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Minimum Accommodation for Aerobrake Assembly Phase II Final Report Integration Team Report

Stephen J. Katzberg, Davy A. Haynes, Robin D. Tutterow, and Judith J. Watson
Langley Research Center, Hampton, Virginia

James W. Russell
Lockheed Engineering & Sciences Company, Hampton, Virginia

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1. Introduction and Multi-element Study Approach.

An aerobrake is a structure that utilizes the drag of a body to reduce the speed of a vehicle as it moves through an atmosphere. However, "aerobrake" is somewhat of a misnomer in the sense that a body normally generates lift as well as drag. In practice, the lift generated can play a very important role in the use of the aerobrake. Direction of flight can be changed by use of the lift and, hence, modulation of the drag can be accomplished, final landing location can be affected, or orbital parameters can be changed. In the Space Exploration Initiative, all other things aside, some minimum vehicle set operates in a round trip mode: from Earth-to-Moon-to-Earth or from Earth-to-Mars-to-Earth. On arrival at the Moon or Mars or return from Moon or Mars to Earth, a vehicle must be decelerated from the high cruise speed to be captured properly into orbit or to land on the surface. To reduce the interplanetary speeds, the kinetic energy of the incoming vehicle must be exchanged or dissipated. Exchange is accomplished by allowing the vehicle to intercept and use the planetary atmosphere to convert the vehicle kinetic energy into thermal energy. Using a propulsive burn requires propellent to be carried outbound and on return. Using an aerobrake also requires some overhead in the aerobrake mass, although less than that for the propellent. Moreover, the aerobrake must be capable of absorbing and dissipating a great deal of heat, requiring specialized materials. Aerobraking offers limited control, even utilizing lift, and is generally restricted to one pass through the atmosphere. With too large an entry angle, vehicle penetration is too deep and the vehicle burns up. With too small an entry angle the dissipation is insufficient to effect the desired capture and the vehicle may be lost. Entry accuracy is obviously critical and, because there may be no second chance, there are major points of concern.

For propulsive braking, the required deceleration burns are also critical, requiring the operation of an engine which may have been used several times and has been idle over a considerable time.

The use of aerobraking has been proposed to be used in several different stages of the Lunar or Mars missions: First, in the precursor Lunar technology and science mission phase, the Lunar Transfer Vehicle (LTV) returns to the earth where it aerobrakes into an orbit properly phased for rendezvous with Space Station Freedom (SSF) or directly into a descent trajectory for landing. Second, in one scenario for the proposed manned Mars mission, the Mars Transfer Vehicle (MTV) separates into two vehicles, both of which use aerobrakes larger than those required for the LTV. The Mars Excursion Vehicle (MEV) aerobrakes further into a descent trajectory for landing. After the Mars ascent stage rejoins the MTV, the two begin the flight back to Earth, where the MTV aerobrakes into Earth orbit. Even then, the crew utilizes a Crew Return Vehicle (CRV) to land on Earth via aerobraking. It can readily be seen that only the Mars entry plus Earth return stages, and the Earth return from the Moon into SSF compatible orbit, represent steps not already well developed in the Mercury, Gemini, and Apollo programs.

Various studies have shown that the use of an aerobrake as part of spacecraft design for both the LTV and MTV offer substantial weight savings over a purely chemical propulsion approach. In the case of the MTV the weight savings could be as much as fifty percent which reduces the mass of the MTV down to the 500-800 tonne range. The case for the LTV, while not as dramatic, is still significant. Studies have shown that using aerobrake can yield nearly twenty per cent savings in "initial-mass-in-low-earth-orbit," (IMLEO). The actual mass saving depends on the final mass fraction of a real aerobrake capable of meeting all system requirements.

Because the earliest use of aerobraking in the SEI scenarios was for Lunar missions, with the Lunar Transfer Vehicle based at SSF, and because the LTV aerobrakes were of more modest, practical sizes, it was decided that the current studies would focus on Lunar missions. Mars missions would be considered later, with the understanding that the concepts and techniques identified from the Lunar aerobrake missions would be extendable to the Mars applications.

The "Aerobrake Assembly with Minimum Space Station Accommodation" study was divided into three phases. The first phase was completed in October 1990. The second and third phases were run simultaneously, starting in early 1991 and completed in early 1992.

The objective of the first phase of the study was to establish feasibility and to define the major areas requiring detailed study. The second study phase was undertaken to develop detailed understanding of the issues identified in the first phase and, thereby, to generate the elements of an engineering conceptual design of an on-orbit assemblable (and maintainable) aerobrake consistent with Space Exploration Initiative requirements as then understood.

Integrated with respect to time in the second study phase was an effort (the third study phase) to identify potential laboratory and flight experiments. These would yield the validation of design and analysis efforts from the second study phase. In addition, manpower and resource requirements were to be developed to permit management decisions with respect to which of the recommended technology activities might be pursued.

By its very concept, the second study phase content was to be several individual activities involving disparate disciplines related only in the focus of specific analysis and design of the SEI aerobrake. It was determined from the very outset that the ultimate relevance of such a multidisiciplinary study effort hinged upon a solid set of requirements and a properly coordinated set of assumptions.

