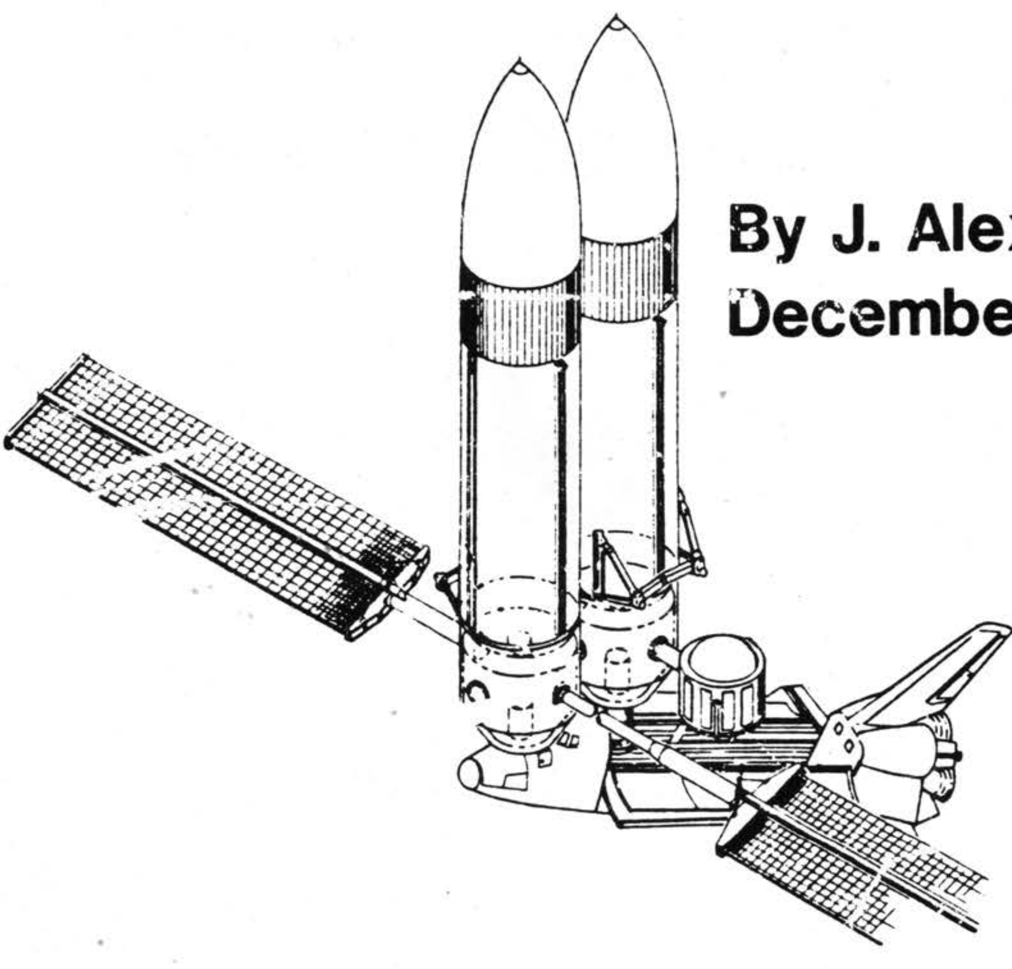
Space Studies Institute

Report on Space Shuttle External Tank Applications



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ET Project - Executive Summary

This report will review possible applications of the External Tank (ET) of the Space Transportation System (STS) in orbit. Enhancements of the space program through ET utilization in orbit will be covered in depth. Problems will be reviewed. Recommendations will be made. This report is intended to make a coherent case for the use of the External Tank in the American space program.

I. Tank Introduction

The ET is carried almost to orbit with the orbiter and jettisoned with approximately 98% of the energy necessary to insert it in orbit. When jettisoned, each ET carries internally an average of 15,000 pounds of residual cryogenic fuels. These residuals are available for scavenging from the tank in a variety of scenarios. The availability of cryogenics already in orbit can potentially fuel planned OTV operations at a cost far lower than if the cryogenics are carried aloft in a tanker version of the orbiter.

The ET mass is over 69,000 pounds. Of this mass, there are approximately 53,000 pounds of aerospace grade aluminium. This aluminium can be cut, melted, powdered, welded, and manipulated to suit any number of present and future structural needs. If the tanks are partially disassembled in orbit, the pieces can also be reassembled in the construction of large structures.

The oxygen and hydrogen tanks making up the ET provide two factory tested pressure vessels that are two to five times larger in volume than any space station yet flown or planned for the future. These large volumes are clean and able to be entered through inspection manholes in the respective tank domes. The on-orbit adaptation of the respective tank interiors for habitation, storage, or maintenence facilities will require minimal time and effort.

There are two major problems with the use of the ET in orbit. The first and most critical is orbital maintenance. This is a result of the desire not to randomly drop large bodies on the surface of the earth from space. At typical STS orbits (160 - 220 nautical miles), the orbital lifetime of a tank inserted into a parking orbit can be measured in days to months. A plan to use the ET in orbit must address this problem. A quick solution would be to install small thrusters that use the boiloff of residual cryogenics to insert the ET in a very long lived (200 - 500 nm higher) orbit. Other solutions to this problem are possible and vary depending on the planned on-orbit use of the ET. They are also not particularly expensive. The second problem is possible contamination due to outgassing of the Spray-On Foam Insulation (SOFI). This may prove to be a pollution problem for a small number of proposed space based operations. However, it will require further study.

There are several relatively inexpensive enhancements to the ET that can be purchased that will enhance STS operations. The most important of these is the AFT Cargo Carrier (ACC). The ACC is constructed using ET tooling and attaches to the aft end of the hydrogen tank. Cost of the ACC is between $150 - 250 million and it can fly three years after the go-ahead is given. The ACC is designed for minimal impact to the ET, orbiter, and operations. It provides an additional cargo volume measuring 27.5 feet by 20 feet for payloads. This is valuable to operations because it deals with the volume restriction imposed by the orbiter payload bay. In other words, there is normally additional mass to orbit capability available in each STS launch. A typical example would be a Spacelab flight. The ACC can carry additional payload or primary payload to orbit. This gives the orbiter additional payload capability that can be sold to paying customers for minimal cost.

II. Tin Can Uses

The ET can be used as a 'tin can' in orbit for a number of applications. These include storage facilities for liquids, gases, and prepositioned vehicles. The ET/ACC combination can be launched with the ACC as a fully functioning manned space station. This type vehicle has an enormous expansion space inside and outside the ET itself for a variety of orbital applications. The ET/ACC as a space station can also be flown with a single shuttle launch. This capability will allow any number of potential customers to purchase independent space stations for the cost of two or three generic commmunication staellites. Potential customers for this capability include DOD, corporations, foreign nations, and private consortiums.

The ET can also be used as a part of any space station. It can be partially disassembled to make a hangar or easily turned into a space station habitation module of a far larger volume than any past, present, or future space station module. The oxygen tank can be turned into a liquid or gas storage reservoir.

The cost savings by ET utilization in these operations are unspecified at this time. However, any specially designed space station module which will fill the needs addressed above must be compared against the ET in two ways. The first comparison is launch cost. With the ET, you get a large rigid body already in orbit. You must lift anything else at $2000 per pound. The second comparison concerns possible future expansion of the structure. If a future expansion is being planned, then the costs of R&D and on-orbit construction from the STS payload bay during an EVA must be compared to the cost of on-orbit modification of a body that is already in space. This analysis should show in most cases, that the adaptation of an orbiting ET will provide enormous cost savings to the program.

In addition, the use of the ET as part of a manned space effort will give the program a new perspective. As soon as the ET is inserted into orbit, the program has made large, massive, structurally strong bodies available to prospective users at a very low cost. The volume restrictions for manned habitations are removed. The storage limitations for liquids and gases are removed. This means that a specially designed structure does not need to be planned, sold to uninterested congressmen, launched, and constructed over a period of several flights. The planning turns to an emphasis on the adaptation of structures already in orbit. This adaptation will take a bit more EVA time, (at over $40,000 per hour), but the savings in launch cost alone will more than cover the difference.

III. ET as a Propellent Resource

Analysis of future requirements for space based operations show the largest mass requirement is for fuels. These include OTV operations, satellite launch and recovery, and space station orbital maintenance. NASA has a requirement for 2.5 million pounds of propellents over the next ten years. Analysis based on this requirement show the scavenging of residual cryogenics from the ET can fill up to 92% of the requirement at a total cost savings of $3.5 Billion over the period. The savings comes primarily from the launch cost savings. The scavenging operation can be performed in a variety of ways. These inlcude scavenging into the orbiter after MECO, scavenging into an ACC, scavenging into the space station after rendezvous, and scavenging into a free flyer. Each tank will provide an average of $30 million worth of residual cryogenics available for scavenging.

Another use of the ET as propellant is to powder the aluminium and use it as reaction mass in a Aluminium - Oxygen - Hydrogen rocket for OTV applications. Analysis of OTV traffic models show that current technology engines (RL-10) are sufficient if the OTV fuel requirements do not exceed the availability of scavenged cryogenics. However an aluminium/oxygen/hydrogen engine rather than an advanced cryogenic oxygen/hydrogen engine appears to be the most cost effective choice. This is once again due to the savings in launch costs because 40-50% of the reaction mass is already in orbit as tanks. The analysis of the aluminium rocket engine includes the $1 - 2 billion R&D costs, the high production costs, and the cost of flying a processing plant to grind the tanks into powder. Even with the inclusion of all these additional costs, the aluminium engine is potentially far cheaper than an advanced cryogenic engine because the mass requirements to orbit are far lower. Each tank used in this application is worth about $107 million in powdered aluminium (computed at $2000 per pound to LEO).

The problems associated with these type engines are known. It is not clear at this time why the choice not to develop these engines in the 1960s was made. There were fairly serious problems with propellent transport that may be solved by zero 'G' conditions in orbit. There was also a problem with the time constraints of the Apollo program. The scientists investigating the Aluminium engine are well aware of the past history of the engine. They feel that the problems are solvable and that the aluminium engine has great potential for OTV applications.

IV. Structures

The ET can be used in any number of structural applications. These range from partial disassembly to complete melting and refining opreations in orbit. The ET can be partially disassembled and reassembled into a variety of rigid structures. The tank domes can be removed and the hydrogen tank barrel can be reattached end-to-end to construct long rigid tubes. The tank can be cut into 5 feet by 60-80 feet long strips using known cutting technologies and welded into any desired shape. Once again, welding is a known technology that has been tested in space.

The ET can be completely melted using electrical or solar methods. The melt can then be used to extrude structural members such as channels, I Beams, or rods. It can be used to make thin metal films by vapor deposition processes. It can also be used to make thin metal shells by an inflation technique. The shells and other manufactured structural members can be used for construction. It can also be powdered and used for casting and forming operations.

Another use of the ET is as a strongback or a testbed for the construction or anchoring of large structures. The advantage in doing this is that the ET is far more massive and structurally sound than planned space structures. This is because it is the structural heart of the STS during launch. A typical strongback use would be the construction of large antennas on the ET. The mass and stability of the tank is also an advantage. Due to gravity gradient effects, the ET will tend to stabilize with the long axis pointing to the center of the earth. Any structure that can use the ET as a base or an anchor will require less active attitude control systems and thus be cheaper to build, fly, and operate.

V. Tethers

The use of tethers with the ET also provide significant advantages to the future space program. These advantages include artificial gravity, momentum exchange, electrical power generation, electric propulsion, and significant enhancements in shuttle and space station missions.

The physics of tethers allows artificial gravity to be generated in two ways. First, two tanks can be attached to each other by a tether and stored in a gravity gradient mode. This is useful in liquid storage applications. Second, the system can be made to rotate. Artificial gravity levels of 1 'G' can be induced by a system 200 meters in diameter rotating at 2-3 rpm. This artificial gravity will negate the undersirable effects of long term weightlessness on the body and lengthen crew stays on station.

Momentum exchange is also useful. This can be done with either a static or a rotating system. Release of an object from the end of a long tether will insert it into a much higher or lower orbit. This could lead to the use of a tethered release from a space station for a shuttle deorbit without an OMS burn. A swinging tethered release could also be used to insert the ET into a high orbit that is long lived and drop an orbiter to a reentry. This exchanges momentum only and uses minimal fuel. A swinging release can also enhance the payload carrying capability of vehicles to higher orbits (including escape orbits). A swinging release 'steals' momentum from the system and can be used to launch a far more massive payload away from LEO than could otherwise be launched with the same onboard propellents. Savings is in fuels and the advantage is that a more massive and more capable payload is possible.

Electrical uses of a conducting tether include the generation of station elctrical power and the orbital raising and lowering of the station. A properly designed tether can generate electricity by interacting with the magnetic field. This induces drag and will lower the station. A current can be forced through the tether with excess electricity and the tether can generate a net thrust. This Alfven Engine can be used for orbital maintenance, orbit changing, and energy storage through momentum. Efficiencies are higher than Ion engines and no propellents are required.

Shuttle and station mission enhancements with a tether include additional payload capability to orbit, the saving of OMS fuel by a tether mediated rendezvous with a station, and storage of tanks and liquids. The tether mediated rendezvous can enhance the payload to station capability of the orbiter. It can also allow the scavenging of excess orbiter OMS fuel to the station for station requirements. Storage of liquid in a tethered tank takes advantage of the gravity gradient to store liquids where they can be pumped using conventional methods.

VI. Miscellaneous

The ET in orbit can also be used in a variety of scientific and military applications. The scientific uses include the use of the ET/ACC combination as a way to launch large mirror arrays for telescopes. The hydrogen tank can be used as an affordable high energy observatory of a far larger size than planned. The exterior of the tank can be used as the structural base for large antenna arrays. The tank itself can also be used to study the interaction of plasmas with bodies in orbit.

The two tanks of the ET can be used to perform biological and life science experiments in space. The large volume of each tank can be used to perform experiments in farming, genetics, and waste management. The large size is advantageous because it provides significant biological inertia. This means that in the event of a problem, the biological system can be changed before the entire system dies. Farming becomes possible in the large volume available. Cost savings here are based on the launch cost of food and consumables produced in space as compared against the cost of launching these consumables. An orbiting 'truck farm' becomes possible.

Additional life support advantages are the use of the ET as a passive lifeboat. If ETs are inserted to long lived orbits while pressurized with oxygen or an air mixture, they can be entered and used by a crew in an emergency. The large volume of air can be used for weeks to months for life support without active equipment.

Military uses are related to the use of the ET as a cryogenic storage facility, space base, or 'Coast Guard' type operation in space. ETs can also serve as decoys, battle stations, 'junk' ASATs, and military space stations. The ET/ACC based space station for military purposes is something that would be affordable and attractive to those interested in manned military operations.

VII. Conclusions

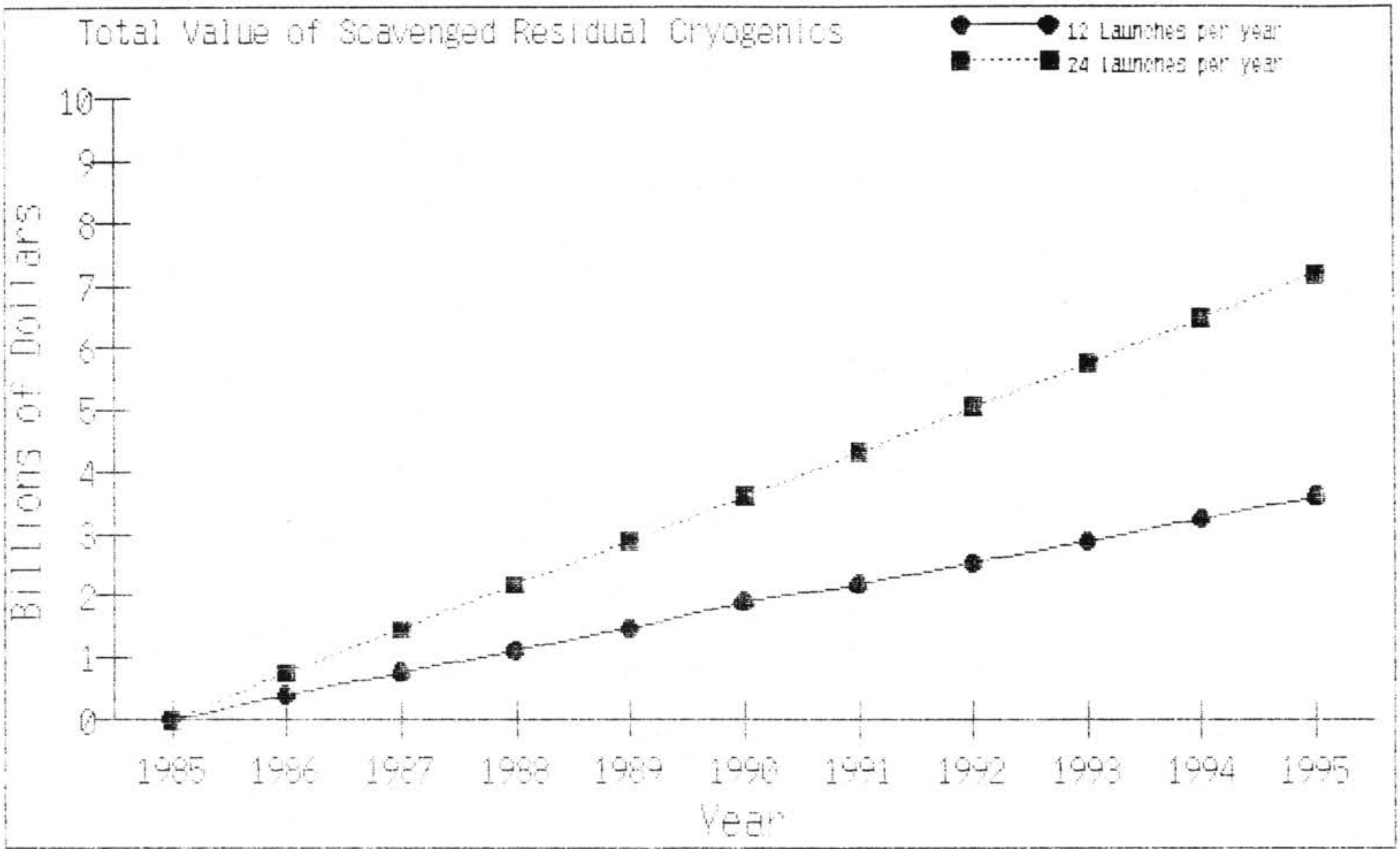
The use of the external tank in the American space program is potentially an enhancement that will have an impact greater than the decision to go to the moon. The reason is that the decision to insert the ET into orbit will make resources available for purchase at a cost far below that of the basic launch cost $2000 per pound. The volume available internally is great. The metals available for use are areospace grade aluminiums. The technical drawings are all in the public domain.

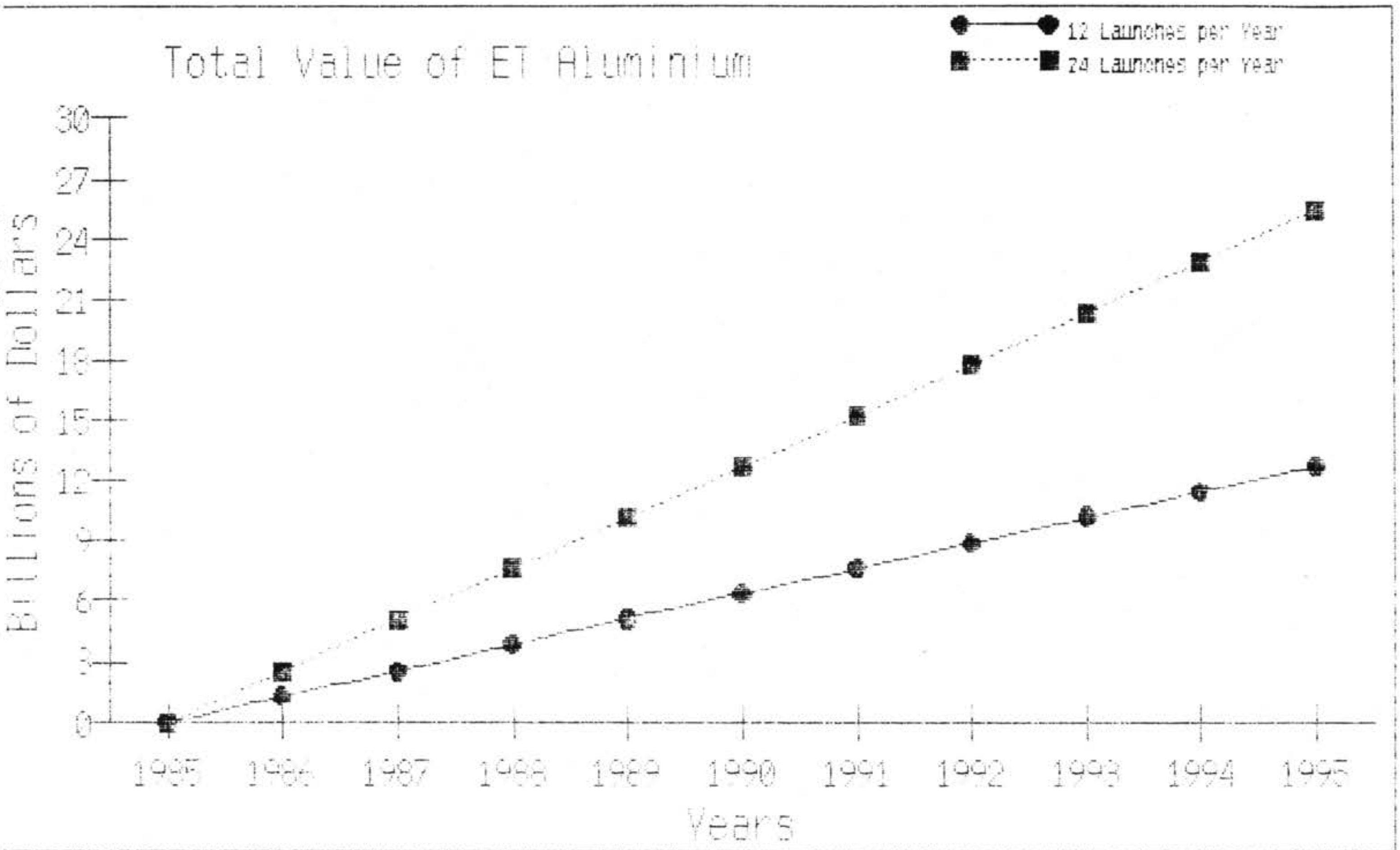
Actual overall return based on the decision to regularly insert the ET are unknown. There are two numbers that may hint at the overall value. They are presented on the graphs to follow. The first number is the value of scavenged residual cryogenics at a rate of 12 and 24 launches per year for ten years starting in 1986. This number is based on the $2000 per pound launch cost. The second number is the value of raw aluminium at 53,000 pounds per ET at the same two launch rates and cost per pound to orbit. Note that each flight which inserts an ET into LEO is worth $30M in residual cryogenies available for scavenging and $106M in aluminium.

Additional returns from the decision to use the ET in space depend on the actual application. Intangibles such as increased commercial interest and business expansion into space due to relativley inexpensive facilities are very difficult to measure. The increased capabilities of a program that extensively uses the ET are also difficult to measure monitarily, but they certainly are extremely valuable in the long run. There is also no way to measure the positive value to the space program that suddenly becomes rich in terms of mass in orbit, structures in orbit, and reaction mass.

The two analyses of actual tank applications involving hardware - the ACC and cryogenic scavenging - have not presented any unpleasant suprises. Both applications appear to be not only possible but are potentially very valuable to those interested in affordable space based operations. At this time there appear to be no unknowns. Other than the materials processing facilities and the aluminium engine, there are no applications that require any great investment of R&D funds to accomplish. With few exceptions, every suggested tank application appears to be possible. These proposed applications also appear to be significant improvements in the capabilities of this nation in space.

The figure that follows lists hardware R&D, and questions to be answered for the future use of the ET in orbit. Most of the major questions have been answered. Most of the R&D is already being done as part of the space station program. Most of the necessary hardware either already exists or is in development for other space-based operations.


Total Value of Scavenged Residual Cryogenics
12 Launches per year
24 launches per year
Billions of Dollars
0
1
2
3
4
5
6
7
8
9
10
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
Year



Total Value of ET Aluminium
12 Launches per Year
24 Launches per Year
Billions of Dollars
30
27
24
21
18
15
12
9
6
3
0
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
Years

The use of the ET in space is limited only by the imagination. Making large massive objects available to customers will open space based operations to every interested party at a reasonable cost. The overall possibilities presented by flying the ET are diverse and extremely valuable to all concerned.

VIII. Recommendations

This report concludes that it is in the best interest of the United States to take the ET into orbit and store it there permanenetly as soon as possible. This will make large scale space operations affordable. Three general recommendations follow:

1. Quickly insert the ET into a permanent storage facility in a relatively high earth orbit.
2. Arrive at a pricing policy that covers the cost of orbital storage and maintenance. Sales cost should cover only the cost of storage. The purchase agreement should simply define ownership issues. The government should not attempt to recover all costs of the last 25 years of spending on the space program through sales of the ET. The intent is to expand space capability. This is best done commercially. It can not be done if the sales costs are set arbitrarily high.
3. Design and fly the ACC as an enhancement of the STS. This will provide additional cargo space at a very low costs.

The external tank is an extremely flexible and potentially valuable enhancement of the space program. There is no other action that can be taken today to expand space capability that will cost so little and provide so much potential. The choice to use the ET will be a welcome addition to the American space program that will pay for itself many times over in the years to come. The tank should be flown to permanent orbital storages for future use early and often.

TABLE OF KNOWNS

	Item	Status
1.	STS direct insertion Trajectory	Already flown
2.	Low pressure thrusters	Under development by JPL and Martin Marietta
3.	ACC	Phase 'B' Study complete Needs launch software
4.	Additional ET Add-Ons	Preliminary study complete
5.	Mylar Blankets	Already flown Sunshade installed on Skylab
6.	Tank Habitation	Preliminary studies complete for Hydrogen and Oxygen Tanks
7.	Tank as a hangar	Preliminary work complete
8.	Inflatables	Preliminary work complete Flown in early 1960s
9.	ET as Spacecraft	Needs further study
10.	ET disassembly tools	Most already flown in STS as satellite repair equipment
11.	Conventional Welding	Experiments in space conducted Actual welding for repairs conducted on Salyut
12.	Conventional Cutting	Experiments in space conducted by American and Soviet

	Item	Status
13.	Solar Cutting	Preliminary work in progress
14.	SOFI Removal	'Cheese cutter' ground tested on SOFI
15.	Induction Furnace	Preliminary work in progress
16.	Grinding/Powdering	Preliminary work in progress
17.	Tether Materials	Short tether already flown Long tether materials under study for Italian subsatellite
18.	Tether Winch	Under study for subsatellite
19.	Tether Dynamics	Under study
20.	Tether Electrodynamics	Under study
21.	Liquid Storage	Experiments already flown
22.	Liquid Handling	Experiments already flown
23.	Military Applications	Under study
24.	Orbital Cleanup	Preliminary proposal only
25.	Market Study	Under study
26.	Contamination/Outgassing	Preliminary study complete
27.	Residual Cryogenics	Preliminary scavenging study complete
28.	Aluminium Rocket	Initial proposal only Likely to involve substantial investment and R&D

Item	Status
29. Mass Driver	Under development - three models already built and operated on the ground
30. Railgun	Under development and testing

I. Introduction

This report was written under a grant from the Space Studies Institute of Princeton, N.J. The scope of the project is to research all the proposed on-orbit applications of the External Tank (ET) and write a report detailing the results of the research. The report is intended first for presentation to the National Commission on Space and second to provide an overview of current and past External Tank applications studies. The list of references in the back of the report, with the listing of those contacted during the research, will hopefully provide a source of additional information to those interested in the ET and its applications in space. I wish to thank all those listed on the pages following for their time, help, patience, and comments in completing this work.

II. Why do we need the External Tank?

The ET is the only portion of the Space Transportation System (STS) currently expended on each flight. A typical launch will retain the ET for the SSME burn of over eight minutes and then jettison it for a controlled reentry in either the Indian or Pacific Ocean. An alternate launch trajectory called a direct injection can allow a shuttle to take an ET, an average of 15,000 pounds of residual cryogenics (16), and up to 2,000 pounds additional payload into a typical space station orbit (68). In other words, it costs nothing to deliver a 69,000 pound, factory tested, aluminium pressure vessel into low earth orbit (LEO). In an era of launch costs running about $2,000 per pound to LEO(69), this is clearly a resource worth utilizing in future space based operations. Each and every shuttle launch can deliver a tank to orbit. This can amount to several hundred tanks over a ten year period. The economic analysis of tank utilization on-orbit typically compares costs between a ground built and launched structure and a similar structure built on orbit out of the ET or parts supplied by the ET. These studies alone make ET applications on-orbit extremely attractive. There are additional benefits that the ET can provide in orbit which can not be provided by a ground based item. These make the ET a better choice for almost every manned space operation currently envisioned. Why do we need the ET? We need it because it will provide the leverage necessary to make future space based operations,industry, and science far cheaper and easier than would be possible without the ET.

III. Current interest in the External Tank

There are several groups interested in possible orbit applications of the External Tank. The interest spans the entire spectrum of all those interested in doing anything in space from hard science to DOD to private industry. The interest in the tank is also international, with papers proposing ET based space stations written by British and Czechzslovakian authors in the last six years (43, 70). Aeritalia has retained the services of a consultant working on the possibilities of ET applications on-orbit for a few years (75). A typical scientific interest is the Smithsonian Observatory which is looking into the possibilities of constructing a variety of ET based telescopes (32). DOD is interested in the ET due to its capability to carry large diameter payloads and serve as targets for SDI experiments. NASA is interested in the ET because they have to answer the question "Why don't you use the External Tank in space?" posed by members of congress frequently. They are also interested in it as a way to get more "bang for the buck" out of money spent in space. In other words, the ET is a way to cheaply conduct a very large expansion of a space based operation with minimal cost to the public. Commercial interests are looking at the tank because it provides a way to conduct possible future manned private space operations at about the same cost as two or three generic communcations satellites (17,57, 58). It becomes possible for a company to fly their own large platform cheaply. This increases national interest in space and involves a larger segment of industry in space. It should create jobs and tax revenues due to the business expansion. Companies such as 3-M, Johnson & Johnson, Wyle Labs (17), Ford Aerospace (88), and Martin Marietta (25) all either have a present interest or possible future interest in the ET on-orbit. The Space Studies Institute is interested in the tank as a way to make the construction of Solar Power Satellites (SPS) and space-based habitats come about. There are additional private groups and consortiums interested in flying the tank. The interest in the ET continues to grow. This interest should continue to grow as long as launch costs remain high and payloads remain constrained by the dimensions imposed by the Shuttle cargo bay.

IV. History

Interest in the spent stages of launch vehicles has been a part of the American manned space program since the days of Gemini. The USAF proposed the Manned Orbiting Lab (MOL) program in the early 1960s as a DOD space station. This utilized the upper stage of a Titan booster and a modified Gemini capsule as the space platform. This program had crews selected before it was cancelled. The Skylab program following Apollo utilized the Saturn V third stage as the heart of a space station. The program used Apollo hardware intended for lunar flight as a space platform. In the planning stage, there was serious consideration given to actual on orbit construction of the Skylab. This did not happen because a Saturn V booster came available to launch a ground constructed platform and because there was concern that Hydrogen leaking out of the spend third stage insulation (inside the tank - not outside, like the ET) would pose a fire hazard. The American space program is historically very good at adapting hardware from the intended to a new use. On orbit use of the ET is nothing new from this perspective.

V. Costs and ramifications of ET applications

As mentioned previously, the ET is attractive primarily due to launch costs and capabilities that do not exist in other launch systems. For example, the scavenging of residual cryogenics from the ET alone can give a program savings of $3.5 billion when compared to the cost of launching the same cryogenics in the payload bay to support an Orbital Transfer Vehicle (OTV) operation (29, 32, 69). A partial disassembly of the ET on-orbit and construction of a hangar out of the hydrogen tank will eliminate the need to design and launch a maintenance structure in the orbiter. The savings here is the difference between on-orbit construction using the ET and the design, launching, and on-orbit construction of a specialized structure.

The capabilities that do not exist with current or planned operations that the ET can provide are limited only by the imagination. These have been broken down into the following areas:

1. External Tank Description - What properties of the ET can we take advantage of? How is it put together?

2. Tin Can Uses - What can you use a 33 ton, 150 feet long, 27.5 feet diameter, pressure tested, aerospace grade, aluminium can for?

3. ET as a Fuels Resource - The use of residual cryogenics available in the ET. What value is a rocket engine that burns powdered aluminium? Can you make the ET itself into reaction mass for OTVs?

4. Structures - What can you do with a structure that carries all the loads imposed by two Solid Rocket Boosters plus an Orbiter and carries over 1.5 million pounds of cryogenics at liftoff?

5. Tethers - How can a tether be used in concert with an ET to expand capabilities in space?

6. Miscellaneous - What science can you do with a very large bottle for biology? What advantage can be taken of a potential payload diameter of 27.5 feet?

The capabilities provided by the ET that are not available elsewhere include large relatively inexpensive masses of aluminium (in excess of 53,000 pounds per tank (56)) in earth orbit, large factory tested pressure vessels, large diameter payload capabilities with small enhancements of the ET, and large enclosed volumes ready for use in orbital storage until needed.

The ramifications that tank utilization can have on the space program in the future are significant. At one stroke, the program changes from one based on limits imposed by high launch costs and relatively small launch and orbital volumes to a program which has started to make use of resources found in space. In this context, the ET is a space based resource which is available for use at at very low cost. This resource can be adapted to a variety of specialized uses depending on the needs and imagination of the user. This resource is also something that has finely detailed engineering drawings available to the general public and is constructed out of Aerospace/MILSPEC grade materials (20). This is clearly a very attractive resource.

