system. In an MSBS equipped facility, only the model of the aircraft would be supported in this manner with the support and model being constructed of a non-magnetic material, such as stainless steel. The model of the store would contain a magnetic core and would be magnetically supported and positioned. The use of magnetic fields as an aid in stores release testing was discussed at least as early as 1967, reference 24.

NEW WIND TUNNEL TESTING TECHNIQUES

The previous sections of this paper have dealt with at least quasi-conventional applications of a near-term technology MSBS. This section assumes the availability of an advanced MSBS equipped with the sensors and control systems to allow a model to be freely manipulated in the test section, including any angle of pitch, roll, and yaw, and motions such as spin or tumbling. Also assumed is the ability to relinquish control of any or all degrees of freedom for intervals of time in order that the model can dynamically respond to the forces being imposed. For example, releasing the roll control would allow a fighter model at angle of attack to oscillate in roll in response to the dynamic forces that induce wing rock.

General Improvements

Computer Controlled Stop Point Trajectories

Figure 12 serves to simultaneously illustrate the concepts of "computer controlled stop point trajectories", and "designer in the loop". The example used is a crew escape module being ejected from a bomber type aircraft. In this case, the bomber is mounted with a conventional blade mount and mechanical balance, and would contain no magnetic materials. The crew module would contain a magnetic core, and could be manipulated by an advanced MSBS. The envisioned purpose of the test is to determine under what conditions of escape module ejection would the crew be able to survive.

The test might be conducted by first testing with the crew module in place on the aircraft. This would provide initial aerodynamic separation forces tending to hold or eject the module; this data point would be enhanced by moving the module very slightly and retaking the data in order to evaluate tare forces due to friction. A non-aerodynamic initial force and trajectory would be assumed consistent with an ejection mechanism, for instance a rocket. This initial trajectory would be the one the module would follow in a vacuum. The next point would be obtained by moving the module along this prescribed trajectory just enough to allow flow to circulate between the module and the cavity as it is leaving in the aircraft. The measured forces and moments would then be used to modify the vacuum trajectory and allow the calculation of the next point along the modified trajectory. At the next point, forces and moments would again be calculated, and so forth. The assumed center of gravity location of the module would be constrained to follow the modified trajectory, but the capsule would be rotated as the measured aerodynamic moments and calculated moments of inertia would dictate.

The above process describes the "computer controlled stop point trajectory." Since this trajectory could be programmed to be run many times during a wind tunnel test, it would be feasible to make parametric investigations of such effects as the orientation of the bomber, the c. g. location in the module, variations of the vacuum trajectory, and settings of the aerodynamic control surfaces of the module. If an experienced designer were present in the wind tunnel control room, and assuming g loads experienced by the crew were continuously calculated, he could identify successful and unsuccessful ejections on line, and in an iterative manner, prescribe the perturbation of the conditions for the next trajectory that would define the boundaries of a survivable escape. This is the essence of the "designer in the loop" concept, which would reduce a process that, accomplished by conventional means, would require months for a partial answer compared to a few hours for a complete answer. Obviously other ground rules could be imposed such as the module remaining upright, or not spinning, and certainly not impacting the vertical tail of the bomber. This information would then be used to decide the safe operational envelope of the crew escape system and allow rapid and knowledgeable decisions to be made as to the desirability of such system or module design.

The hypothetical example just described serves to illustrate the manner in which an advanced MSBS might be employed to use designer in the loop and/or pilot in the loop to greatly improve both accuracy and productivity in system design.

Safe-Box Concept

The "safe-box concept," figure 13, is an example of a magnetically controlled tunnel injection system that would have the advantages of conventional ejection systems, e.g. to permit heat transfer testing, as well as to provide simulation of a bomb bay or silo launch. Such a device might also serve well to determine the aerodynamics of stores in cavities, as well as the dynamics of stores release from cavities.

Fighters

Testing of fighter models has always offered the wind tunnel experimentalist a challenge; a straightforward problem is the high angle of attack required. To maintain force balance measurement accuracy as angle of attack is increased, it may be necessary to change balances several times since the ratio of beam loads can change by factors of two or greater. Also, it is not usually possible to use a single support, and it may be necessary to employ one or more bent stings. Finally, at the higher angles and with the attendant massive separated wake, some of the aerodynamic coefficients become extremely sensitive to the presence and type of support structure, as discussed in reference 16.

The use of an advanced MSBS eliminates these problems simultaneously with adding new capabilities. Once at high angle of attack, a fighter may exhibit the tendency to buffet, wing rock, nose slice, or otherwise depart from a stable condition. Since any constraint on model motion imposed by the MSBS may be relaxed of abandoned, these tendencies may be explored, or artificially induced and allowed to amplify or decay. In addition, high angle of attack characteristics may be determined instantaneously. This would allow the determination of, for instance, any overshoot in lift coefficient that may occur as a result of the pitch rate employed to deliver the fighter to the high lift condition; the next step, and one easily permitted by MSBS, would be to examine various pitch rates to establish acceptable values of maximum rate.

The high angle of attack capabilities discussed above serve as an example of new capabilities offered by an advanced MSBS in this one area of fighter testing. Other capabilities offered are transient maneuvers including both translations and rotations, pilot-in-the -loop, magnetically varied c. g. location, real time computer generated stability augmentation systems, computer generated artificial damping, out of flight path pointing, simulated carrier landings, and simulated refueling. Further details of fighter testing are beyond the author's ken, and it is left to the readers imagination to fill in the details of using such a MSBS to solve his particular problem.

Missiles

The technique of studying two-body or stores separation problems with the aid of an MSBS has been discussed in other sections of this paper. The following example is intended to provide the philosophy for additional application of advanced MSBS to missile problem solving.

The safe-box concept, as discussed earlier (figure 13), is an example of a magnetically controlled injection system that could provide simulation of a bomb bay or silo launch. If this system were available in a trisonic tunnel, a special naval problem of shipboard defense is envisioned as an example MSBS application. Since the direction from which a threat might approach is not known, it is assumed that the missile launcher would be vertically mounted. The most demanding task from such a launcher is interception of a sea level threat. To simulate this mission, the missile would first be moved magnetically from a simulated launch tube as shown in figure 14. Air blowing from the tube could be used to simulate booster exhaust. This portion of the test could be repeated using variations in tunnel speed to simulate different levels of crosswind.

The next phase of this type of launch is a high g turn, requiring the missile to fly at very high angle of attack to the oncoming flow. (Since the typical missile of this type has no wings, it turns by having some component of thrust normal to the flight path, and the angle of attack is actually negative in the aerodynamic sense.) During this maneuver, the Mach number, pitch rate, and angle of attack are simultaneously changing. These variables can be studied one at a time or all together by the computer controlled stop point trajectory technique discussed earlier. Finally, the model will be taken to the supersonic lock-on phase with static stability, dynamic stability, and control force requirements having been determined at every point in the trajectory.

Obviously, other problems involving internal stores release or silo launch could be investigated in a similar manner.

Helicopters

Figure 15 illustrates an additional capability offered by MSBS in the testing of helicopters. The testing underway in the photograph is conducted with the rotor turning from an attachment in the tunnel floor. The helicopter body is being tested in the downwash of the rotor but is detached from the rotor. The body can be turned through 360 degrees to produce a crosswind due to the tunnel flow. This will allow the determination of the static stability of the body in the hover mode and under the combined effects of rotor downwash and crosswind. An MSBS is an ideal candidate to replace the support used here to turn the body, providing support interference free data and greatly increased ease of operation. Also, in this case no particular beam of a mechanical balance can be optimized since the maximum load can come from any direction. Conceptually, the magnetic balance components can be optimized for the load condition by changing the sensitivity constants with each increment of rotation.

Transports/Bombers

Figure 16 illustrates an advanced subsonic transport concept typical of the "family concept" of more efficient aircraft, reference 25. The use of the twin fuselage scheme presents the wind tunnel engineer with the immediate problem of finding a location for a balance. A MSBS can ease this problem by locating a magnetic core in each fuselage, creating a virtual core in the center of the vehicle. Also removed is the vexing problem of supporting such a configuration, both for static and dynamic stability tests. An MSBS also offers a unique capability to determine aeroelastic behavior of this type of configuration by supporting one fuselage with a mechanical balance while supporting the other fuselage magnetically thus allowing determination of the aero/mechanical coupling of the wing and horizontal stabilizer.

The advanced transport configuration depicted in figure 17 presents a different sort of testing problem in that the main lifting surface is so far aft as to preclude any sort of mechanical support without severe support interference problems. An MSBS not only erases the support problem, but also offers the opportunity to fly this canard dominated design with varying degrees of positive or negative static margin, assuming the incorporation of an appropriate active control system for the canard.

Hypersonics

Most of the advantages of wind tunnel testing with a MSBS at other speeds are also applicable in the hypersonic speed range. The problem of alteration of vehicle geometry due to supports becomes particularly acute for airbreathing configurations optimized for cruise range. In order to reduce both drag and heating, it is necessary to have highly swept, thin wings and stabilizing surfaces, as depicted in figure 18. It is obvious that the empennage section of this configuration would be grossly distorted by the conventional balance and sting.

At the present stage in hypersonic research, fundamental studies of wing alone aerodynamics are necessary in order to develop optimization methodology. Since the wings are typically as shown in figure 19, that is very thin, there is no place for a mechanical balance, and without a magnetic balance, quality data is very difficult to obtain. For configurations intended for airbreathing cruise, the wings also tend to be very thin, leaving no volume in the model for a conventional strain-gage balance. For these configurations, the entire wing would be made of a magnetic material in order to be suspended by a MSBS.

Hypersonics has other special problems that may be well addressed by the use of a MSBS. One of the problems of conventional balances which may occur in hypersonic tunnels is high model heat transfer rates which induce temperature gradients in the balance. In the hypersonic environments necessary for simulation of turbulent boundary layers, these gradients are sufficiently large as to require water cooling of the balance, and in a few cases even this is not sufficient to reduce balance temperature gradients to acceptable levels. Obviously, a MSBS eliminates this difficulty.

Figure 20 is a photograph of a "parasol wing" configuration. This is essentially a two-body configuration since the wing is supported on pylons and there is flow between the body and the wing. The performance of the wing is improved in "wave rider" fashion by the compression of the flow of the fuselage forebody, and the drag of the fuselage is reduced by the aft body high pressures induced by the wing compression. An MSBS would be employed in several ways in this case, first to measure the wing alone performance of the very thin wing and then to determine the optimum location of the wing, with respect to the body, for maximum wing performance. Then a non-magnetic wing would be blade supported and the fuselage magnetically flown to determine a similar data set. Finally, the entire optimized configuration would be tested magnetically to measure its aerodynamic performance.

It is possible to obtain this data with a mechanical balance, but the particular advantage of a magnetic balance for this type of testing is the ability to mechanically decouple the wing and body, support one component mechanically and the other magnetically, and vary the parameters of separation distance, fore and aft location, and relative pitch angles. As observed earlier, these optimizations can be carried out with one set of models and one set of tests. This procedure not only results in increased tunnel productivity and a reduction in models and supports required, but also allows the relative positioning of the configuration to be carried to a true optimum during the actual testing, thus saving large amounts of data reduction of isolated points, which can only approach an optimum.

Stage Separation

Another simulation task which may be presented to the wind tunnel engineer is stage separation of airbreathing stages. Figure 21 is an artist's rendition of a follow-on Space Shuttle concept. For this concept, two "tugs" with large turbojets are used for take-off and acceleration to supersonic speed where they separate and return to the airport. The Shuttle then accelerates on a mixed mode scramjet to hypersonic speeds, and finally uses rocket boost for insertion into orbit (consult reference 26 for additional information on this concept). The MSBS would assist this test by determining the supersonic separation characteristics by magnetically flying away the tug in a manner similar to the crew escape scheme discussed earlier. In this case, the MSBS would also be used to efficiently optimize the orientation of the tug with respect to the Shuttle; in a trisonic tunnel, this could be done across the speed range.

Aero Systems

Aero systems is a catch-all term for the systems not considered elsewhere in this paper, but for which a MSBS would be advantageous. For instance ground effect machines or hovercraft. These craft could be supported in sub-scale with working propulsion plants to determine optimum design parameters, crosswind effects, dynamic responses, and, with a moving ground plane, effects of roughness or surface obstacles.

Automobile Testing

The use of an MSBS also offers unique advantages in the wind tunnel testing of automobiles. Figure 22 is a photograph of a racing car under test in the Fiat Research Centre Aerodynamic Wind Tunnel. Reference 27 describes this type of testing and its validity for Formula 1 racing cars. This reference discusses several testing limitations, and it appears that an MSBS could eliminate the support interference problem as well as enhance the testing capability. For instance, by supporting the car in axial and lateral translation only, and permitting the suspension and wheels to support the weight in the normal manner, the car would be able to assume its natural angle of attack; internal mechanical balances attached to the wheels could then determine the remaining forces. While the authors do not purport to understand the intricacies of this type of testing, it is fairly obvious that a MSBS would be a powerful tool in automotive testing.

Towing Tanks and Water Tunnels

A MSBS could be used with a conventional towing tank by supporting the MSBS on a carriage which would roll down the length of the tank as is presently done with mechanical support systems. However, the model would "fly" freely either above or in the water as well as throughout the air-water interface. The craft could also be allowed to respond dynamically in a natural manner; for instance, by turning off the magnetic roll control, the natural roll and roll rate cycles could be established. Hydrofoils could be tested in a similar manner and by turning off the magnetic lift force, the ship could be allowed to seek its equilibrium depth, and by turning off pitch, its natural angle of attack.

The real forte of the MSBS in water facilities, however, is probably underwater towing, where support interference is a more vexing problem. This leads naturally to the application of MSBS for water tunnels. Not only is the support interference eliminated but complex model dynamics are also easily accomplished.