The approach taken to satisfy these objectives was to execute a set of individual studies, interlocked by means of a propagation of requirements and results. In addition a separate activity was organized that represented an overarching integration whose purpose was to resolve broad technical issues across the entire study, and to serve as a design synthesis group. Moreover, the integration team provided interface to the next higher level in requirements definition at Marshall Space Flight Center.

During the existence of the integration team effort several technical issues were addressed, and it is the purpose of this report to present the results of the more important investigations.

The organization of the study was made up of six parts as illustrated in figure I.1. The aerobrake integration function whose purpose has been described above was responsible for serving as interface back to MSFC to ensure that the aerobrake being studied was one that met the requirements for the Lunar Transfer Vehicle. In addition the integration activity was responsible for interpreting the MSFC requirements to the rest of the study participants. The major study elements were: Study Integration, Aerobrake as Vehicle, Thermal Protection System, Structural Design, Inspection and Verification, and On-orbit Dynamics and Accommodations.

The second study area, Aerobrake as Vehicle, had as its objective the definition of the aerobrake as a "flying machine" capable of supporting the mission requirements of the Lunar Transfer Vehicle. Thus, this activity was concerned with the lunar return trajectories, the shape of the aerobrake, its L/D, the pressure loads, the size of the aerobrake, wake impingement, flight stability, G loads, and the heating and heat loads.

The third study area, thermal protection, was concerned with designing a thermal protection system capable of withstanding the Earth's atmosphere heating associated with the Lunar return trajectory. In addition this study area extended the investigation of the expected heating to include such things as non-equilibrium radiation heating, CFD analysis for flow fields, and radiative and convective heating for this large, blunt aerobrake shape for which there is limited flight data.

The fourth study area, structural design, took the maturing results from the Aerobrake as Vehicle and worked in conjunction with the Thermal Protection System study to produce a conceptual design capable of supporting the return trajectory forces, interfacing to the Lunar Transfer Vehicle, being assembled on-orbit, and supporting the required thermal protection system. All of this taken within the context of a constrained mass fraction for the aerobrake.

The fifth study area was related to inspection and verification of the aerobrake and was concerned with a more complete look at inspection requirements and techniques than was done in the first study phase. Included in this area was a consideration of the effects of orbital debris and micrometeoroid impacts, external and internal sensors (with a considerably expanded look at non destructive evaluation, embedded sensors), and reviews of Shuttle Orbiter inspection, verification, and refurbishment practices.

The sixth study area defined the robotics and operations support required to assemble, inspect, refurbish, and maintain the aerobrake. This study area, in effect, added the dynamics of the associated supporting operations to the aerobrake as a complete system. During definition of the on-orbit assemblable structure, this study area was required to maintain close cognizance and cooperation with the structures definition to ensure appropriate accommodations for robotics systems.

2. Lunar Transfer Vehicle and Aerobrake Derived Requirements.

The relevance of this study is built on a propagated set of requirements whose source is the next higher level of NASA mission definition activity. In the SEI case the designated lead for the Lunar Transfer Vehicle has been Marshall Space Flight Center. Marshall was responsible for developing the LTV and MTV concepts and thereby generating a set of requirements that the LTV and MTV subsystems must meet. The aerobrake, a major subsystem, was thus given "high level" performance requirements to fulfill.

It should be noted that the aerobrake study being reported was directed at the lunar mission alone, but there are compelling reasons, to be discussed later, for direct relationships to the Mars Mission.

It is these high level requirements that are then given interpretation and definition to yield both an aerobrake concept and a further propagation to still more basic subsystems. By means of the above technique, it is possible to trace each activity back up a chain that responds to a "higher level" requirement.

The MSFC activity consisted of study contracts and in-house concept development that generated a vehicle (the Space Transportation Vehicle, or STV) derived from the "so-called" Stage and One-half of the original "90-Day Study." Unfortunately, the detailed selection of a baseline LTV faltered in some important stages of the synthesis process because of the restructuring of Space Station Freedom and other reasons. Thus, as this study intensified, the required LTV definition process stalled. The vehicle definition had a fairly well defined set of gross physical characteristics: outline, dimensions, mass allocations, number of engines, crew and payload module concepts. However, there were two competing concepts from the study contractors and only an informally synthesized NASA version. Consequently certain major uncertainties remained: On which side of the aerobrake the propellant tanks were attached, whether the aerobrake went to the Lunar surface or not, and what the major mechanical interfaces of the aerobrake to LTV "core" were, to name some of the larger ones.

Nevertheless, the aerobrake study team, in conjunction with the MSFC STV study team were able to focus on an LTV concept that was more than adequate to ensure solidly useful results. Given such things as a very reasonable size and mass of the LTV and the requirement to rendezvous with SSF, for example, it is possible to develop a Lunar return trajectory. Such a trajectory would in turn yield pressure loads, heating, and pressure profiles. Because the trajectories compatible with an SSF return require a low L/D, they are fairly insensitive to modest changes in vehicle shape and mass, the study results were guaranteed to yield results very close to whatever similar vehicle might ultimately be chosen.

Shown in Figure II.2 is the Lunar Transfer Vehicle used for this study. Included as Table II.1 are the appropriate mass allocations and dimensions of the LTV. The total mass of the LTV is 21.5 tonnes and the aerobake mass is 4.3 tonnes.