VI. Problems and Solutions

At the present time, there are several obstacles to the proposed use of the ET in orbit. The most significant problems are orbital lifetime (Skylab syndrome), and potential contamination (foam outgassing). The Skylab syndrome, which is tied to the orbital lifetime of the tank, is driven by the desire not to drop large massive objects in the earth in an uncontrolled manner. This is perceived as the primary problem in the use of the tank on-orbit. As a result of the altitude of delivery and its size, the ET has a finite orbital lifetime due to aerodynamic and solar drag. Any program which will rely on the tank has to plan to expend reaction mass of some sort in order to keep the tank in orbit. Orbital lifetimes can be as long as years or as short as days depending on the altitude the ET is released, the attitude at which it is stored, and the activity of the sun (56). There are several tradeoffs which can be utilized to solve this problem. First, the residual cryogenics can be used to power low thrust gas burning hydrogen/oxygen thrusters which can boost the ET up to a very long lived orbit over the period of a few days (46). If this is done, little to no recoverable cryogenic residuals will remain in the ET, but the ET will be in a very long lived orbit. Second, the orbiter can attach a tether, set up a libration with the tank, release at the proper point, and send the ET into a much higher orbit and deorbit the shuttle. There are two problems with this technique. First, it rotates a billion dollar spacecraft and a massive ET around one another on the end of a rope. Second, it has never been done on this scale before.

Contamination is the second major problem with the ET. The entire ET is coated with Spray-On Foam Insulation (SOFI) which will outgas on orbit in space. This pollution may not be tolerable in the evironment inhabited by the space station. A potential fix is to strip the foam off the ET after release in orbit. Most of the foam can be stripped by the equivalent of a hot-wire cheese slicer. The remainder can be polished off by leaving the ET 'hanging in the breeze' over the period of a month or two exposed to the molecular oxygen present in the proposed orbits (14). There are other problems with the ET on orbit. Having more mass and volume available than is required for currently planned operations in orbit are factors. The partial disassembly of a tank has never been attempted in space and needs to be demonstrated. These problems are all solvable and in some cases may not be problems at all but advantages.

VII. Conclusions

It is clearly in the national interest to do whatever is reasonable to better utilize equipment already purchased. With the External Tank, we have the potential to provide for an enormous expansion in space capabilities for minimal expenditures - Extremely Low Cost and Extremely High Return. With this in mind, the following suggestions are made:

A. Initiate immediately a program to deliver the ET into orbit. This program should plan for on-orbit maintenance of the delivered tanks and the possible inclusion of ET based structures and modules in the US Space Station.

B. Arrive quickly at an ownership and sales policy. Suggest sales price be set to reflect ONLY the cost of operating the ET orbital storage facility, not an attempt to recover the costs of the entire STS. The rationale here is twofold. First, the ET is essentially a salvaged article. R&D funds expanded were spent in making the STS operational, NOT in using the ET. Second, the ownership issue should be solved quickly and early. This will encourage private investors who want to purchase inexpensive space capability and not feed lawyers. The precedent for this issue comes from the experience with the KC-135. This aircraft was constructed to fill a defense need. The sale of aircraft of the same or a similar design was not constrained by any attempt to recover the cost of monies already spent. Boeing and other American aerospace companies sold no small number of these KC-135 class aircraft to airline companies worldwide. The net result was an unexpected creation of new jobs, new industries, and the generation of more tax revenues. The utilization of the ET will have a similar impact.

The External Tank is a very important item in the future of this nation in space. It provides the leverage necessary to make large scale space based operations of almost any kind affordable and therefore able to be done privately. The possible applications of the tank on-orbit are constrained only by the imagination. The ET should be stored in orbit for future use as soon as possible and the sales and ownership questions settled. This action will likely have an impact on this nation's future in space comparable to Apollo.

ET Project - Tank Information

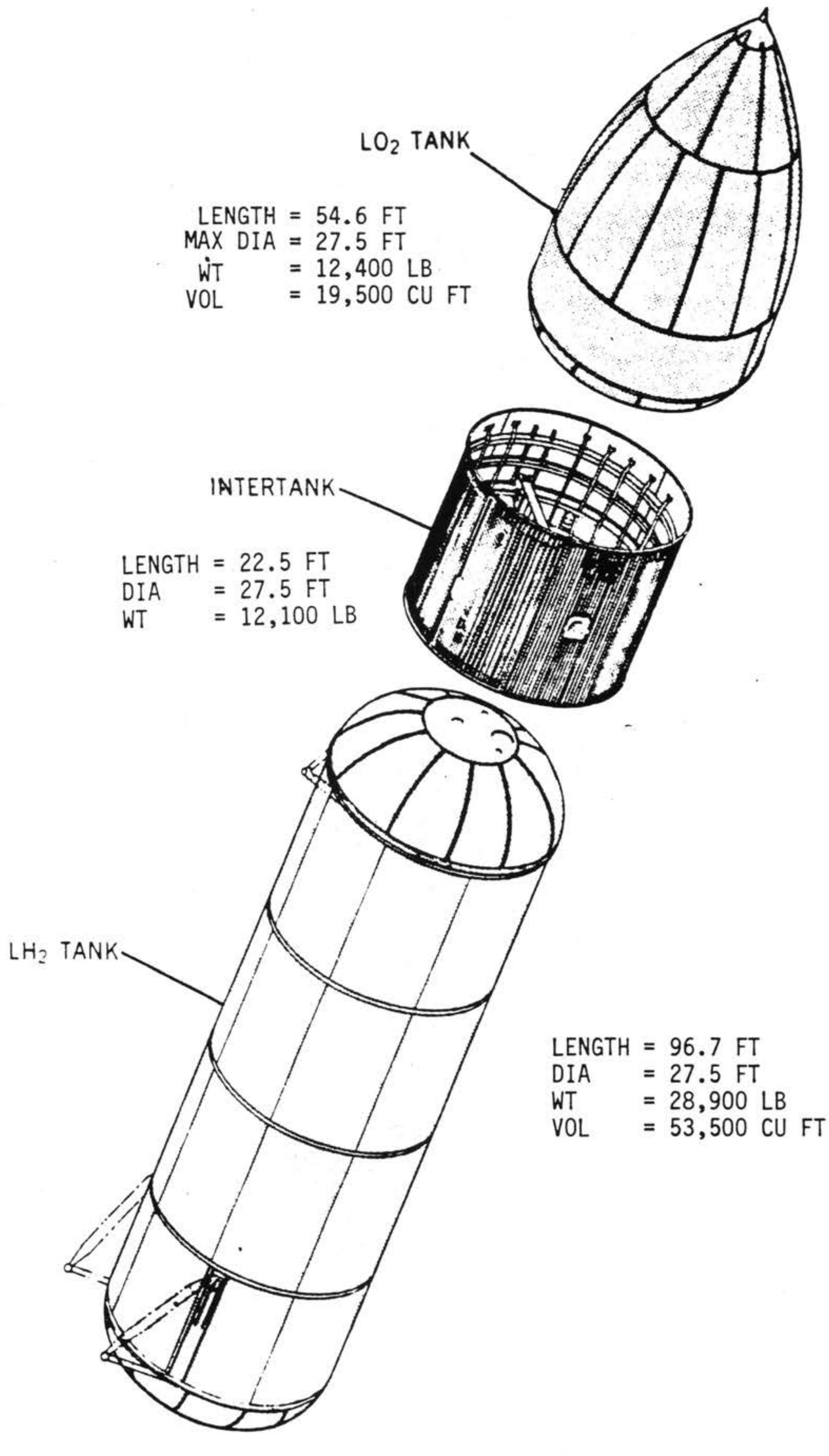
I. External Tank Description

The External Tank of the STS is designed to fill two primary needs. These are to safely carry sufficient cryogenics to deliver the orbiter into Low Earth Orbit (LEO) and to serve as the structural heart - the strongback - of the STS during the launch phase. The basic empty weights, volumes, and dimensions are detailed in the first figure.

The tank is constructed in three primary segments which are the hydrogen tank, the intertank, and the oxygen tank. The oxygen tank rests on top of the stack. It is constructed of aluminium in four sections and includes internal slosh baffles. It is bolted to the intertank section which carries its' loads in compression during flight. The intertank is the primary strength member of the tank. It is unpressurized and constructed using a skin stringer and ringframe arrangement. It also carries a beam which carries the thrust loads of both solid rocket boosters (SRBs) during flight. The intertank is bolted to the top of the hydrogen tank, the largest section of the external tank. The hydrogen tank is designed to carry the required liquid hydrogen during launch. It also carries the loads imposed on the stack by the orbiter engines (SSME) during launch. The entire tank is covered with Spray-On Foam Insulation (SOFI) which serves primarily to prevent ice buildup on the tank before launch and to prevent excessive boiloff of the cryogenics. Typical depth of the insulation is between one and one and one half inches (1-1 1/2"). There are also additional items attached including range safety hardware, feedlines, sensors, electrical lines, tumble valve, and venting systems (63).

II. Current ET Operations

After construction and testing, the ET, with low pressure in both the hydrogen and oxygen tanks, is shipped by barge to the launch site. The hydrogen tank is pressure tested to over 36 psi. The oxygen is pressure tested by filling it with water at the factory. Neither can tolerate an outside pressure differential greater than .2 psi. (48) Shipping it



EXTERNAL TANK STRUCTURE

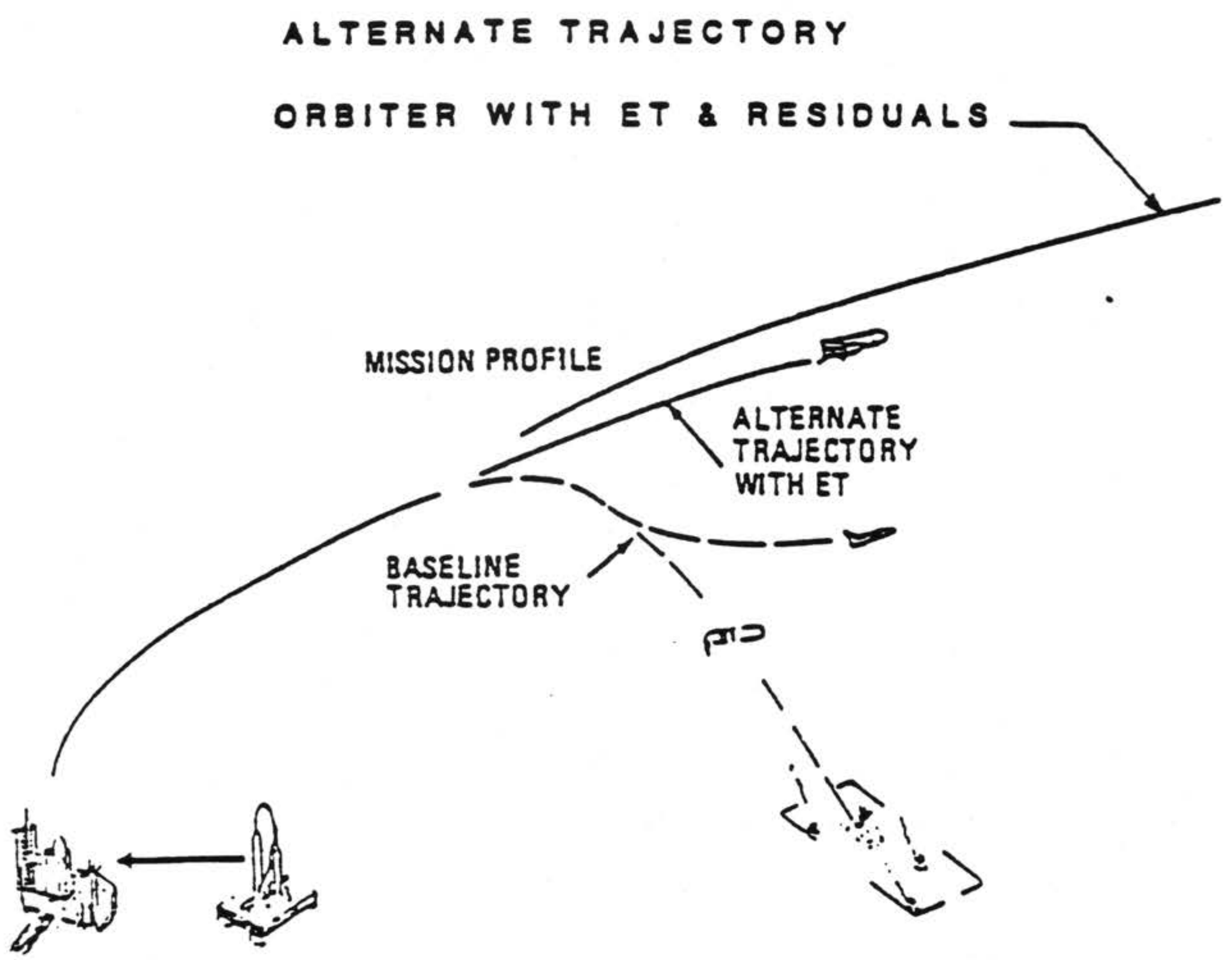
pressurized also keeps the interior clean. The tank is then checked out, attached to the appropriate stack and launched in normal sequence.

A typical launch inserts the orbiter and ET into a very low earth orbit where the tank is jettisoned to reenter somewhere over the Indian or Pacific Oceans (56). The orbiter then conducts an OMS burn to loft itself into the desired orbit. The tank is jettisoned with over 98% of the energy required to keep it in orbit. It is important to control the reentry of the tank to insure that it comes down in an unpopulated area. There is an alternate trajectory for launch called a direct insertion. This trajectory has been flown successfully with the ET splashing down near the Hawiian Islands. If the tank is retained even longer and taken into orbit, the orbiter can deliver the tank, orbiter payload, and additional orbiter payload into all possible STS orbits. It attains this capability by flying a more efficient trajectory and using the more efficient SSMEs to put it all the way into orbit. The following figure is a comparison of Shuttle performance to orbit without the ET, with the ET, and with an ET enhancement called the AFT Cargo Carrier (ACC) which will be discussed later. It is important to note that if the ET is taken to orbit, this action alone improves the STS payload capability by as much as 2,000 pounds to orbit (56). At an average launch cost of $2,000 per pound (69), this is a substantial enhancement of the STS capability.

III. The ET on Orbit - Problems and Solutions

Taking the ET into orbit presents several opportunities and capabilities that we do not yet have. It also produces some additional problems. The opportunities available are related to the mass and size of the tank itself. The capabilities are related to things that can be done with the tank on-orbit. The primary problem is related to safety considerations. All will be discussed in the following section.

The size and mass of the external tank on-orbit compare favorably with past and proposed future orbital facilities. The 53,500 cubic foot volume of the hydrogen tank alone is far larger than any facility flown or planned. It is more than twice as large as the Skylab at 18,300 cubic feet (70). It is more than five times the volume of the proposed Space Operations Center (SOC) module of 7,100 cubic feet (75). The volume available in the oxygen tank at 19,500 cubic feet is also larger than all the above mentioned facilities.



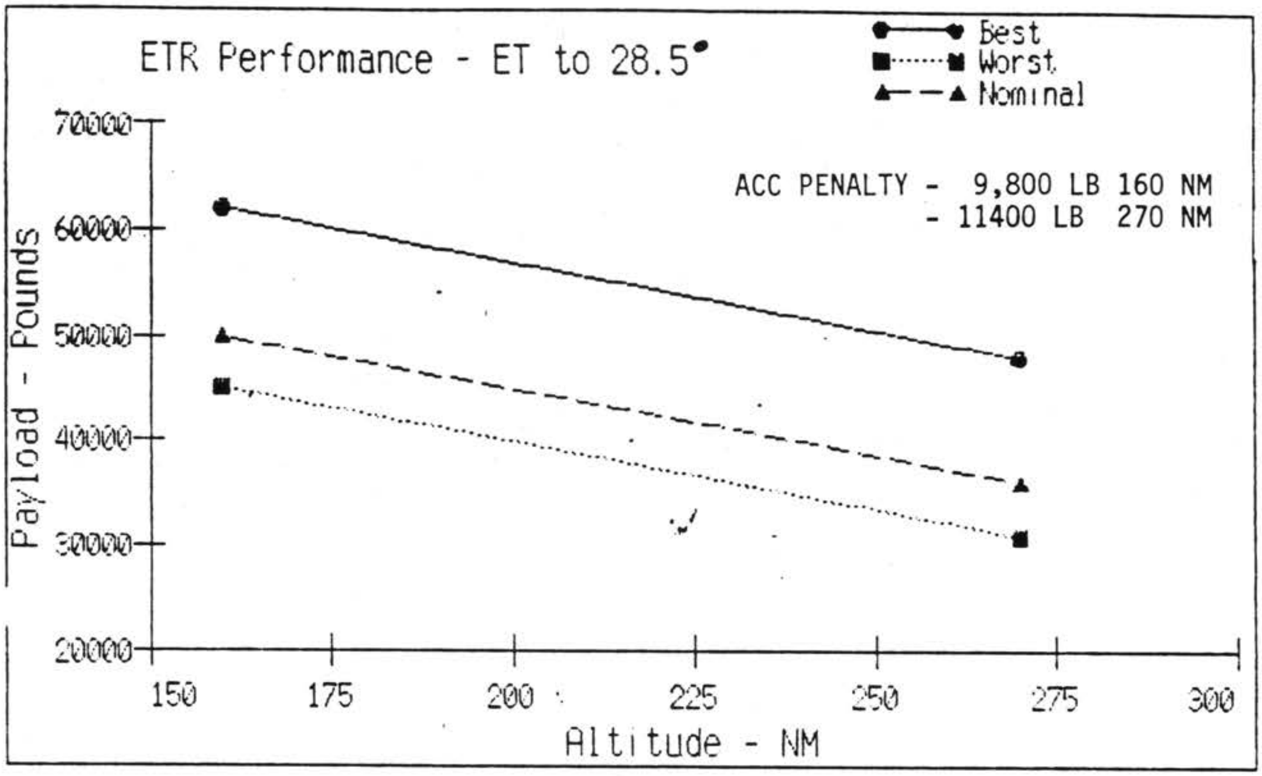
SPACE SHUTTLE ORBITAL PERFORMANCE DATA (160NM 28° INC)

CONFIGURATION	PAYLOAD (LBS)
ORBITER ONLY	54,000
ORBITER WITH ET	56,000
ORBITER WITH ET/ACC	44,000
ENHANCED STS WITH ET/ACC	62,000

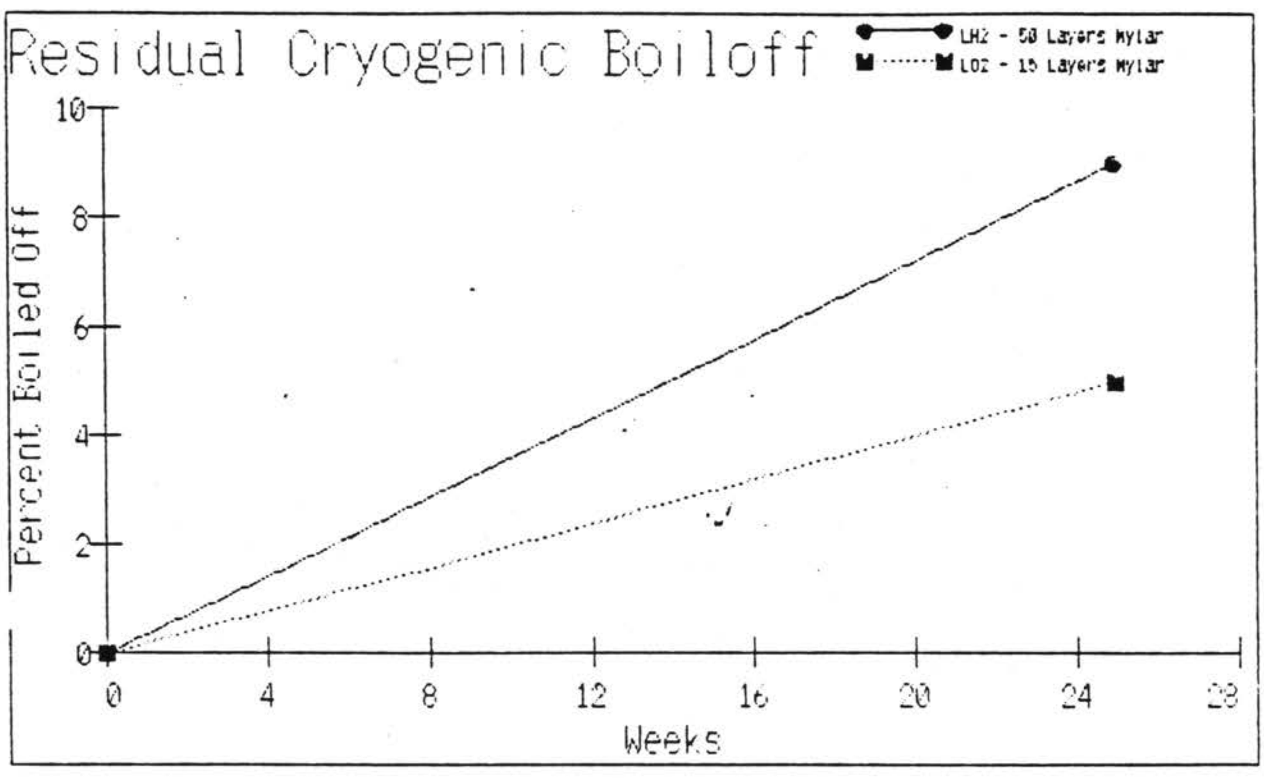
These volumes can be accessed through three foot diameter inspection hatches in the respective tank domes. The domes can also be completely removed by pulling the attachment bolts if the desire is to open the entire end of the tank.

The mass of the tank is also an advantage. At an average mass of 69,000 pounds apiece, the tank can provide the inertia and strength required for large scale operations in space. Once released, the tank will assume a gravity gradient stabilized attitude with the long axis pointing at the center of the earth (56). A telescope mounted on this platform could rely partialy on the mass and inertia of the tank itself rather than an active three axis stabilization system. The tank can be used as a workbench or a strongback in orbit. This concept utilizes the actual structural strength of the tank itself as a construction platform. The construction of large space structures need not be based on specially designed lightweight members that could not support their own weight on the surface.

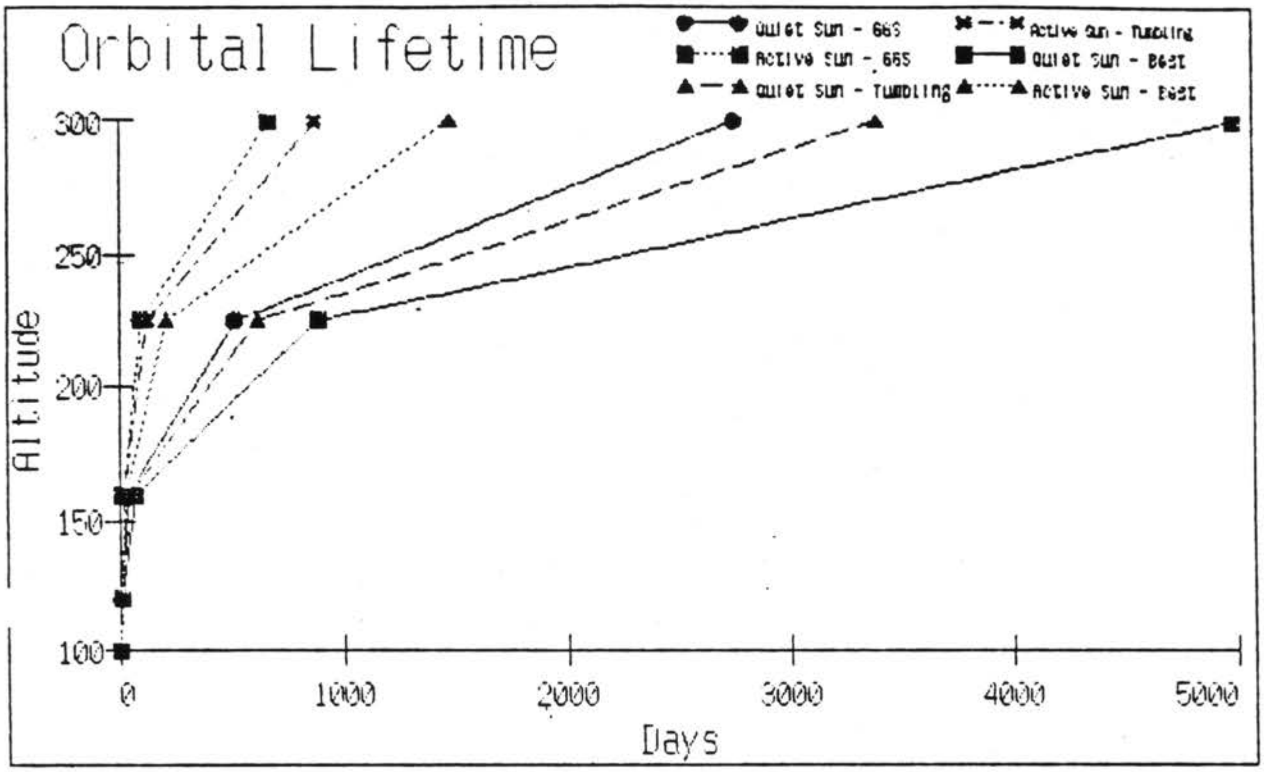
Due to reserve, pressurization, and ullage requirements, the tank should contain an average of 15,000 pounds (5,000 to 40,000 pounds) of residual cryogenics when it arrives in orbit (16). This liquid hydrogen and liquid oxygen can be scavenged from the tank shortly after launch for a variety of uses on-orbit (69). These residuals also pose a safety problem which must be addressed. The current use of the liquid oxygen tank pressurization gas is to tumble the tank after it is jettisoned for reentry. The on-orbit problem is that there is concern about the boiloff rate and possible overpressurization and rupture of the tank. There are several ways to deal with this problem. The first is to scavenge the residuals relatively early with a set of catch tanks located on the aft end of the tank. This can also be done with the required equipment located in the payload bay of the orbiter but is less desirable because it uses payload bay space that can be better sold to customers. A second method would be to install a heat reflector to keep the sunlight off the tank. The first Skylab crew did this to the Skylab to make if habitable. The ET could be made a better storage container for cryogenics by wrapping it with mylar blankets to retard boiloff (46). The next figures detail boiloff rates for residual cryogenic propellants.

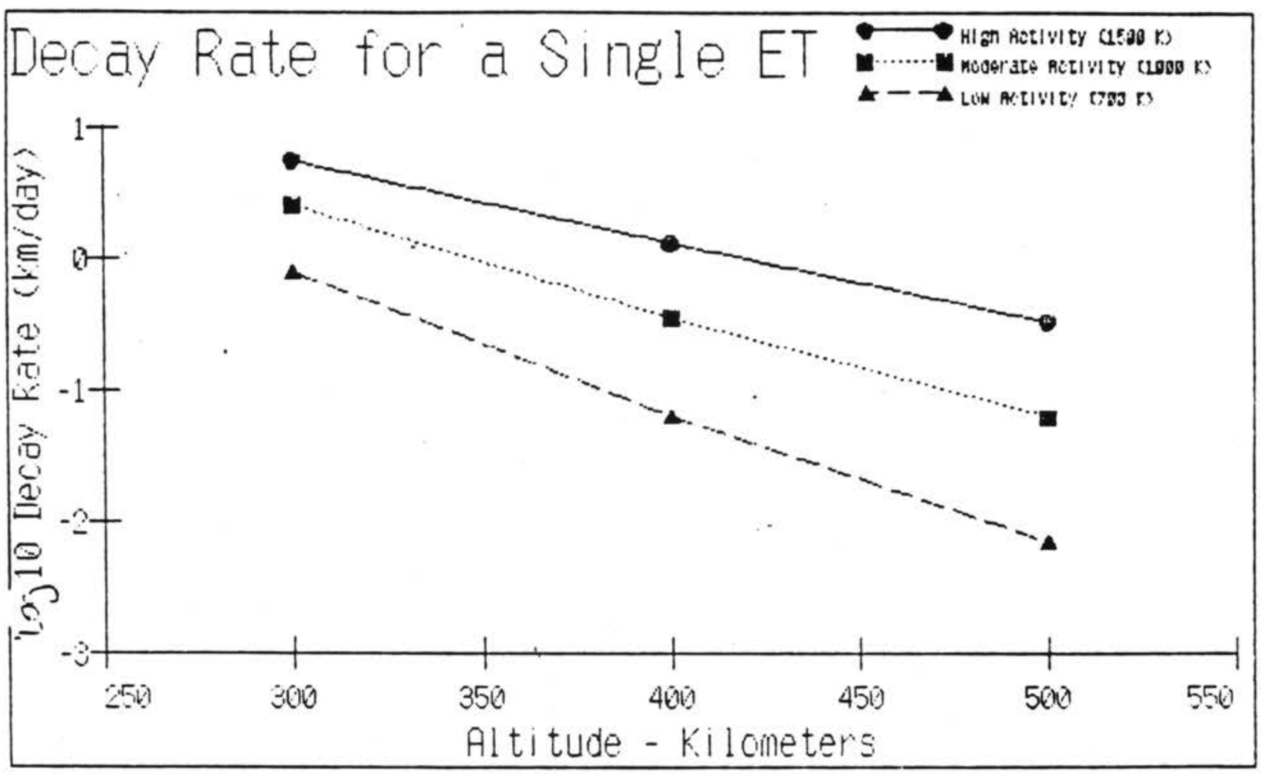


ETR Performance - ET to 28.5°
Best
Worst
Nominal
ACC PENALTY - 9,800 LB 160 NM
- 11400 LB 270 NM
Payload - Pounds
70000
60000
50000
40000
30000
20000
150
175
200
225
250
275
300
Altitude - NM



Residual Cryogenic Boiloff
LH2 - 50 Layers Mylar
LO2 - 15 Layers Mylar
Percent Boiled Off
10
8
6
4
2
0
0
4
8
12
16
20
24
28
Weeks


Orbital Lifetime
Quiet Sun - 66S
Active Sun - 66S
Quiet Sun - Tumbling
Active Sun - Tumbling
Quiet Sun - Best
Active Sun - Best
Altitude
300
250
200
150
100
0
1000
2000
3000
4000
5000
Days


Decay Rate for a Single ET
High Activity (1500 K)
Moderate Activity (1000 K)
Low Activity (700 K)
Log10 Decay Rate (km/day)
1
0
-1
-2
-3
250
300
350
400
450
500
550
Altitude - Kilometers

A third method involves trading the cryogenics as they boil off for orbital altitude. There have been several proposals for low thrust, gas burning hydrogen - oxygen rocket engines for station keeping and orbit raising. The engines proposed by Martin Marietta are 1,500 lbf thrust with a specific impulse (Isp) of 375 seconds (46). A proposed arrangement of four of these engines mounted on the intertank as thrusters using the residuals left. The tradeoff here is between orbital lifetime desired and the amount of scavenged cryogenics desired.

As was demonstrated by the reentry of Skylab, the orbital lifetime of large space objects is often far less than predicted. One of the primary considerations with taking the tank into orbit is keeping it there. The orbit of the tank will decay over time due to aerodynamic drag and effects of the solar activity. The desire is to put the tank into the highest possible orbit. Cross section 'into the wind' is also a factor. The gravity gradient stabilized tank with the 'nose down' attitude is in the worst possible attitude for long orbital lifetimes because it presents the largest area to the wind. The best attitude is either end into the direction of motion. The following graphs detail calculated orbital lifetimes for a single external tank in three different storage modes (56).

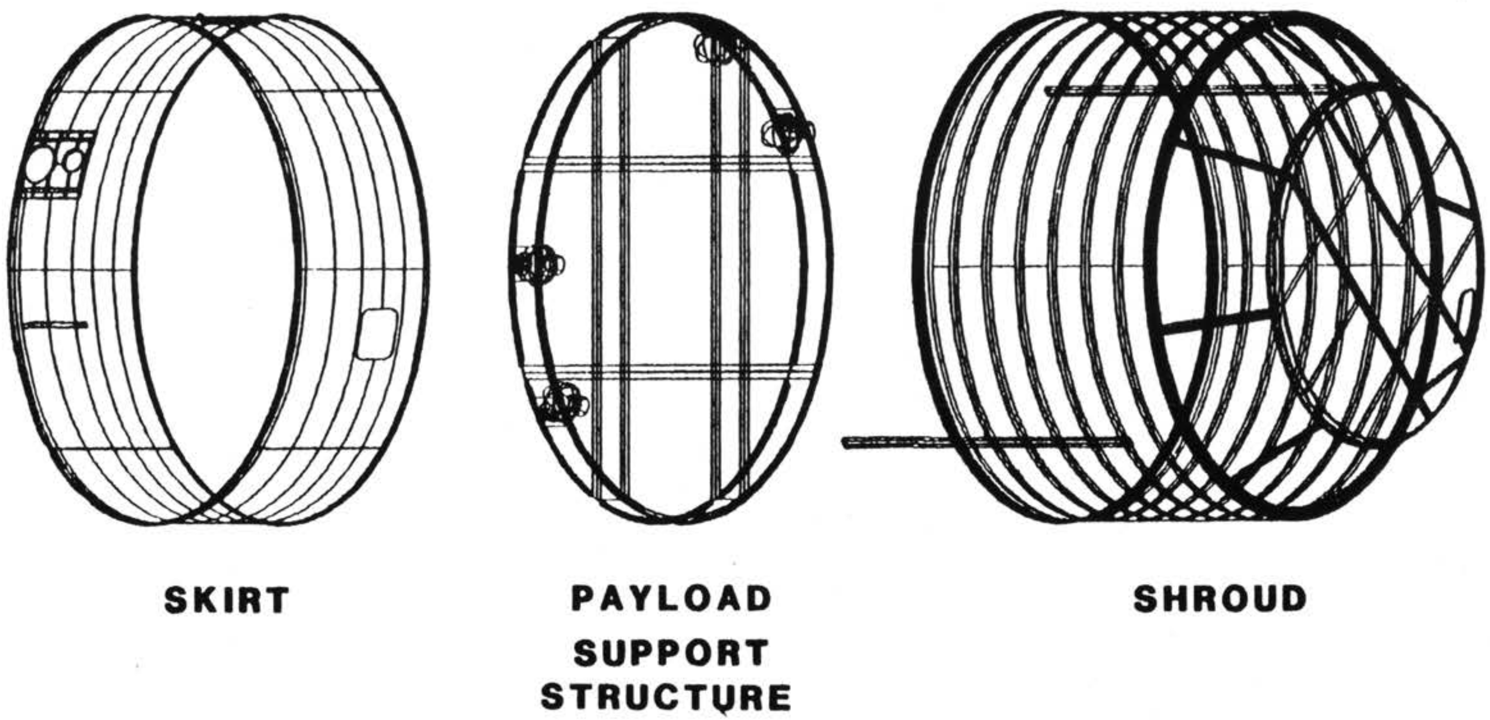
It is particularly important to control the orbital altitude of the tank if brought into orbit. The reentry point and impact footprint are extremely difficult to predict for an uncontrolled reentry (56). The leads to a requirement to reenter the tank after launch, reenter the tank after it has served its pupose on orbit, or to keep it in orbit using active measures. Thus, any plan which proposes external tank applications on-orbit must address this issue. Some form of active propulsion like small thrusters or an alternate form of orbital maintenance such as momentum transfers involving tethers or the low pressure cryogenic boiloff thruster needs to be used. This is not a particularly difficult problem to solve. It is however, a fact of life for every structure in earth orbit. There are current studies of appropriate propulsion for keeping the NASA space station in orbit.