POTENTIAL SPINOFF OUTSIDE OF WIND TUNNELS

Although the development of an advanced magnetic suspension and balance system is justified by its potential benefit to aeronautics alone, it is appropriate to consider spinoff applications to other technological disciplines. Schemes employing simple magnetic levitation, such as is practiced with magnetically levitated trains or magnetic bearings, are well documented and are not considered to be a potential MSBS application since there is no active control and usually only one degree of freedom.

MSBS in Medicine

The use of an MSBS in the field of medicine does not require speculation in this document to give it birth since it is already in use and well documented in its own right. Reference 28 describes its use to "fly" a cylindrical body in the blood stream of an animal test subject in order to assess the tendency of blood to clot on materials intended for use in the manufacture of artificial organs. The clotting rate could be inferred from the increase in drag of the cylindrical body as clots adhered to its surface. Additional uses in medicine are further documented in the bibliography.

Yet another use is imagined as pictured in figure 23, where a magnetic "pipeline pig" is being flown through the body circulatory system to the location of a clot. Upon arrival at the clot a rotating field will be used to spin the cutter blades to grind away the clot and avoid the trauma of conventional surgery. It is also possible that such an application could find use in areas of the body that are generally considered to be inoperable, such as deep in the brain.

MSBS In Robotics

The capability to handle heavy loads is inherent in magnetic suspension systems for large transonic wind tunnels. Based on design studies, these loads will be in the range of 1000 pounds for magnetic cores and several tons for superconducting cores. This large load handling capability is coupled with a very sensitive position indicator and force and moment measurement. The reader is asked to envision such a freely suspended core equipped with arms, clamps, grapplers or other appropriate manipulators; a core so equipped could then perform industrial tasks. For instance, a suitably programmed MSBS robot could rapidly load heavy pallets from a rail siding into a boxcar; or unload munitions from a military transport; or load shells in a naval gun tub. Such a robot could also perform hazardous tasks such as cleaning the inside of fuel tankers. More intelligently equipped robots could perform inspections and take corrective actions in toxic or radioactive environments.

Orbital Applications

Space may be an ideal location for application of large MSBSs since the maintenance of the low temperatures necessary for the operation of the superconducting magnets is much easier than on the Earth's surface.

Figure 24 illustrates a fanciful ore processing plant in space with several docking ports, which have a similarity to protruding wire baskets. Figure 24b is a close-up of one of these docking ports illustrating the location of the magnets and the relative size of the ship and docking port. The magnetic core aboard the ship is envisioned to consist of a superconducting coil.

The advantage of such a system might be most obvious for a ship such as a robotic ore carrying vessel. Such a ship would be programmed to match speed and maneuver within the sphere of influence of one of the docking systems. At this point, sensors aboard the station would determine the relative velocity and location of the ship and the MSBS would align the ship and bring it through the docking doors. Once inside the station, magnetic systems would handle positioning and unloading of the ship. Departure would be accomplished by the same system with a "magnetic push" to launch the ship away from the station.

Figure 25 is an artist's concept depicting a beam weapon mounted within a spherical MSBS system. The "barrel" of the weapon is free to swing through more than a 300 degree arc, with no friction and precise pointing. Also there are no electric motors, gears, exhaust jets from vernier rockets, or expendables. A similar concept might be employed to aim cameras, antenna, telescopes, mirrors, etc.

EPILOGUE

In the conservative view, the use of magnetic suspension and balance systems (MSBS) in large wind tunnels will eliminate or greatly reduce errors due to supports, restraints due to supports, tunnel occupancy time, the number of models required, and data analysis required to evaluate support interference.

In the slightly less conservative view, the use of MSBS will improve data accuracy, high-angle-of-attack test capability, dynamic stability test technique, two-body/stores-release testing, and provide nearly free flight test conditions in many circumstances. The summation of these changes due to MSBS is predicted to be large improvements in wind tunnel productivity.

In a speculative view, the addition of pilot and designer-in-the-loop concepts may improve productivity and at the same time open new vistas in wind tunnel test technique. Although the research and development necessary to bring about the fruition of large MSBS's should pay for itself in wind tunnel productivity improvement alone, the technology spinoff may be even more valuable.

Some of the new capabilities envisioned in this paper will not evolve due to engineering difficulties, and the authors have deliberately allowed their reach to exceed their grasp in many areas. However, experience teaches that the unforeseen uses of new technology frequently surpass even the most speculative of forecasts.

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Magnetic Suspension and Balance Systems

Organization	Degrees of Freedom	Size, cm	Mach number	Use	Dates of Operation *
ONERA	5	8.5 x 8.5	1 to 3	Drag, base pressure	1957 – 1958
ONERA		6.0	7	Drag, base pressure	1958 – 1962
Mass. Inst. of Tech.	5	10.2 x 10.2	4.8	Static & dynamic	1962 – 1971
ONERA	6	30.0	7	Base pressure and heat transfer	1962 – 1971
U. of Southampton	6	15.2 x 20.3	0 to 1.8	Static and dynamic	1962 – present
NASA Langley	1	12.7	– – –	Research & Development	1964 – 1965
Princeton Univ.	3	15.2	16	Wake studies	1964 – 1970
Univ. of Virginia	5	10.2	7.6	Cone & sphere drag	1964 – 1977
AEDC/NASA Langley	5	33.0	8/0 to 0.5	Wake studies / R&D	1965–'70/'79–present
RAE/U. Southampton	5	17.8 x 17.8	8.6	Sting effect & magnus	1966 – 1977
U. of Michigan	1	5.1	Subsonic	Low RN sphere drag	1969 – 1971
MIT/NASA Langley	6	15.2 octag.	0 to 0.5	Aero testing / R&D	1969–'82/'84–present
Oxford Univ.	3	7.9 x 12.0	5 and 9	Low density sphere and cone drag	1971 – 1975
U. of Virginia	3	15.2	3/Subsonic	Dynamic stability / R&D	1973 – 1982
Oxford Univ.	3	7.6 x 7.6	Supersonic	Low density sphere and cone drag	1975 – present

* Dates given are only approximate.

Table 1.– Chronological list of facilities equipped with magnetic suspension and balance systems.

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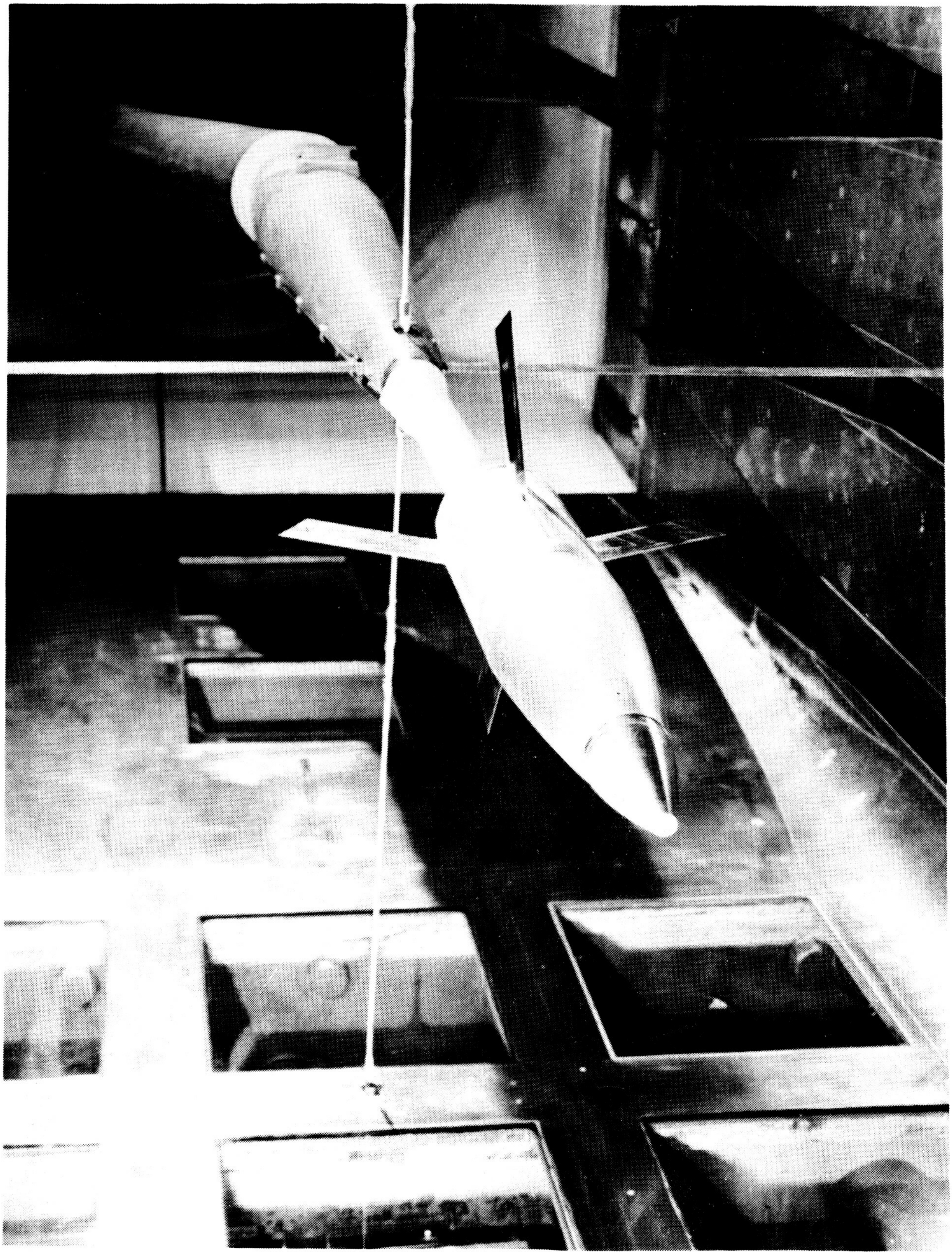

Figure 1.– Wind tunnel model and support.

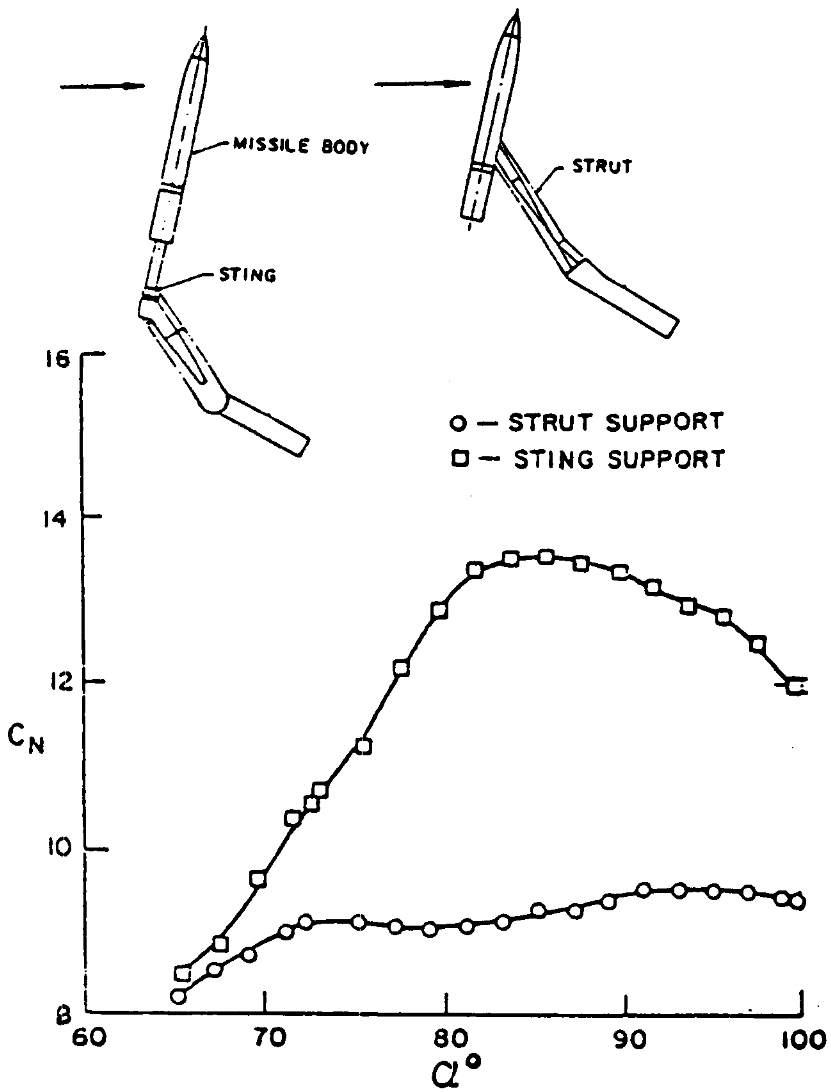

Figure 2.— Support interference on cylindrical body at high incidence.