3. Aerobrake Shape Selection.

One area that received considerable attention was the selection of an aerobrake shape. A fairly obvious overall system optimization would appear to be the selection of an aerobrake shape that would be both acceptable in flight characteristics and simultaneously well adapted to on-orbit assembly. Given a set of aerobrake shapes that are similar in performance and a set of shapes, some better adapted to on-orbit assembly than others, a major trade-off would be to strike a "best" balance between flight and assembly.

One result from the Phase I study was the presumed desirability of a minimal number of different parts required to assemble the aerobrake and if many parts are required, they should be interchangable. Given the fact that launch costs are expected to be a major fraction of overall cost, a high degree of commonality was expected to reduce spares and enhance launch packaging requirements. Moreover, the more different parts, the more difficult the manufacturing and verification, as well as the probability of more complex on-orbit operations tasks.

The initial thoughts were that the more symmetrical the aerobrake, there would follow an increase in parts commonality. By extension, the expectation was that the most symmetrical shape, a spherical section, would yield the highest degree of commonality. Other shapes such as ellipsoids or the complex shape of the Aeroassist Flight Experiment, which has sections of prolate hyperboloids, and ellipsoids, as examples would be expected to be less characterized by parts commonality.

It became clear later in the study that the first thoughts on which shapes yielded the greatest commonality were erroneous. Based on the early reasoning, the spheroid was selected for analysis in meeting the mission flight requirements. As noted in the related report "Minimum Accommodation Aerobrake Assembly-Vehicle Analysis," a spherical section can work well as an aerobrake shape.

Several guidlines grew out of the Phase I Study (essentially a feasibility study) which were felt would have ultimate influence on the "best" integrated aerobrake design. In order to begin the process of detailed definition, it was important to determine which of the apparently adequate aerobrake concepts identified in the Phase I Study should receive most attention. The hope was that one concept was the far-and-away leading candidate, allowing a reduction in options.

A set of criteria were identified that were felt to capture the major end-to-end aerobrake design considerations. These criteria were: (1) Thermal Protection System and Structural Commonality, (2) Structural concept, (3) Assembly Difficulty, and (4) Operations Support. The first of these refers to the desire to have as few different parts as possible to ease the problem of on-orbit spares and inventory complexity. The second of these, Structural Concept, refers to the inferred difficulty to produce a particular structure vis-a-vis some other. The third is self-evident, while the last, Operations Support referred to the difficulty in launch support, on-orbit operations, complexity in inspection systems, support systems, etc. It is interesting to note that the particular aerobrake concept selection was not a major factor in the aerobrake performance or mass.

Inherent in the identification of the above criteria was the clear knowledge that they were not of equal importance. The integration team proceeded to develop a weighting for each area to yield the final rankings. Moreover, because the TPS and Structure Commonality were felt to be sufficiently different, a ranking was first developed and then the two were recombined before the weights were applied. Shown in Table 3.1 are the categories and their weights along with the final ranking of the aerobrake shapes. The shapes were the ones developed during the Phase I Study and represent a complete cross-section of the proposed aerobrake shapes compatible with the SEI Lunar mission.

The final ranking showed only that the very complex shape of the Aeroassist Flight Experiment was clearly a loser while the Spheroid and Sphere-cone were close together and at the top. The final decision was to maintain the Spheroid and Sphere-cone as the two options for this study. This selection was passed on to the study group doing an assessment of flight characteristics to determine detailed performance.

4. Baseline Deflection and Tile "Pop-Off" Limits.

One important input to the structural analysis study in this group was the question of how much deflection of the aerobrake was permissible. The question of deflection represents a derived requirement since it does not come from the MSFC vehicle concept development, and is, rather, a direct result of the pressure loads experienced during the (model) trajectory. Moreover, the deflection has two major and unrelated impacts: First, the deflection causes a distortion of the aerobrake surface, which, it must be assumed, is covered by some thermal protection system. In general, thermal protection systems are rigid and applied in sections. Thus, the possibility of the thermal protection system "popping off", on the one hand, or separating and allowing hot gas to penetrate to the inner mold line on the other hand, exists. Second, the deflection of the aerobrake has the effect of possibly allowing the hot shock wave to envelop parts of the Lunar Transfer Vehicle, affecting the minimum required aerobrake size and hence mass and flight characteristics.

The approach taken to quantify the "pop-off" was to rely on the only currently existing practice in this general area: the Orbiter. While it was understood that the TPS selected for LTV application might represent a somewhat different case, requiring reassessment at a later time, sufficient similarities were expected to warrant this approach.

There are a few interesting points to note concerning the Orbiter tiles. First, the tiles are not rigidly attached to the Orbiter inner mold line. Instead, the tiles tend to "float" on the Orbiter skin. Aerodynamic pressure during reentry tends to press the tiles against the Orbiter, while tangential flow tends to try to dislodge the tiles. A very blunt shaped aerobrake similar to the one in this study would be expected to experience very little tangential flow. Second, in the case of the Orbiter, the dominant source of flow into the intertile regions would be a pressure differential. Flow would carry hot gas to the inner mold line, so "gap filler" is used as a preventative. In a case of no pressure differential or very low flow, the expectation (subject to laboratory or other test verification) would be that the gap filler might not be needed if some way could be found to prevent direct heating.