The last problem with the External Tank in orbit concerns outgassing from the SOFI on orbit. This amounts to an unwanted fouling of the environment and the equipment in the vicinity of the tank. Outgassing has been called the fatal problem with the use of the tank on-orbit (14). Like most problems in the past that have been refered to as fatal flaws, this is not insoluble. Preliminary calculations suggest that the SOFI will deteoriate at a rate of about 0.8 grams per second for the entire ET (3). This rate is purely an order of magnitude prediction subject to change with further investigation. Outgassing may be a problem to vehicles and structures in the vicinity of the ET. Possible solutions include bagging the tank in a mylar blanket which will retard the rate, applying metals by vapor or liquid deposition to the outside of the tank on orbit, removing the SOFI from the tank, or keeping the tank based structures lower in orbital altitude than the rest of the operation by the use of tethers (14). The ramifications and the magnitude of this problem warrant further investigation as tanks are proposed for orbital applications.

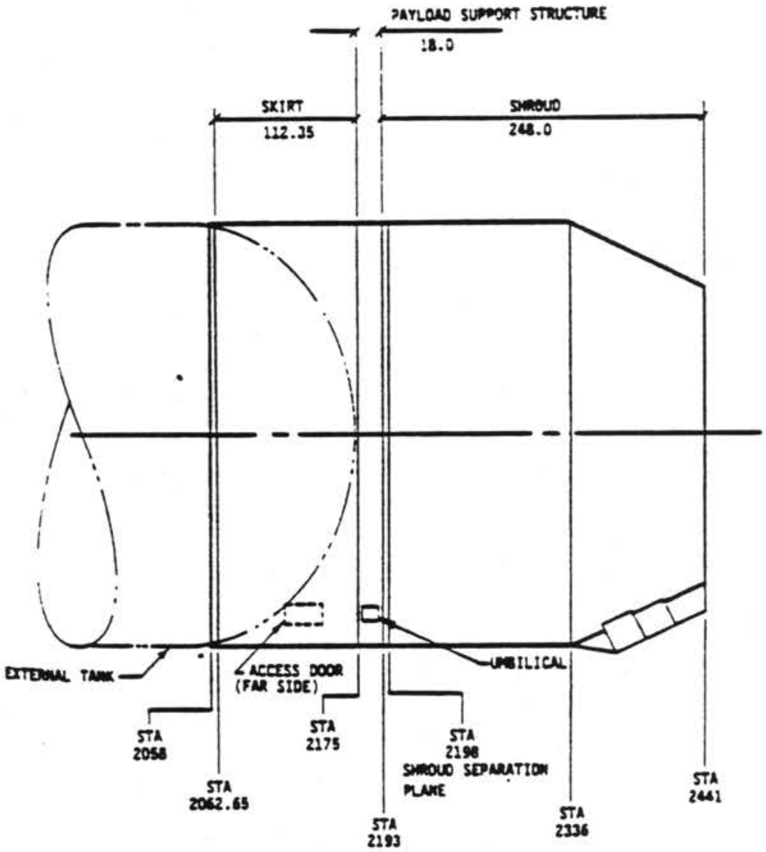
IV. The Aft Cargo Carrier

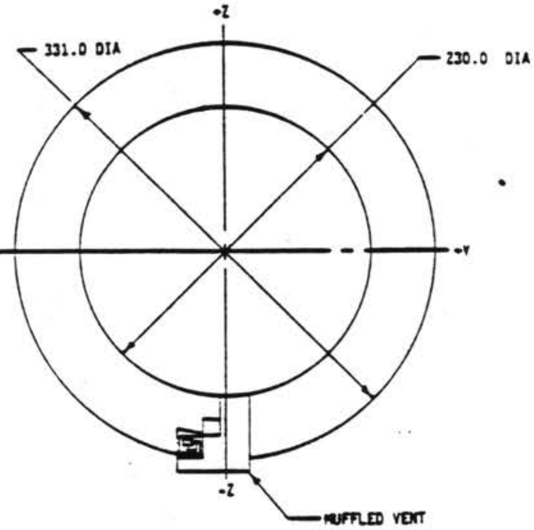
The first actual enhancement of the STS is likely to be the Aft Cargo Carrier (ACC) (4). The ACC is detailed in the figure below. It is basically a cargo volume constructed similar to the ET components using the same tooling and bolted onto the bottom flange of the hydrogen tank. There are three basic advantages to the ACC. The first is that it provides a volume nearly equivalent to the cargo bay of the shuttle that is not constrained by a diameter of 15 feet. Its volume of 9,100 cubic feet compares well with the orbiter cargo bay of 10,600 cubic feet. The ACC dimensions of 27.5 feet in diameter and 20 feet in height allow large diameter relatively low mass payloads to be flown without the constraints imposed by the 15 feet diameter orbiter cargo bay. A typical ACC weighs near 14,000 pounds (4). It consists of a skirt which connects to the ET, a payload support structure and a shroud and is insulated for protection from the SRB plumes and blast effects. Payload penalty to orbit for an ACC is from 9,800 - 11,400 pounds (68). This is below the actual ACC weight as a result of shroud jettison after SRB separation. Center of gravity problems during flight have been addressed and do not appear to be a problem.

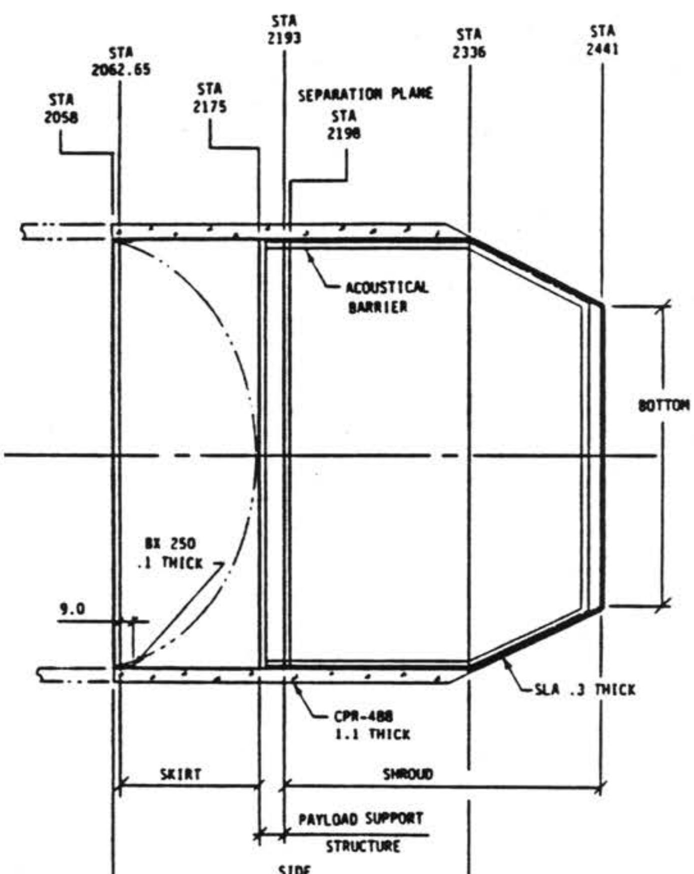
The beauty of the ACC is that it provides another cargo volume at a minimal cost. This is important to the STS program because it helps remove a payload constraint. The orbiter imposes two constraints on payloads. These are volume and mass limitations. The mass limitation can not be changed without changing actual orbiter performance. The volume constraint can be

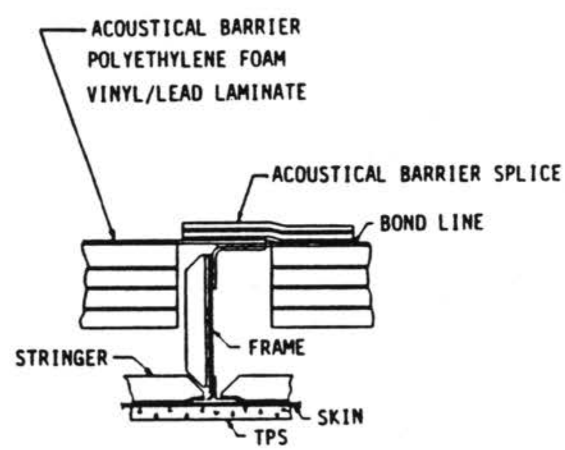


THE AFT CARGO CARRIER









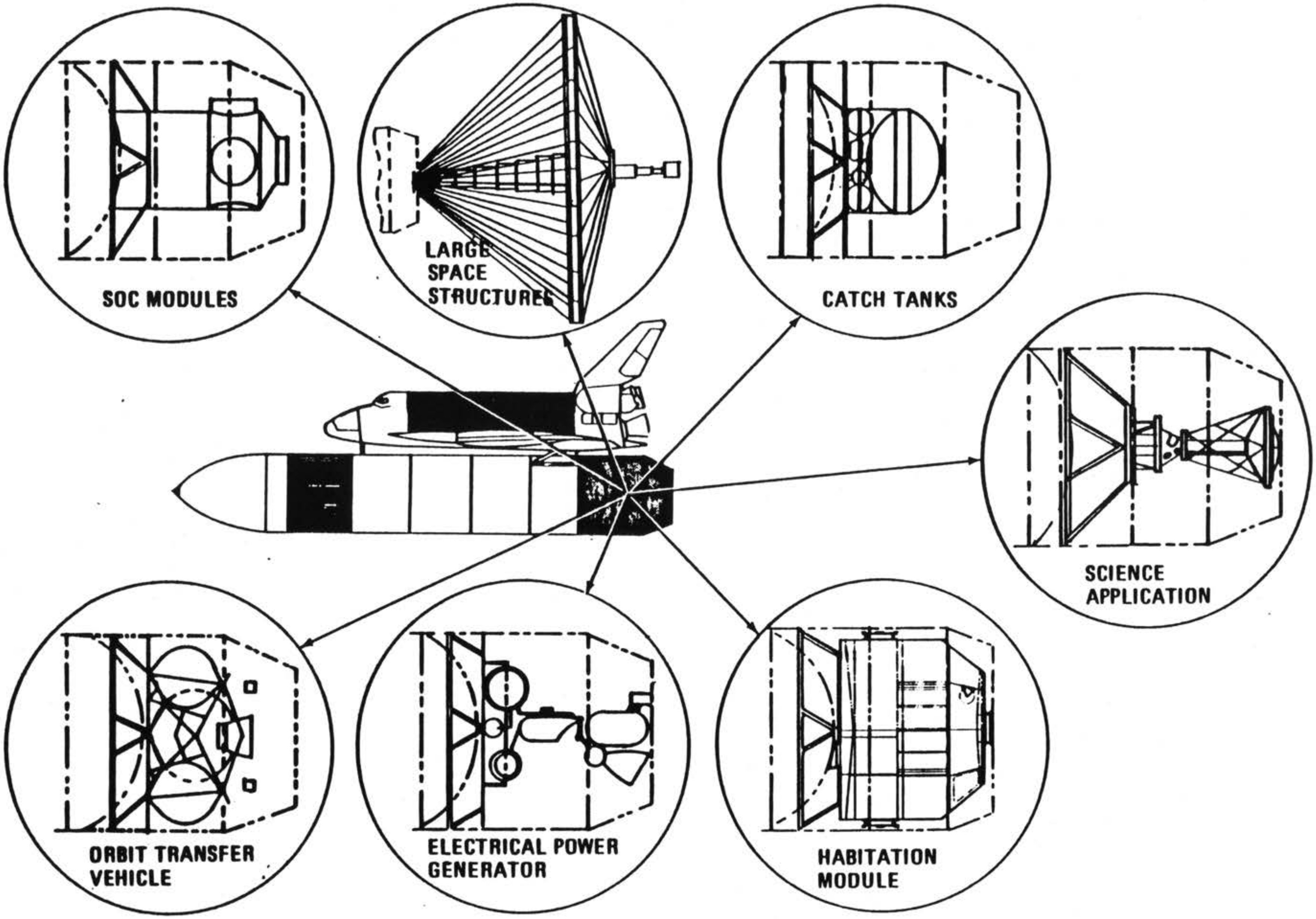
ACOUSTICAL BARRIER SPLICE

DETAILED AFT CARGO CARRIER

changed by the addition of the ACC. If the STS is launched carrying less than the maximum mass, this leaves excess mass to orbit capability which may be exploited by mission planners using an ACC. This could be payload such as communications satellites that will generate additional revenue for that particular sortie. This would allow non-revenue generating sorties such as planetary missions, science missions, DOD missions, Spacelab missions, or Space Station vists to generate revenue that they would not be able to do otherwise. It also gives the mission planner and scheduler an option that can be used to recover from the impact of a mission cancellation. If a flight is cancelled, rather than impact the entire flow for years to come by bumping payloads from flight to flight, the planner could fly a few loaded ACCs on appropriate future missions to catch up.

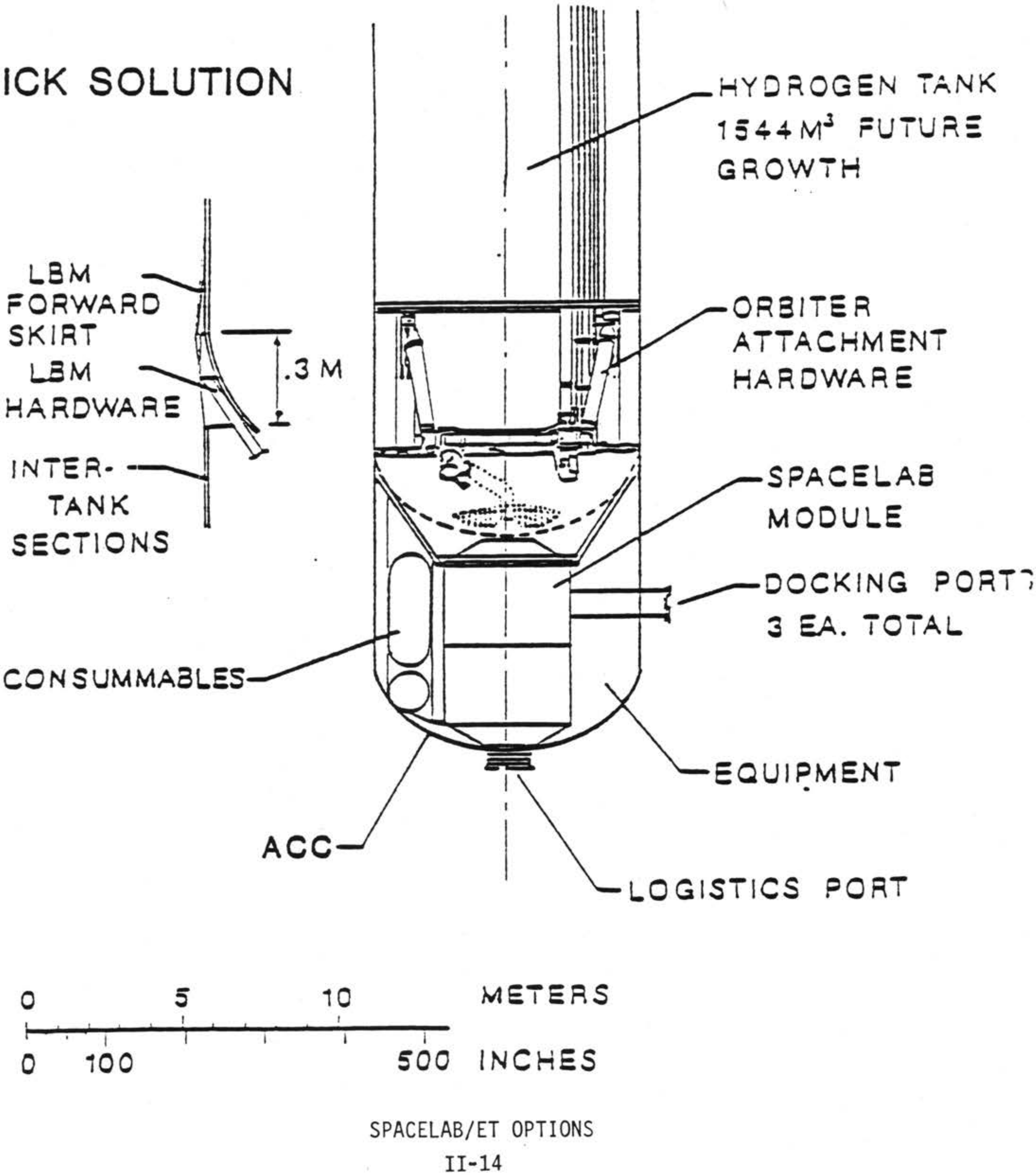
The ACC can be configured to carry almost everything that can be currently carried in the cargo bay within the limits of a length of 20 feet (26). If a payload is designated for an ACC mission which makes the ACC the primary cargo carrier, the volume remaining in the cargo bay can carry additional payload. The figure that follows shows a cross section of possible ACC payloads including Space Station modules, storm shelters, satellite modules, Centaur G booster, wide OTVs, cryogenics scavenging, large diameter mirrors and antennas, service modules, lifeboats, entry ports for ET based structures, and shuttle mission enhancements. A proposed ACC payload includes the servicing structure for the Space Telescope. A typical mission scenario would be to launch the Orbiter, deploy satellites from the payload bay, retrieve the service structure from the ACC with the RMS while the rendezvous with the Space Telescope is conducted, and conduct the necessary servicing of the telescope (45, 48). The ACC can also carry thrusters in the skirt which can be used to either boost the tank into a higher orbit or deorbit it to a cotrolled splashdown in the ocean.

The ACC is designed for minimal impact in current STS operations. It can be constructed using available tooling within the Michoud facility. It has minimal impact on the tank itself and the interfaces between the ACC and ET are relatively simple. The largest impact on the orbiter will be adapting the flight software to an ACC mission. Total cost of the ACC is around $150 - 250 million (4, 48) and it can be flown within three years of the decision to buy. Like the rest of the ET based applications studied, this is a relatively simple, low cost enhancement which has a very high return and significant positive impact on the STS.

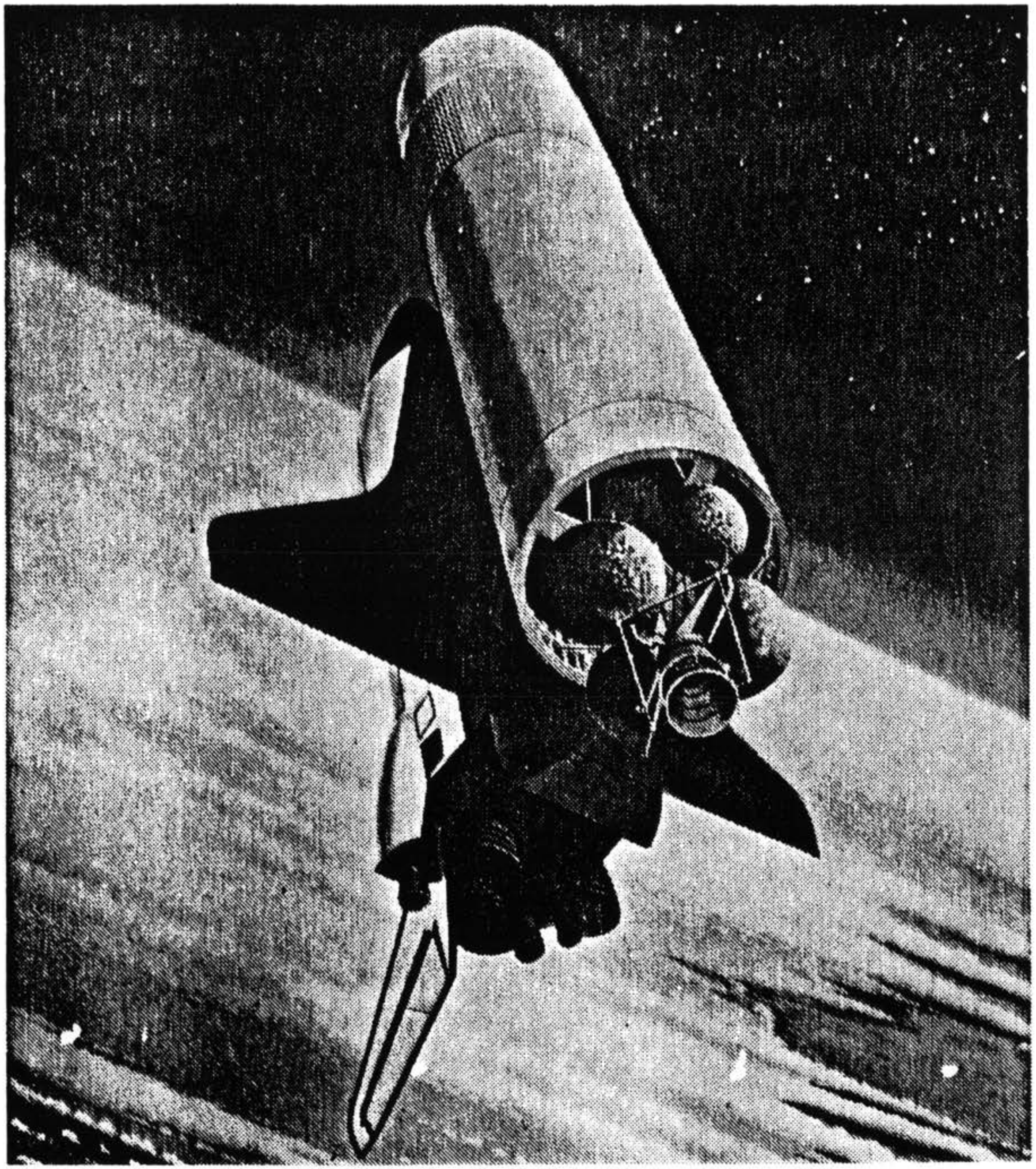


POTENTIAL ET APPLICATIONS IN SPACE

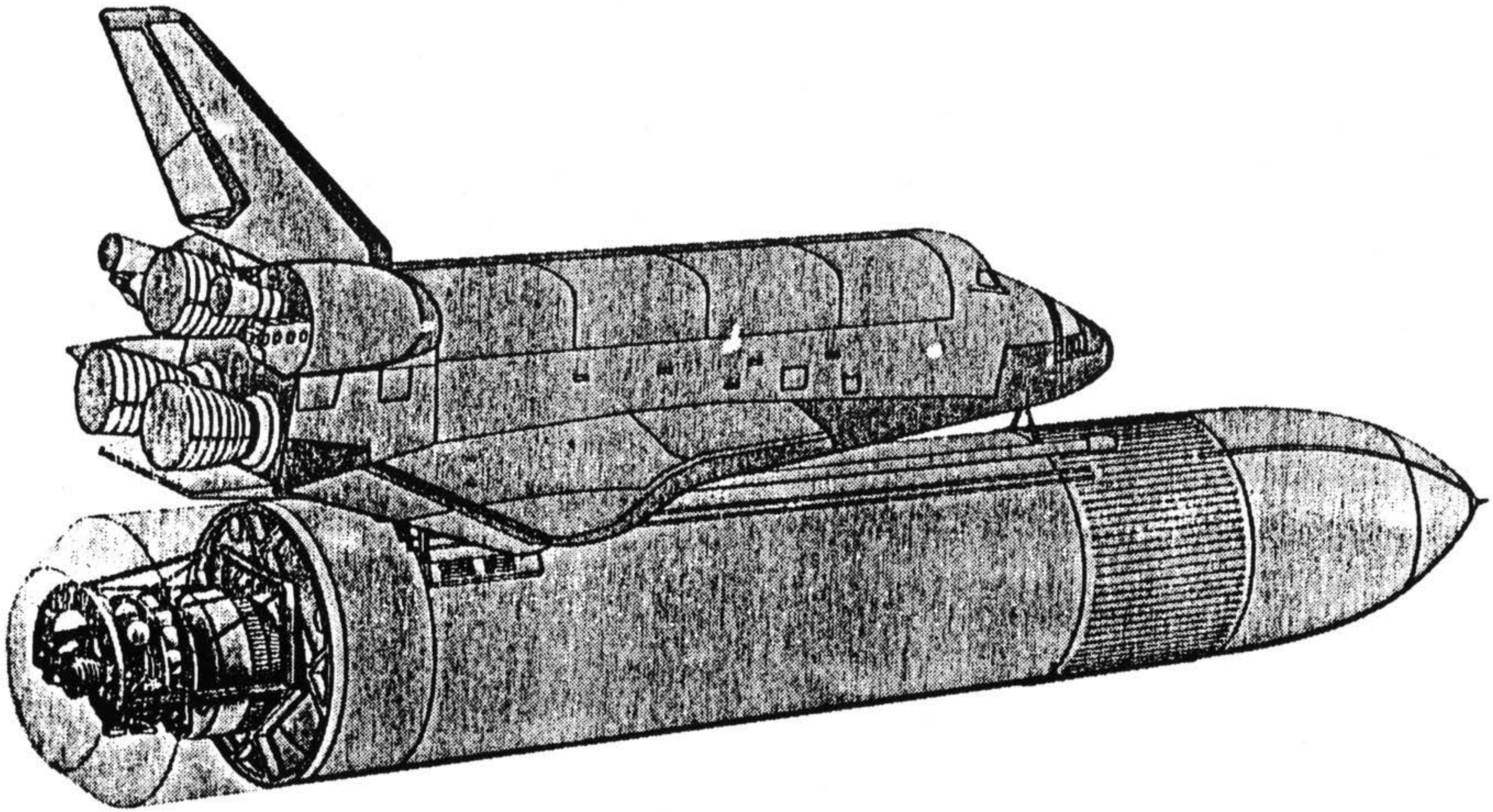
QUICK SOLUTION



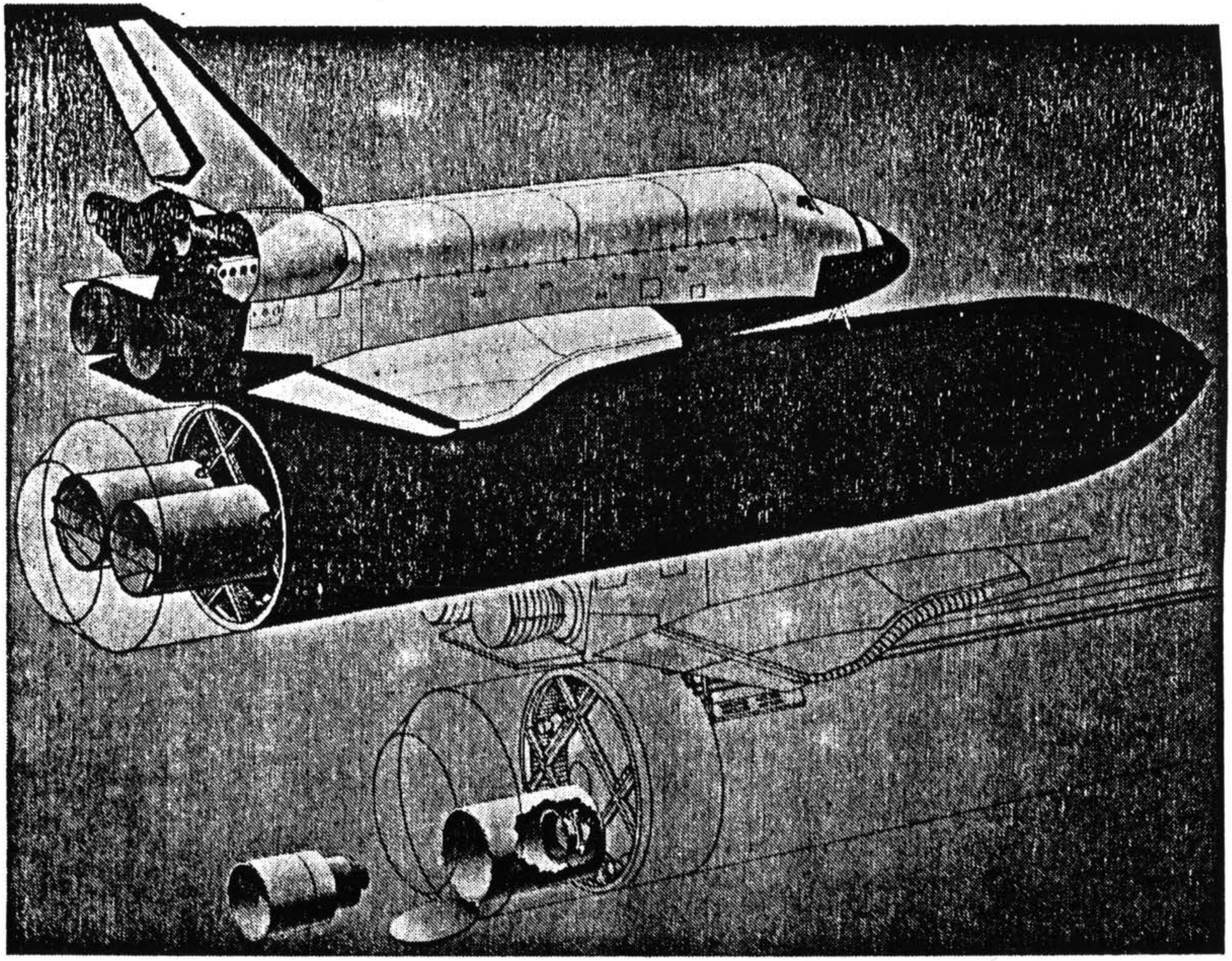
SPACELAB/ET OPTIONS



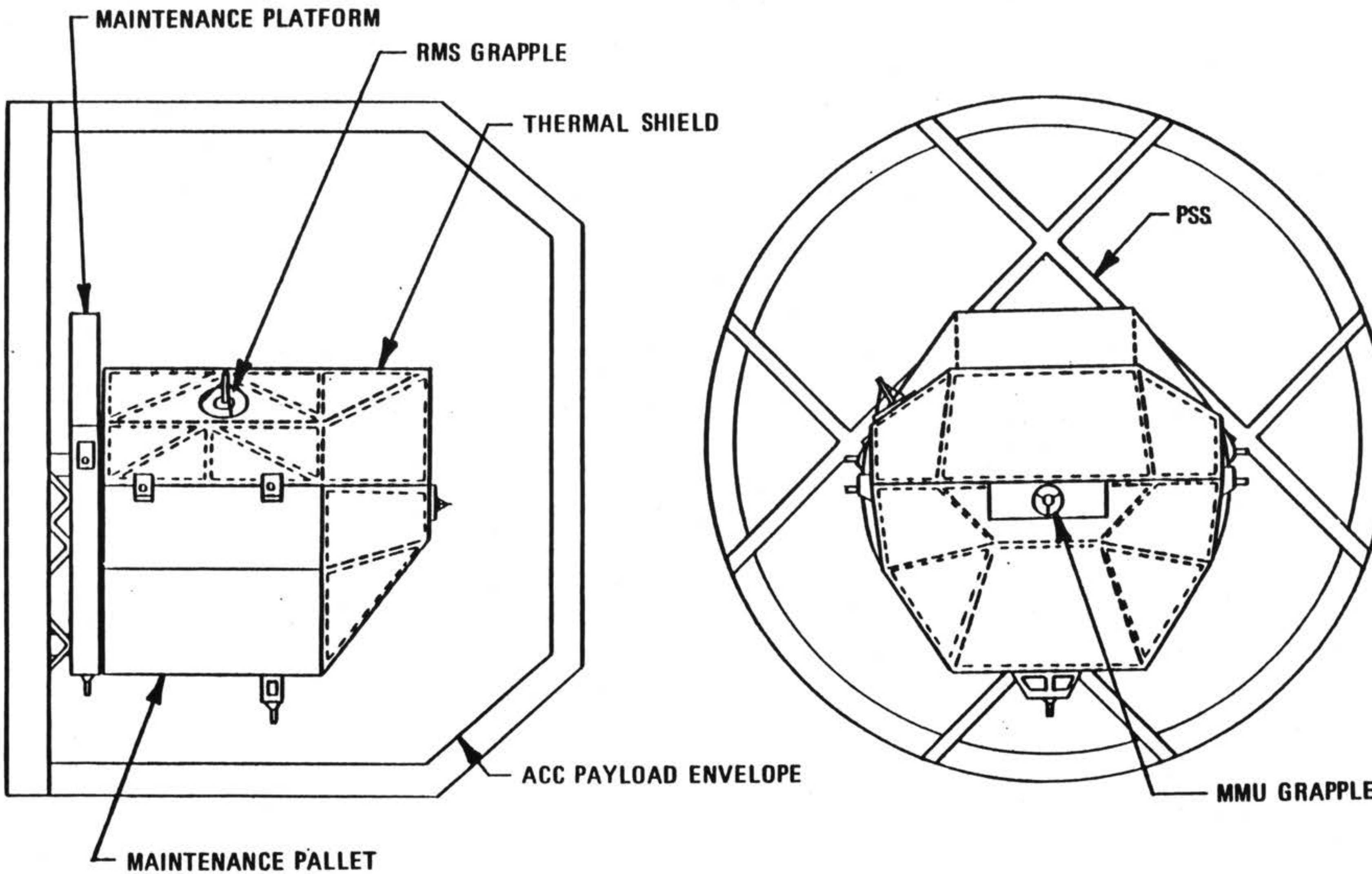
ACC/OTV ON ORBIT



ACC/CENTAUR – G



ACC/PAM



SPACE TELESCOPE MAINTENANCE MISSION - ACC/ORU
CARRIER CONFIGURATION

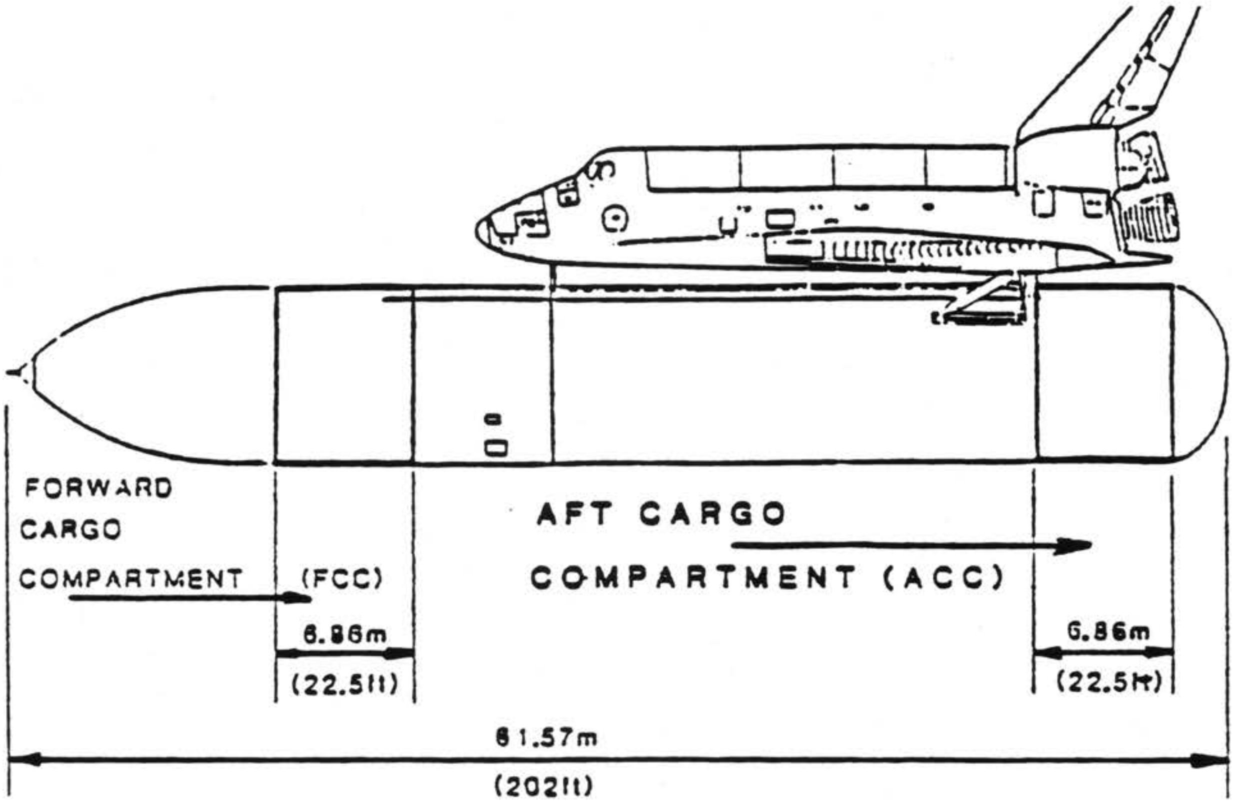
V. Additional ET Enhancements

There are several additional ET enhancements which have been proposed (25). These include a Forward Cargo Carrier (FCC), an exterior track system, an interior track array, and a variety of flanges for opening the end of the tank for orbital applications. With the exception of the FCC, all the enhancements are relatively inexpensive and easy to add to the tank.