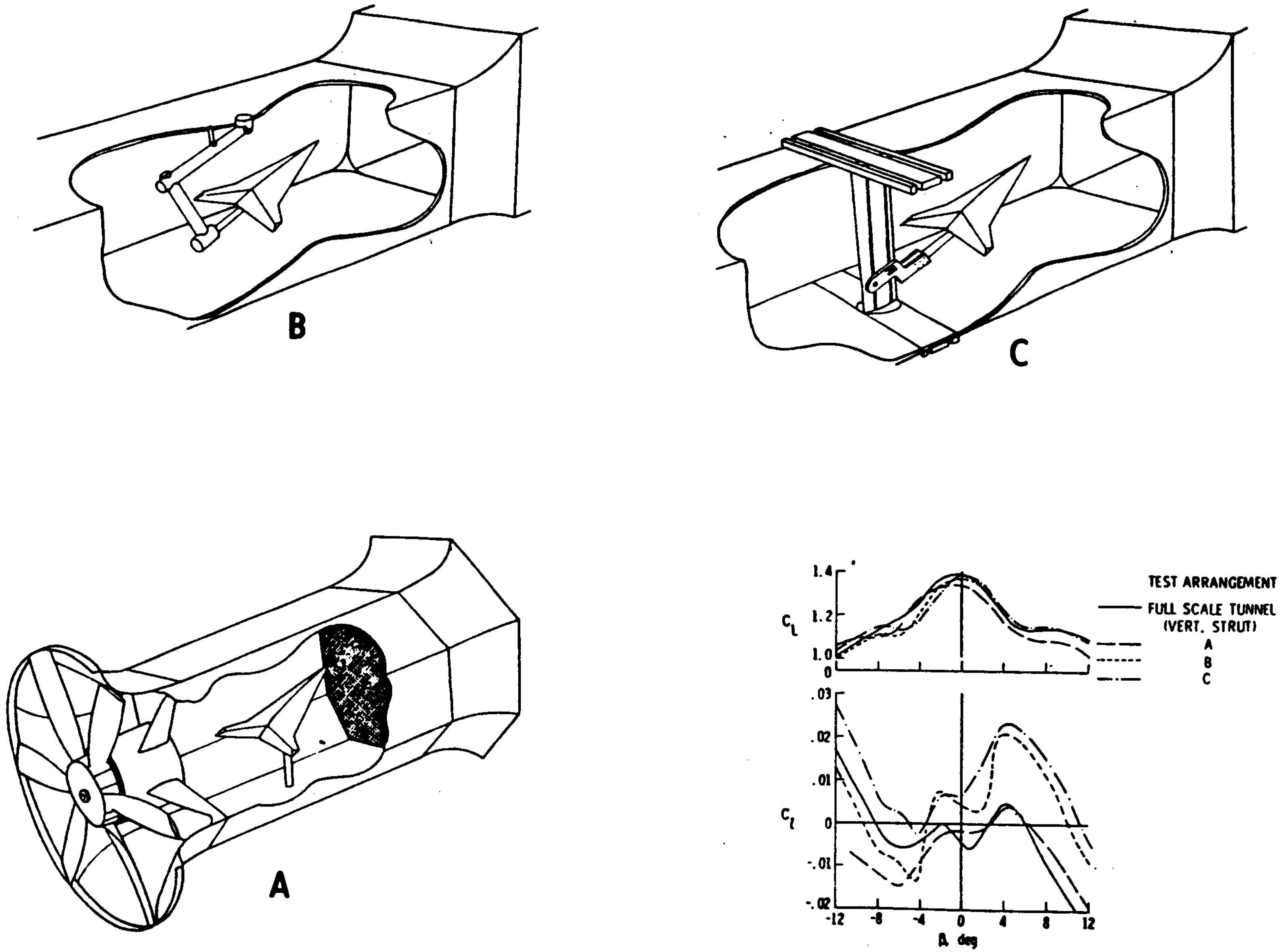

Figure 3.– Support interference for a wing producing vortex lift.

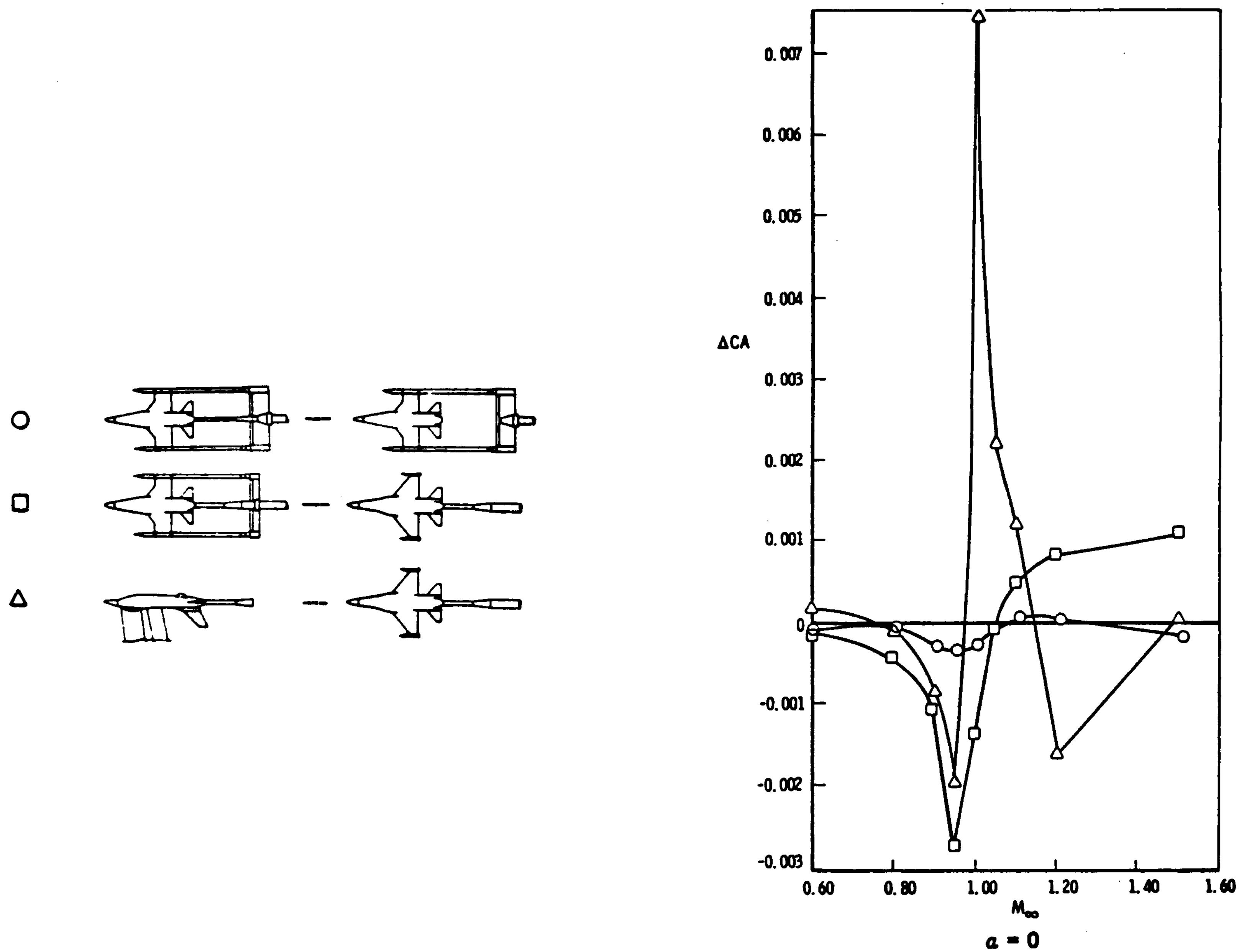

Figure 4.— Support interference at zero angle of attack and transonic Mach numbers.

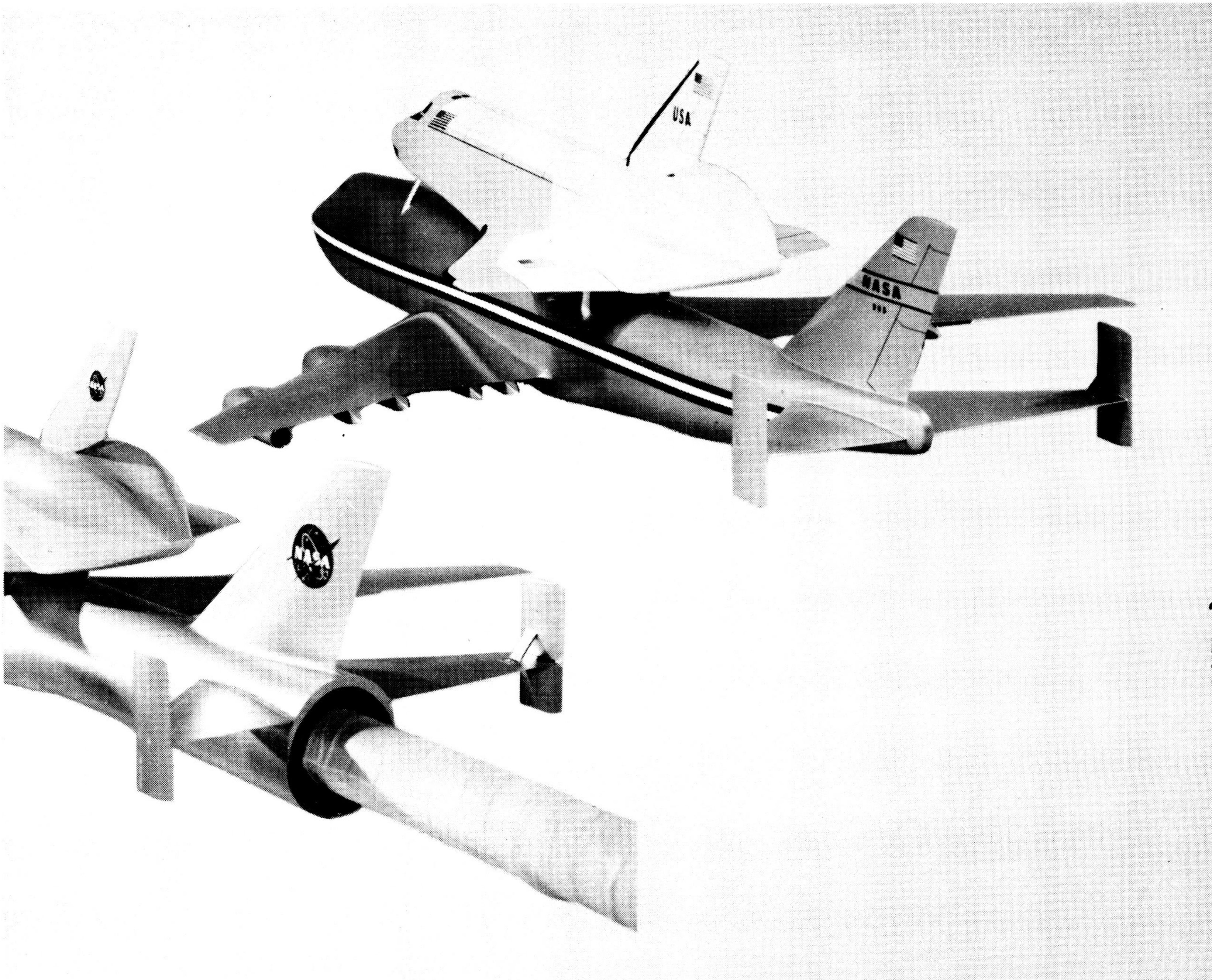

Figure 5.– Models of flight and wind tunnel configurations showing distortion required to accommodate mechanical balance and support.

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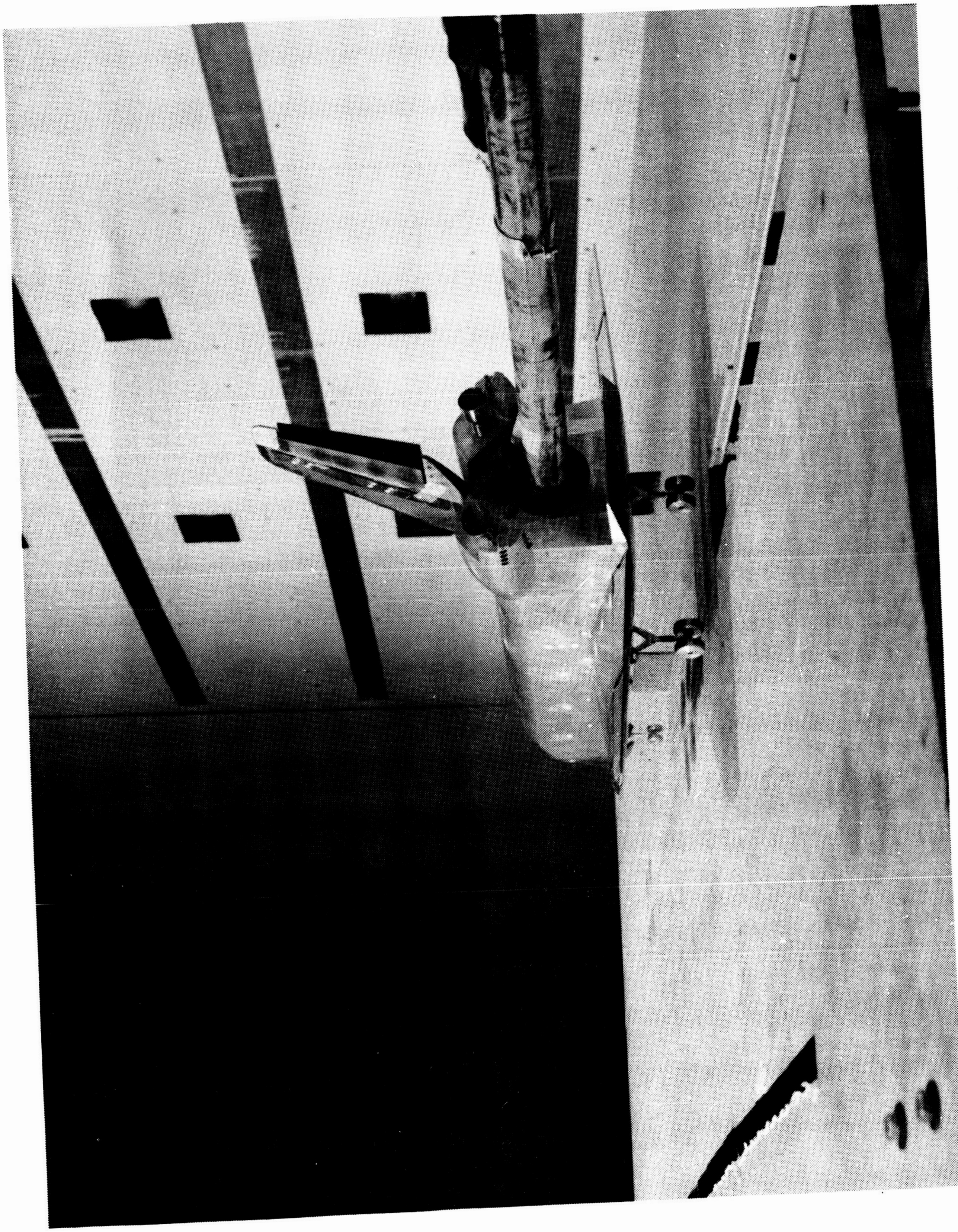
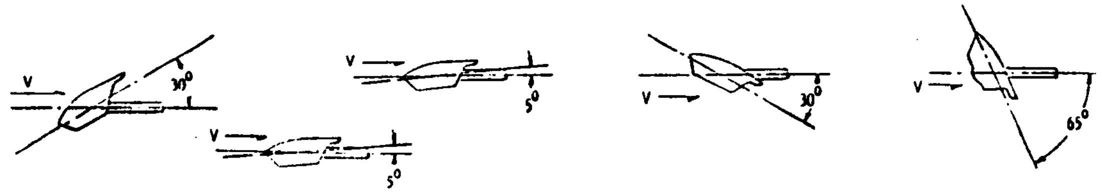


Figure 6.– Raised ground plane rig used to overcome support restriction in landing attitude testing.