What was required for the study to proceed was a specification on the amount of deflection the aerobrake structure could accommodate without inducing some failure in other important subsystems. The largest first order effects of deflection on the aerobrake come from the increasing curvature as the aerobrake experiences a pressure load and the possible effect of wake closure in impinging on the LTV core. The integration activity attacked both of these questions.

The tile debonding was studied by first establishing the tolerance limits in Orbiter practice. Discussions with Orbiter Processing Facility staff and with Rockwell International employees yielded information that indicated there would be two problem areas: First, an increase in the tile-to-tile separation and second, a stretching of the bonding material due to increasing curvature at the inner mold line.

As shown in Figure 4.1 the force load on the aerobrake is modelled as a simple change in the curvature of the aerobrake. This curvature, in turn, displaces the tiles from their original positions giving rise to a new top to bottom tile separation (gap) and a pulling away of the inner mold line from the tile bottom. The latter would be expected to be greatest at the outer edges of the tiles, assuming equal bonding elasticity. A simple analysis shows that for small ratios of deflected-to-normal effective radii, the amount of gap increase is as shown in Table 4.1. Even for normalized radii of curvature variations as high as 0.5 (defined as r/r_0 the resulting radius of curvature divided by initial radius of 45 feet) the gap only increases to 0.147" Orbiter pillow type gap insulators are capable of compression (expansion) of 0.180", adequate for the required 0.147" at the 0.5 r/r_0 ratio and well satisfying the requirement at the lower values. Note that the assumed tile width was one meter and the tile separation varies linearly with tile width.

For tile debonding, the case is similar, with the results of the calculations shown in Table 4.2. In that table, it is seen that the debonding excess gap only approaches that of the original gap when the curvature ratio approaches 0.5 r/r_0. It should be noted again that the calculations were done for a tile width of one meter, and that the gap varies directly as the square of this tile dimension.

5. Tile Shape and Commonality.

One important aspect of the selection of the aerobrake shape, mentioned above, was the desire to maximize commonality of the various component parts. As will be discussed later, it became less important to achieve this commonality, but even so, it was and remains a desirable goal.

One very numerous subelement of the aerobrake is obviously the thermal protection system tiles. While the initial integration of the tiles with the structure appears to be best done before launch, repair and refurbishment entails the expected replacing of some or all the TPS tiles. Consequently a considerable effort was made to minimize the number of differently shaped tiles, and this section will present the results of this surprisingly difficult task.

A very naive approach to shape would assume that something similar to the shapes that tile ("tesselate") common surfaces would be appropriate. For example, hexagonal shapes will cover a plane surface perfectly and might be expected to be able to do the same thing for the aerobrake. However, simple geometric considerations show that the hexagons cannot cover the curved surface and keep the same shape. If a series of rings is started on a section of a sphere, for example, it is readily found that the circumference of the rings must vary and that they do so without maintaining an integer relationship. Moreover, the outer circumference for a particular ring of hexes is different from the inner ring. Hence the hex's cannot remain hex's and fill the area.

The problem is more fundamental still and is related to the problem of solid geometry of creating solids from identical polygonal figures. That this is so follows from the construction which would solve the current tessellation problem. The solution consists of simply circumscribing a sphere on a regular polyhedron and projecting the polygonal faces onto the sphere's surface. Such a construction would create curved, identical areas on the sphere's surface, each of which would be the TPS shape.

Unfortunately, there are only five regular polyhedra, called the Platonic solids. These are the tetrahedron (four faces), hexahedron (six faces), octahedron (eight faces), dodecahedron (twelve faces), and icosahedron (twenty faces). For an aerobrake based on a spherical section whose total area would be near 2200 square meters, a reasonable tile size of approximately 0.5 square meter would require a Platonic solid with 4400 faces.

Other classical polyhedra with groups of different shapes exist and are called the thirteen Archimedian solids. Unfortunately these too are limited to only a few tens of faces.

Another approach was investigated based on the modern architectural constructions developed by R. Buckminster Fuller: Geodesic Domes. Geodesic Domes were originally developed from great circle arcs, but were generalized so extensively that great circle arcs almost completely disappeared, leaving only the name. Geodesics commonly take as their starting point the icosahedron or dodecahedron and

6. Integrated Aerobrake Design Selection

As the multipart study progressed, certain initial plausibilities began to erode. On the other hand, certain other guiding concepts began to emerge. This section will present what grew to be a set of overarching principles resulting from the synthesis activity. These principles were referred to as the Grand Canonical Assumptions with an apology to Statistical Mechanics. The Grand Canonical Assumptions represent six heuristic conclusions and are listed in Table 6.1.

The first of these reflects the fact that the amount of squared velocity change for a SSF rendezvous is the same as for an Orbiter reentry. However, the rendezvous with SSF represents a much shorter and sharper heating pulse than in the Orbiter case. In addition, the Orbiter experiences primarily convective heating while the aerobrake-Lunar Transfer Vehicle endures high radiative heating. Because the shock wave stands off from the aerobrake and there is only a small (per unit area) flow, it was decided by the integration team to ignore flow into the tile gaps. This assumption, backed by experience with NASP-like experiments, allows the elimination of any requirement for "gap-filler" such as used in the Orbiter. For the model LTV aerobrake, the approach was tile overlap, backed up by a requirement of laboratory experiments to confirm the assumption. One of the concerns in using gap-filler is the inspection, repair, and refurbishment on-orbit in zero-G and in the confines or neighborhood of SSF. As to be discussed later, there is ample reason not to aid in the proliferation of debris external to SSF. The difficulty of extracting and replacing the gap-filler inside SSF makes it a complex task.