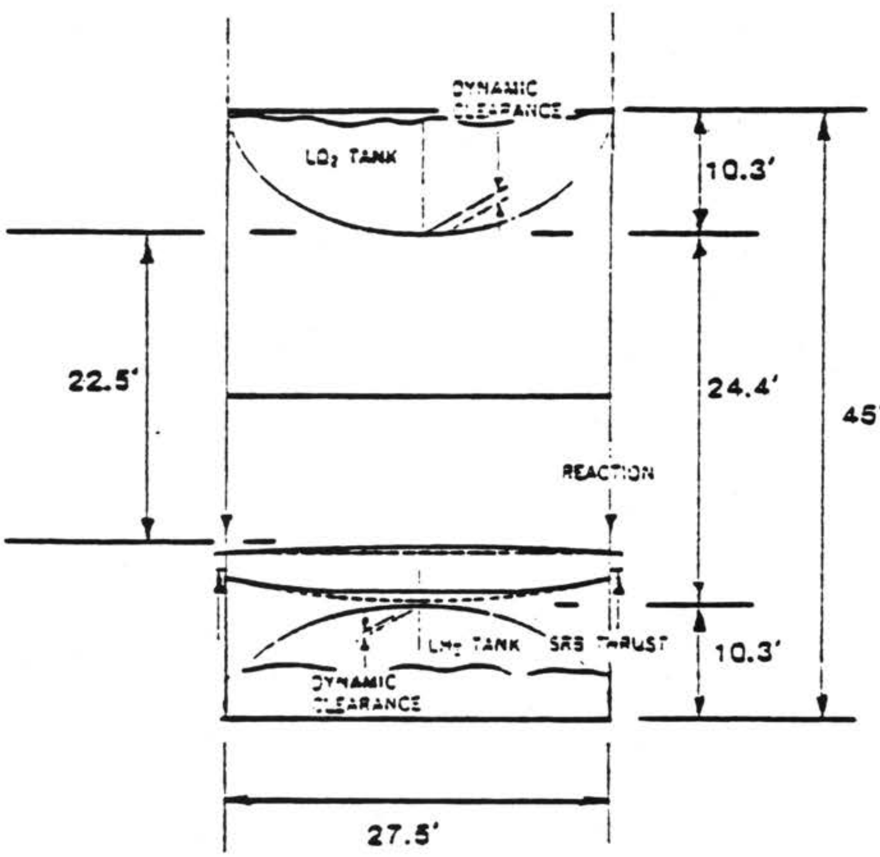
The FCC is the same size as the ACC and can carry a similar payload. It does not require the protective shroud that the ACC does. However, it poses a larger problem than the ACC because it will require additional mass and structure in the intertank and possibly the hydrogen tank to support the loads imposed by it on the tank. This makes the impact of the FCC greater on the STS program and thus increases the potential costs of the FCC. This cost increase due to program impact and increased tank costs may not be as attractive as the ACC.

The next enhancements are the interior and exterior rails or tracks. These tracks allow things like mobile robots, mobile cranes, interior hangar operations, the attachment of station modules to the exterior of the tank, and the possible use of the tank itself as a linear accelerator. The track/rail enhancement will allow a variety of tank enhancements which utilize the structural strength and inertia of the tank (25).

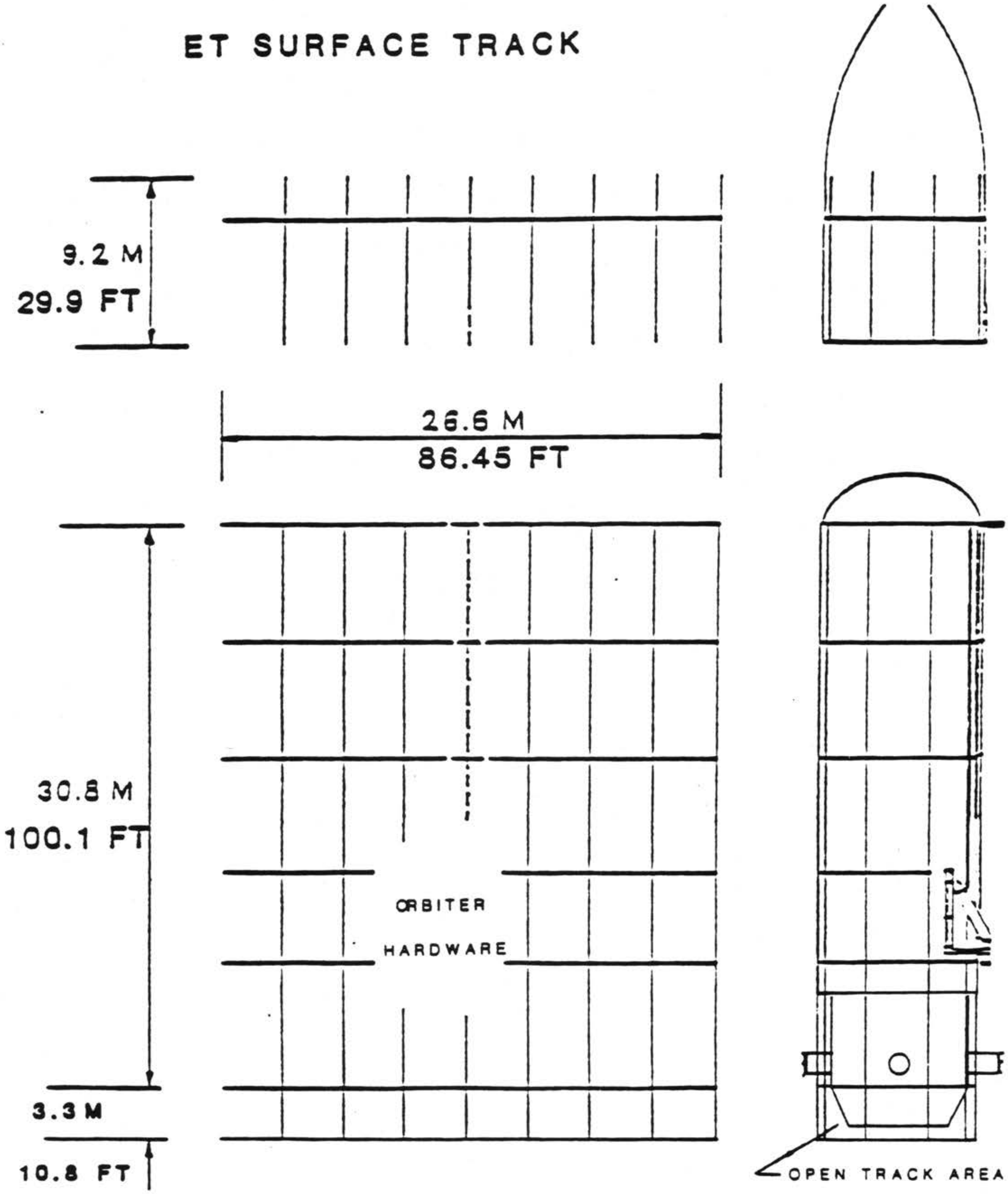
The last class of proposed enhancements are lumped together as things that will make the tanks easier to attach together end to end, easier to enter, and easier to attach external payloads for launch. These include flanges, attach hardware, large seals, hangar hinges, a variety of entry hatches, and additional hardware. These all are relatively simple enhancements that are inexpensive, lightweight, and easy to add to a tank (25).



FORWARD CARGO COMPARTMENT



FORWARD CARGO COMPARTMENT OPTION



STANDARD ET SURFACE TRACK LAYOUT

ET Project - Tin Can Uses

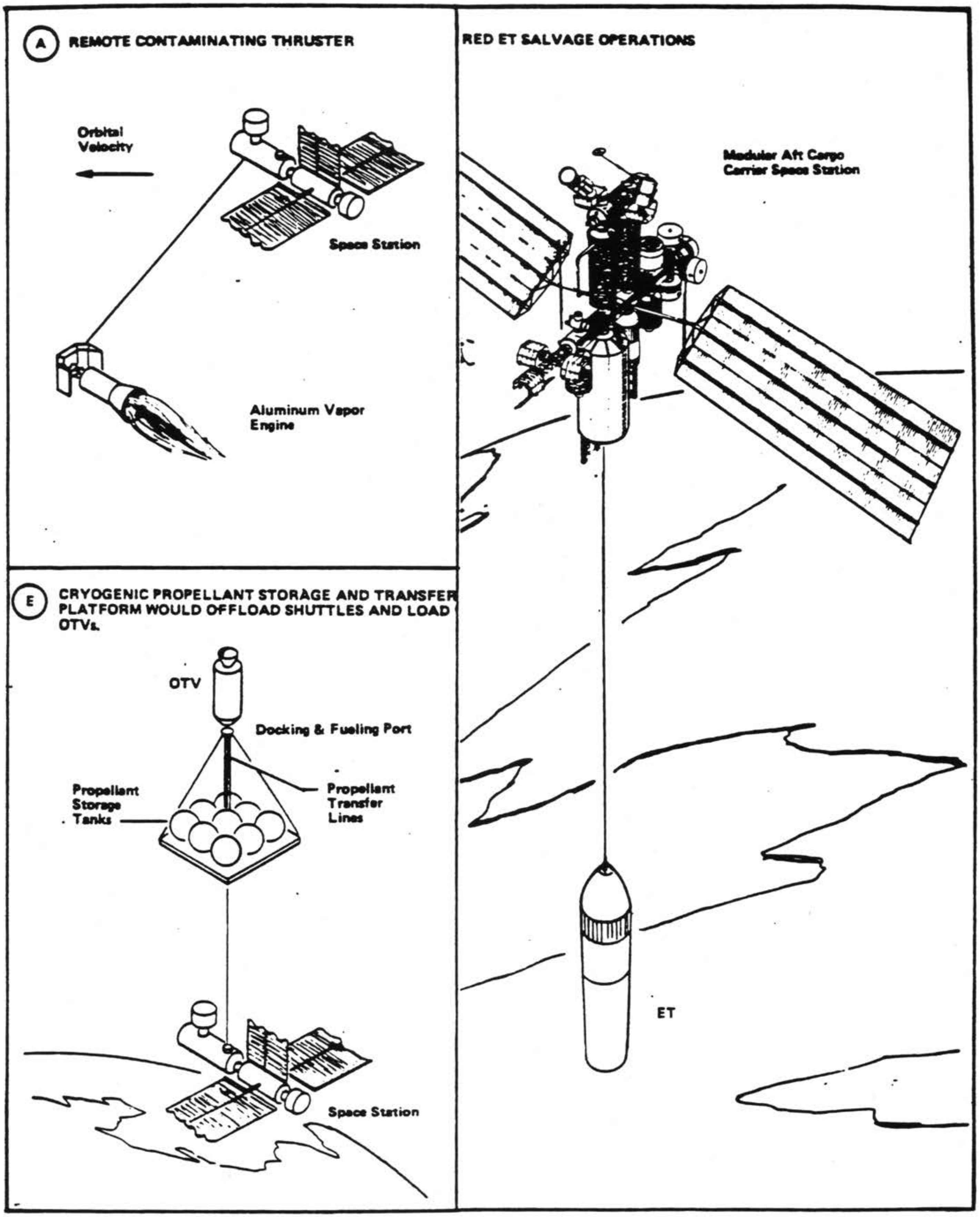
This section considers what is blithely refered to as Tin Can Uses. In spite of being less than technical, this title is the best overall classification of these type External Tank Applications. The following section will discuss uses of the ET as the basis of orbital habitats, storage facilities, hangars, and other 'can' type uses. This class of tank applications is likely where the ET can be put to the first use and possibly best advantage by the future space program.

I. Storage containers

As mentioned previously, the External Tank contains two separate tanks designed to hold liquid hydrogen and oxygen before and during STS launch. The respective capacities of 53,500 and 19,500 cubic feet are important in this context. NASA has a need for storage of some sort of volatiles on orbit to fuel Orbital Transfer Vehicles (OTVs), supply Space Station needs, and refuel existing and planned satellites. The current (Sept 1985) requirement for volatiles storage does not yet require a large storage facility on orbit. There is also a NASA projected requirement to supply 2.5 million pounds of cryogenic propellent in a ten-year period that a scenario which utilizes the External Tank can fill far quicker and cheaper than any other plan (69).

A. Cryogenic storage

On-orbit storage of cryogenics in the ET is possible. The tank can be wrapped with mylar reflective blankets to retard boiloff. This technique should be quite effective giving untended storage times of both residuals and additional stored cryogenics on the order of months (46). A single ET can provide all the volume required for storage of volatiles on-orbit for a space station or an OTV servicing operation. The tank can be stabilized in a gravity gradient mode either free or attached to a tether to keep the liquid on the 'bottom' available for use (30). Cryogenics are also useful in providing backup power. A set of fuel cells designed for emergency operation can use residual or stored cryogenics as a separate backup power supply for the station. Fuel cells are mature technology with which we have extensive experience in space. The problem with the on-orbit storage of cryogenics in the ET is that there is simply too much volume available in the ET oxygen and



SINGLE TETHERS APPLIED TO SPACE STATION

hydrogen tanks for currently planned operations. However, if the expansion of scientific, commercial, and military operations occurs, the capability to store vast quantities of cryogenics will become very important.

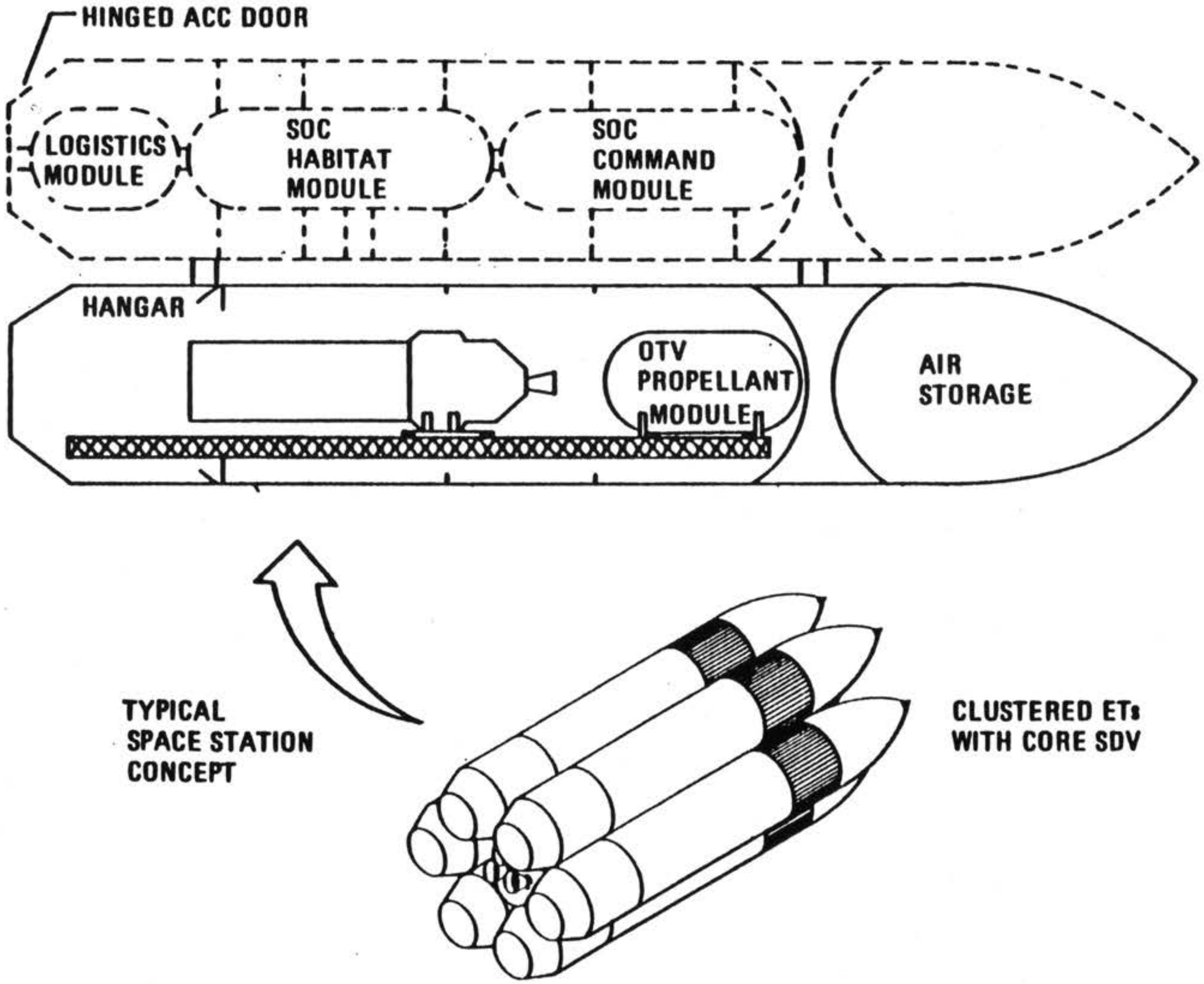
An additional application of the cryogenic storage capabilities of the ET would be to partially disassemble the manned mission to the plantes. The tradeoff here is a slightly heavier than required tank already in space versus a specially designed lightweight fuel tank brought to orbit (82). As is currently flown, the ET is too heavy to use as a fuel tank in this application (51). However, if the tank is partially disassembled and only the hydrogen tank used, this may be a possible application. The program cost savings will once again be in launch and developmental costs for the specialized equipment.

A cryogenic storage facility also has military applications (25). These would include a refueling base for a small earth to orbit vehicle, a refueling base for military OTVs designed to fly classified payloads, and an ET based battle station for SDI purposes. The battle station could use liquid hydrogen stored in the ET with NERVA engine based generator flown in an ACC to power any desired high energy weapon.

B. Gas and Water Storage

The ET can also be used to store gasses and water on orbit. The ground testing of both tanks provide a more than sufficient safety margin for 14.7 psi (one atmosphere) pressurization (48). Gasses can be stored in the ET indefinitely on orbit (95). Due to its structural design, a hydrogen tank can also be used as a structural member if pressurized.

Water is also an important item in LEO and can be stored indefinitely in the tank. The temperature can be easily controlled by both external and internal techniques. The available storage volumes of 147,000 and 405,000 gallons in the oxygen and hydrogen tanks are far larger than required for planned future operations. For example, a single oxygen tank can store the water equivalent of 50 - 150 shuttle visits of scavenged residual cryogenics (95). Water also becomes a energy storage medium. Fuel cells in the station can convert the scavenged cryogenics into water. This excess electrical energy can be used to electrically raise the orbit of the station. This would save fuel and shuttle visits by allowing orbital maintenance without the use of



DOD HARDENED SPACE STATION CONCEPTS

propellent. The water can then be used aboard the station as desired or stored for future use. One future use would be to separate the water back into hydrogen and oxygen, liquefy it, and use it for the cryogenic uses mentioned earlier. This could be done during times of low energy use onboard the station.

C. Salvage Container

One of the significant problems growing in LEO is debris. Every launch dumps something into orbit that could later become a threat to future operations. The ET can be partially disassembled (oxygen tank and intertank removed) and used as an orbital garbage can (25). The large volume of the hydrogen tank can be used to advantage in keeping a particular orbit clean.

An additional use would be orbital storage of recovered inoperative satellites or captured debris. The satellites could be disassembled for spare parts, melted to provide raw materials for manufacturing, or ground up into powder to provide reaction mass for propulsion systems. The tank diameter is large enough to store a large number of recovered items. Artificial gravity can be induced by use of two tanks connected with a tether. The tanks can either be rotating about another or 'hanging' in a gravity gradient stabilized mode depending on the gravity level desired.

D. Storage of orbital assets before use

A tank that is part of a space station can be used to store spares in orbit. These satellites can be serviced, checked out as needed, and stored indefinitely for future use. When the spare is required, it can be serviced, checked out, and outfitted for launch with an extremely short notice. This will solve the problems inherent in a short notice change to shuttle launch manifest. The spare can be launched at leisure, stored until needed, and quickly flown. Program savings here are tied to manifest changes, bumping payloads, training requirements, and money lost due to not having the services provided by the broken satellite until it is replaced. An additional advantage of on-orbit storage or assets where a crew can get to them is the ability to do preventative maintenance in space before launch. For example, an operational satellite shows problems after a year or so of operation. The problem is solved on the ground so that the repair can be made in space to the spare. This is a large advantage to space operations.

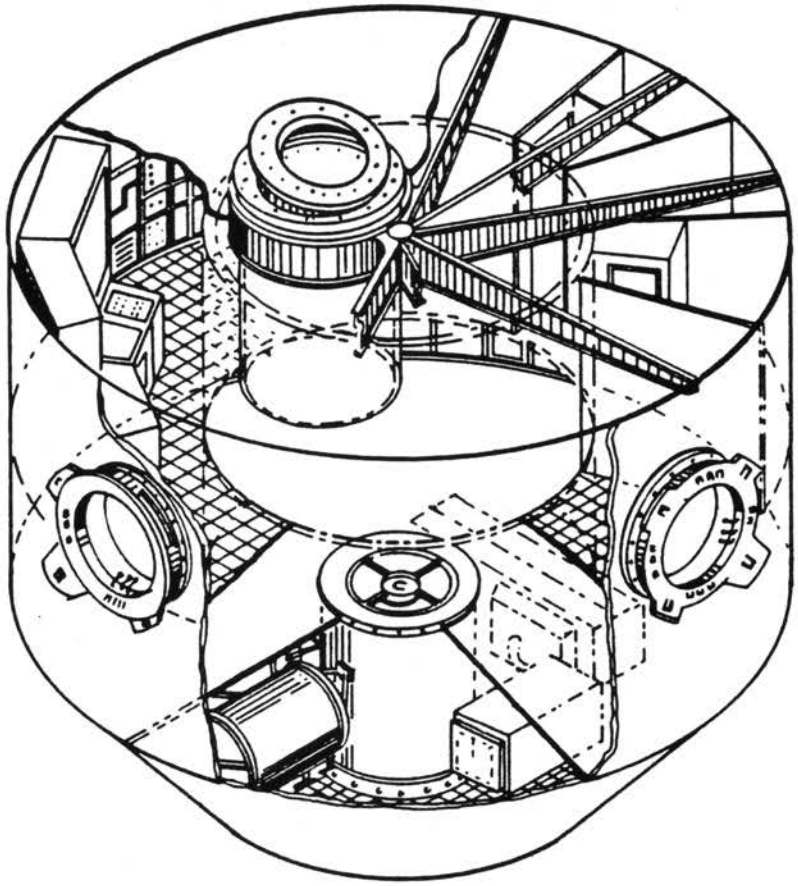
II. Space station applications

The ET can also be used to enhance the space station. The uses are limited only by the imagination of the respective planner and/or buyer. On the surface, it may seem that the recycling of 'thrown away' space vehicles is less than a desirable practice in manned spaceflight. This is simply not the case. The use of leftover parts of launch vehicles is something that the American space program is historically very good at doing as mentioned previously. Orbital construction and repair of satellites, space stations and other structures is a required skill in which astronauts are becoming proficient. Recent experience in satellite capture and repair by shuttle astronauts and major repairs on space stations conducted by Salyut and Skylab astronauts show that on-orbit construction is not only possible, but the most cost effective choice for many applications. Indeed, the US is planning to construct the space station in orbit starting in 1992 (8).

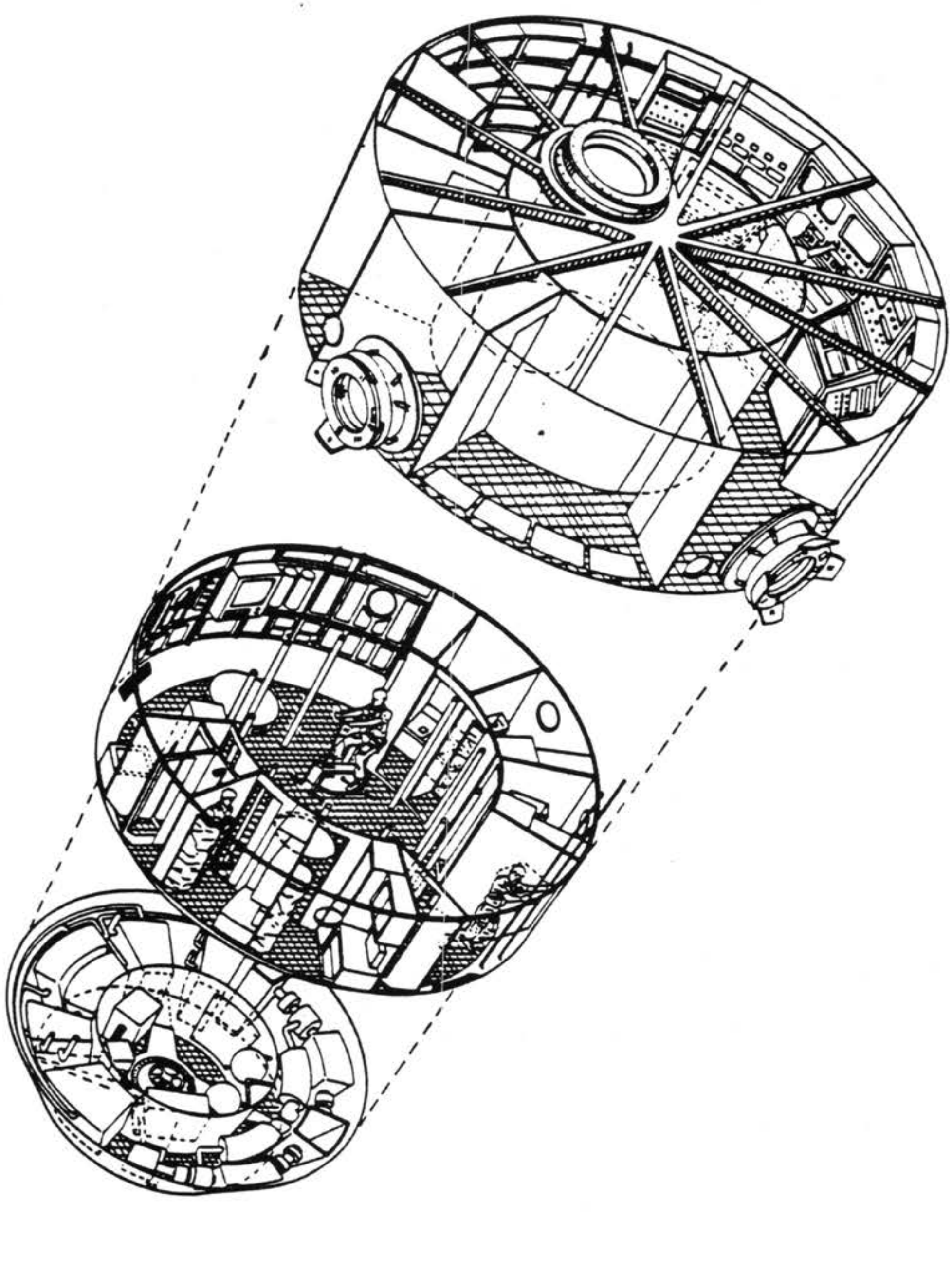
A. Habitations - ACC, Oxygen, and Hydrogen Tank

As described previously, the Aft Cargo Carrier (ACC) is a relatively inexpensive enhancement of the ET which allows a myriad of shuttle and space station enhancements to be flown. One of the attractive enhancements of the ACC is the capability to construct a fully functioning self-contained space station module capable of supporting a crew of up to seven, attaching it to the end of a tank, and launching it into orbit (4, 25). Possible missions of a manned ACC module include a workshop, corporate research facility, corporate space station, space station module, spare segment, attach segment, initial living quarters for a future expandable station, etc. Literally, anything that a space station module can offer, the ACC based module can provide more of for a lower overall price (4, 25, 31, 77).