Potential Productivity Increase

An Example

Determination of dynamic stability parameters using conventional oscillatory balance techniques



(5 segments pitch) x (4 segments yaw) x (4 segments roll) = 80 test section entries =

Months of Testing

****

Using MSBS testing techniques

One test section entry =

A Few Days Testing Time

Figure 7.– Comparative example of testing time with conventional dynamic balance and magnetic system.

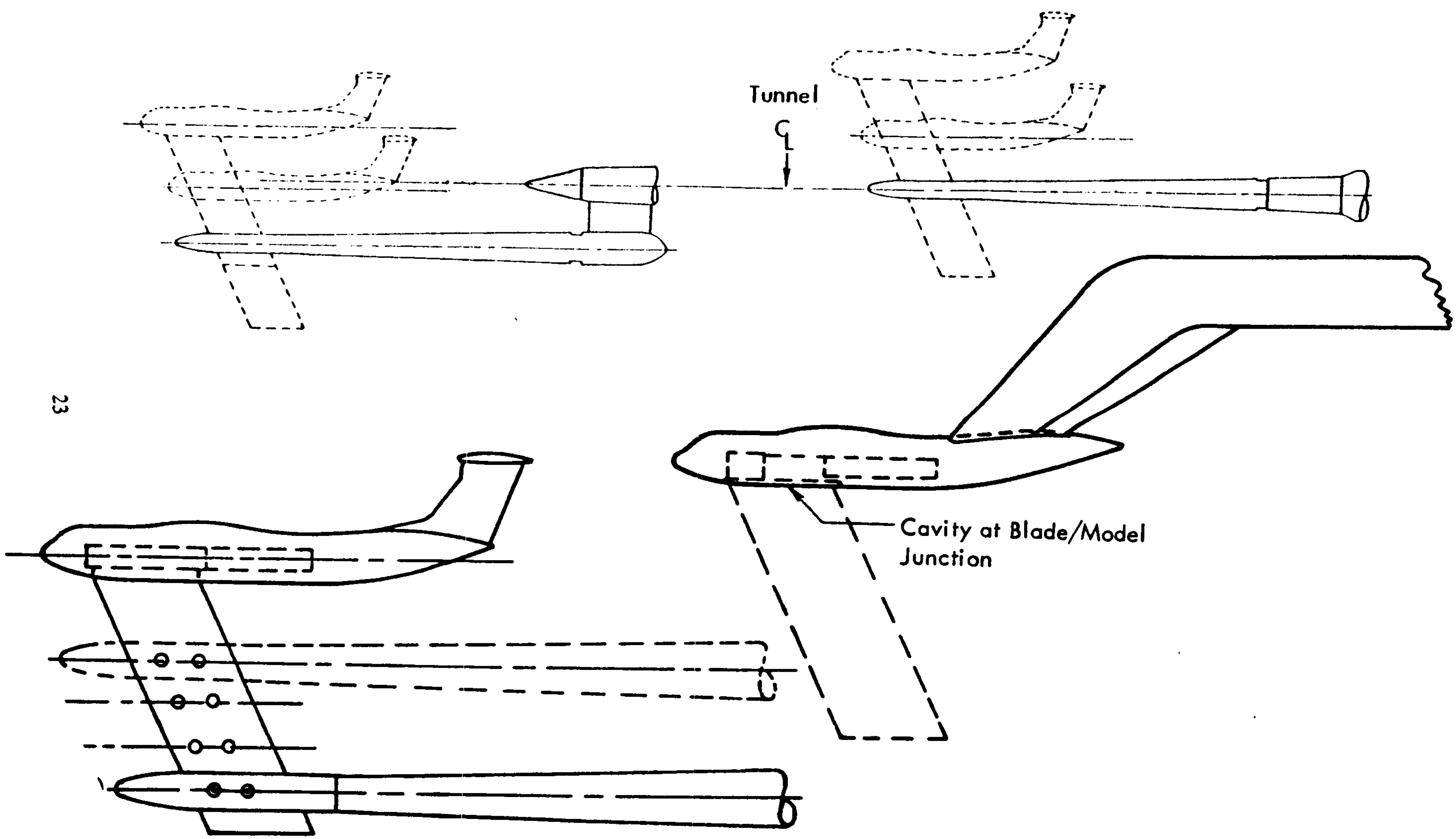


Figure 8.– Support hardware used to evaluate support interference for transport model.

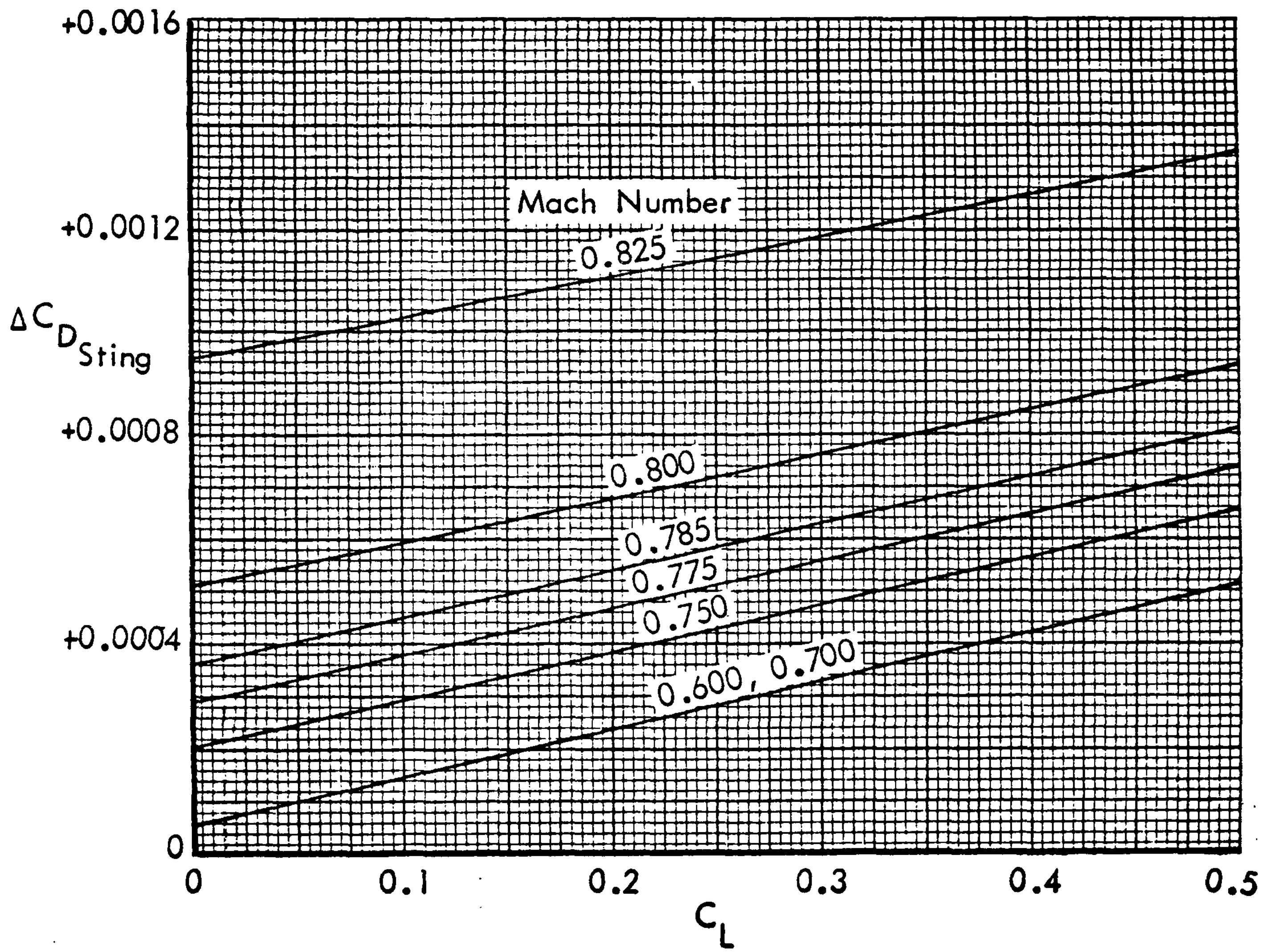


Figure 9.– Final corrections to flight configuration for drag increment due to support interference.

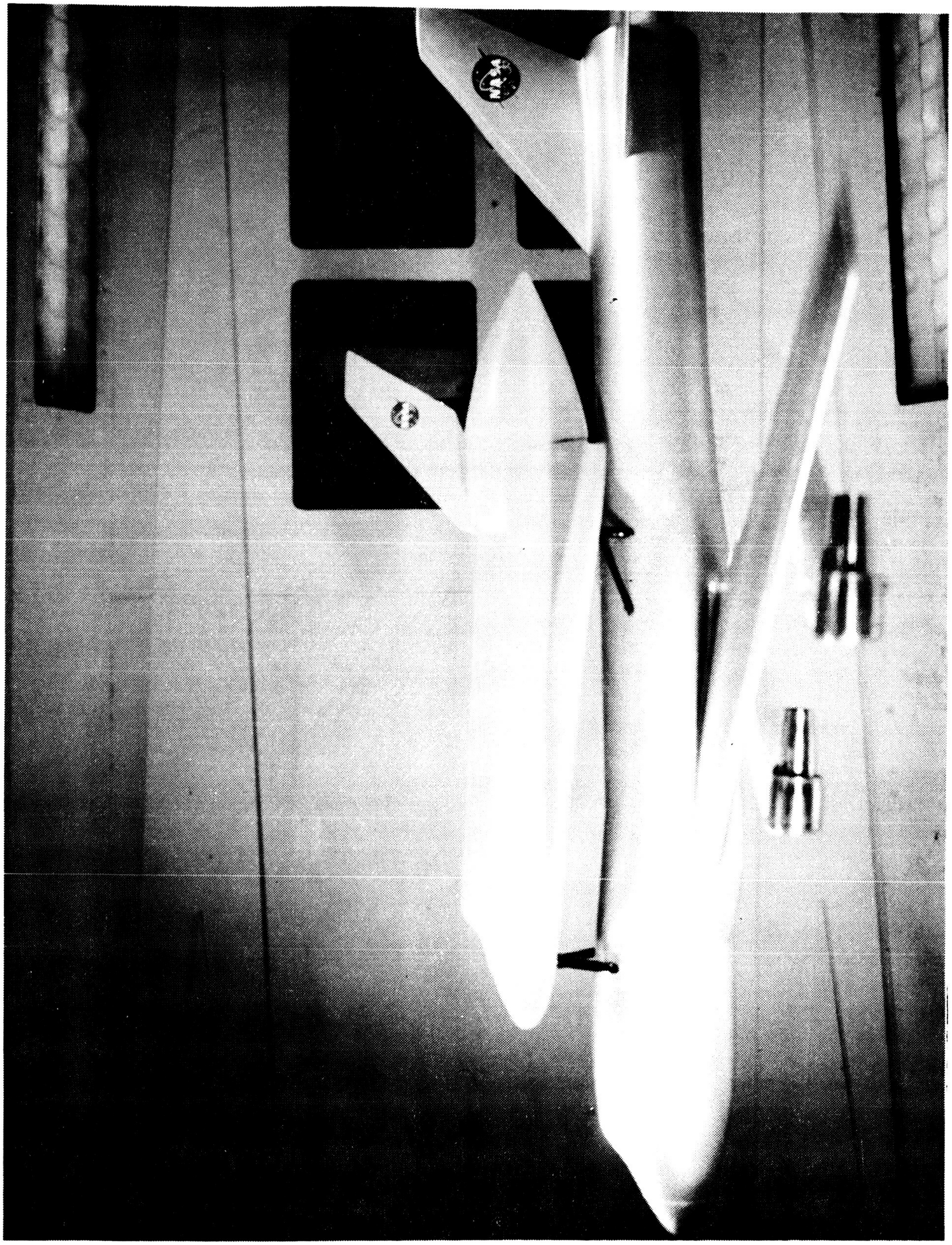


Figure 10.– Typical configuration for determining optimal stores carriage.