The next Canonical Assumption is that the aerobrake can be put together easily, but only the TPS is designed for ease of assembly and disassembly. This assumption results from consideration of the results of an on-orbit event that would make it necessary to repair some part of the aerobrake structure. Because of the critical role that the aerobrake plays in LTV survival, the question of reuse of a damaged aerobrake is one of considerable importance. After some physical problem severe enough to require rebuilding, it is difficult to see how it would be possible to develop sufficient confidence that all damage was satisfactorily repaired. Therefore, it was decided to assume that the aerobrake structure would be designed to be disassembled, but only with times compatible with disposal.

A question that arose from time-to-time concerning the benefits of deployable or in toto launched aerobrakes versus an on-orbit assembled one gave rise to the third Assumption. In considering options other than assembly, it became clear that for a multiple use aerobrake some rather substantial accommodation structure would be required. On the other hand it was found that forms of the erectable aerobrake could fit in the Orbiter, a Titan IV or possibly smaller vehicles. Given the dominating requirement for multiple uses and the attendant support structure, it was felt that it was only a small step to assemble the aerobrake with the same hardware. On the other hand, launching an aerobrake in toto requires a specially modified launch vehicle (greater than 14 meter shroud) or some development of a (possibly removable) deployment mechanism with the use of a whole Heavy Lift Launch Vehicle (HLLV) for this one purpose.

Canonical Assumption four captures the progression of technology from the Lunar Missions to the Mars Missions. Options to perform the SEI Missions show the possibility of bypassing SSF with HLLV's for the Lunar Mission, eliminating the need for assembly, reuse, or other operations at SSF. However, the Mars Missions, involving vehicles (including nuclear) all are in the IMLEO mass range of 500 metric tons or greater. No HLLV's exist or are currently proposed that are capable of launching such vehicles into orbit. On-orbit assembly, checkout, fueling and other operations will be required. Thus, recurrent Lunar operations based at SSF are obvious candidates for use in developing the technology and techniques to enable the Mars Missions.

Assumption five refers to the belief that it is less costly to reuse a vehicle than to replace it given the two options are reasonably close in performance and cost. An example is the suggested use of an ablator-expendable aerobrake rather than a reusable one.

Assumption six refers to the fact that the concern over on-orbit assembly times and complexity for a multiple reuse aerobrake ignore the fact that overall operations are dominated by the refurbishment and reflight activities. Assembly is a one time activity which can be accomplished in parallel with other activities. The length of time required to assemble an aerobrake when prorated over its operational lifetime yields a considerable effective mitigation of assembly overhead.

7. Debris.

A consideration thought to be of major impact was the question of on-orbit debris. During the period of time encompassing the Phase I study activity and the beginning of the Phase II study, the Space Station Freedom Program was still in a very active consideration of the problem of on-orbit debris, including the development of program and project policies and requirements. To be more precise, the issue was both on-orbit debris and the far better known problem of micrometeors. It is important to note the latter point because the debris issue had grown to such proportions that the far better documented danger of micrometeors had tended to recede from consideration.

To better assess the problem of on-orbit damage, several of the Phase II study participants attended a short course. The short course was intended to develop an analytical understanding related to on-orbit debris and micrometeors. In addition, the study activity was fortunate to be able to examine raw results from the LDEF experiment related to on-orbit damage. Both of the above mentioned activities will be reviewed, as well as the expected importance either or both might play. In addition, some comments related to the more general question of on-orbit damage from all sources will be presented.

8. Recapitulation and Summary

It is worth noting at the conclusion of this part of the suite of reports some of the overall findings with regard to the LTV aerobrake. The major impetus behind the use of aerobraking was the reduction in the amount of IMLEO propellent since a minimized aerobrake mass fraction allows the maximum IMLEO savings. The goal for the structural and thermal protection system studies was to keep the mass fraction of the aerobrake below 25 percent. The two study areas mutually apportioned target mass fractions with a small reserve for items such as avionics, thrusters, and so forth. The final mass fraction resulting from thermal protection system, structural design and overhead items was 22 percent. The actual IMLEO savings for the baseline LTV can only be estimated without additional study, however from past studies it is to expected that the savings would be in the 18-20 percent range.

9. Conclusions

This six-part study was done to provide depth to the Phase I Study (reference 1) and to continue the assessment of the practicality of a Space Station Freedom-based Lunar Transfer Vehicle-Aerobrake design. The depth to which this study went might be considered similar to a phase A study in conventional project activity. Moreover, certain parts were at a level commensurate with a phase B study. In effect, a "baseline" aerobrake concept was generated which is sufficient to identify necessary advanced development activities. Concepts were generated for the shape of the aerobrake, its thermal protection system (including robotics and automation systems,) realistic trajectories, heating and pressure profiles, and detailed structural analysis and assembly concepts and designs.