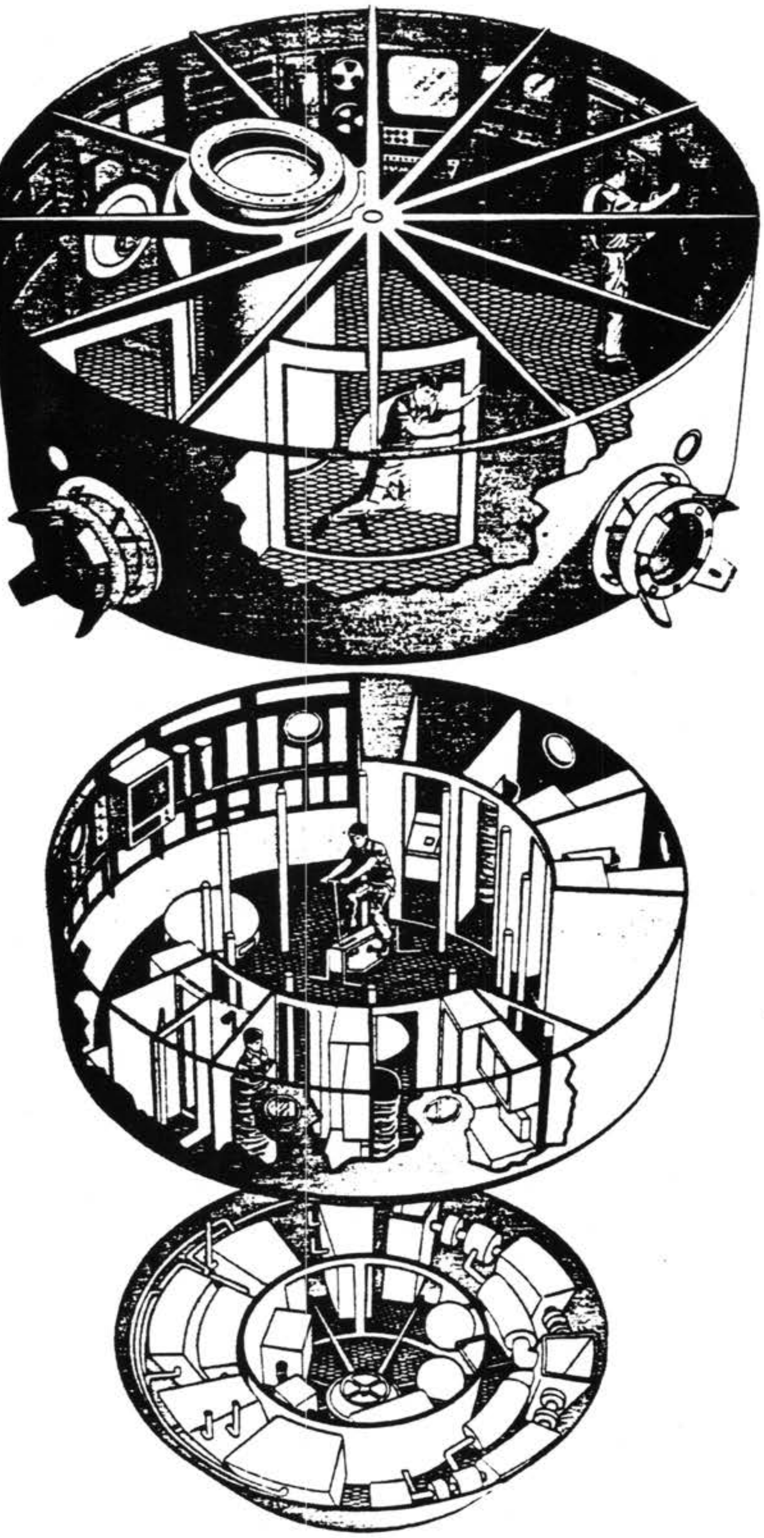
There are several very attractive advantages that a space effort can get out of flying a manned ACC. The first advantage is that it becomes possible to launch a small (in crew size - large in actual volume) manned space station that can be greatly expanded in the future with a single shuttle flight. The program savings in launch costs alone over conventional designs are staggering. The ACC can be constructed to contain all the life support, living, and initial working space. The External Tank attached above provides gravity gradient stabilization, an average of 15,000 pounds of residual cryogenics available for immediate use or scavenging, structural strength of a



ACC SERVICE MODULE



ACC HABITAT

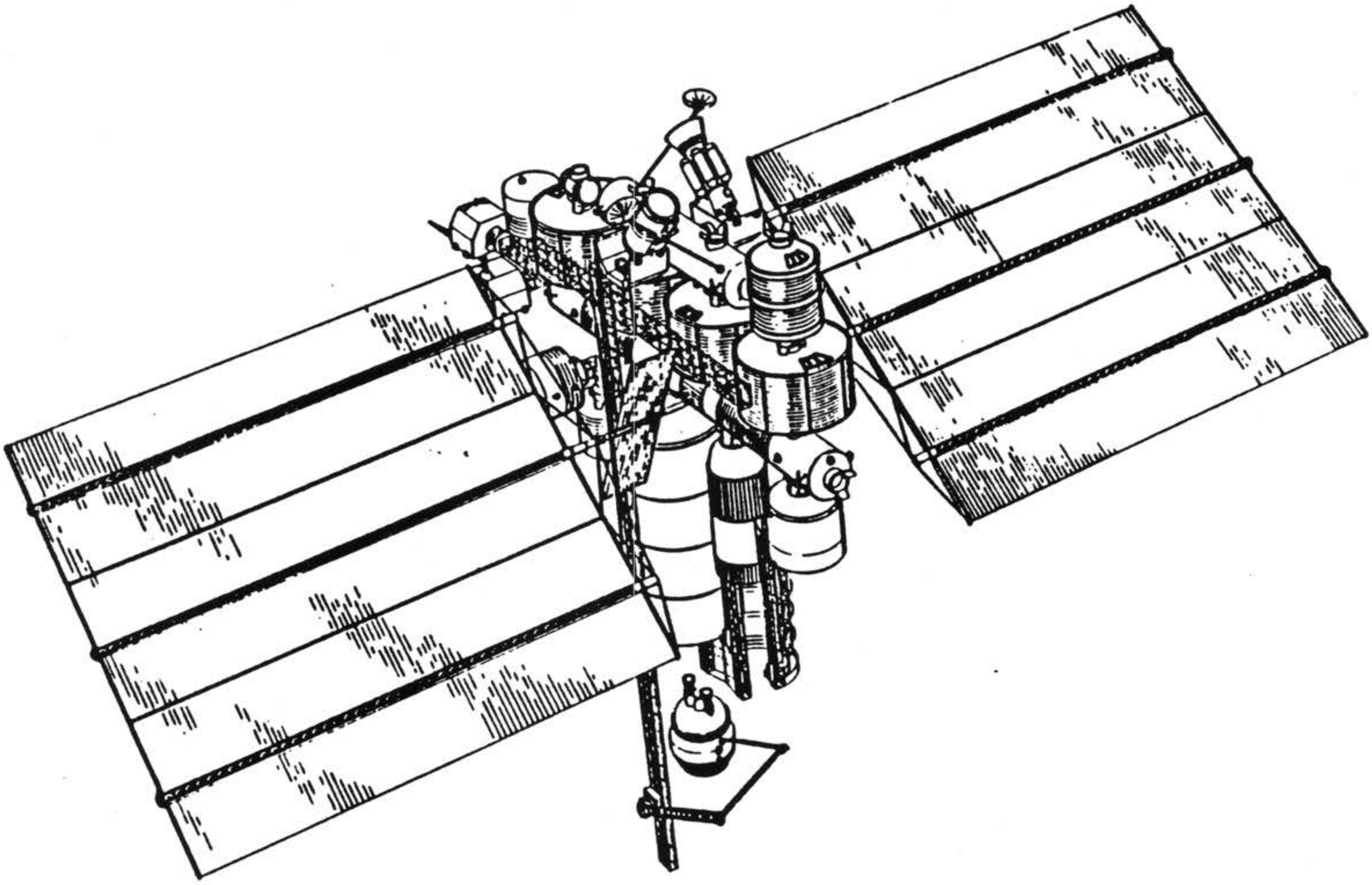


HABITATION MODULE - INNER HULL

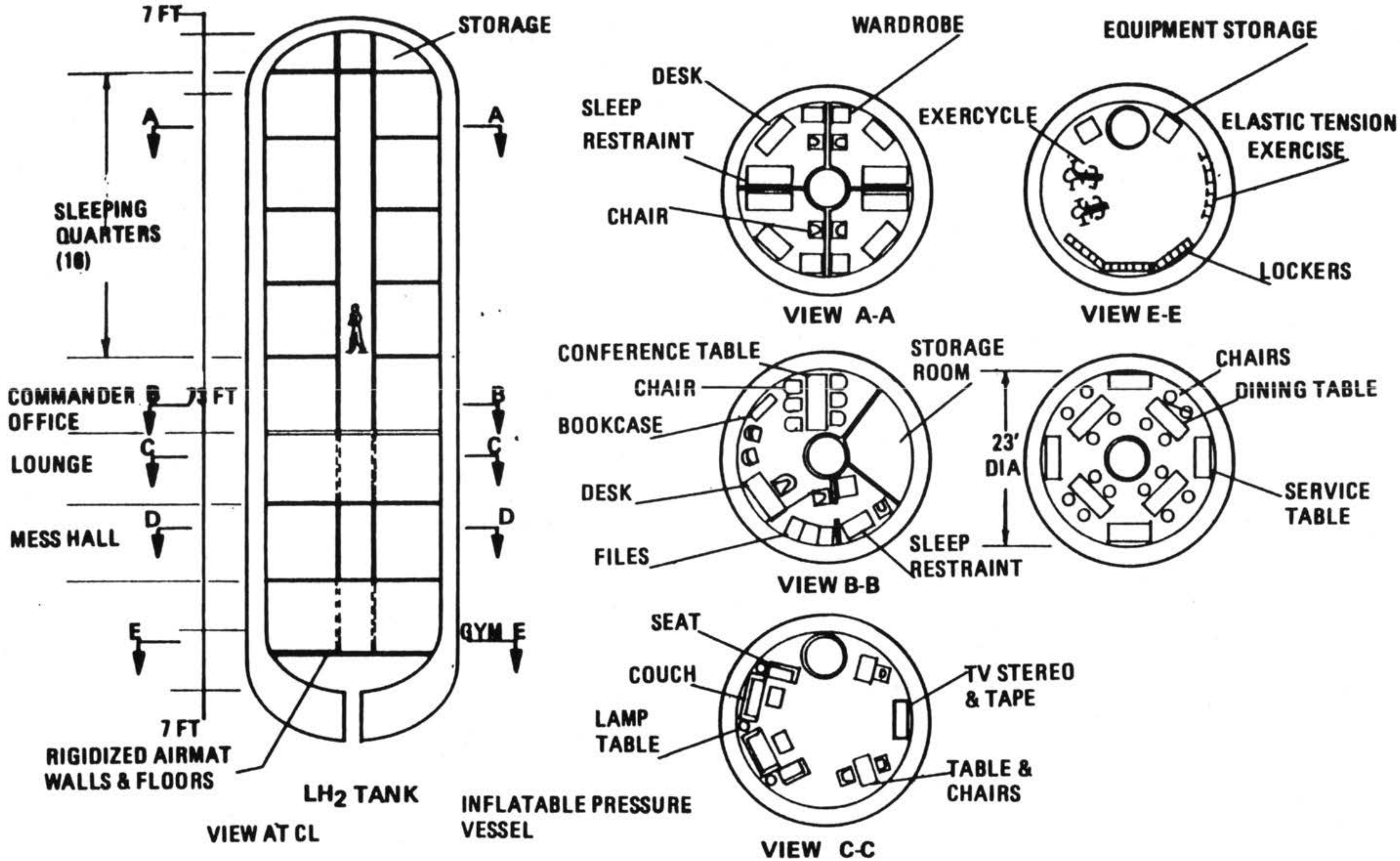
69,000 pound pressure vessel, and additional space of 53,500 cubic feet above the ACC inside the hydrogen tank that can be easily entered and turned into work areas, living quarters, hangars (pressurized or unpressurized), or storage facilities with a minimum of effort (25). The orbiter payload bay can carry the additional equipment necessary for station setup such as tools, solar panels, and radiator arrays. This concept lowers the cost of flying a manned space platform from the current cost reachable only by governments or government agencies to a cost that corporation can reasonable meet. It also gives the United States the capability to launch and fly a large space station with a single launch - something that we have not had since the Saturn V was operational.

The manned ACC is attractive for several other reasons. It provides a differently shaped volume than the payload bay - wide as opposed to long. This volume shape is more akin to that which people are used to living and working in on the earth and may possibly ease adaptation to space by visiting crews. A size comparison of the ACC based station shows that an ACC module is almost a third larger than the current volume available in the shuttle payload bay - 13,000 versus 10,000 cubic feet (4, 25). You get a major increase in Shuttle capability with minimal modifications. The ACC, as mentioned previously, can be configured to any mission and any role. In addition to the habitation module, it can be configured to a multiple docking module, a lifeboat, a 'storm shelter' for solar flares, a spare, an on-orbit farm, etc. Carrying the space station module outside of the payload bay frees up the remaining payload bay volume and/or mass capability for additional paying customers. Conversely, the ACC can be used to launch other payloads with minimal mission impact if the payload to orbit capability. The ACC based module also can be designed to attach to anything that any other space facility module can be attached to.

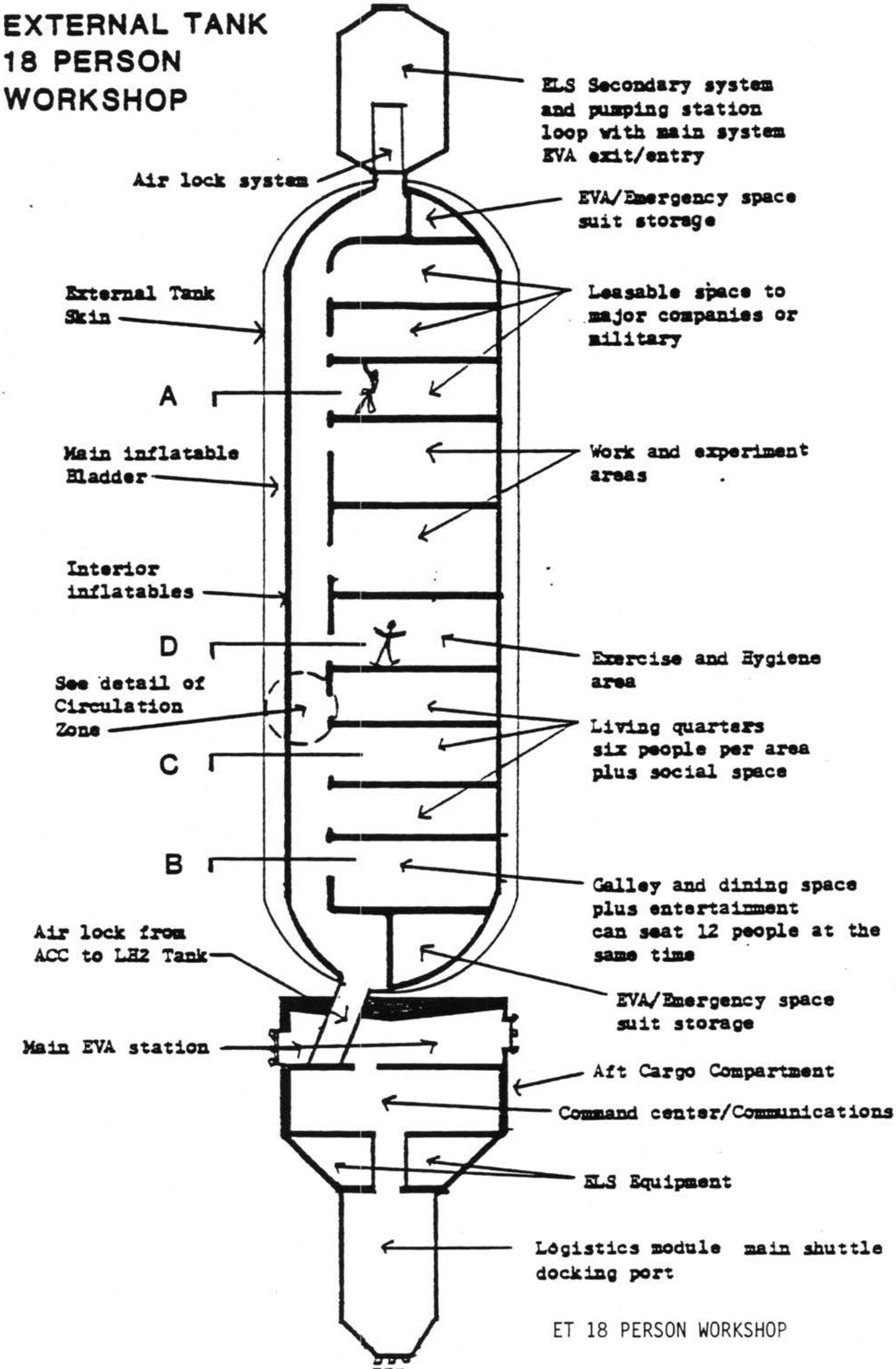
As mentioned earlier, the Hydrogen tank is also available for future expansion in an ET based space station concept. Entry can be made into the tank by a variety of means with entry diameters ranging from 3 feet (through the inspection manhole) all the way up to 27.5 feet if the dome is removed. The manhole is large enough for an astronaut with a spacesuit to fit through. The tank is clean, has a minimum of protrusions, and is ready for immediate habitation or ready with a minimum of effort (25). One of the concepts for internal modifications of the Hydrogen tank on-orbit is to use a large



ACC SPACE STATION CONCEPT

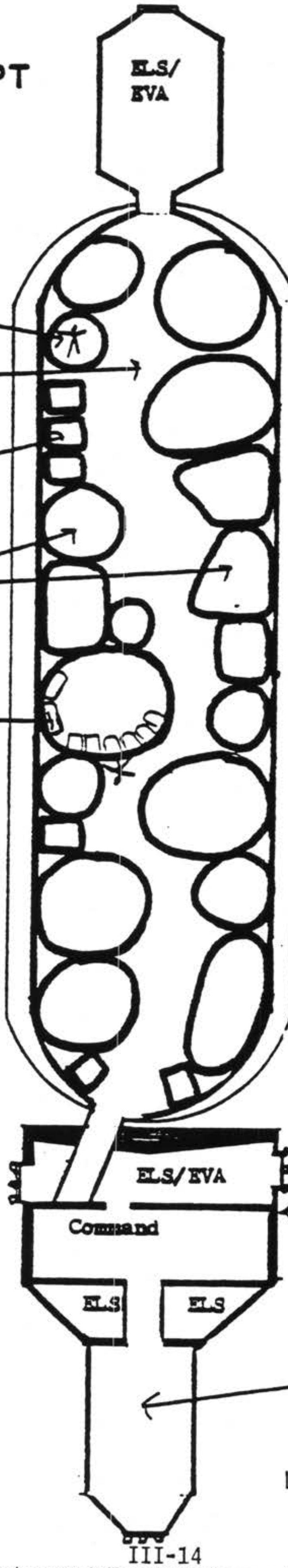


LH2 TANK LIVING QUARTERS



ET 18 PERSON WORKSHOP

INFLATABLE TENT STRUCTURE CONCEPT



Indivual Crew Space

Free form Circulation

Hygiene Units with privacy schreens

Inflatable/Tent Structures

Equipment is belted to sides and battery powered.

Main utilities and ELS duct runs can be on exterior of ET using existing pipe lines

A Combination of three main systems: The main inflatable bladder, the inflatable/tent structures, and the hard systems gives this concept great flexibility.

Consider the early space personnel to be on an extended camping trip. They must bring everything with them. It must be light weight, strong, and flexible to respond to different situations. Their eq. can be battery-powered or plug into a portable power supply. Their living structures are a combination of inflatables and tents. They provide privacy and insulation. Since the personnel will be staying for a short time, they will be willing to put up with some discomforts. However the less discomforts they experience the more productive they will be.

The inflatable/tent structures are brought into space in the Aft Cargo Compartment and in resupply missions. The personnel use them in what ever combination needed.

AFT Cargo Compartment

Environmental Life Support (ELS)

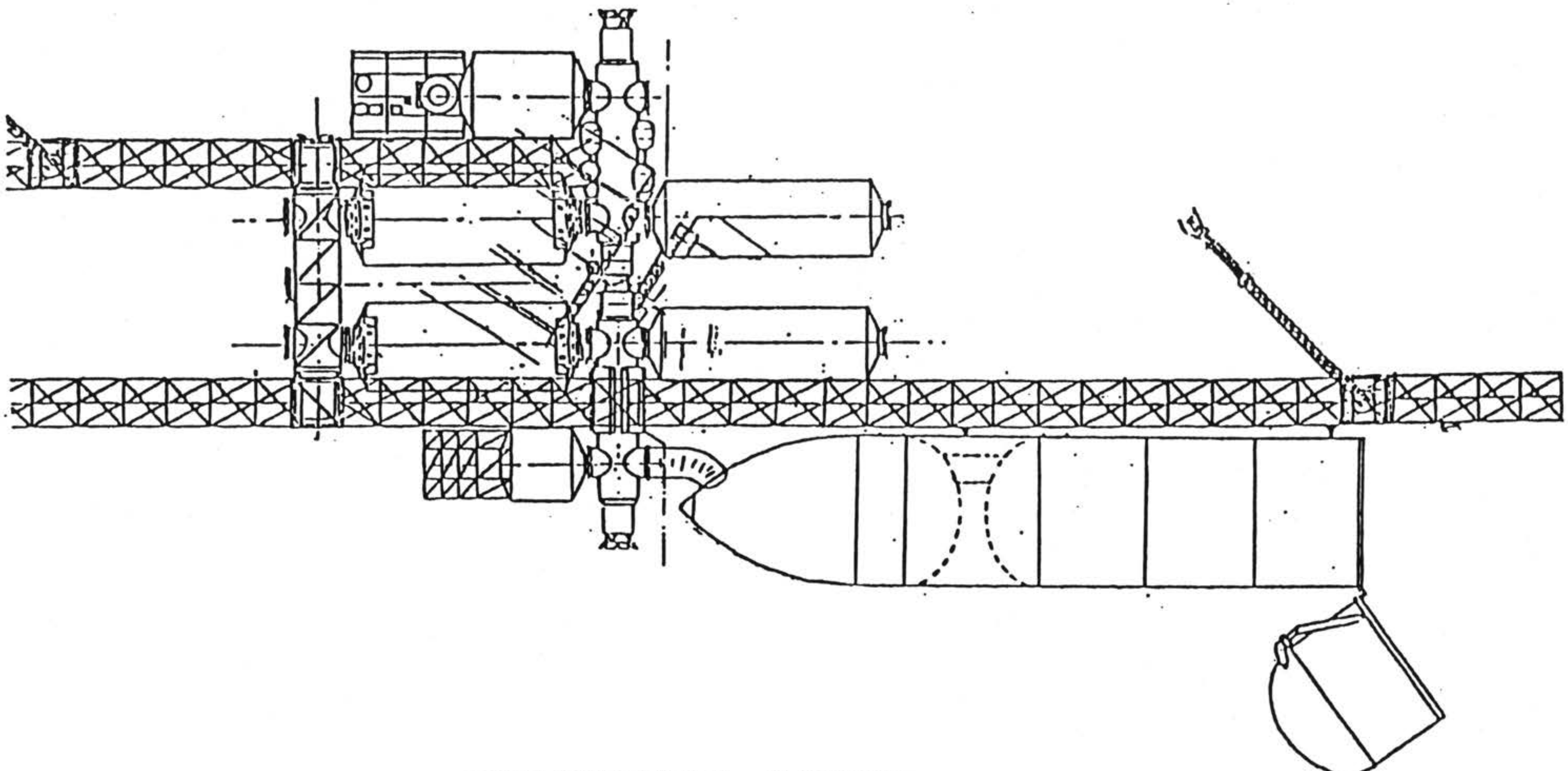
LH2 INTERIOR DEVELOPMENT

FEATURES

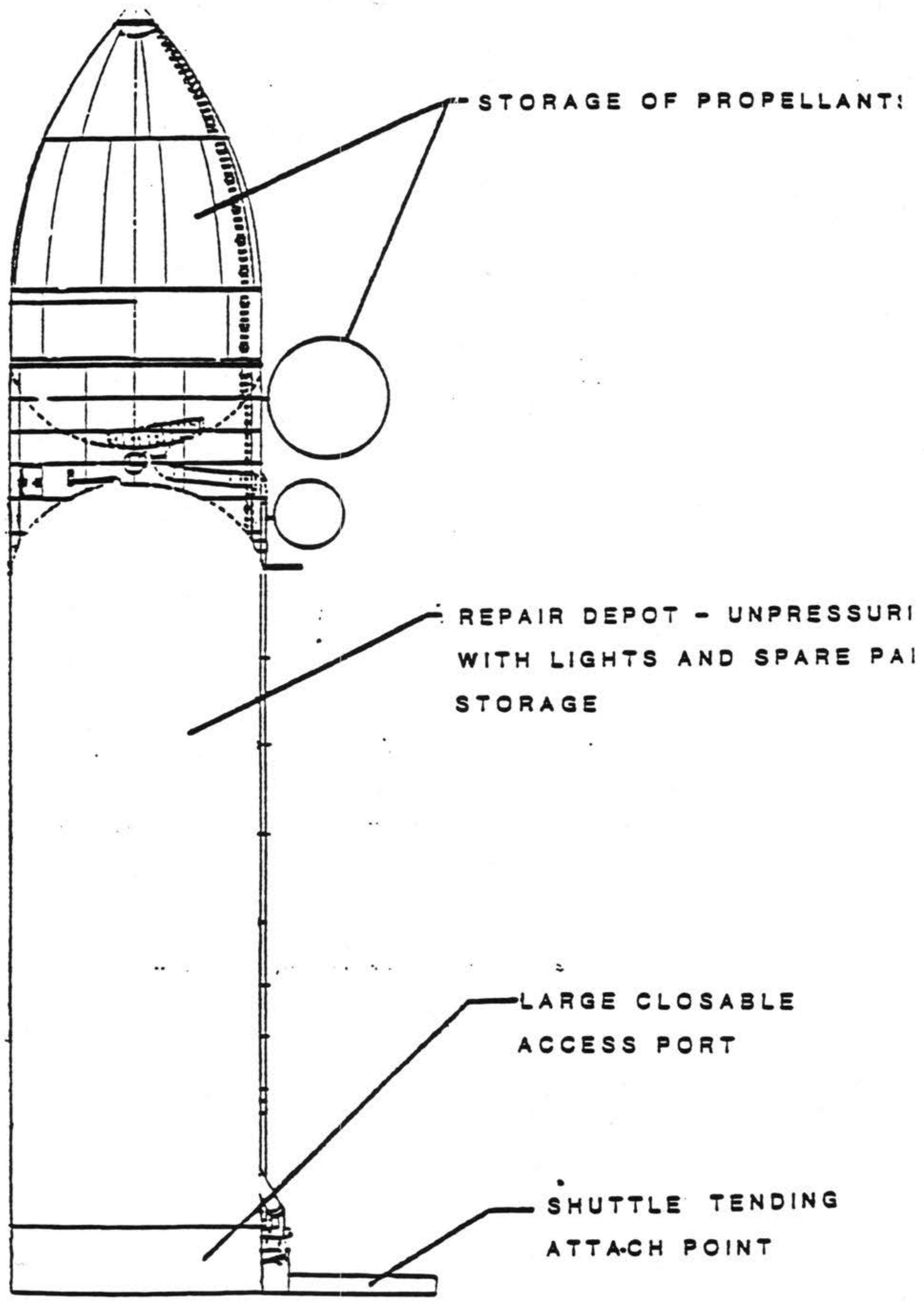
- LO_2 TANK ACCESS
- LOCATED IN FLIGHT SUPPORT AREA

DISADVANTAGES

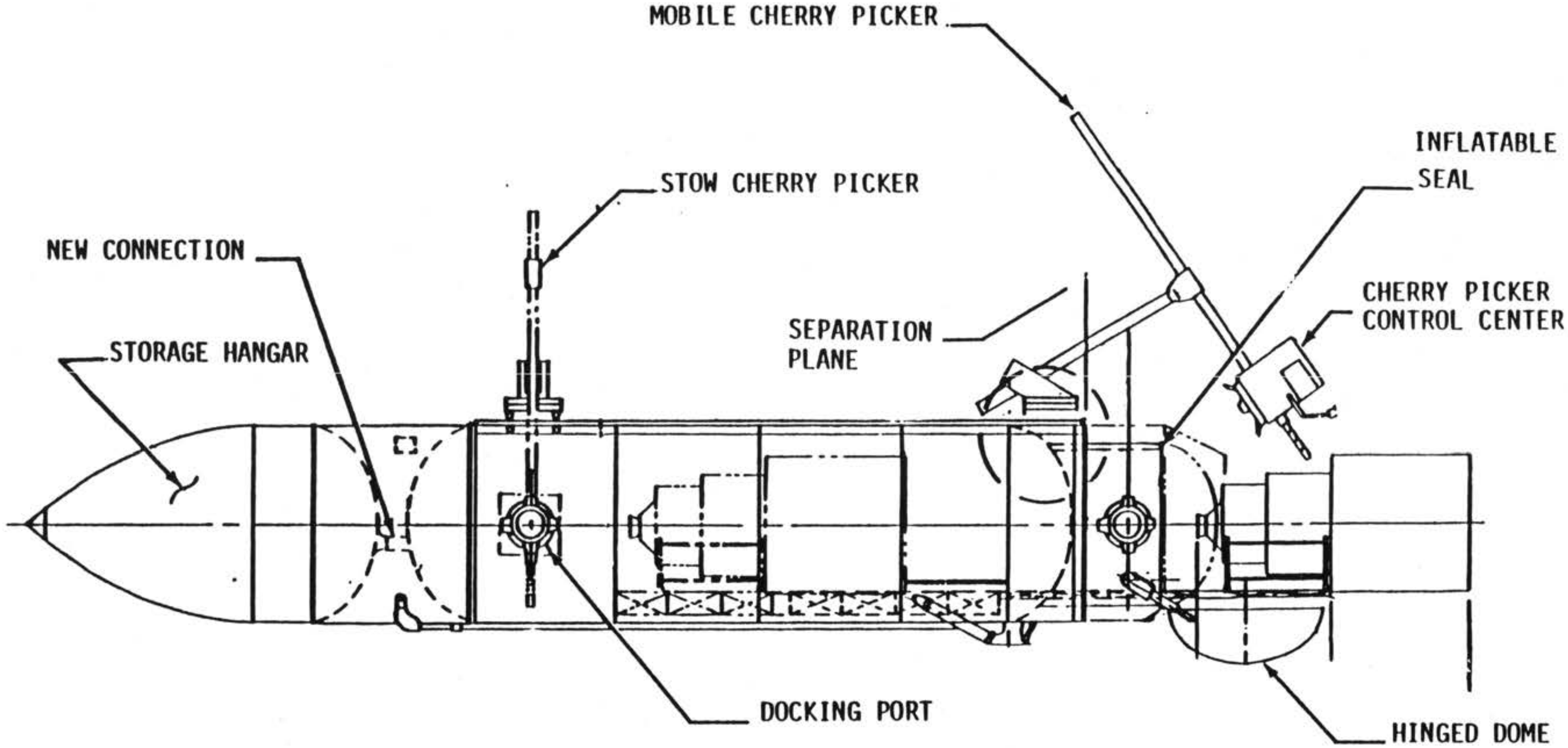
- LH_2 TANK ACCESS
- SHUTTLE DOCKING ORIENTATIONS LIMITED TO 3 POSITIONS



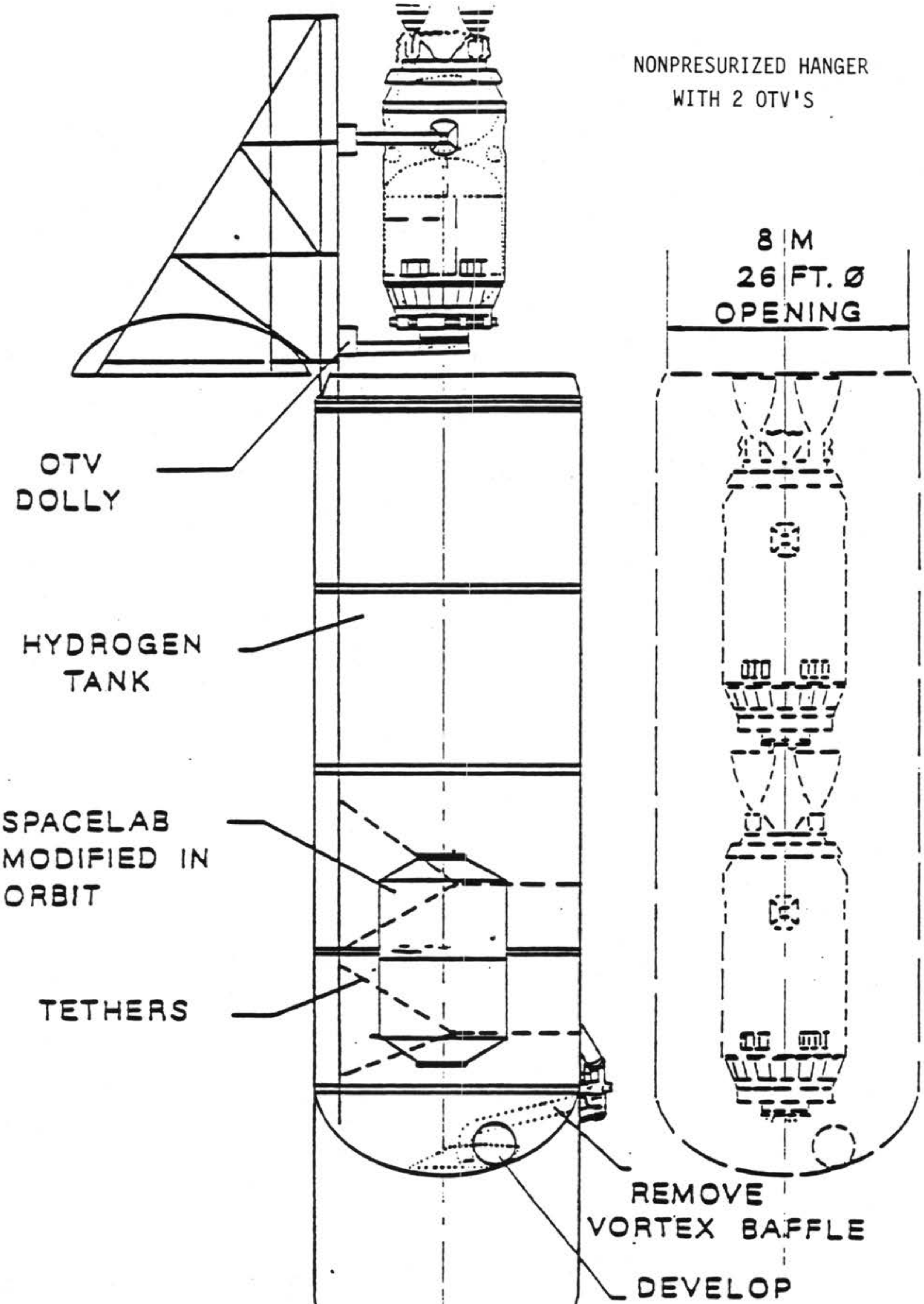
SOC/ET CONFIGURATION - ET OUTBOARD



ET BASED REPAIR DEPOT



ET/ACC HANGER CONCEPT


NONPRESURIZED HANGER
WITH 2 OTV'S
8 M
26 FT. Ø
OPENING
OTV
DOLLY
HYDROGEN
TANK
SPACELAB
MODIFIED IN
ORBIT
TETHERS
REMOVE
VORTEX BAFFLE
DEVELOP
AIRLOCK

inflatable bag to provide the interior of the tank. This uses the tank primarily for micrometeorite protection and insulation. Setup is quick, clean, and very simple. Additional partitions can be inflated, erected, or unfolded in the tank to fit the needs and requirements inside. As an aside, inflatables also have a long successful history in the American space program. These inflatables were the Echo I and II reflective communications satellites flown in the early 1960s.

The hydrogen tank will provide a huge space - over 53,500 cubic feet - which is five to ten times larger than any proposed space station module that is known of at this writing (25). Once again, the advantage to the use of the ET is large size and availability for use after a single launch. The program savings here are mainly in launch and orbital construction costs.

In addition to the Hydrogen tank, the liquid oxygen tank is also available for use as a habitat. The early studies on External Tank applications by Marshall Space Flight Center proposed the adaptation of the oxygen tank to a manned mission as a first step (12). There are a few disadvantages to its use which are useful to mention. These include a slightly more difficult access problem due to the location of the manholes and intertank section, more internal hardware to consider due to the slosh baffles, and a shape that is less than optimum for the use of the entire tank for habitation. These disadvantages make the early use of the oxygen tank less attractive than the hydrogen tank and the ET/ACC combination. However, it may serve very nicely as water storage facility, a lifeboat, a passive life support habitat, a cryogenics storage facility, a biological experimentation station, or a farm in conjunction with an ET/ACC based space station (25,56, 95). It also has a very large volume - comparable with Skylab (70) - which will be useful in future applications in orbit.

B. Hangar or servicing platform in the Hydrogen Tank

The Hydrogen tank can also be turned into a hangar for satellite and vehicle servicing and repair. The top dome of the tank can be removed completely, swung aside, or removed and converted into a hangar door. The tank can also be left open as an unpressurized servicing facility. The Space Operations Center (SOC) studies of the late 1970s suggested a hangar and/or berthing facility be developed for this purpose. As a hangar, the ET can serve this purpose quite nicely with a minimum of modifications. If a pressurized work volume is desired, the tank can fill this need also by the addition of a hinge and a pressure seal. Entry diameter can be made anywhere from 3 feet to the 27.5 feet diameter of the tank itself. This will allow the servicing, testing, and construction of large space systems.