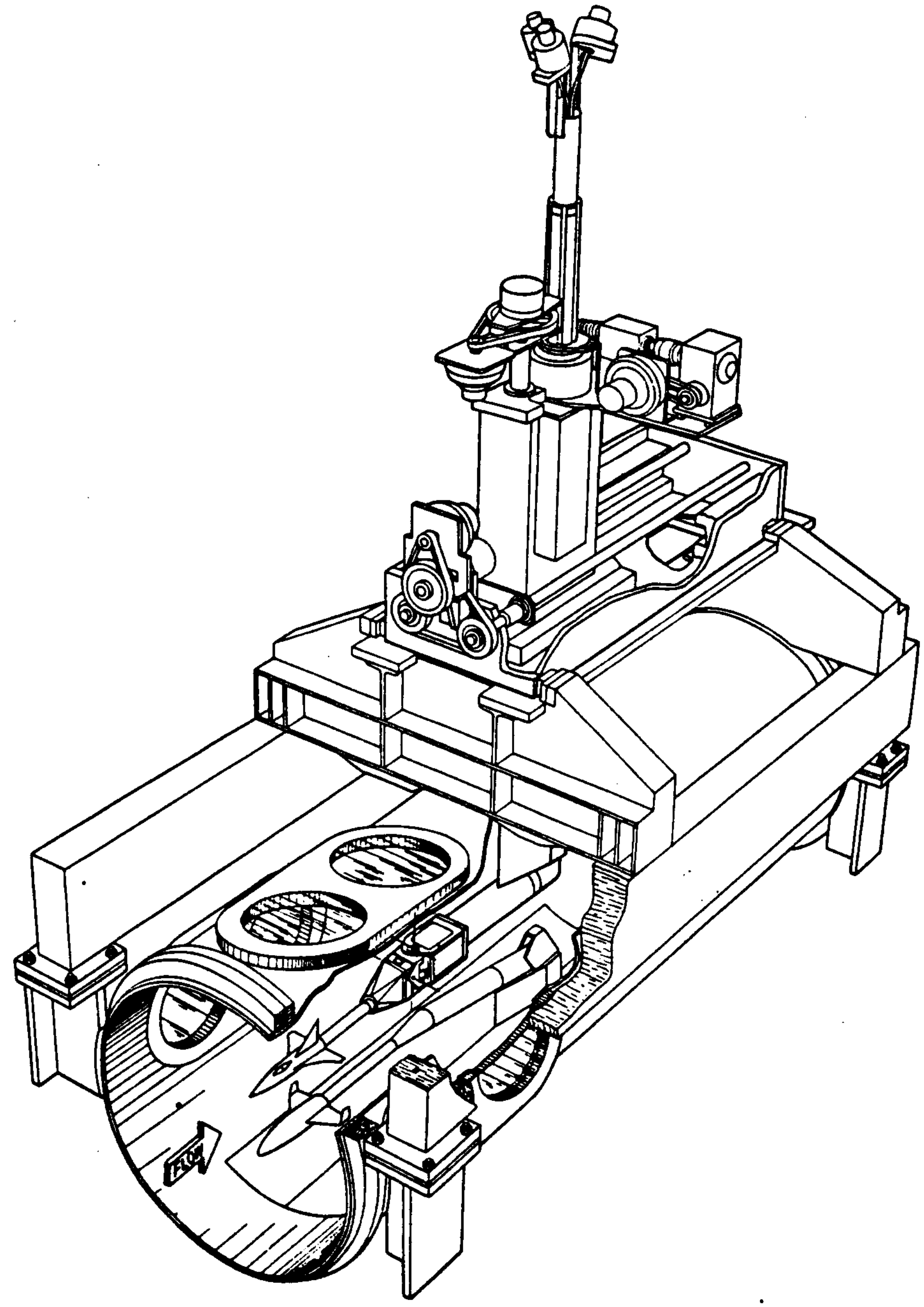
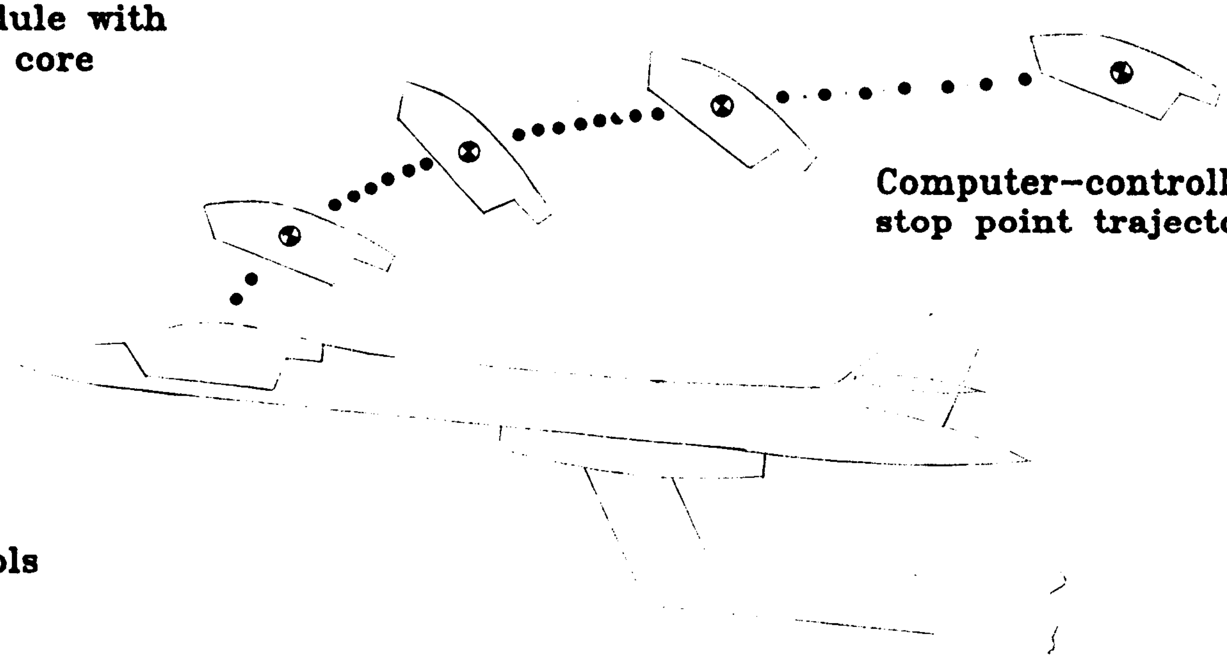


Figure 11.– State of the art captive trajectory system for stores release studies.

Crew Escape Module



No restrictions on:
  orientation
  c.g. location

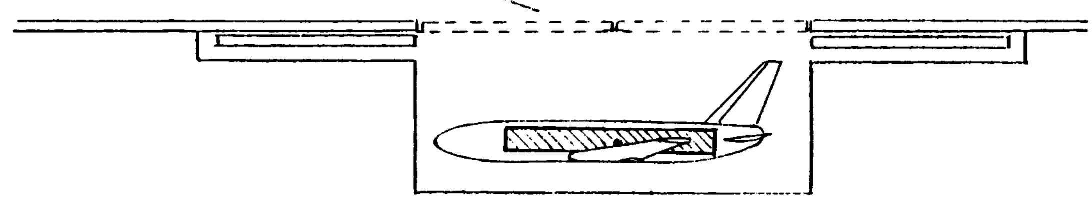
Full control of initial conditions for ejection trajectory, kinematics and aerodynamic controls

Allows real time Designer-In-The-Loop optimization of ejection parameters

Similiar techniques for pilot/seat studies

Figure 12.– Stores release testing scheme using advanced magnetic suspension and balance system.

'Safe Box' Concept



Model "flown" magnetically in and out of box to:

Substitute for injection system
Access model for configuration changes
Permit heating and cooling of model
Allow cleaning and reoiling for oil flow test
Allow cleaning and repainting for phase–change paint test
Simulate bomb–bay stores release
Simulate silo missile launch

Figure 13.– Model injection scheme using advanced magnetic suspension and balance system.

Shipboard Defense Missile; Tri–sonic Tunnel

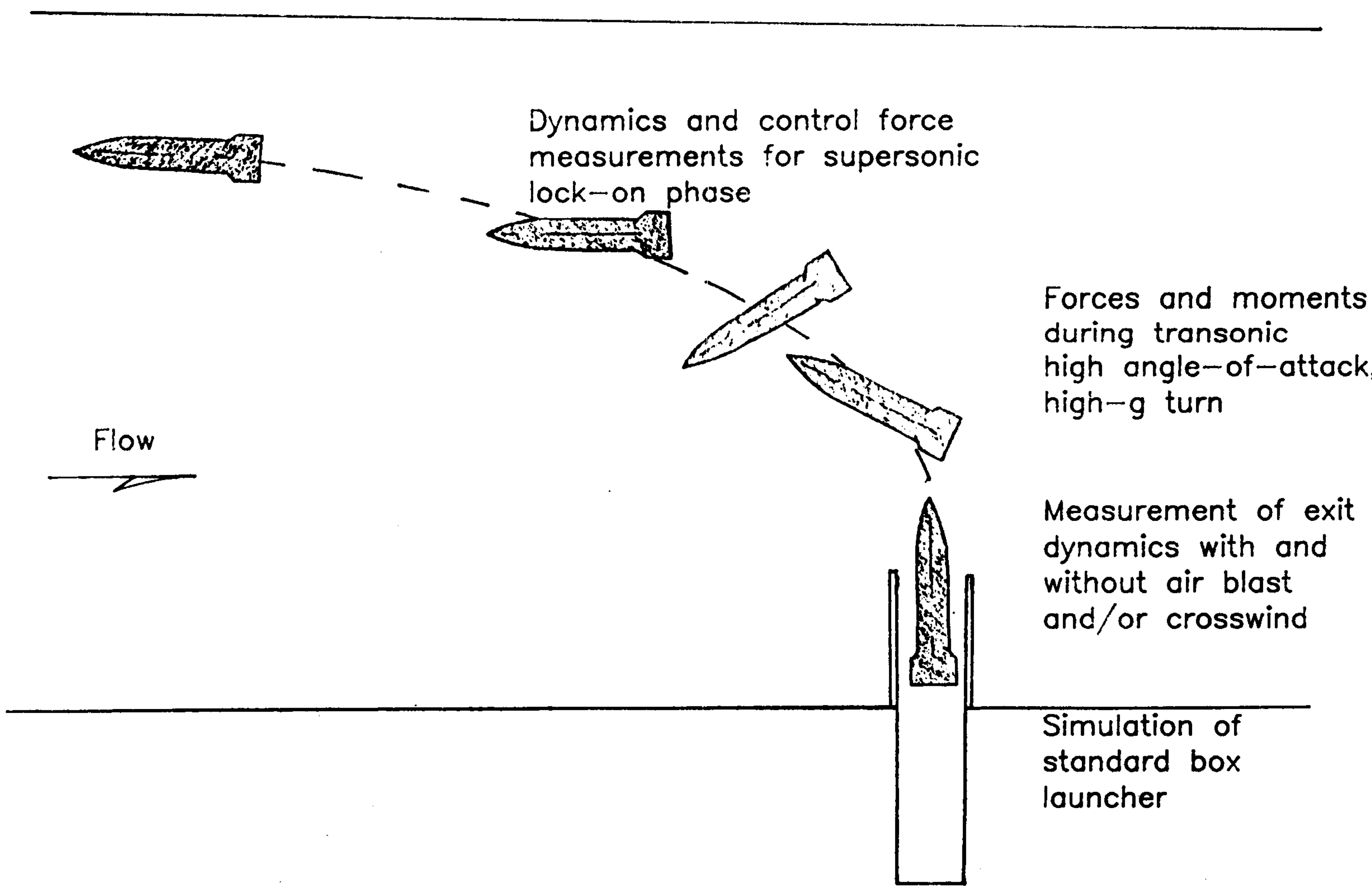


Figure 14.– Use of advanced magnetic suspension and balance system in a trisonic tunnel to study missile launching.

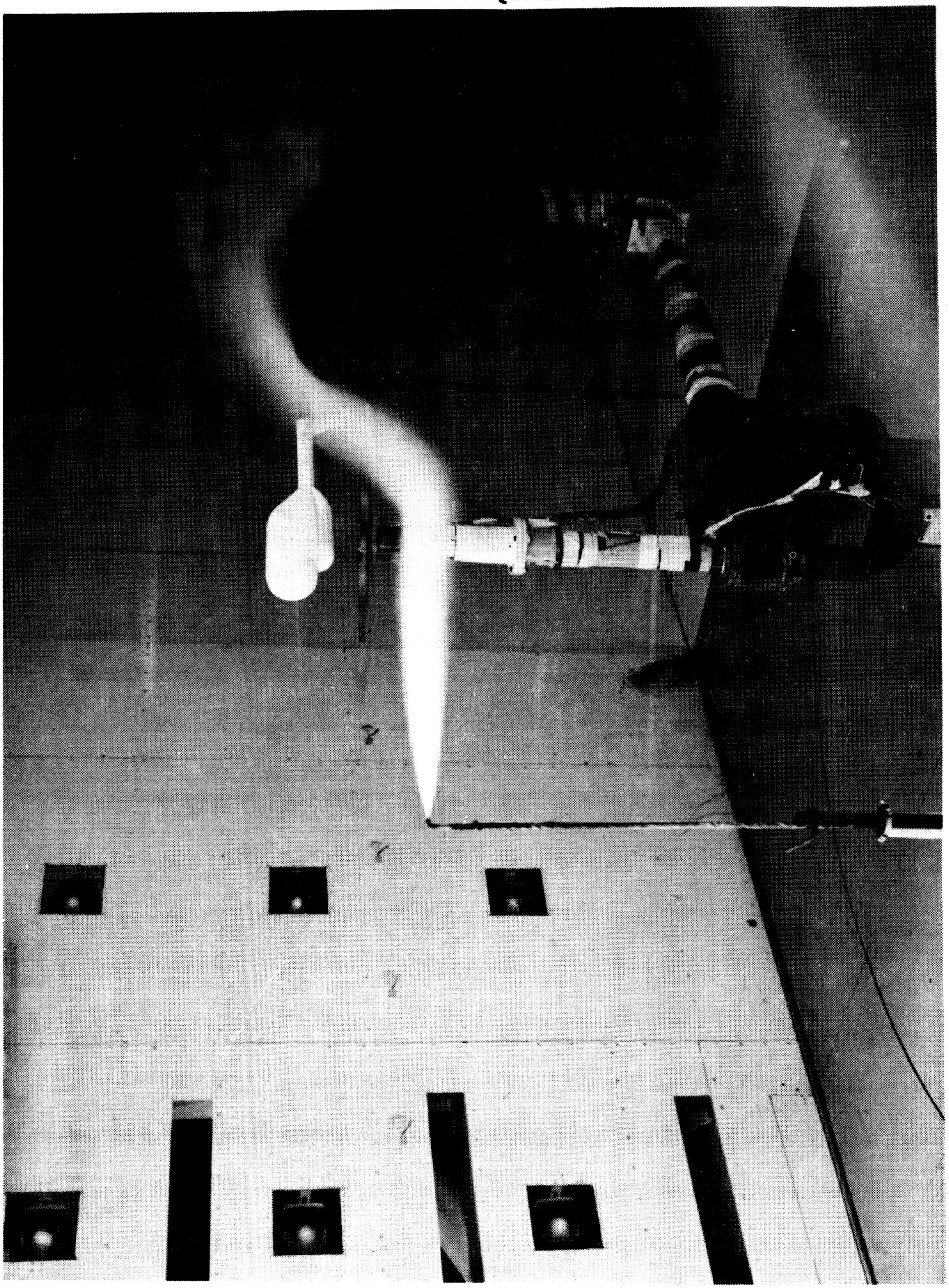


Figure 15.– Helicopter testing in rotor downwash with crosswind.