It is the conclusion of this work that a Lunar transfer vehicle based at Space Station Freedom and incorporating an aerobrake is feasible from an engineering perspective. It is also the conclusion of this study activity that the aerobrake can be maintained for five or more reuses, including a five-reuse ablator option. Some areas of concern remain in the discrepancies among various CFD-driven equilibrium and non-equilibrium heating models. The mix of radiative and convective heating has not yet been determined to be within comfortable bounds. Nevertheless, there was sufficient agreement to permit the selection of a thermal protection system with adequate margin to encompass the expected heating.

Finally, it should be noted that the concept of using a "hot structure" made up of carbon-carbon composites was only briefly considered. Time did not permit the investigation of this very interesting alternative. The potential benefits of a composite aerobrake are such that further work in developing a detailed assessment would be well worth while .

Candidate Aerobrake Shapes
Spheroid AFE Shape Sphere-cone Biconic Ellipsoid

Weighting	
Criterion	Weight
TPS and Structure Commonality	32%
Structural Concept	29%
Assembly Difficulty	29%
Operations Support	10%
	100%

Final Ranking		
Rank	Shape	Score
1	Spheroid	4.00
2	Sphere-cone	3.84
3	Biconic	3.06
4	Ellisoid	2.11
5	AFE Shape	1.34

Table 3.1-Initial Selection Criteria, weightings, and rankings for aerobrake shapes.

Deflected to Undeflected Radius of Curvature Ratio	Increase in Gap Width (Inches)	
1.0	0.0	$x10^{-3}$
0.9	15.0	"
0.8	33.0	"
0.6	57.1	"
0.7	88.9	"
0.5	133.0	"

Table 4.1a

Deflected to Undeflected Radius of Curvature Ratio	Lift-Off (Inches)	
1.0	0.0	$x10^{-3}$
0.9	40.0	"
0.8	92.0	"
0.7	156.0	"
0.6	244.0	"
0.5	365.0	"

Table 4.1b

Tile thickness:	2 inches
Undeflected aerobrake radius:	45 feet
Tile width:	3 feet
Undeflected Gap:	$133x10^{-3}$

Table 4.1-(a) Variation of tile-to-tile gap as a function of aerobrake effective radius of curvature ratio, and (b) tile lift off versus radius of curvature ratio.

1. The large blunt shape has little intertile flow and mostly radiative heating. The Lunar aerobrake is not the Shuttle.

2. The aerobrake and the TPS can be assembled easily, but only the TPS is designed to be disassembled easily.

3. The infrastructure required to support the assembly of the aerobrake is the basis for the refurbishment infrastructure.

4. The development of techniques and infrastructure of the Lunar aerobrake enable major Mars mission operations elements.

5. Reusablility where possible, expendability where necessary.

6. Refurbishment operations outweigh single-shot assembly operations.

Table 6.1- Some major underlying heuristics resulting from, and guiding, the Phase II Study integration process.

References

1. Katzberg, Steven J., Butler, David H., Doggett, William R., Russell, James W., and Hurban, Theresa, "Aerobrake Assembly with Minimum Space Station Accommodation," NASA Technical Memorandum 102778, April 1991.