The SOC studies of the late 1970s suggested on-orbit construction of a hangar facility based on the size and support structure for payloads in the orbiter payload bay. The hydrogen tank interior can be easily adapted to this role for a faw lower cost than what was envisioned by the SOC studies (25). Once again, the program savings are primarily launch costs. Additional savings are realized by on-orbit modification of an existing structure rather than developing, purchasing, and launching a new module for the same purpose.

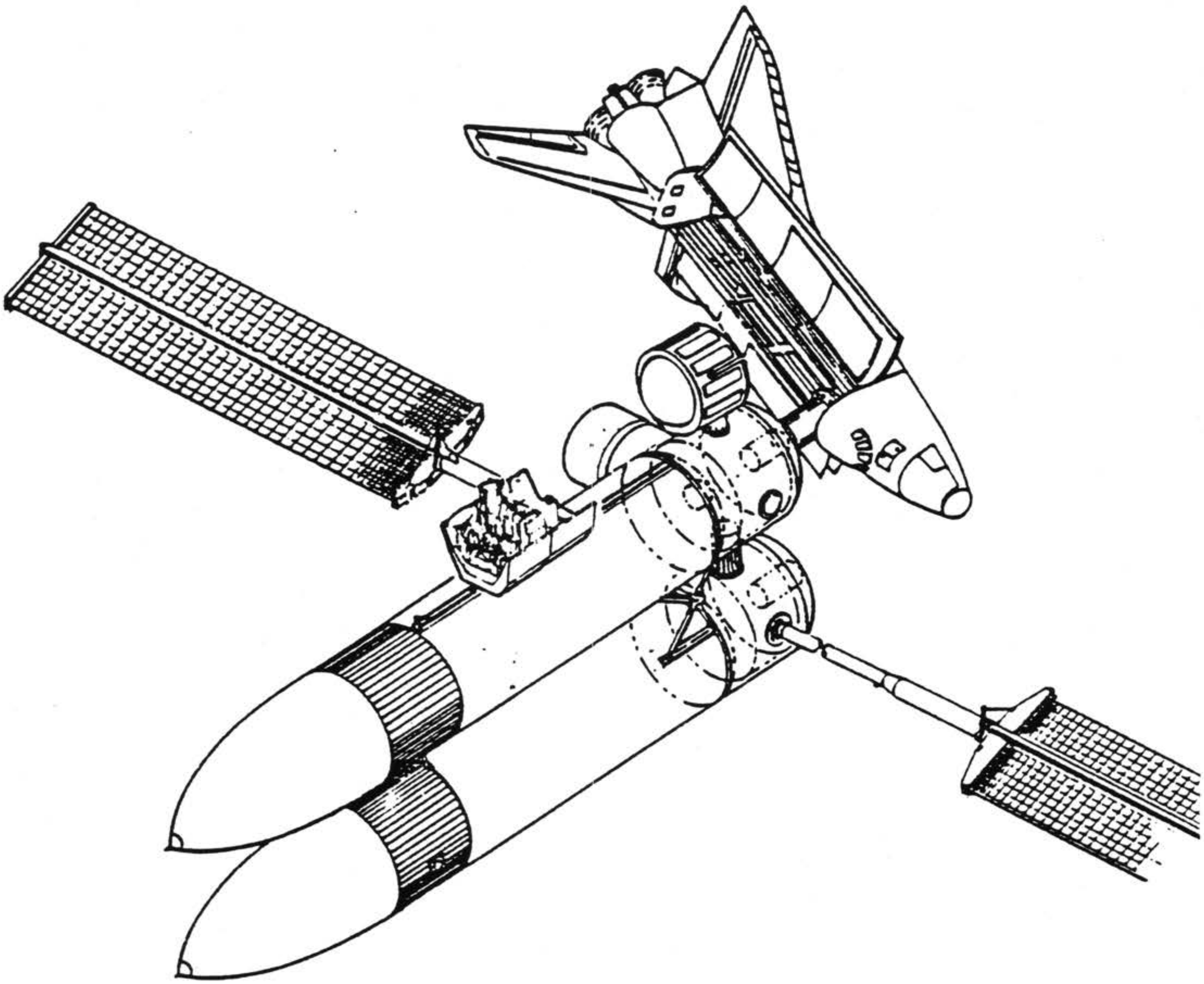
C. Corporate space stations or platforms

As the United States works toward a continuous manned presence in space, interest in a similar presence by industry becomes stronger. Using the ET or the ET/ACC combination as Corporate Space Station will provide a way for various companies to make this happen. As mentioned in the manned ACC section, the launch of fully functional manned space station in a single shuttle flight for a total cost of two to three generic communications satellites - $200 - 300 million - is something far more attractive to corporations than the $8 billion planned cost of the Space Station. The scenario including a corporate space station would do several things:

1. Promote industrial interest and investment in space by keeping costs down. This would enhance the current space station by keeping the industrial activities separate from the scientific and research activities aboard the space station.

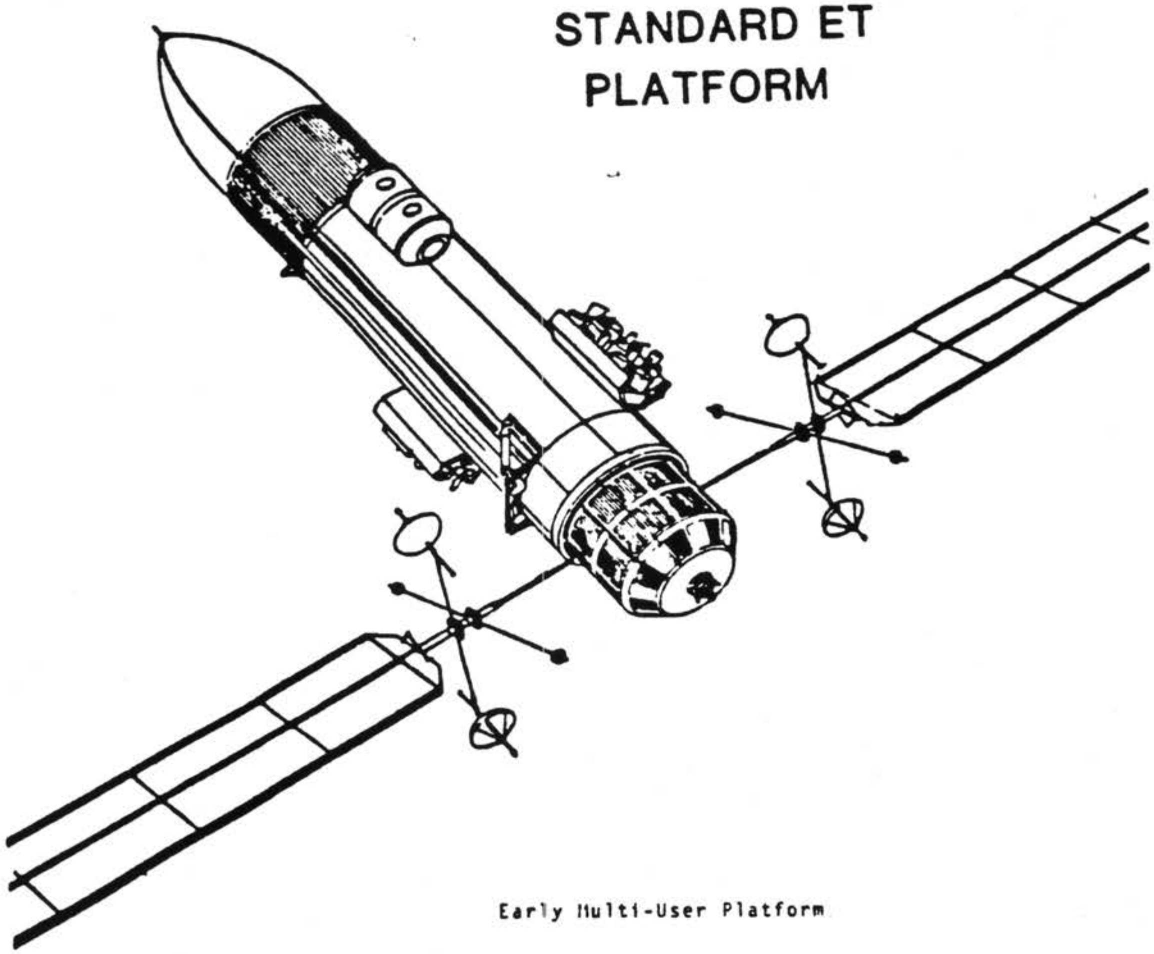
2. Allow industrial users to keep their own on-orbit work a corporate secret. There is better security in the use of separate facilities in space.

3. Allows DOD or DOE to conduct tests, experimentation,and evaluation in orbit with sensitive systems that will not attract the attention that a secret shuttle launch from the Cape or Vandenberg will. As the SDI expands, the space-based requirements of currently proposed systems will require on-orbit testing. This will make an ET based station attractive to other governmental agencies. It also allows the space station to be a platform dedicated to civilian purposes in its entirety. This is an attractive political option.

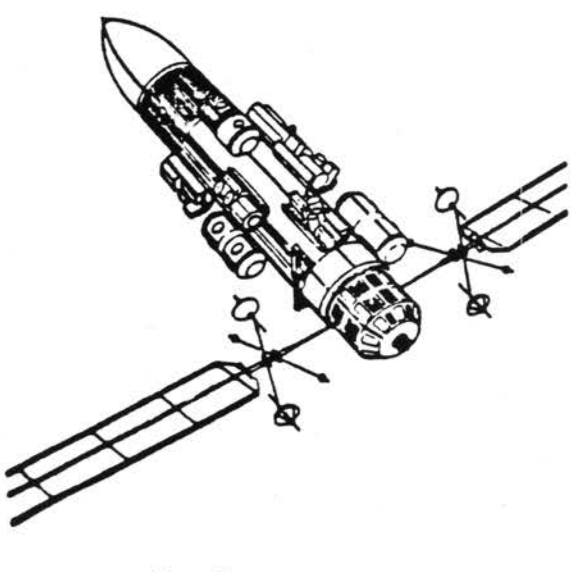


SPACE FACILITY

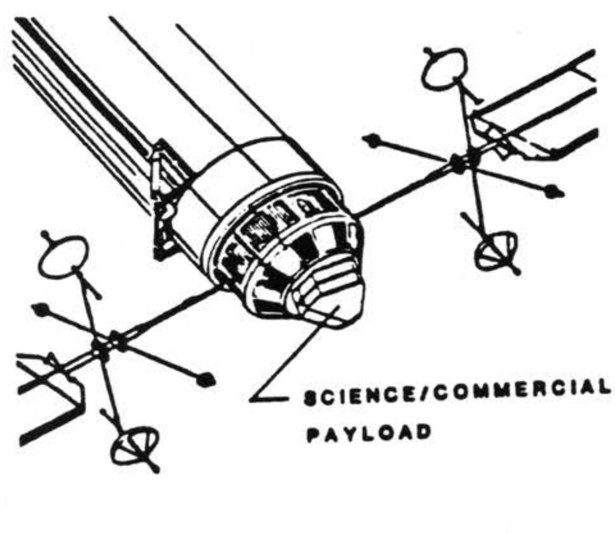
STANDARD ET PLATFORM



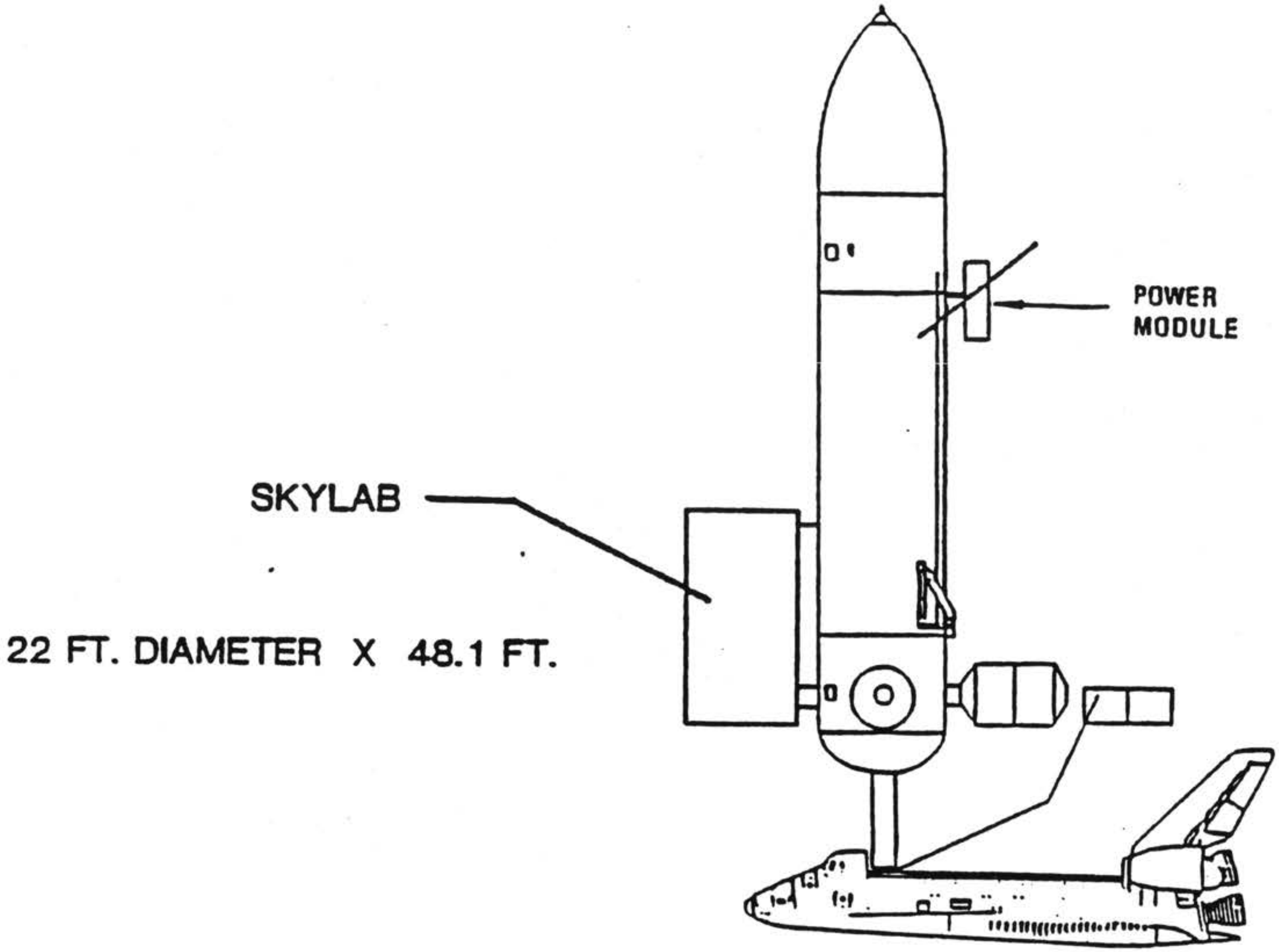
Early Multi-User Platform



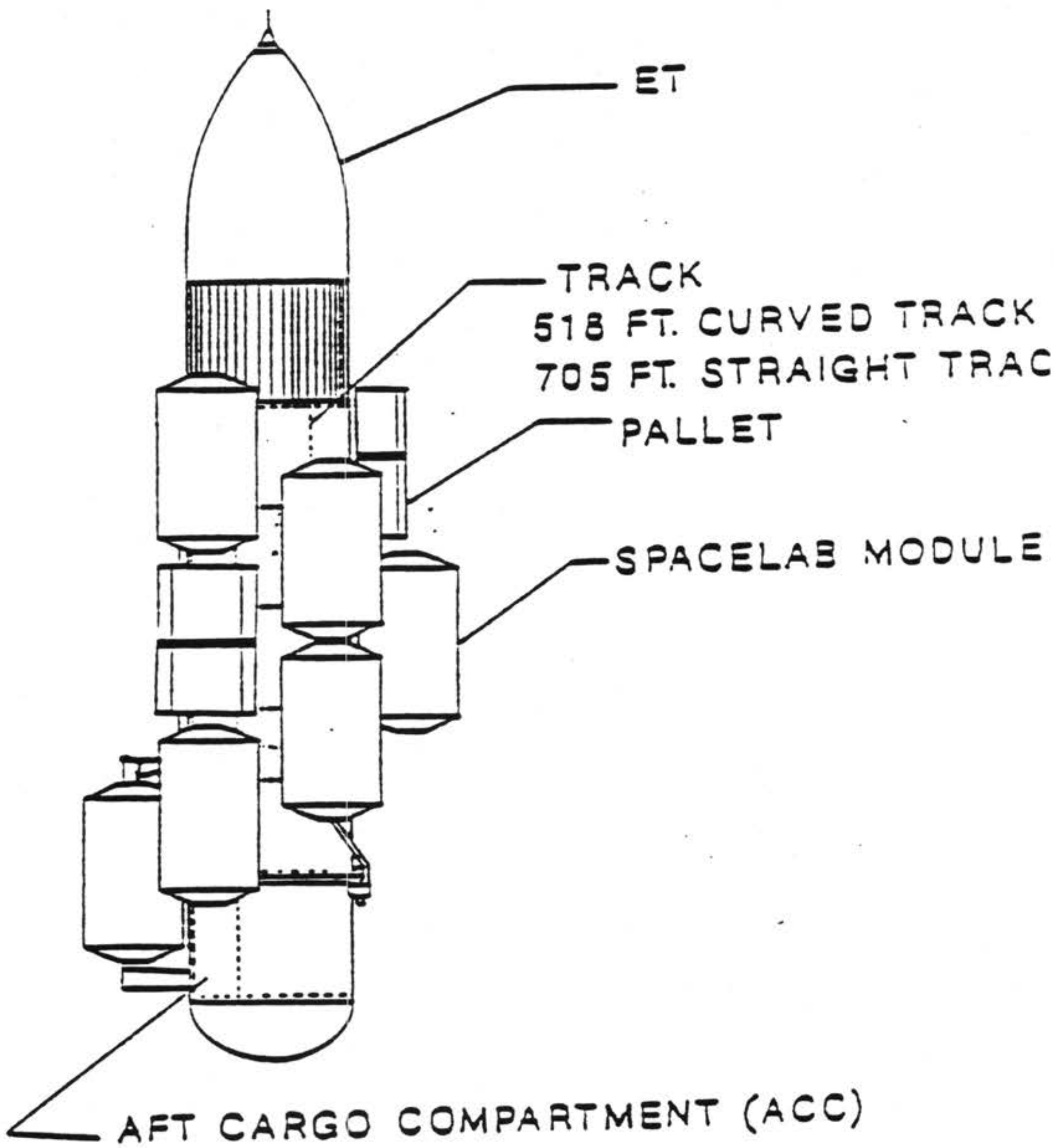
Near Capacity Multi-User Platform



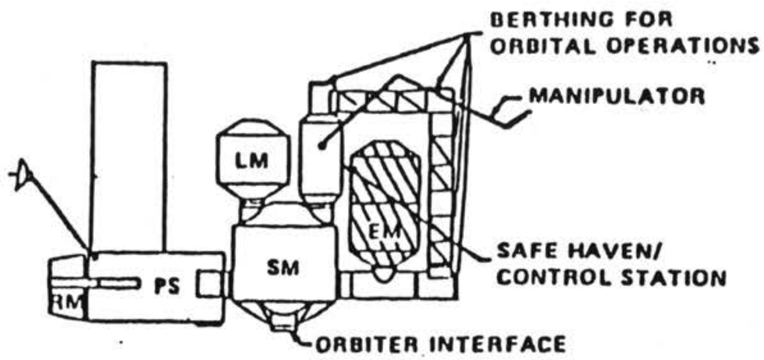
Early Electrophoresis Facility

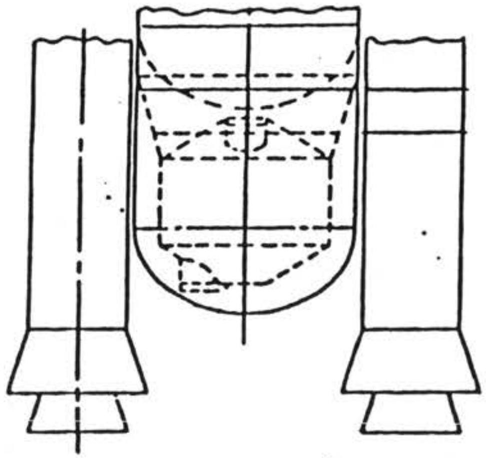


EXISTING SYSTEMS/ET COMBINATION



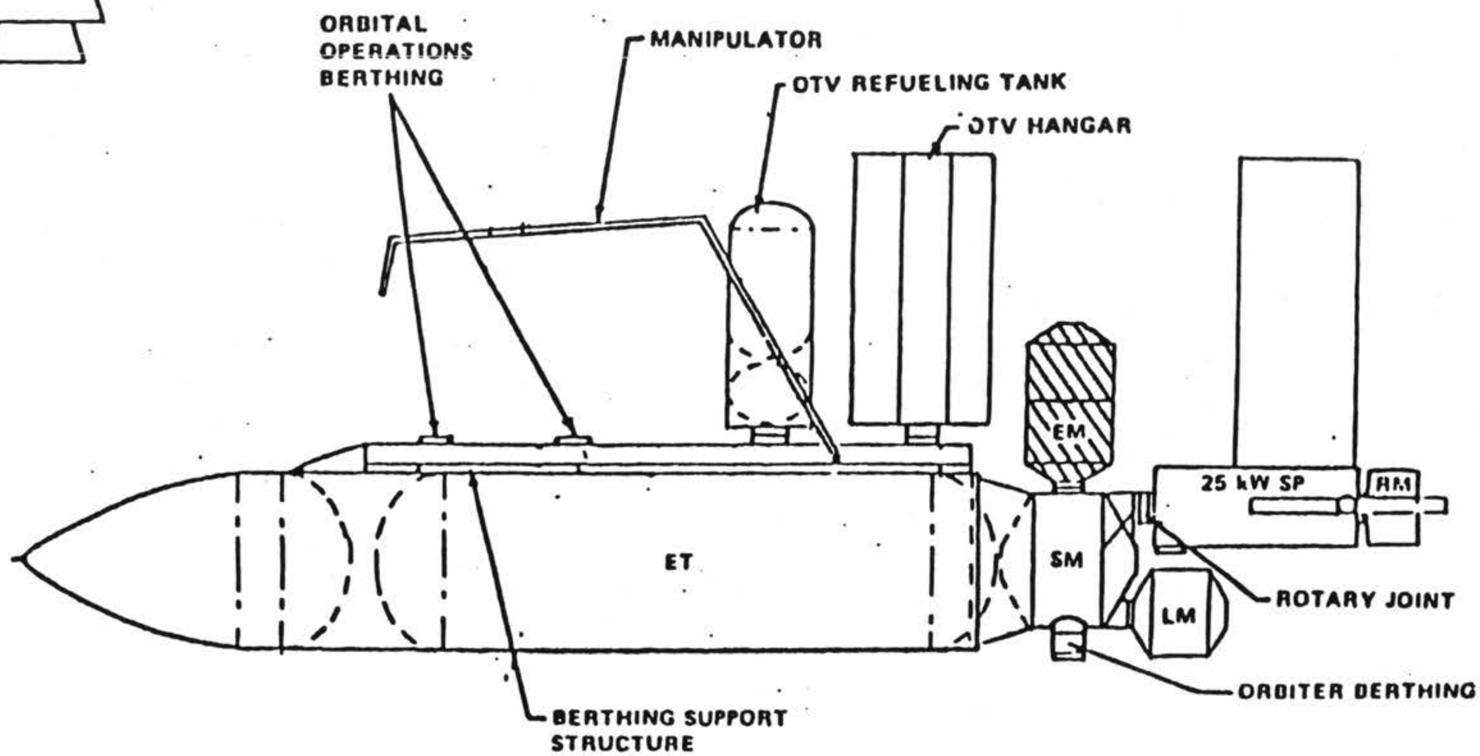
SPACELAB PARTICIPATION





LAUNCH CONCEPT

RM – REBOOST MODULE
PS – POWER SYSTEM
LM – LOGISTICS MODULE
EM – EXPERIMENT MODULE
SM – SYSTEMS MODULE



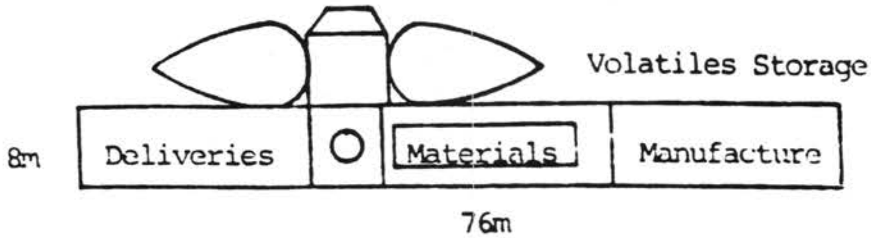
ACC SYSTEMS MODULE

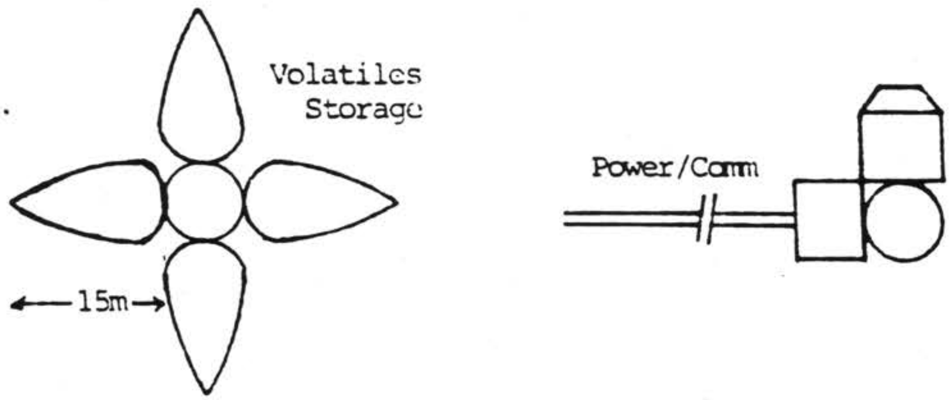
4. Allows companies to conduct environmentally sensitive experimentation in space as needed. Issues which are very sensitive to the general public become far less sensitive when the experimentation is a few hundred miles in space and the experimenters have to live with their experiments for months at a time. The advantage here will be to remove a potential problem from the surface and make those involved responsive to safety concerns.

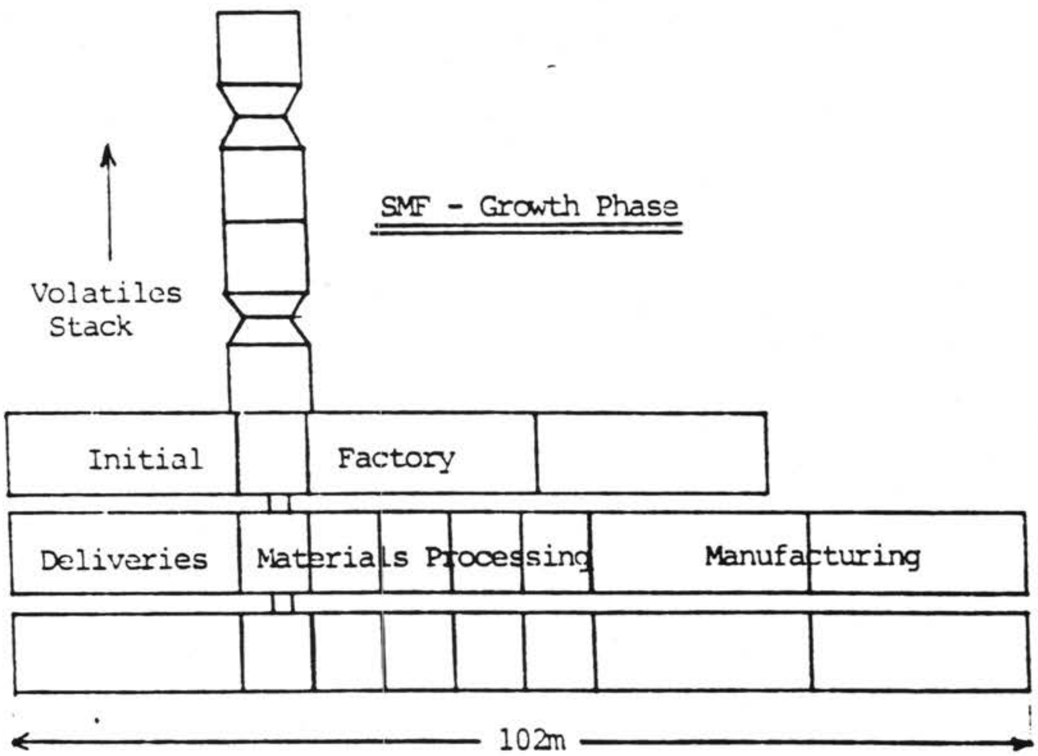
5. Allows countries which are interested in space operations to purchase from the US an autonomous manned space station for the same cost that a US company can buy one (75). Those countries that are interested in the space station would also be interested in the ET. If we remember the lesson of foreign sales of the F-20, foreign customers want to be actual owners and operators of the best equipment available. They will likely want a space station of their own and the ET/ACC combination is an excellent choice for their needs. This will also make the ET and ET based facilities an export item which will in turn improve the balance of trade. The ET as an export item is potentially a very attractive possibility.

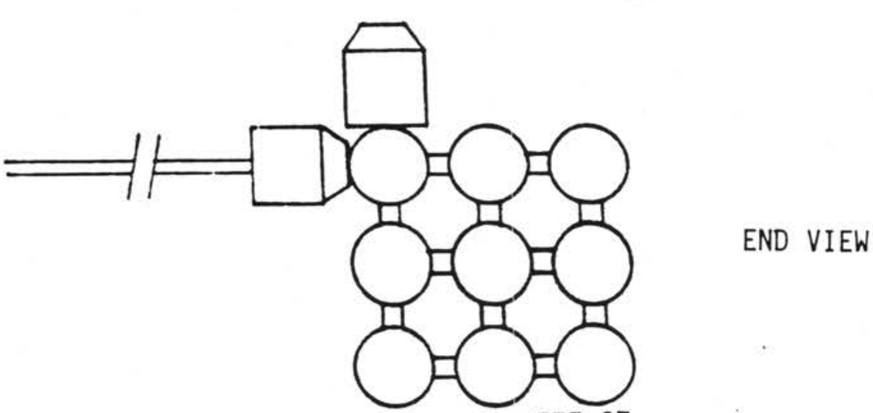
6. Enhance the space station by getting a significantly wider range of customers involved in flying and operating in orbit. The space station could be a central point in a fleet of space platforms which will provide servies to that fleet of domestic and foreign customers. It will provide an impetus for the permanent manned presence in space to become more permanent.

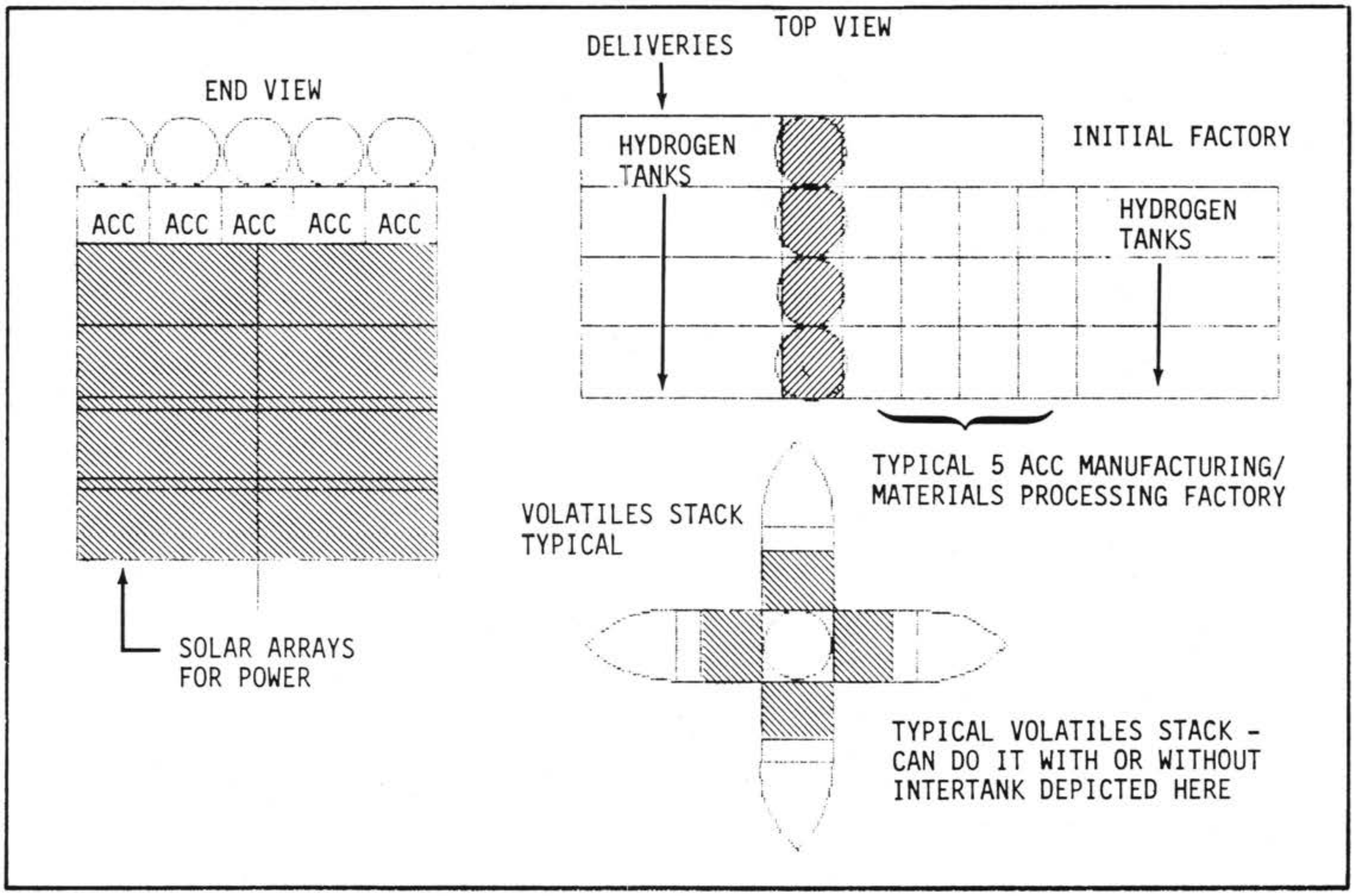
Another adaptation of the corporate space station concept was presented at the 7th Princeton Conference on Space Manufacturing as a way decrease the start-up costs of the High Frontier scenario proposed by Dr. G. K. O'Neill (33, 52). A version of the ET based corporate space station was proposed which would be useful in two ways. The first is the generation of revenues for future R&D toward the goal of Solar Power Satellite construction out of lunar soils. The second is a place where orbital testing, development, and work on actual hands-on space construction could be conducted. The basic idea is to initially rent floor space and support services to customers to generate cash flow (72). The funds are to be reinvested to expand the facility and to conduct the expensive R&D associated with setting up a construction base on the moon and in high lunar orbit. This is an example of a way that the ET can act as a catalyst for large scale activities that would otherwise rely on the whims of governmental funding.