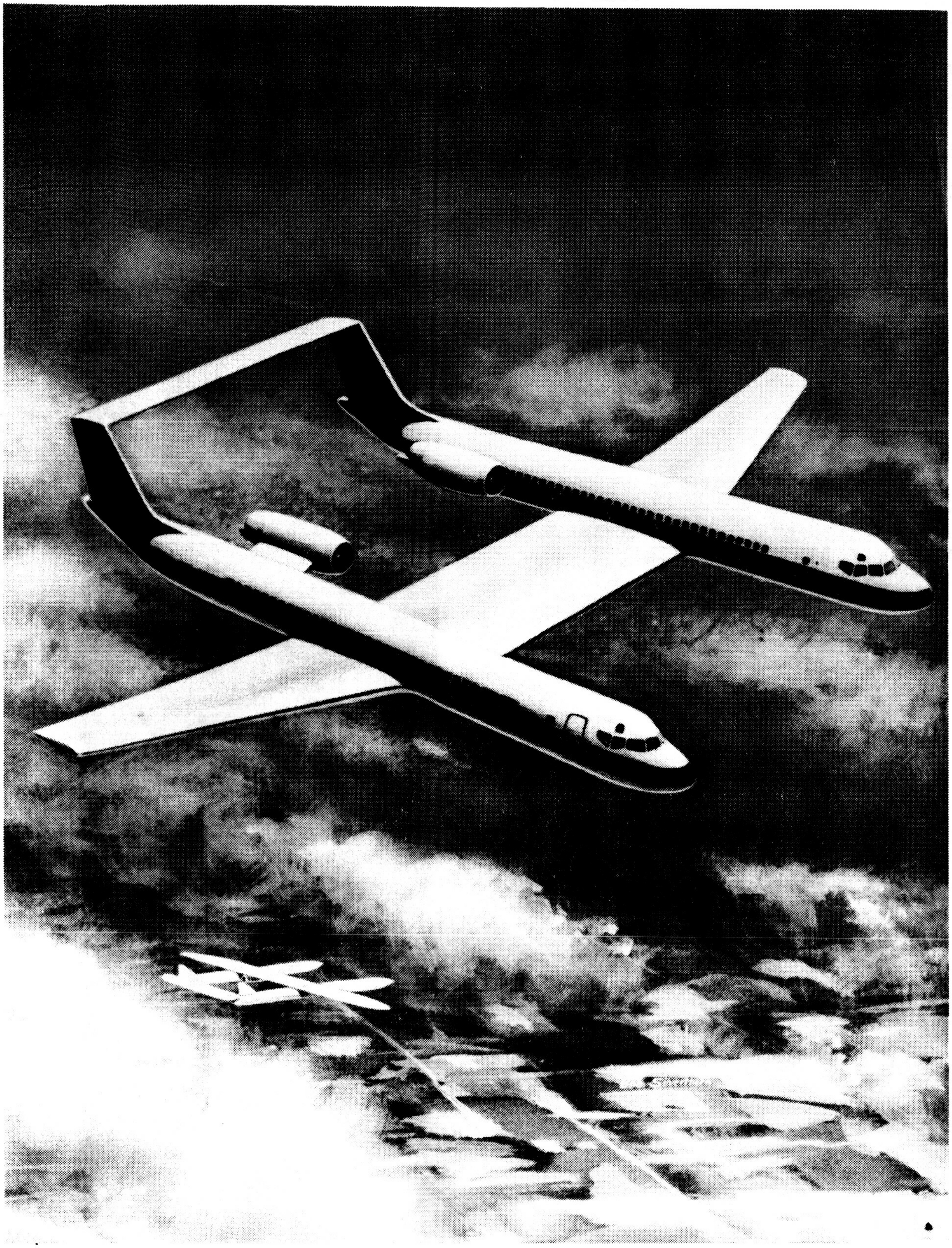


Figure 16.– Twin fuselage subsonic transport concept.

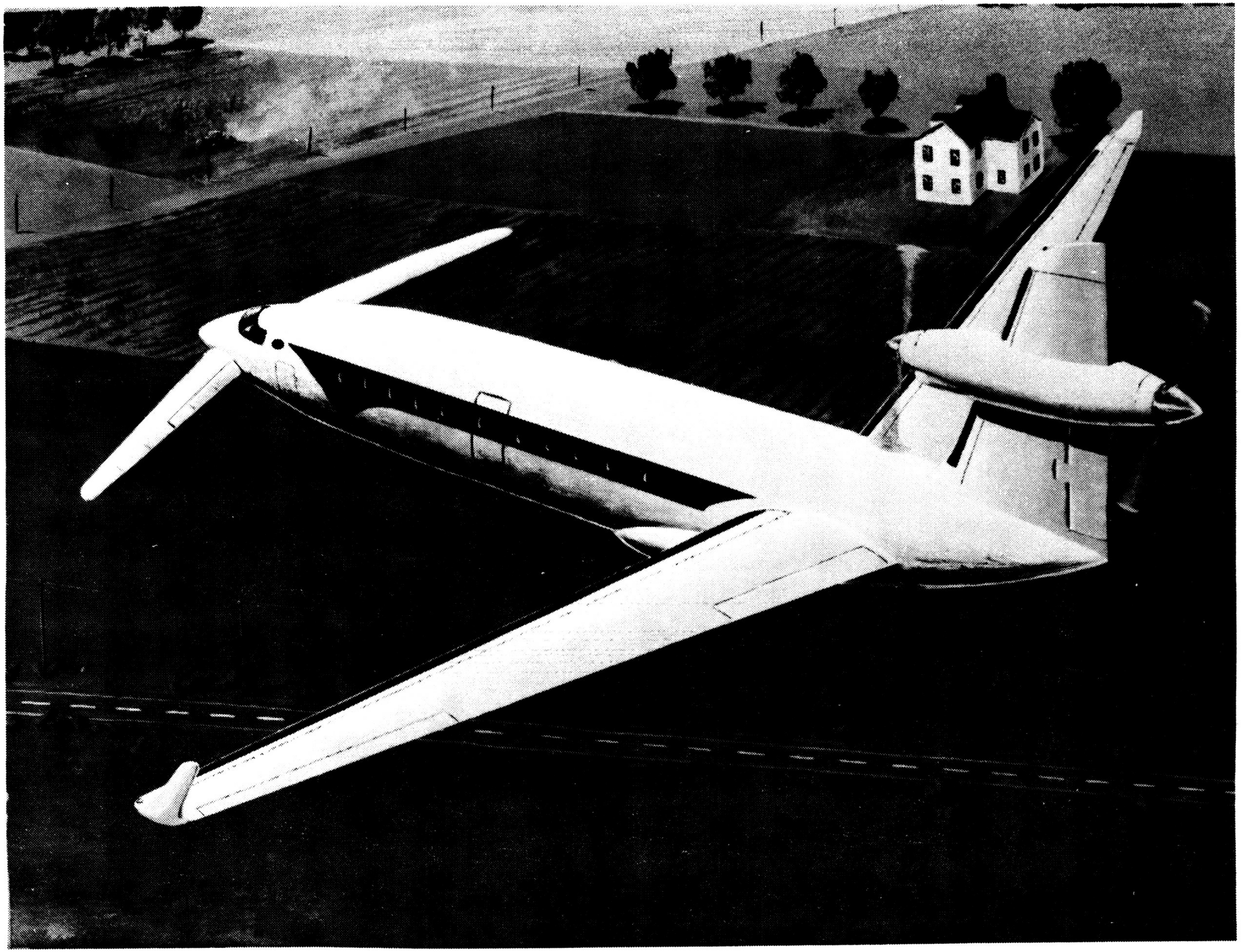


Figure 17.– Subsonic transport with rearward wing.

Figure 18.– Supersonic concept with thin, highly–swept surfaces.

HIGH ALPHA WINGS
TYPICAL ASSEMBLY

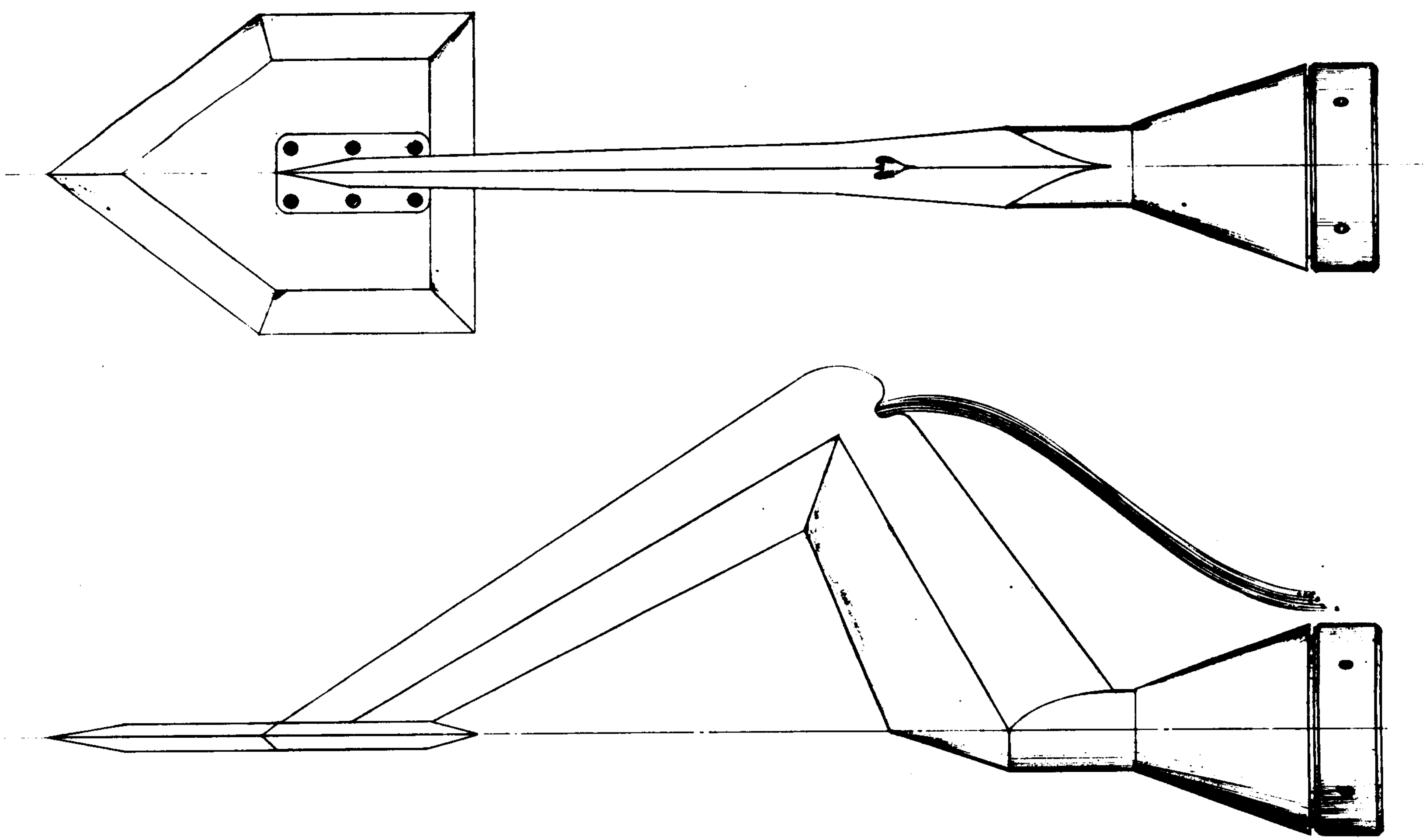


Figure 19.– Thin wing for basic aerodynamic research at hypersonic speeds.