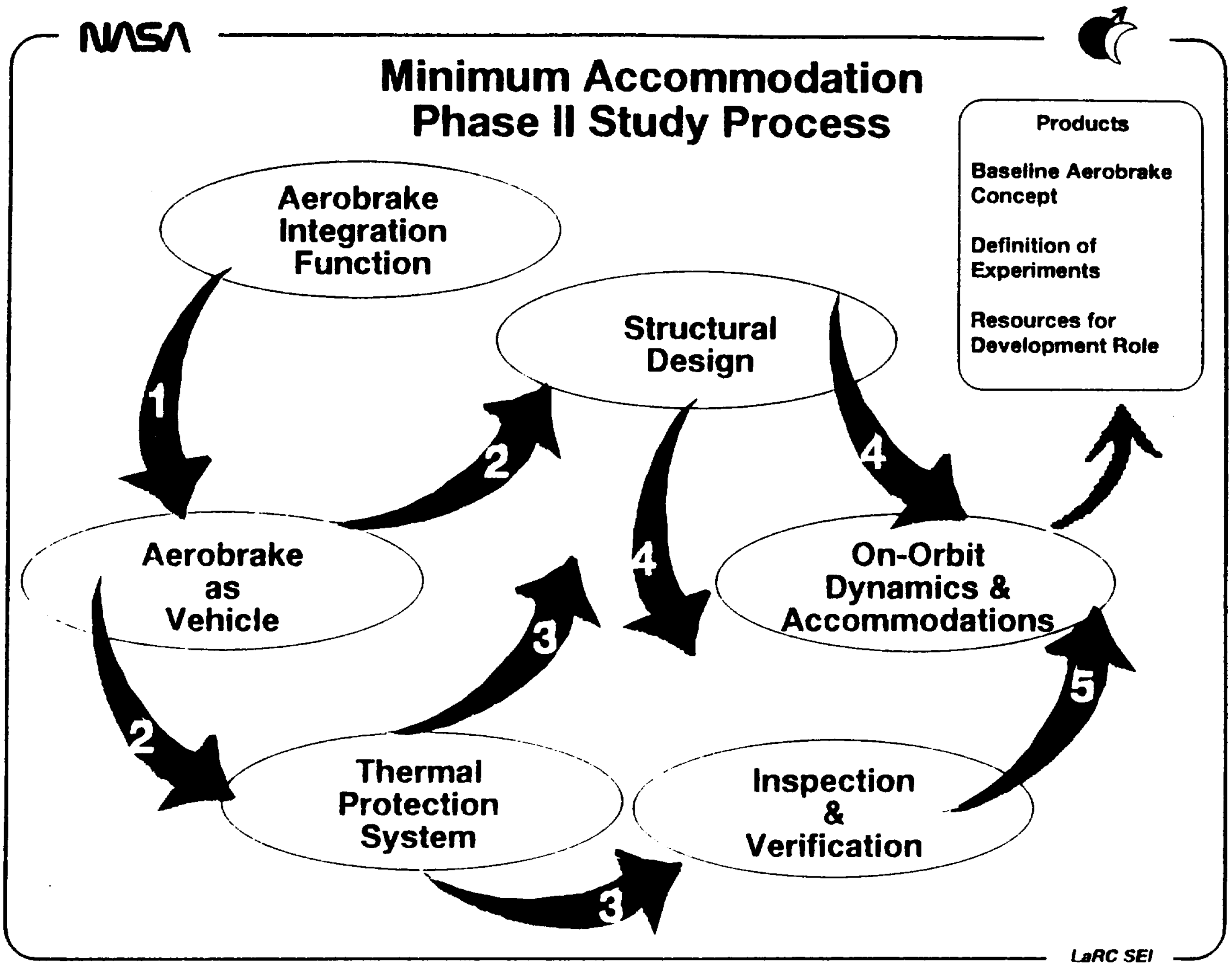

Figure 1.-Outline of the multidisciplinary study process. Arrows indicate the flow of interim engineering results and generally indicate the more fundamental drivers by the lower numbers.

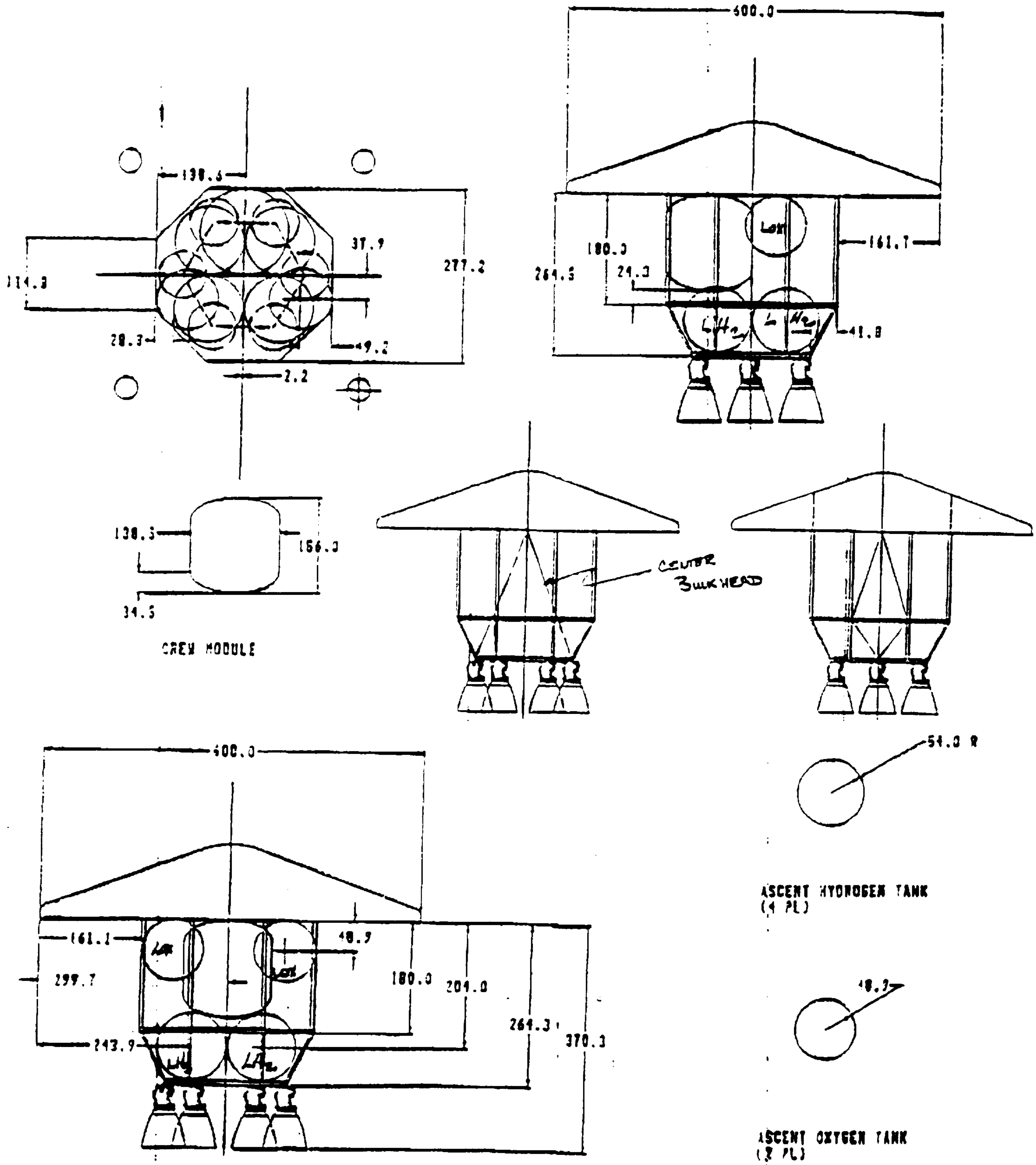

Figure 2.-Schematic of the Single P/A (propulsion/avionics) design concept developed by Marshall Space Flight Center. This concept served as the basis for the aerobrake design study.