Volatiles Storage
8m
Deliveries
Materials
Manufacture
76m


Volatiles
Storage
Power/Comm
15m


SMF - Growth Phase
Volatiles
Stack
Initial
Factory
Deliveries
Materials Processing
Manufacturing
102m


END VIEW



ALTERNATE ET BASED SPACE MANUFACTURING FACILITY

III. Miscellaneous Applications

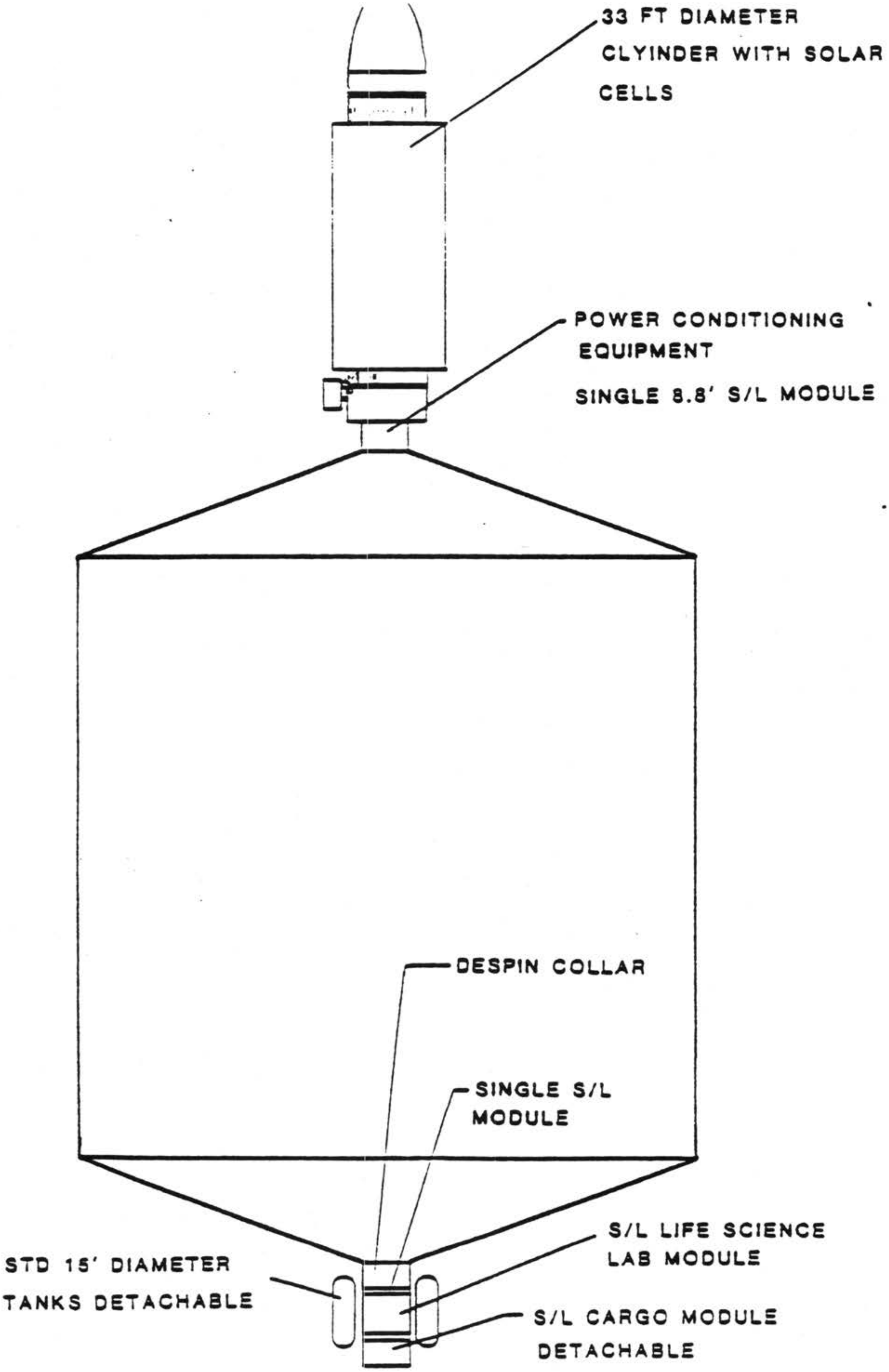
The majority of effort in the 'Tin Can' use of the ET has been spent in the area of habitable structures as discussed above. There are additional concepts to mention which include the use of the ET with inflatables, the ET as reentry and landing modules, and wake shields.

A. Inflatables

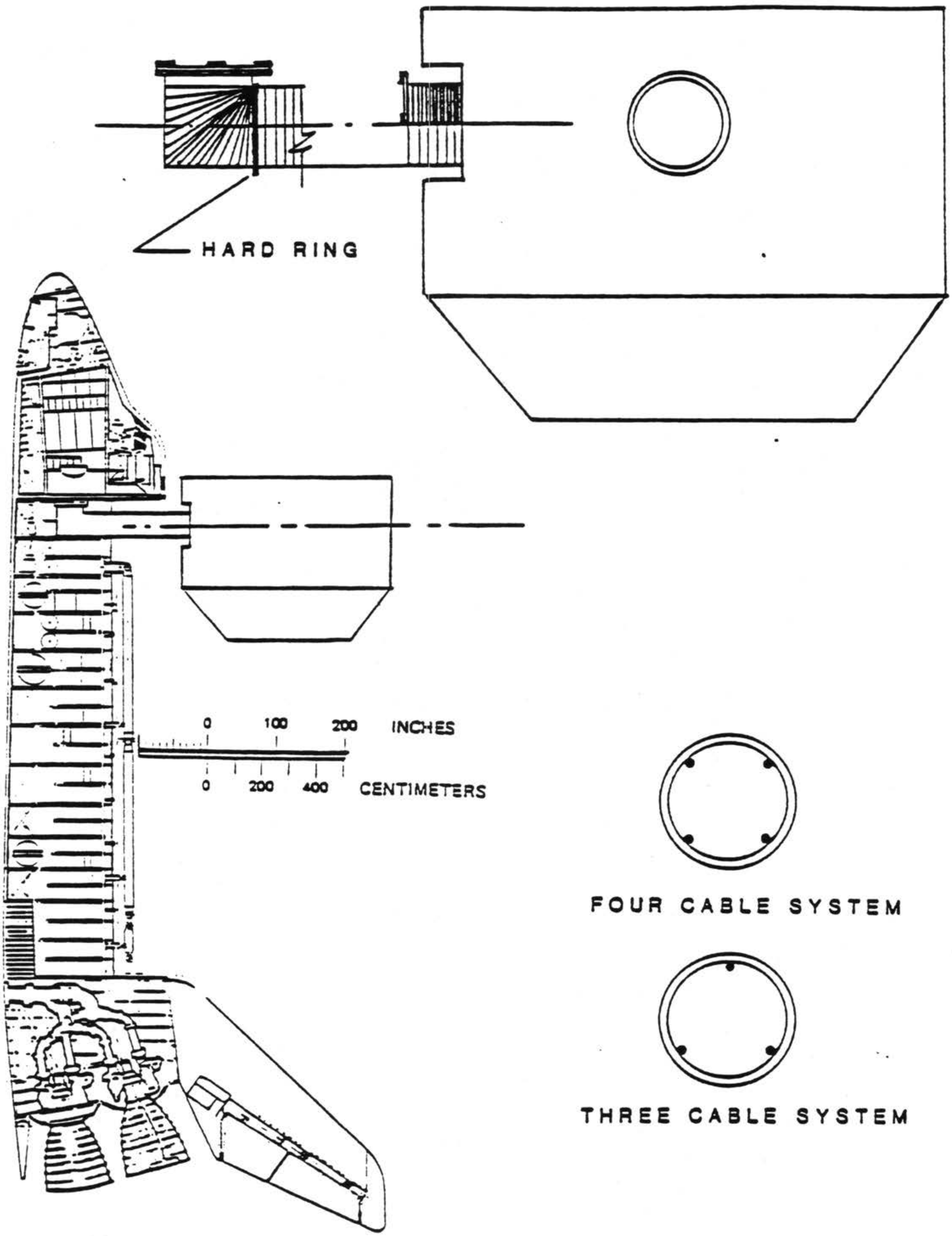
One of the proposed type applications involves inflatable structures (25, 95). As mentioned in another section, it has a large potential in a space operation. It is attractive to use inflatables with the ET/ACC because an inflatable is typically a low mass, large volume item. These structures could be used in conjunction with an ET to provide the interior of an ET based space station. They could be used to provide an orbital farm or growing facility. If it proves feasable to grow food in space, the work could be traded off against the $2,000 per pound launch costs for resupply from earth. This serves as sort of an orbital truck farm (59). The last proposed inflatable is the flexible docking tunnel concept (25). If there is a flexible docking tunnel attached to the space facility, this would save payload bay space in the orbiter in each trip to the station. The orbiter could conduct the mission for the paying customers and visit the station last. There would not need to be payload bay volume or lift capability used in carrying the docking adapter. Overall savings are in volume and lift costs. These have been projected at $180 million over a ten year period (25). They may be far greater, especially if the additional volume can be used to support paying customers.

B. Landing and Reentry modules

There have been two papers proposing the ET in various configurations as a reentry module (39). The direct use of the ET as a reentry module is not structurally possible according to the manufacturer (48). There are however, vaiations in this concept which involve indirect ET use that may be possible. It may be possible to use the SOFI removed from the ET in structural processing as an ablative material (56). It may also be possible to form melted aluminium from the ET into an areodynamic shape, cover it with ablative materials, and recover the aluminium itself after reentry for salvage and



FUTURE LIFE SCIENCE INFLATABLE



CONCEPTUAL TUNNEL

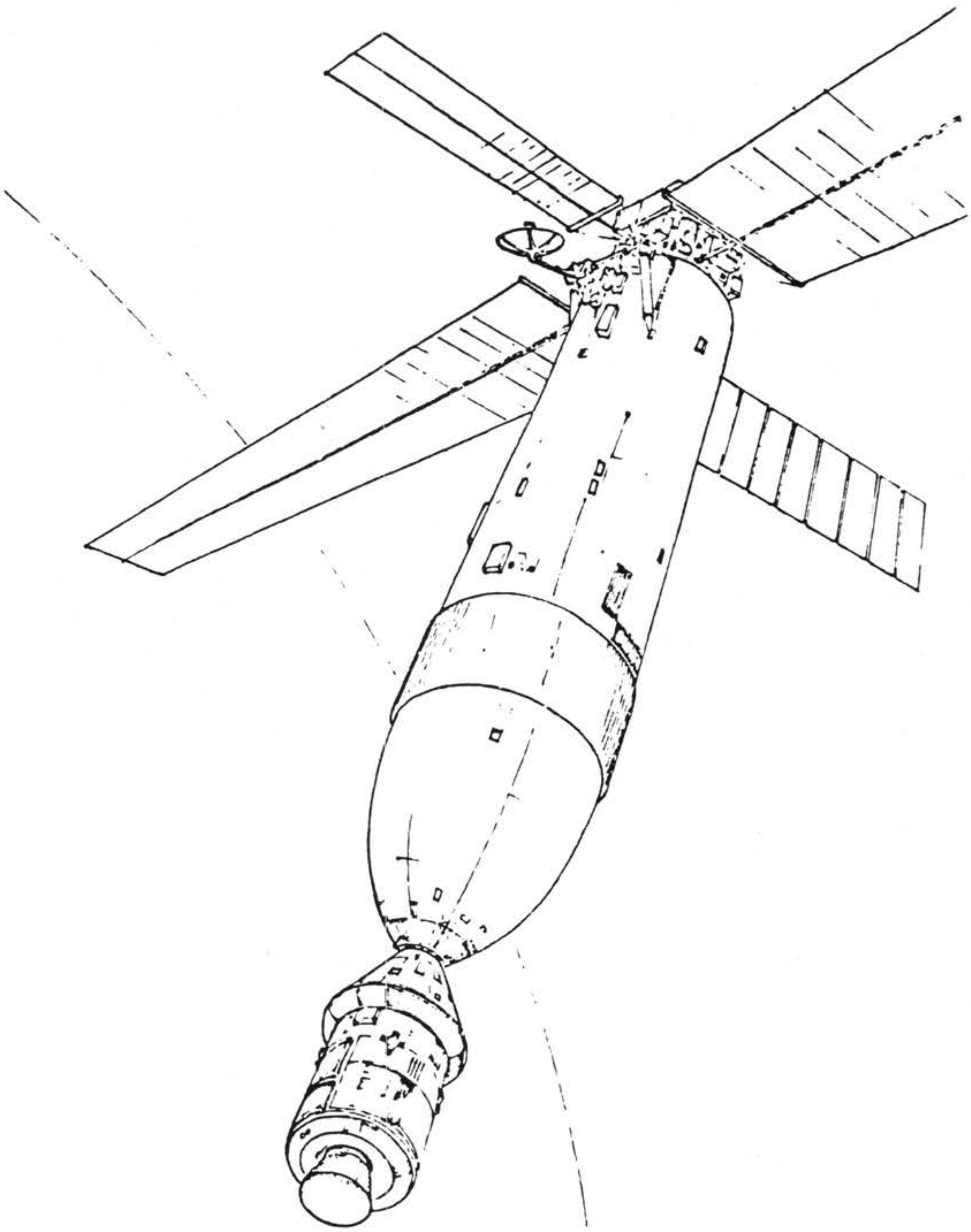
sales. The other class of applications include the use of the ET as a landing module. This either crashes the ET as a raw materials carrier on the Lunar or Martian surfaces or drops it in a controlled soft landing using the crushing of a portion of the ET as a large shock absorber in the landing.

C. Spacecraft

Any structure that can be used as a space station can be used as a large spacecraft (43,82). The ET and ET based structures are no exception. The advantages are available volume and structural strength. As mentioned previously in this section, the primary problem is excess mass. The ET as it flies, may be a bit too massive to fly manned missions to the planets without partial disassembly in orbit (51, 80). The oxygen tank and intertank can be removed and the hydrogen tank can be used for habitats and fuel tanks. However, the use of a space station as a spacecraft is well within the realm of possibility if the designers are careful about mass and propulsion problems (82).

D. Wake Shield

This is the use of the ET as large windshield in orbit (17). On the lee (or downwind) side of an orbiting body, it is possible to achieve vacuum enhancements orders of magnitude better than ambient. The ET can be cut lengthwise, opened, and flown to provide this advantage for materials processing or experimentation in orbit. This application is highly drag intensive in that it aggravates the orbital maintenance problem of the ET. It also might not work out as desired due to the tendency of vehicles to collect orbital plasmas (48).



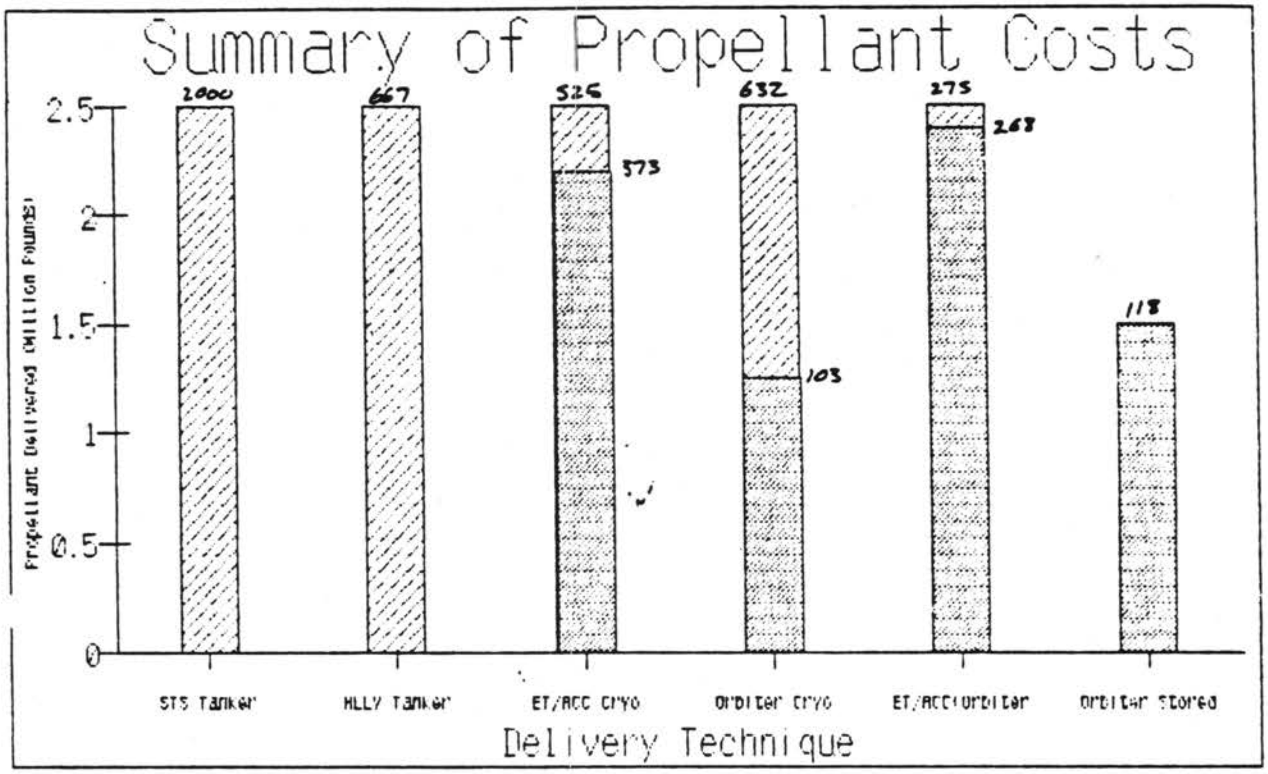
ET BASED SPACECRAFT

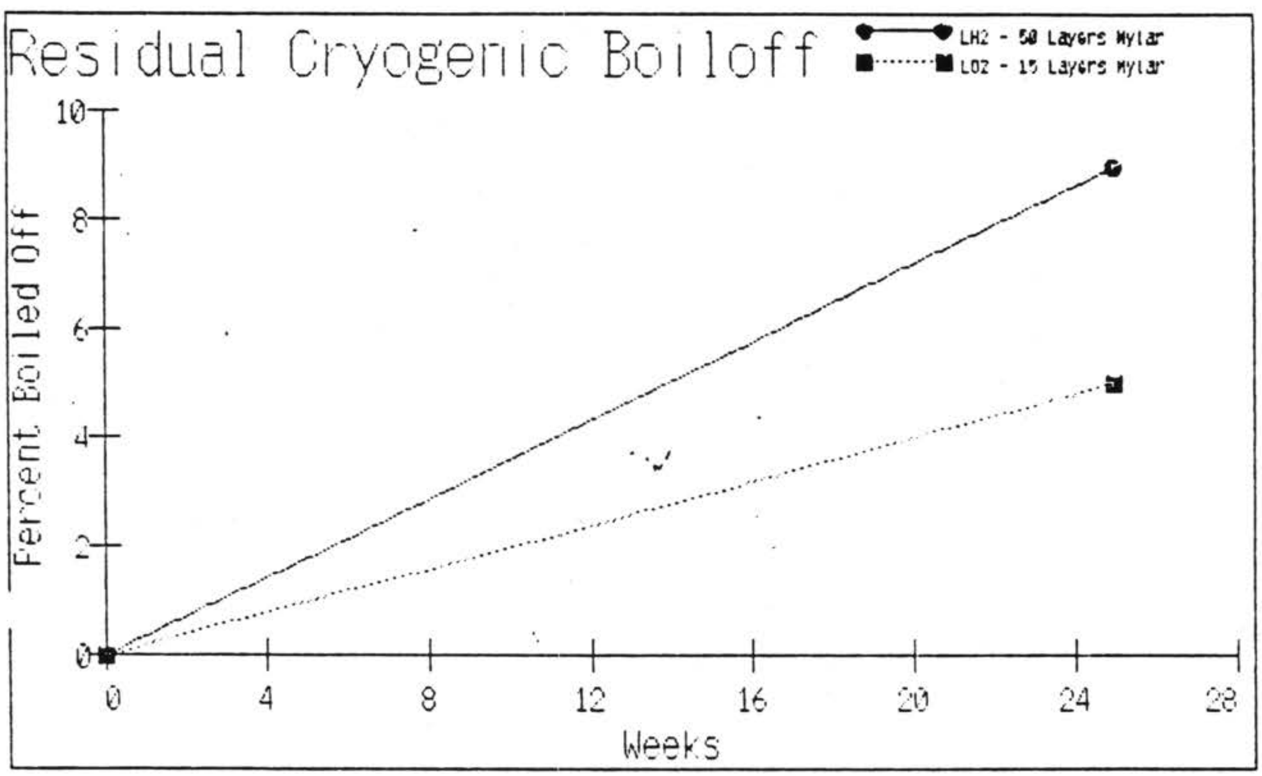
This section details external tank applications that are related to the use of the tank and what it carries as a fuels resource. The possibilities include scavenging the residual cryogenics remaining after launch, powdering the ET and using it as fuel in a special rocket engine, and the use of ETs as reaction mass in electric space engines. NASA has a requirement for 2.5 million pounds for cryogenic fuels in low earth orbit (LEO) based on potential orbital transfer vehicle (OTV) traffic models. The scavenging of residual cryogenics from the ET can fill over 92% of this requirement at a very low cost (69). The potential cost savings of these type operations is great when compared to the basic launch cost of $2,000 per pound to LEO (29, 32, 69).

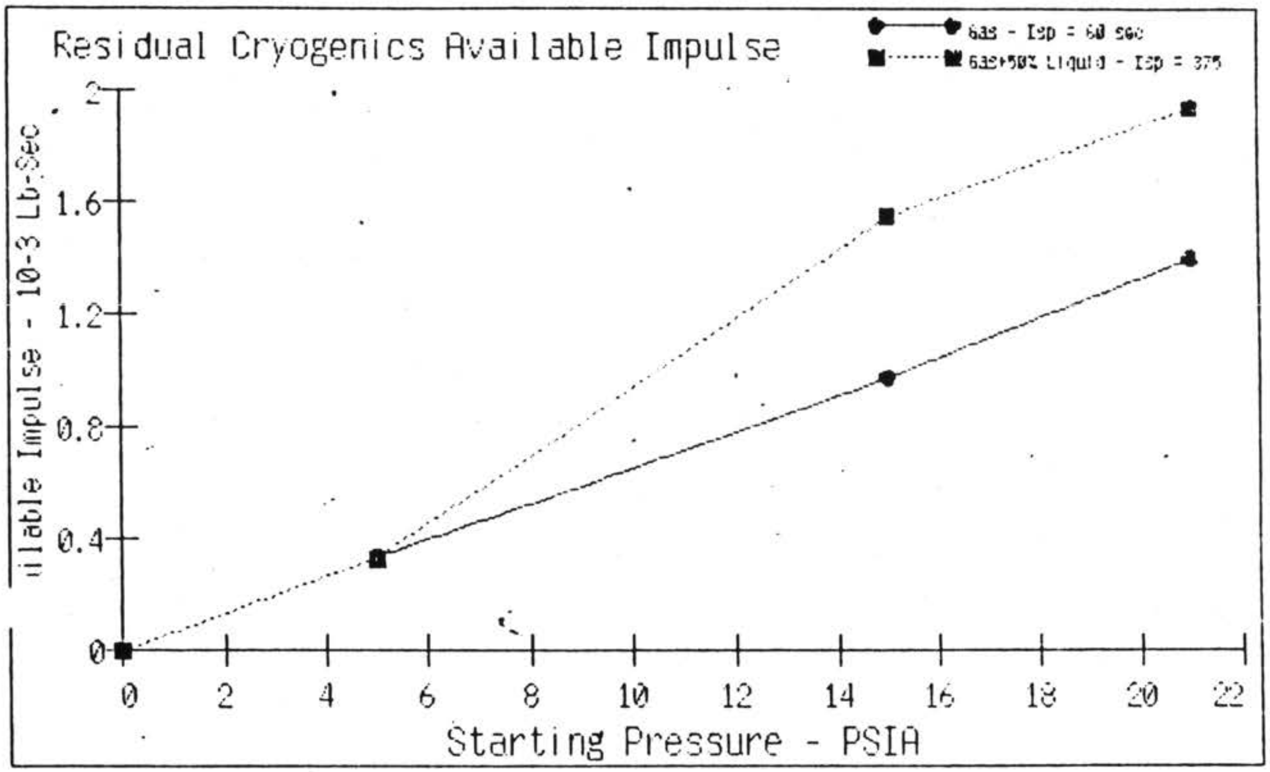
I. Scavenging of Residual Cryogenic Fuels

As mentioned previously, the direct insertion trajectory will also deliver an average of 15,000 pounds of residual cryogenics into orbit. These residuals are available for scavenging, storage, or use immediately after MECO or longer if steps are taken to retard boiloff. In a propellent scavenging study, a plan utilizing residual cryogenics in the ET will meet the requirements of 2.5 million pounds of OTV fuels over a ten year period. The scavenging of residual cryogenic is cheaper than launching the required fuels into orbit in an orbiter based tanker by almost an order of magnitude. The numbers on the figure below are costs per pound of fuel delivered to orbit. Note how the ET/ACC based scavenging is by far the most economical fuels supply choice (69).

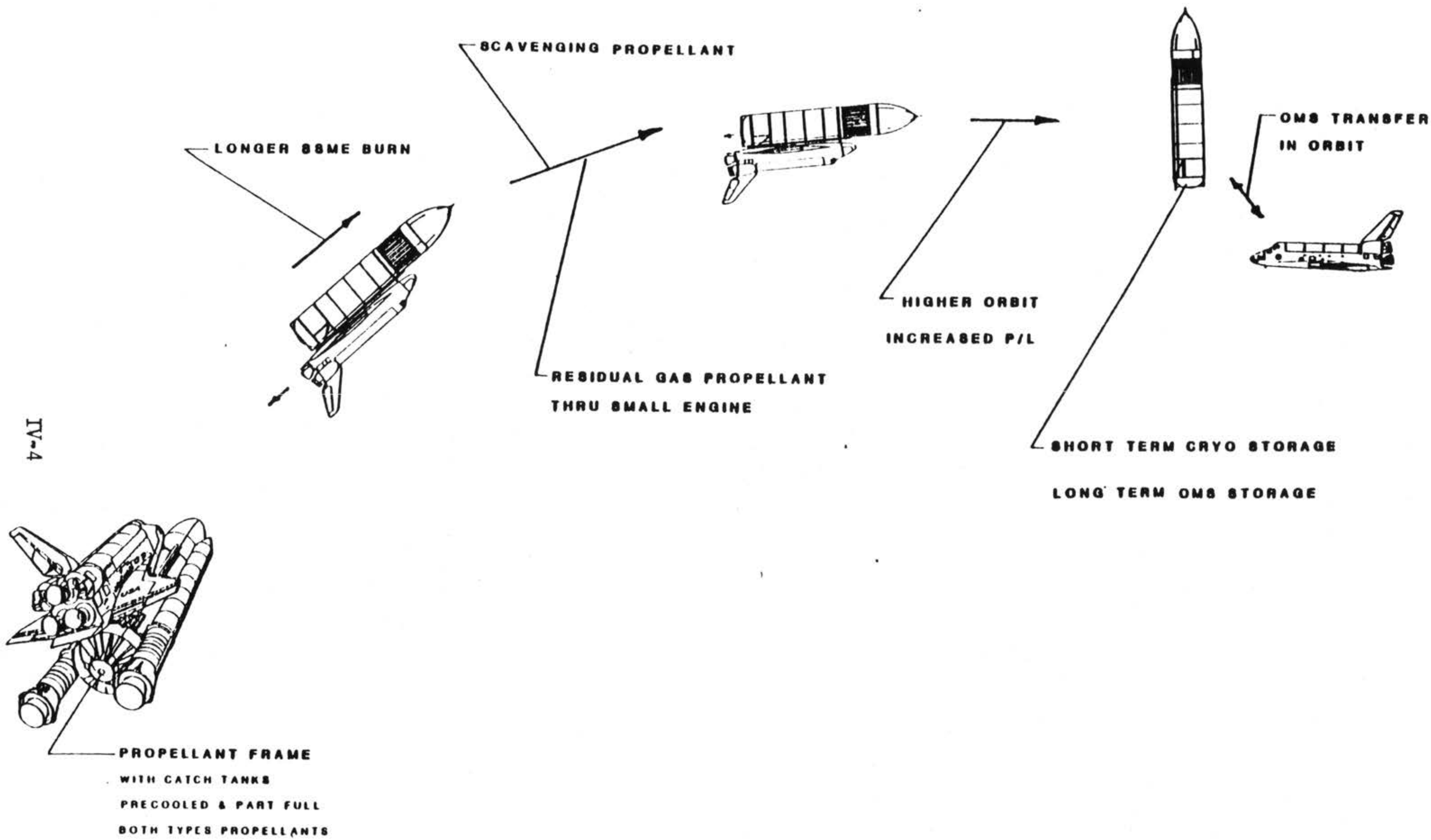
The scavenging operation can be conducted in a variety of ways. If there is a requirement to dispose of the tank, the scavenging operation needs to be done in the 20 minutes of time available after MECO. This can be accomplished using equipment carried in the payload bay of the shuttle or in an ACC. If the ET is carried into orbit, the scavenging operation can be done later. This could use scavenging equipment carried in an ACC or a separate facility located at the space station. It could also use a free flying scavenging flyer carried in the ACC, the payload bay, or already on orbit. It could also use the payload bay based scavenging equipment. The payload bay based method is the most expensive way to scavenge residuals because it takes up payload bay space, payload mass, and requires orbiter modification. The ACC based


Summary of Propellant Costs
2000
667
526
573
632
103
275
268
118
2.5
2
1.5
1
0.5
0
Propellant Delivered (Million Pounds)
STS Tanker
HLLV Tanker
ET/ACC Cryo
Orbiter Cryo
ET/ACC+Orbiter
Orbiter Stored
Delivery Technique

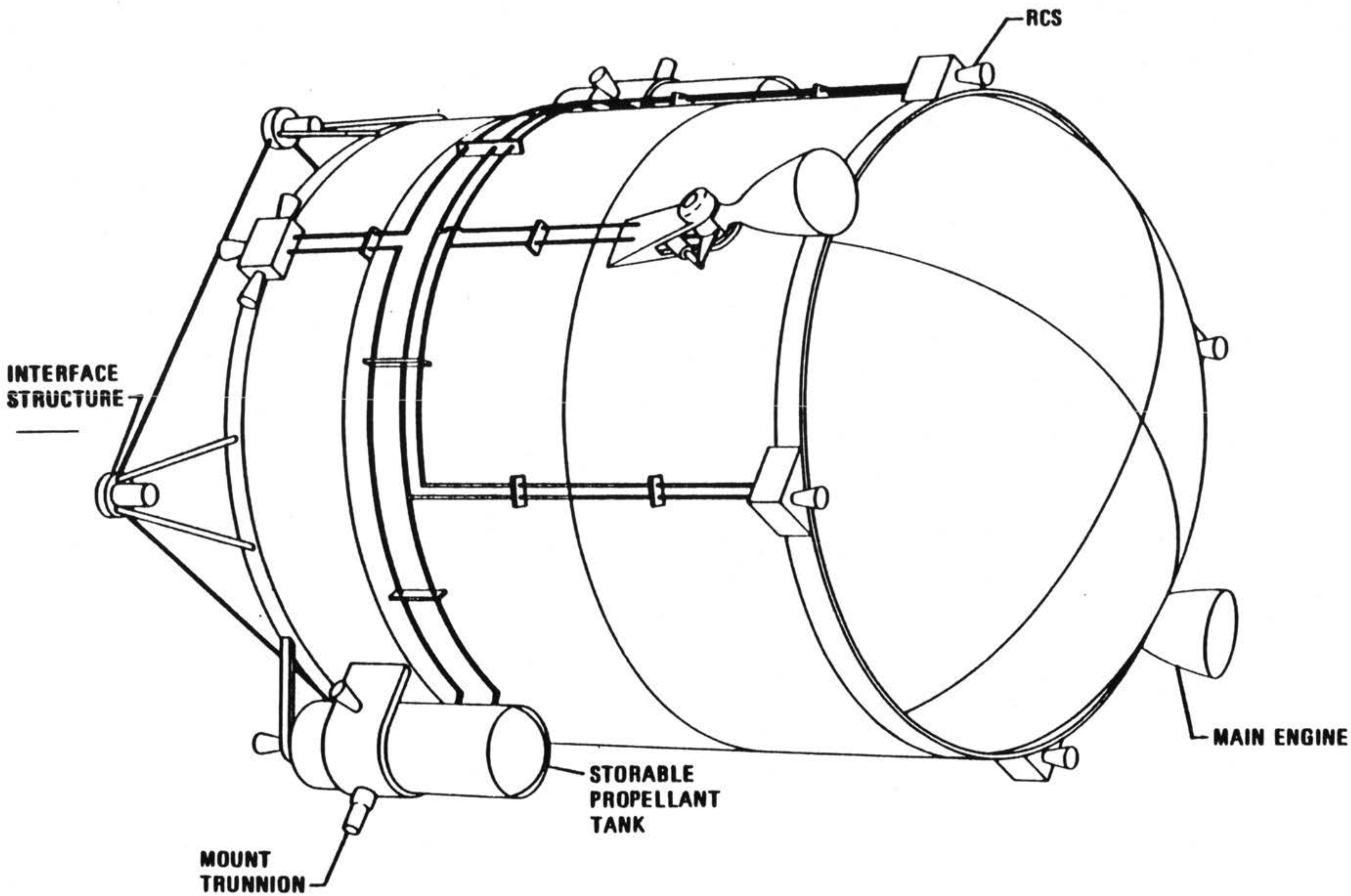

Residual Cryogenic Boiloff
LH2 - 50 Layers Mylar
LO2 - 15 Layers Mylar
10
8
6
4
2
0
Percent Boiled Off
0
4
8
12
16
20
24
28
Weeks