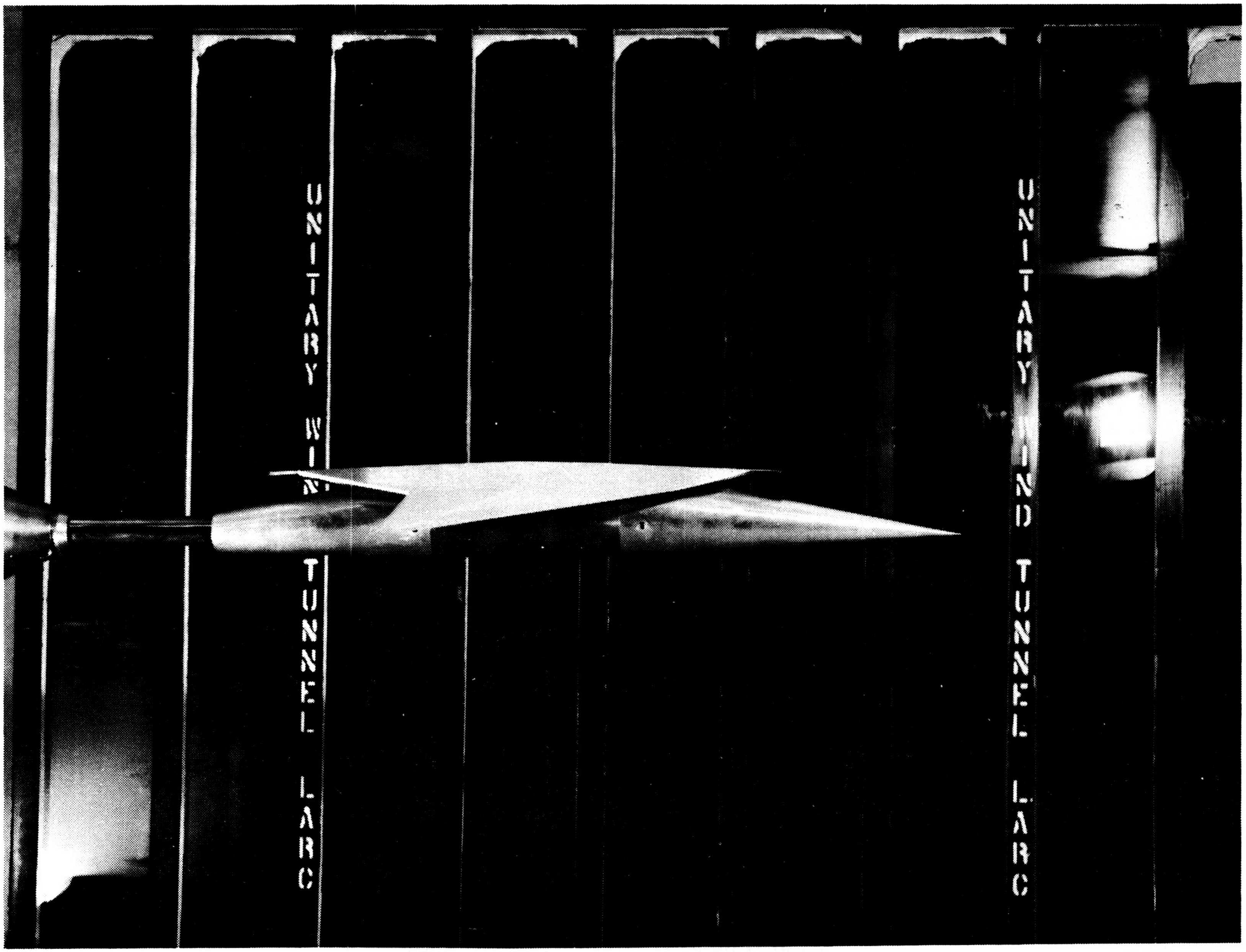


Figure 20.- "Parasol wing" concept for hypersonic speeds.

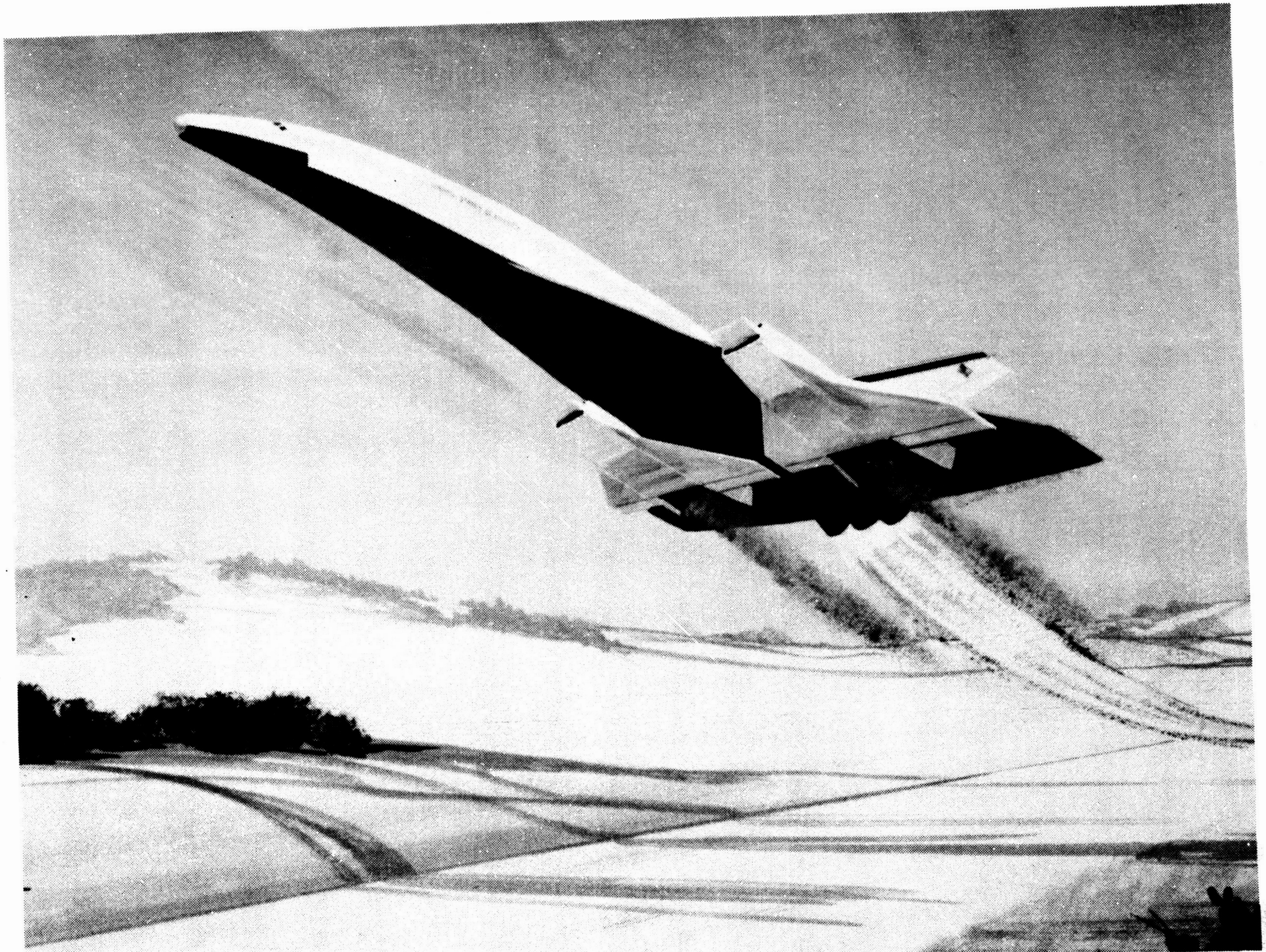


Figure 21.– Shuttle follow–on concept using detachable turbojet "tugs".

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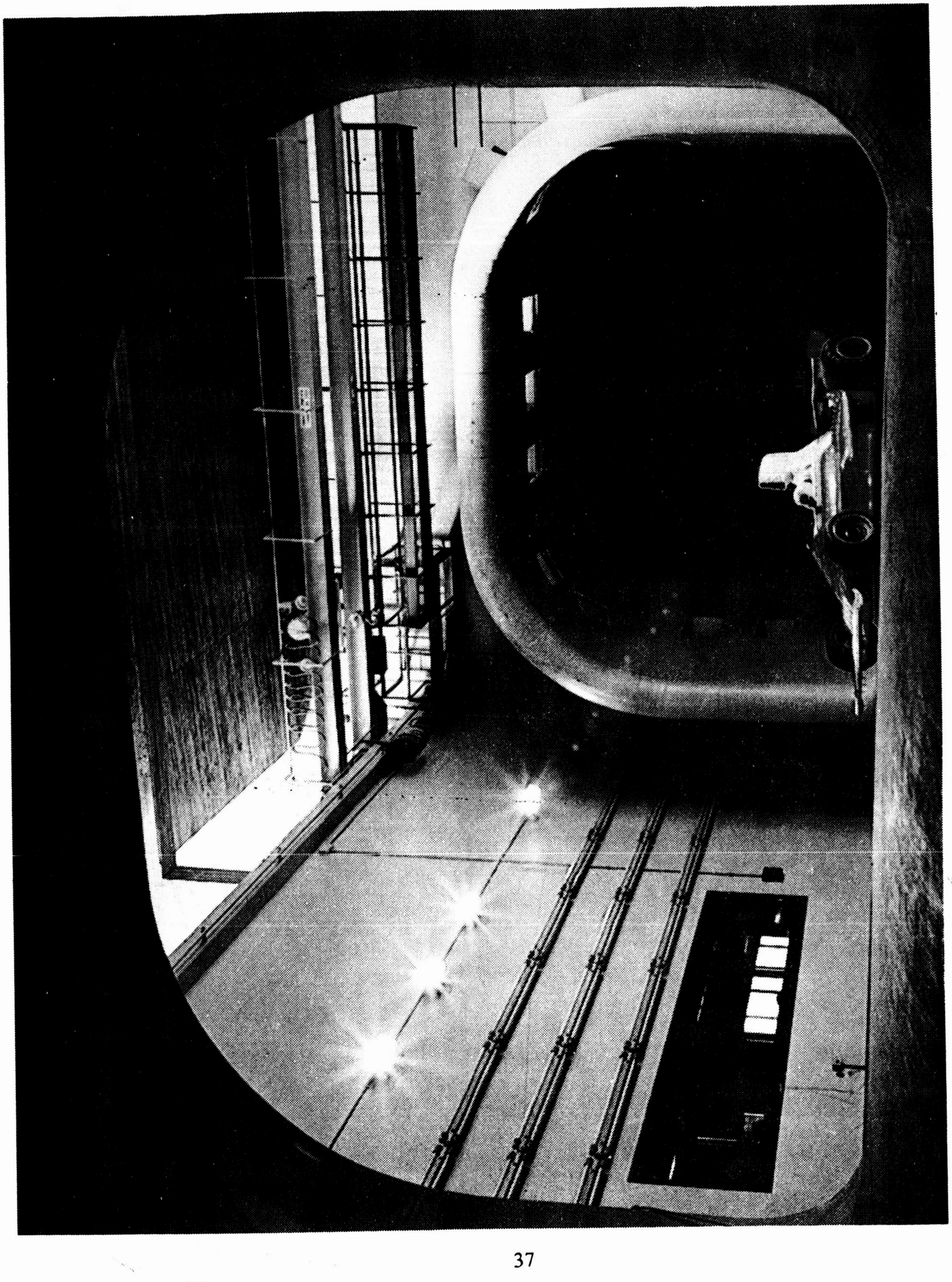

Figure 22.– Automobile testing using a turntable to allow for cross-wind components.

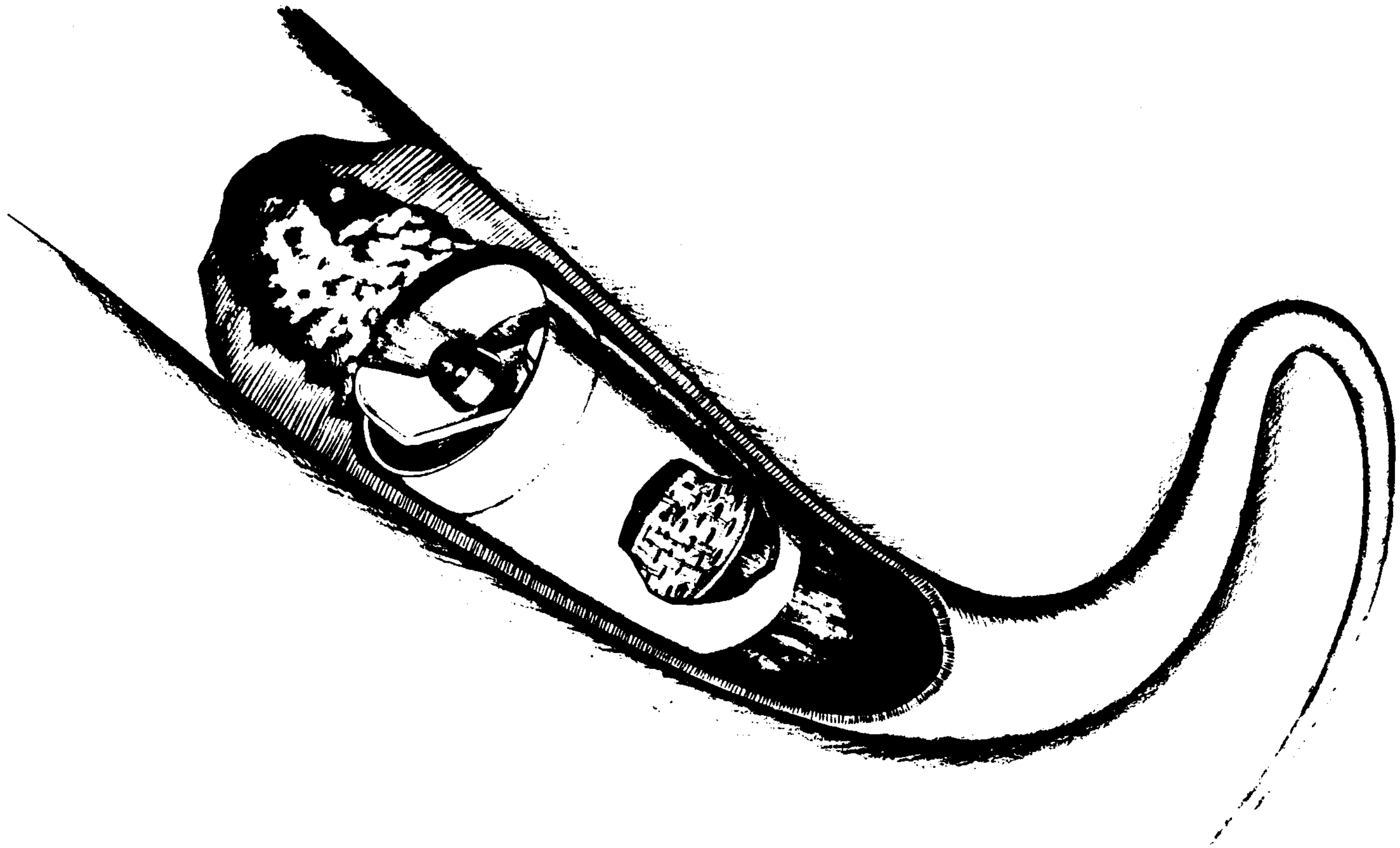

Figure 23.– Proposed device to be "flown" through the circulatory system to clear obstructions.