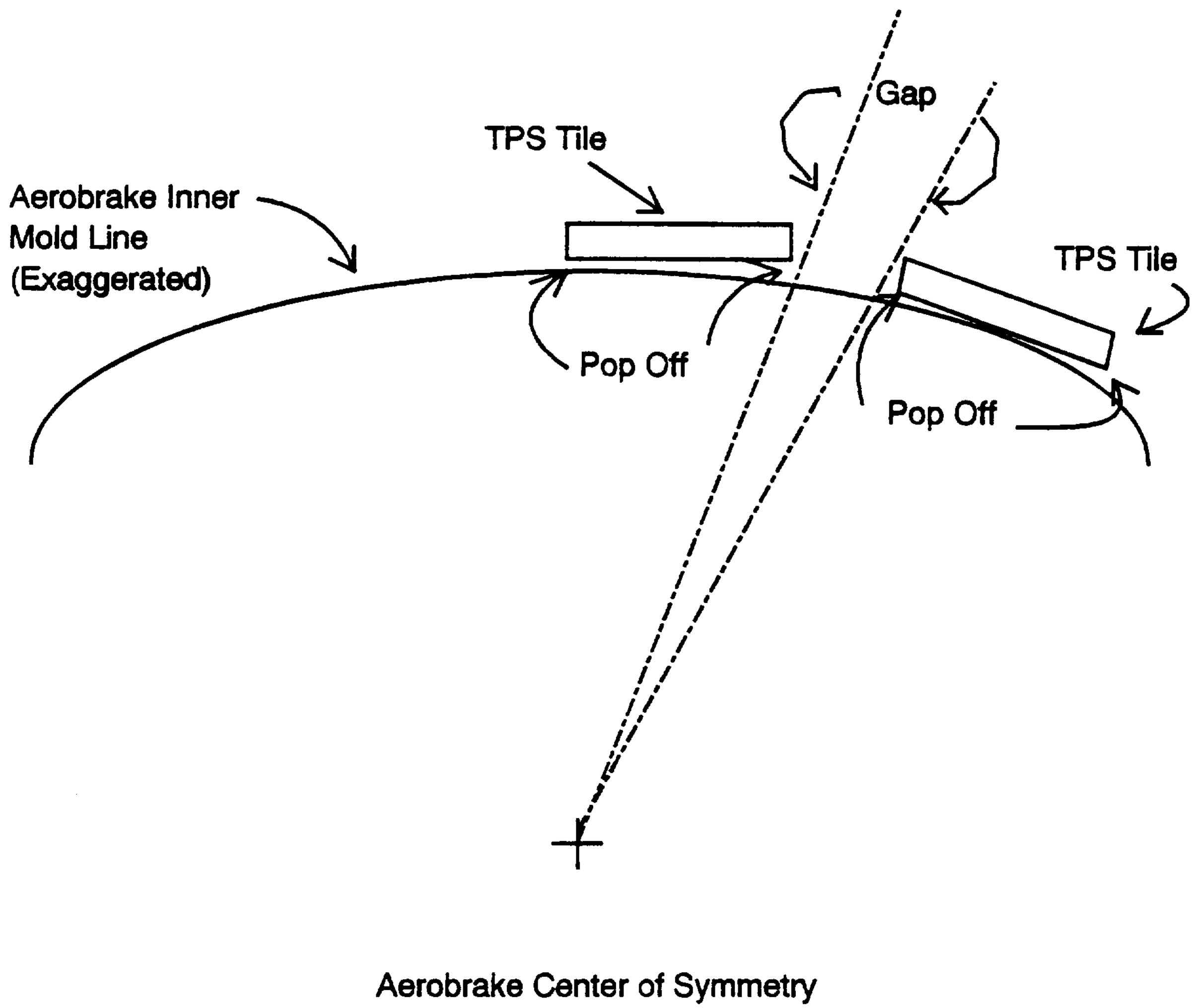

Figure 3.-Illustration of intertile and the tile-to-inner mold line "pop-off" effects. Decrease in radius of curvature causes greater severity in the extent of separation and gap.

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Stephen J. Katzberg, Davy A. Haynes, Robin D. Tutterow,
Judith J. Watson, James W. Russell

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Hampton, VA 23681-0001

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Stephen J. Katzberg, Davy A. Haynes, Robin D. Tutterow, Judith J. Watson - NASA LaRC, Hampton, VA
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13. ABSTRACT *(Maximum 200 words)*
A multi-element study was done to assess the practicality of a Space Station Freedom-based aerobrake system for the Space Exploration Initiative. The study was organized into six parts related to structure, aerodynamics, robotics and assembly, thermal protection system, inspection and verification, all tied together by an integration study. The integration activity managed the broad issues related to meeting mission requirements. This report is a summary of the issues addressed by the integration team.

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