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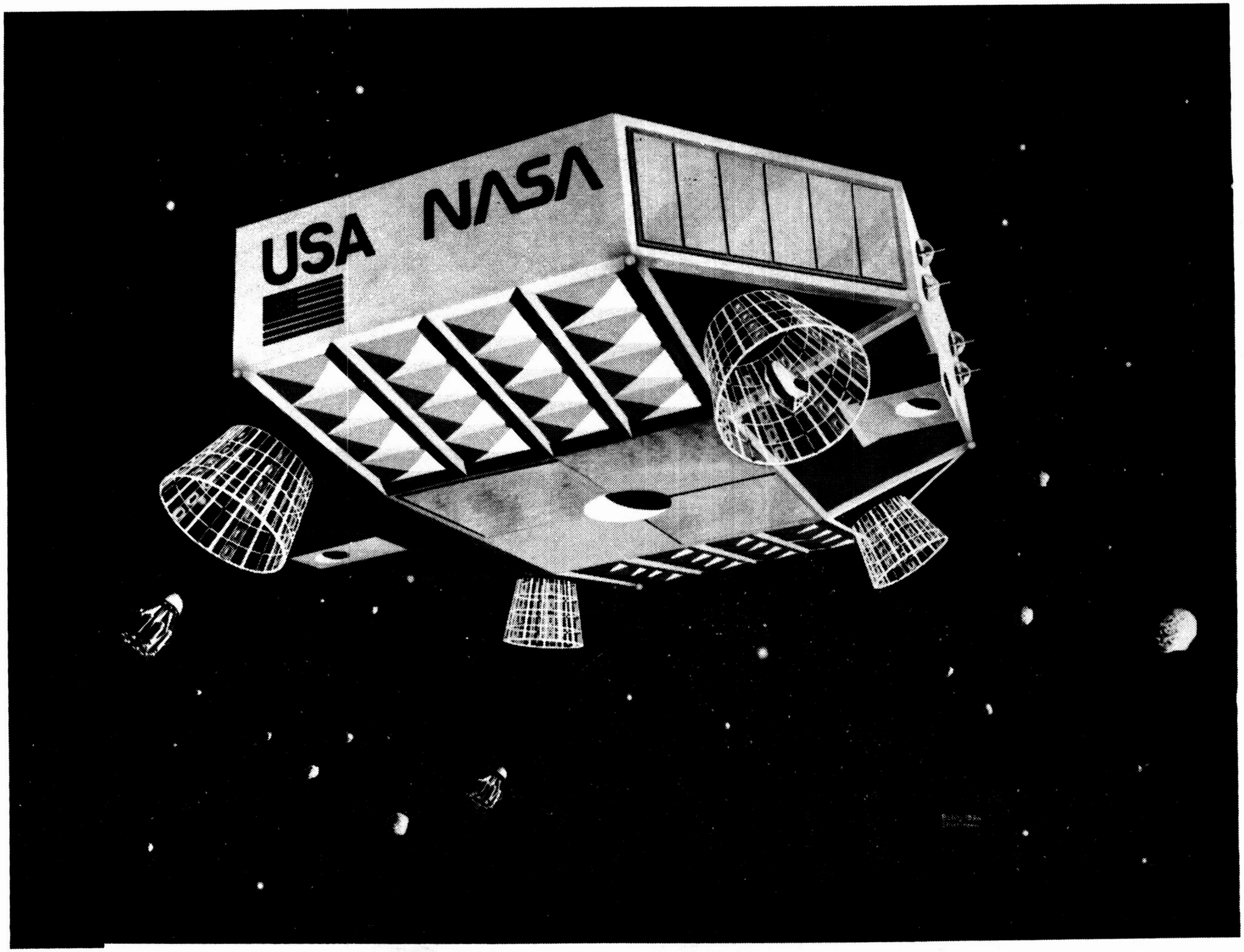

Figure 24 a.– Ore processing space station using magnetic suspension systems to control ore vessel docking and departure.

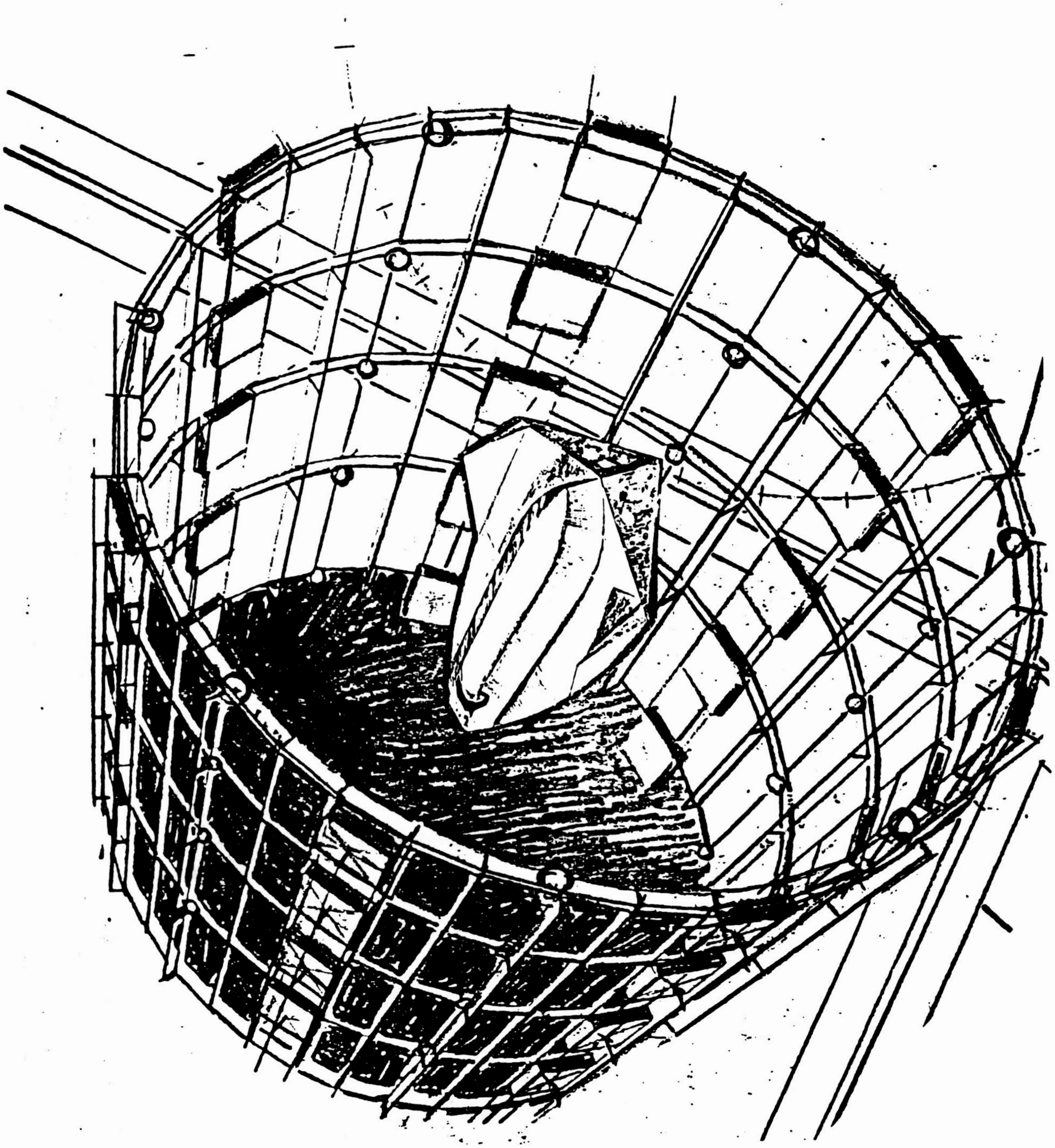

Figure 24 b.– Enlargement of the magnetic docking system portion of the ore processing plant.

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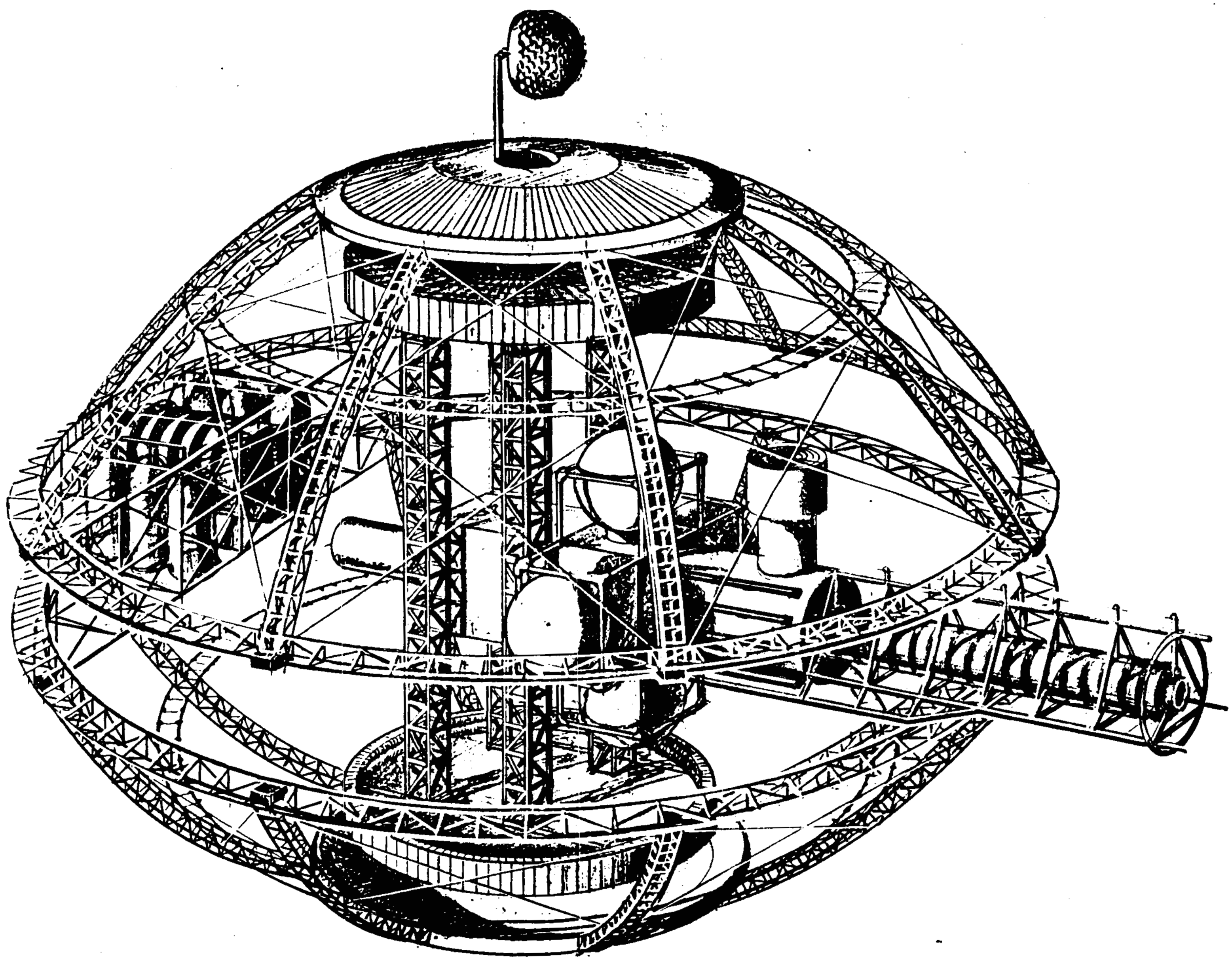

Figure 25.– Artist's conception of beam weapon in space; supported, aimed, and controlled by a magnetic suspension system.

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15. Supplementary Notes

16. Abstract

The potential of Magnetic Suspension and Balance Systems (MSBS) to improve conventional wind tunnel testing techniques is discussed. Topics include: elimination of model geometry distortion and support interference to improve the measurement accuracy of aerodynamic coefficients; removal of testing restrictions due to supports; improved dynamic stability data; and stores separation testing. Substantial increases in wind tunnel productivity are anticipated due to the coalescence of these improvements.

Specific improvements in testing methods for missiles, helicopters, fighter aircraft, twin fuselage transports and bombers, stage separation, water tunnels, and automobiles are also forecast.

In a more speculative vein, new wind tunnel test techniques are envisioned as a result of applying MSBS, including "free-flight" computer trajectories in the test section, pilot-in-the-loop and designer-in-the-loop testing, shipboard missile launch simulation, and optimization of hybrid hypersonic configurations. Also addressed are potential applications of MSBS to such diverse technologies as medical research and practice, industrial robotics, space weaponry, and ore processing in space.

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