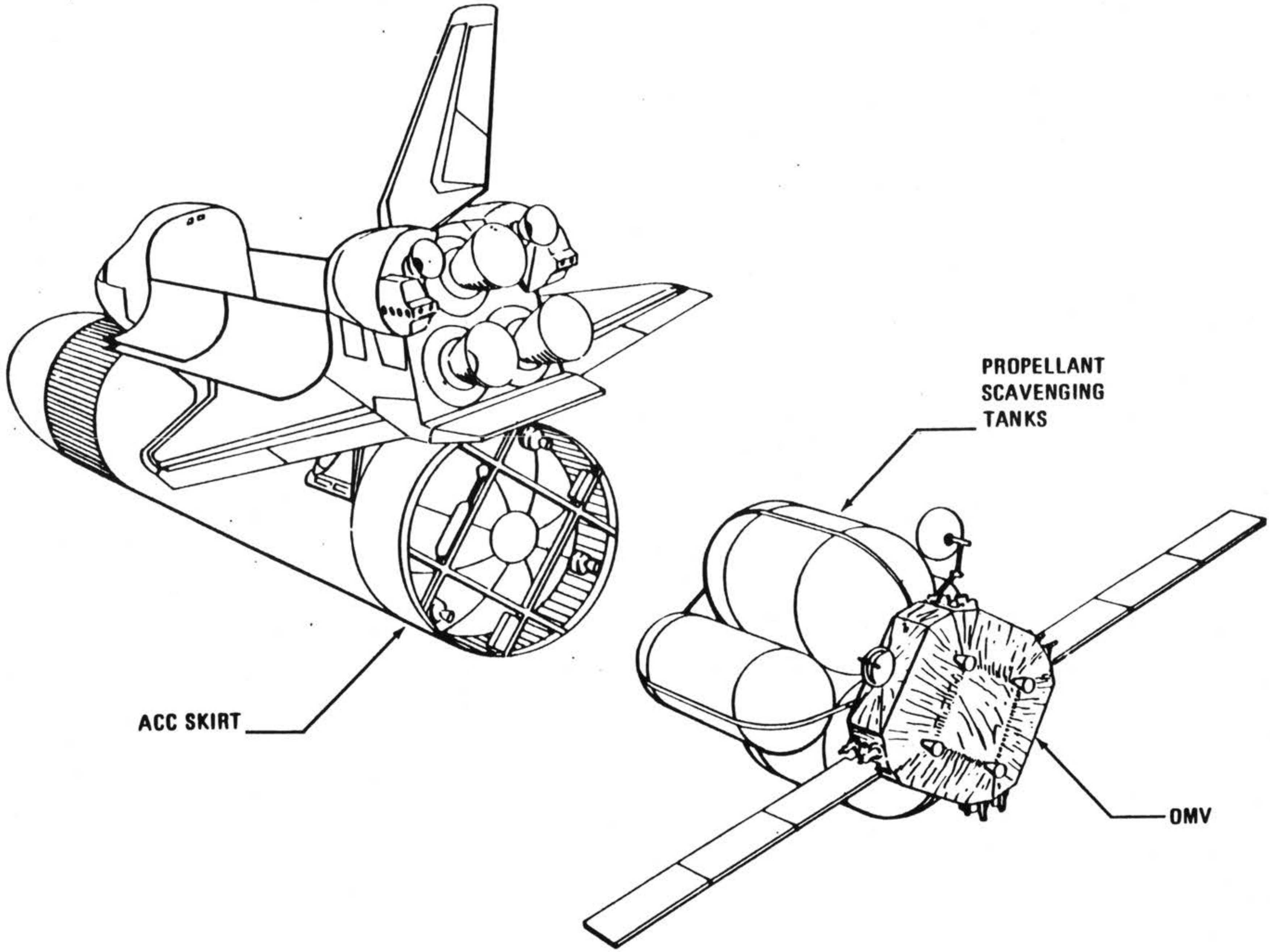
Residual Cryogenics Available Impulse
Gas - Isp = 60 sec
Gas+50% Liquid - Isp = 375
ilable Impulse - 10-3 Lb-Sec
2
1.6
1.2
0.8
0.4
0
0
2
4
6
8
10
12
14
16
18
20
22
Starting Pressure - PSIA



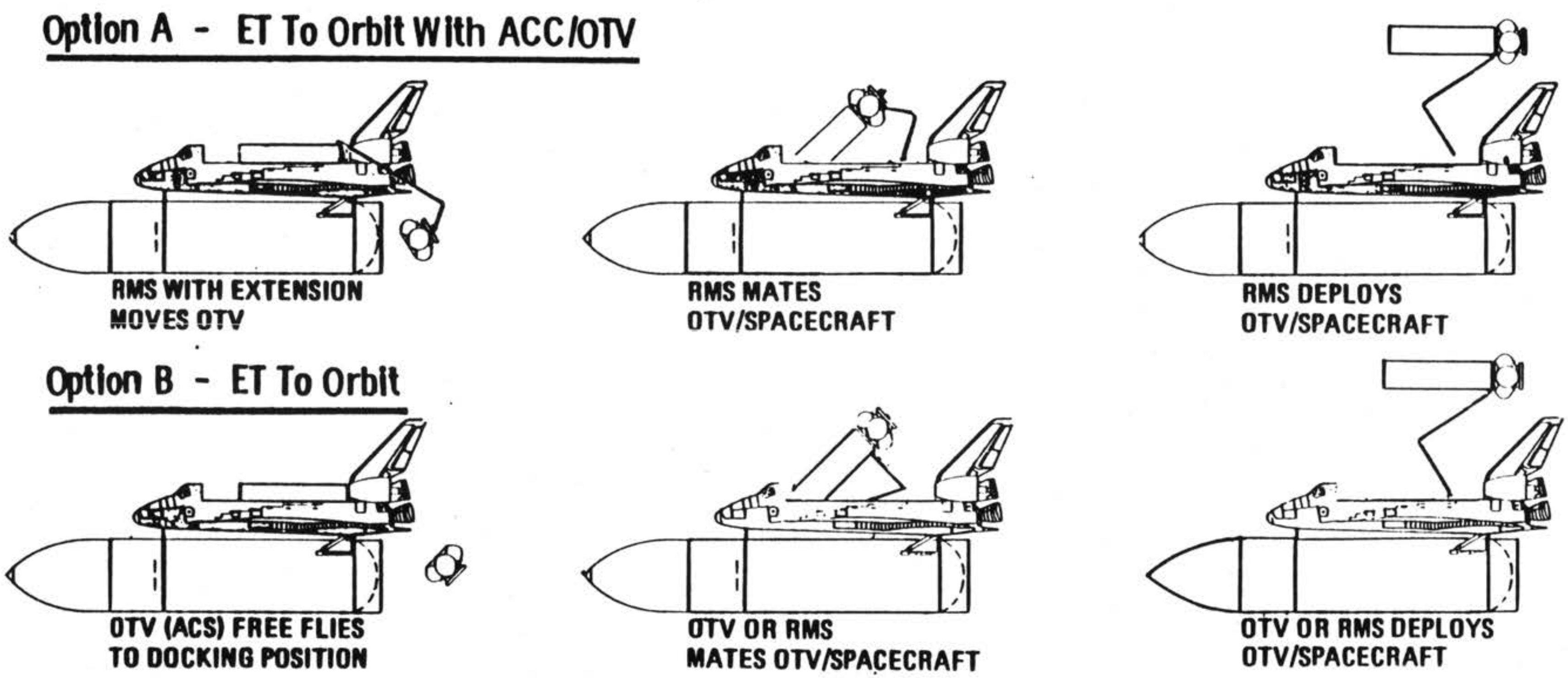
PROPELLANT MANAGEMENT LOGIC



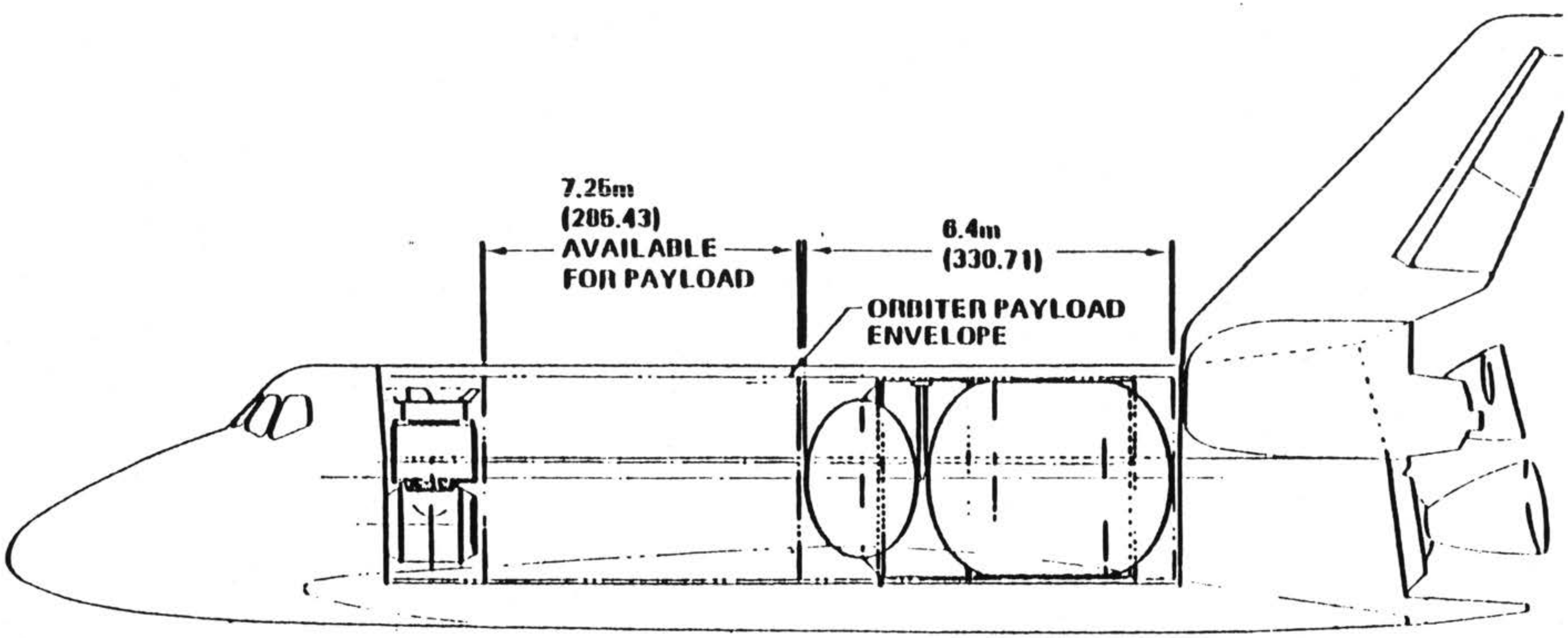
PROPELLANT SCAVENGING CONCEPT



PROPELLANT SCAVENGING CONCEPT USING ACC



VARIOUS METHODS OF ACC PAYLOAD DEPLOYMENT



MINITANKER CONCEPT

tanker does not impact the orbiter payload bay or the orbiter and can be used any time inflight after launch. An ACC based tanker and cryogenic scavenging operation can supply 2.3 million pounds of fuel (92% of the requirement) at a cost of $350/lb over a ten year period (69). If the required cryogenics are brought into orbit by STS tanker, the projected cost runs about $2,000/lb (69). Over ten years the program savings due to this ET application alone will be on the order of $3.5 billion primarily due to launch costs. Cryogenic scavenging also enhances the space station program. Every shuttle visit to the vicinity of the station can deliver an average of 15,000 pounds of cryogenics at almost no cost per mission. This is clearly an important advantage to an operation limited by congressional funding.

II. Reaction Mass

Support requirements have been extensively studied for future space based operations. One of the results from these studies has been the identification of a requirement for large quantities of reaction mass for orbital operations (19, 56). This reaction mass is used for such things as orbital maintenance of large space platforms (prevention of orbital decay due to drag), fuel for an OTV operation, fuel for satellite launch and recovery, fuel for future large manned space expenditions, and fuel for emergency requirements (56). Typically, the studies focus on some sort of liquid fuel either supplied by an orbiter based tanker, scavenged from the ET itself, or the orbiter OMS system in orbit. The reaction mass applications to follow suggest reaction mass applications based on using the mass of the tank itself as the reaction mass applications based on using the mass of the tank itself as the reaction mass. The mass of the tank on-orbit of about 69,000 pounds, can by itself fill all refueling requirements proposed with no additional shuttle visits. Once again, the program savings are primarily in launch costs for the 69,000 pounds already in orbit.

A. Aluminium Fuelled Rocket

The first proposal is to powder the aluminium of the tank structure and use it as fuel in an Hydrogen/Oxygen/Aluminium based rocket engine (18, 19). As mentioned before, each ET delivered to LEO will also deliver an average of 15,000 lbs of residual cryogenics and over 53,000 lbs of aluminium. Performance studies of advanced propulsion engines have indicated that an

H2/O2/Al based engine that burns fuel on a H:O:Al = 1:3:4 mix will give a specific impulse (Isp) over 400 seconds (18). This Isp is somewhat less than proposed advanced H2/O2 engines (480 - 490 sec) and less than state of the art H2/O2 engines (460 - 490 sec) proposed for OTV applications. However, a comparison of the economics of using powdered aluminium as a primary component of the fuel burned in a rocket versus the economics of burning only liquid fuels suggests that this is a capability well worth the time and effort to study. The energy advantage of the Aluminium fueled rocket is that the Aluminium - Oxygen reaction delivers 22% more energy per unit mass than the Hydrogen - Oxygen reaction does (18, 19). The economic advantage is that the aluminium burning engine utilizes already orbiting ETs as a primary source of fuel.

In two studies of advanced propulsion for OTV applications by Dr. A. H. Cutler of the California Space Institute, the Aluminium fueled engine is compared with an advanced technology engine and the Centaur RL-10 (a proposed OTV candidate) (18, 19). The comparison was made through models of future OTV traffic levels and mass requirements. The assumption was made to use scavenged ET cryogenic residuals as the primary OTV fuel for all three rockets. Analysis of costs showed that if the fuel demand for OTV traffic models remains below the available scavenged cryogenics, it is more economical to use the RL-10 for primary OTV propulsion. However, if there are not enough scavenged cryogenics available, then it becomes far more advantageous to develop and use the Aluminium fueled rocket. This engine is a better choice for two reasons. First, it reduces the mass required in LEO for both fuel and tankage by about 30% over the RL-10 and about 15% over the advanced engine. Second, it is about 40 - 50% cheaper to fuel because ET aluminium is used for reaction mass and does not need to be launched.

The problem with the Aluuminium engine is a very expensive development cost - on the order of $1 - 2 billion (18). This cost, the processing facility cost, and the engine production cost all were added into the analysis. Even with these high costs, the Aluminium engine is far more economical to develop and operate in a scenario which includes a shortfall of scavenged cryogenics. The cost savings is entirely due to the availability of Aluminium at a low cost in LEO.

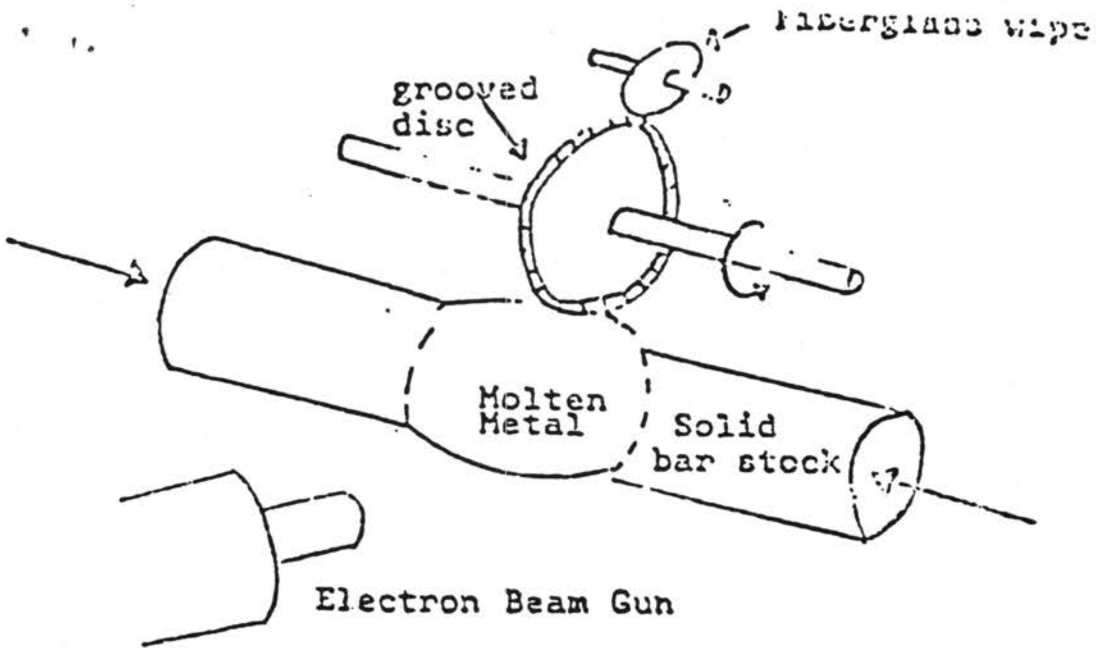
Support equipment for this application includes SOFI stripping equipment and a method of melting the aluminium cut from the ET (15, 18, 20 92). The cut aluminium is fed into an induction furnace for melting. The asymmetric winding of this furnace pools the molten aluminium at one end where it can be drawn off and powdered. These are examples of space operations that use tools and techniques which are familiar to industry on the earth and can be adapted to on-orbit operations.

B. Mass Driver Fuel

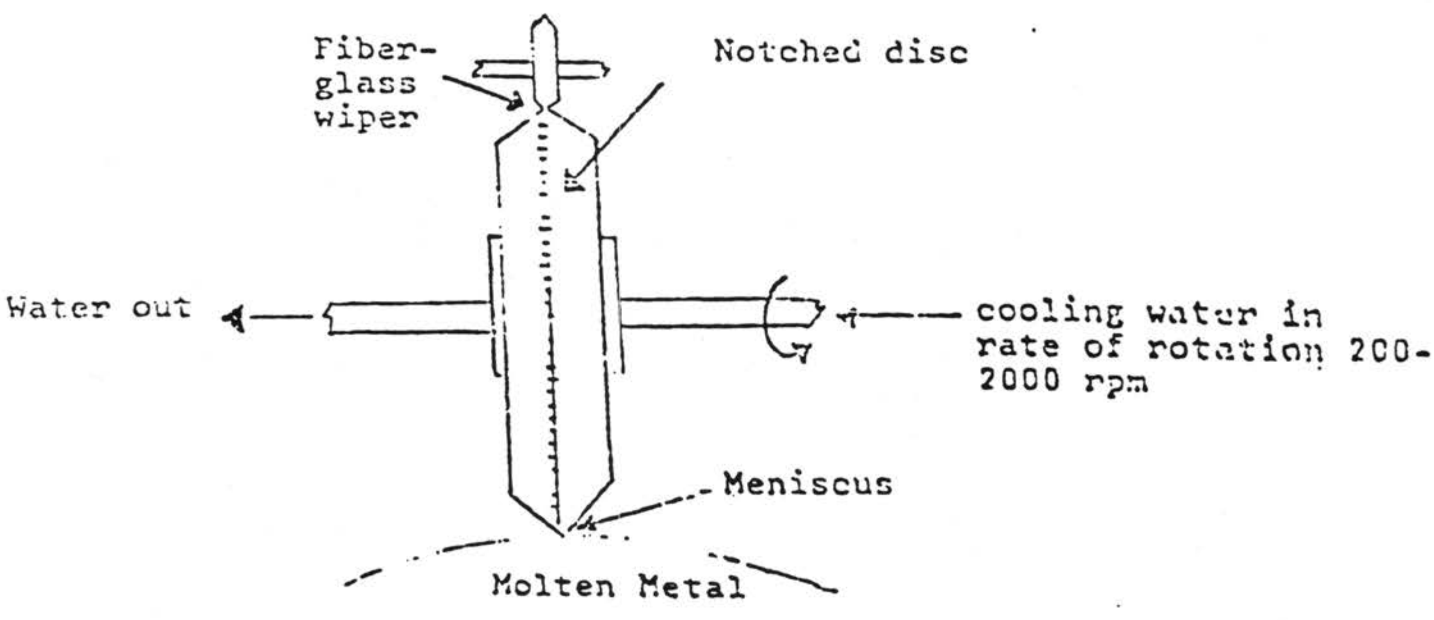
In the middle 1970's, Dr. O'Neill proposed the Mass Driver as a tool necessary in the construction of very large structures in space (52). It was proposed as a means of recovering asteroids, launching large quantities of lunar soils off the moon, and even as a very large OTV for use in Cislunar space. The beauty of the Mass Driver is that it is not sensitive to what is used as reaction mass. In this context, Dr. O'Neill proposed powdering the tanks and using them as reaction mass for a mass driver. A moderately efficient mass driver was proposed that could mover 850 tons from LEO to Lunar orbit expending 1,050 tons (about 30) of powdered tanks (62). This is a possible use of the ET which may be significant if there are no competing uses of the ET in an unpowdered form.

C. Reaction Engines

There are two other possible reation mass applications. The Railgun, currently being discussed in SDI research as a kinetic kill weapon, was proposed as a space engine (11). A railgun reaction engine could use powdered ET materials as reaction mass. It is not as efficient as the mass driver or the aluminium rocket, but may serve as an emergency manuvering system for military battle stations. Problems with the railgun include a fairly serious polution problem due to large masses of debris being thrown away behind the engine. A similar device with the same capabilities and the same problems is the coilgun also being researched in the SDI effort.

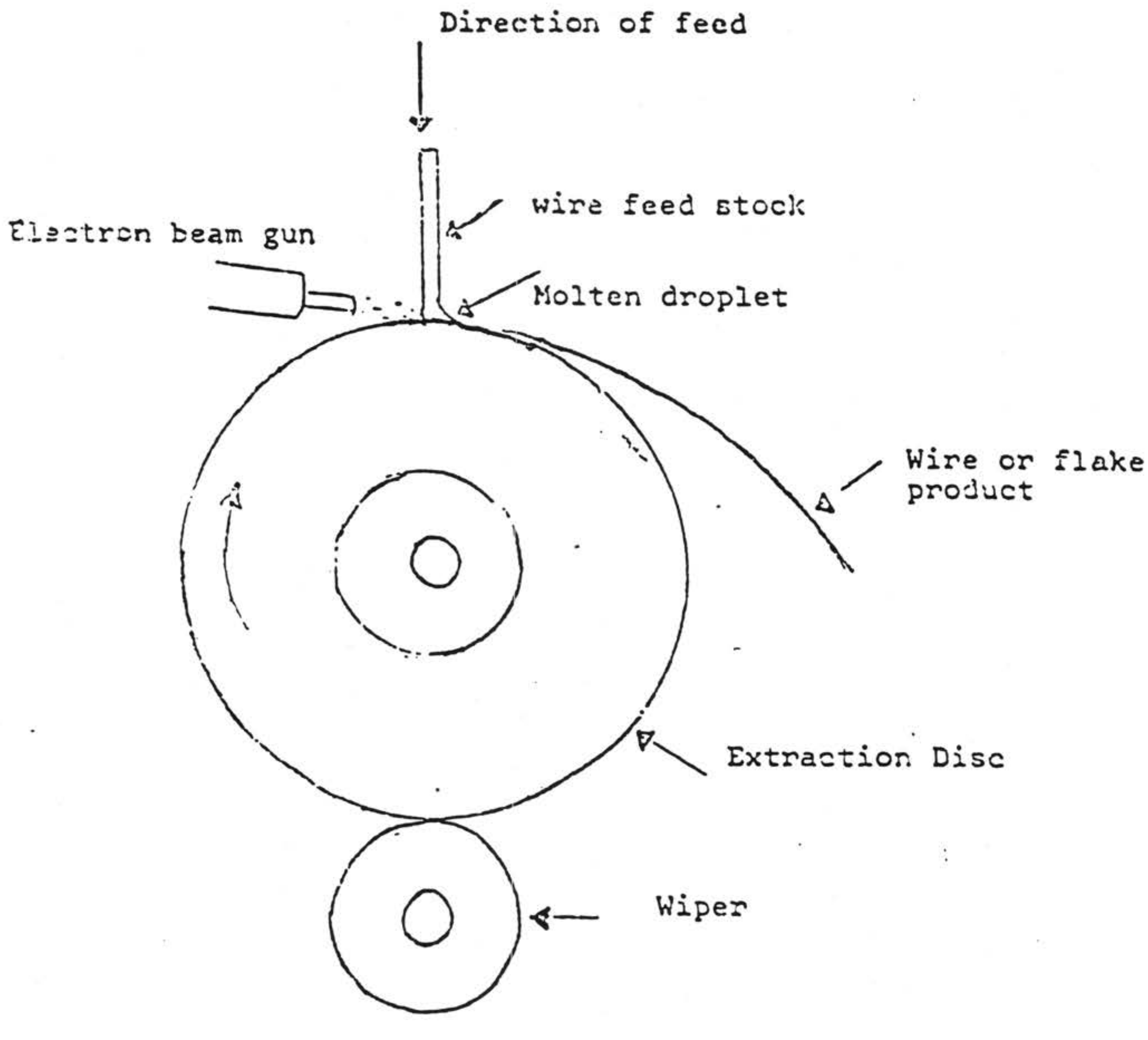


A. Production of metal flakes by Crucible Melt Extraction (CME) Process.

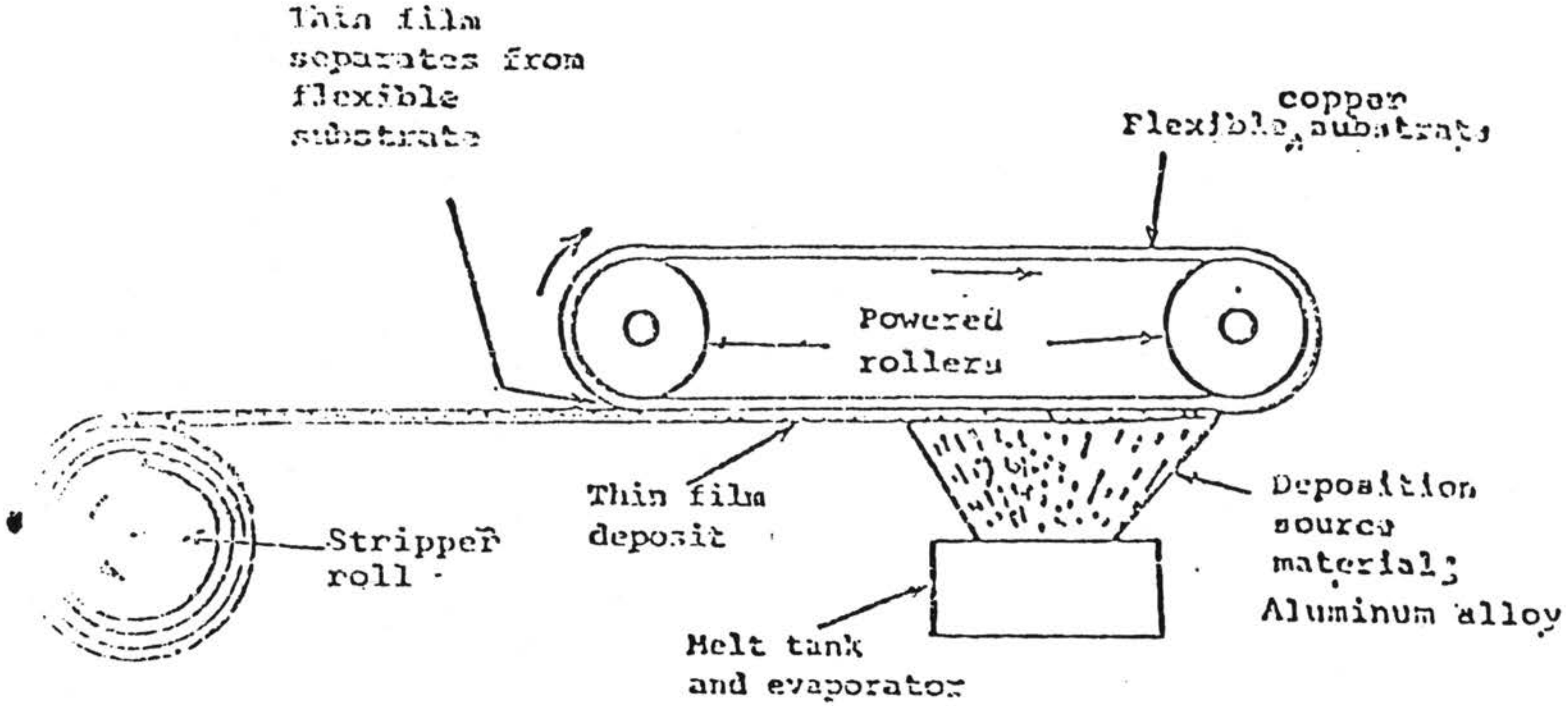


B. Profile view of notched disc for producing metal flakes by CME process.

Battelle Crucible Melt Extraction (CME) Process for flake and wire production modified for use in zero-gravity environment.



Schemetic of Battelle Pendant Drop Melt Extraction (PDME) Process.



Aluminum Film Deposited and Removed from
Flexible Substrate

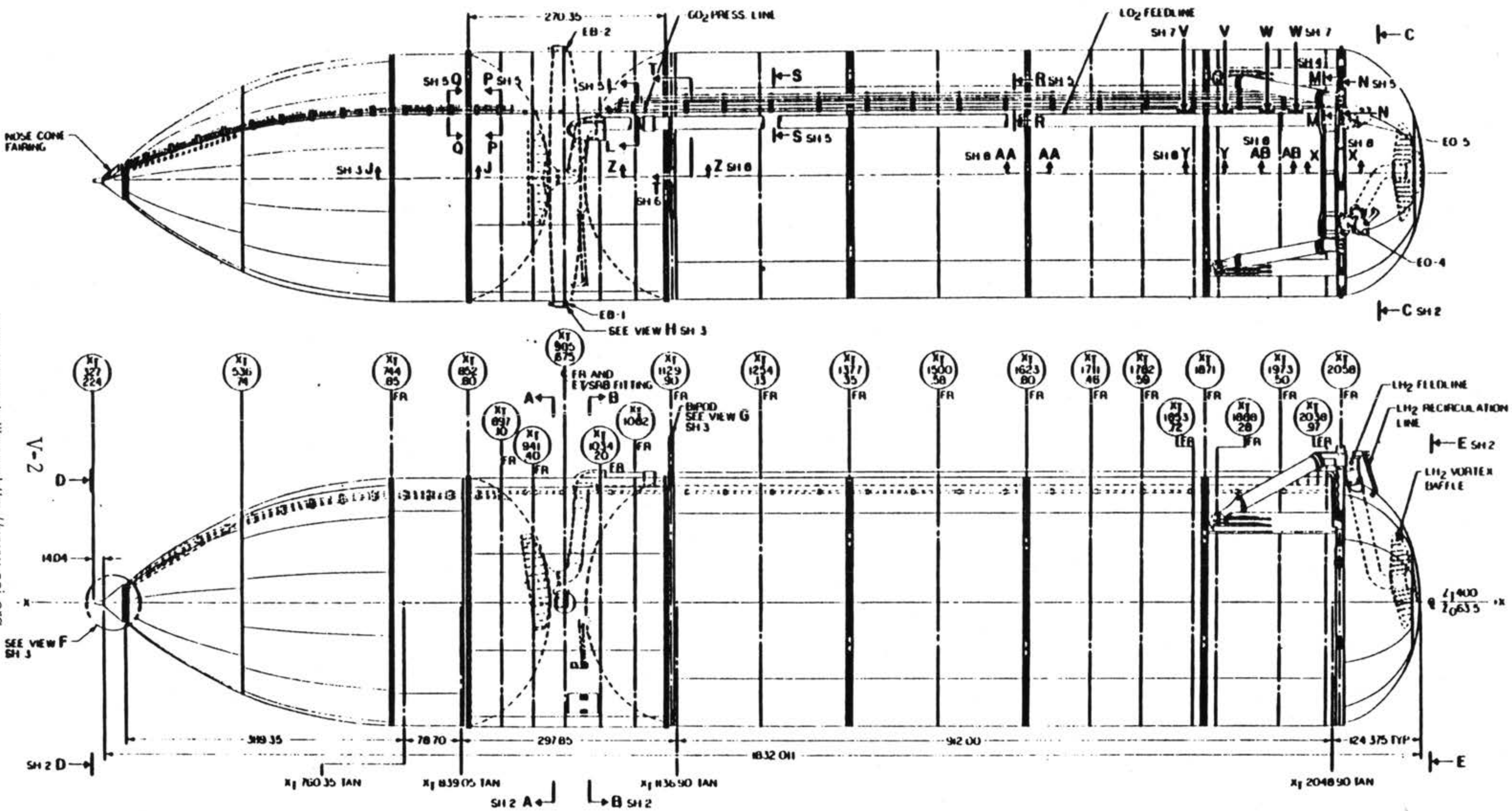
This section will discuss the structural advantages in an ET based operation. The tank can be partially to completely disassembled in orbit without excessive difficulty. The SOFI can be stripped and discarded or used for other needs. The tank can be cut into pieces and those pieces either used for construction or melted or powdered for other needs. In addition to applications mentioned in other sections, the ET itself can be used as a structural member, workbench, or platform for the construction or deploment of large structures. It also can be used to conduct experiments on large structures as a testbed. The advantage of the strongback/testbed concept is that the ET is fully suited for future growth and expansion with the addition of more ETs, ET/ACC combinations, ACCs, or other modules.

I. Disassembly of the ET in orbit

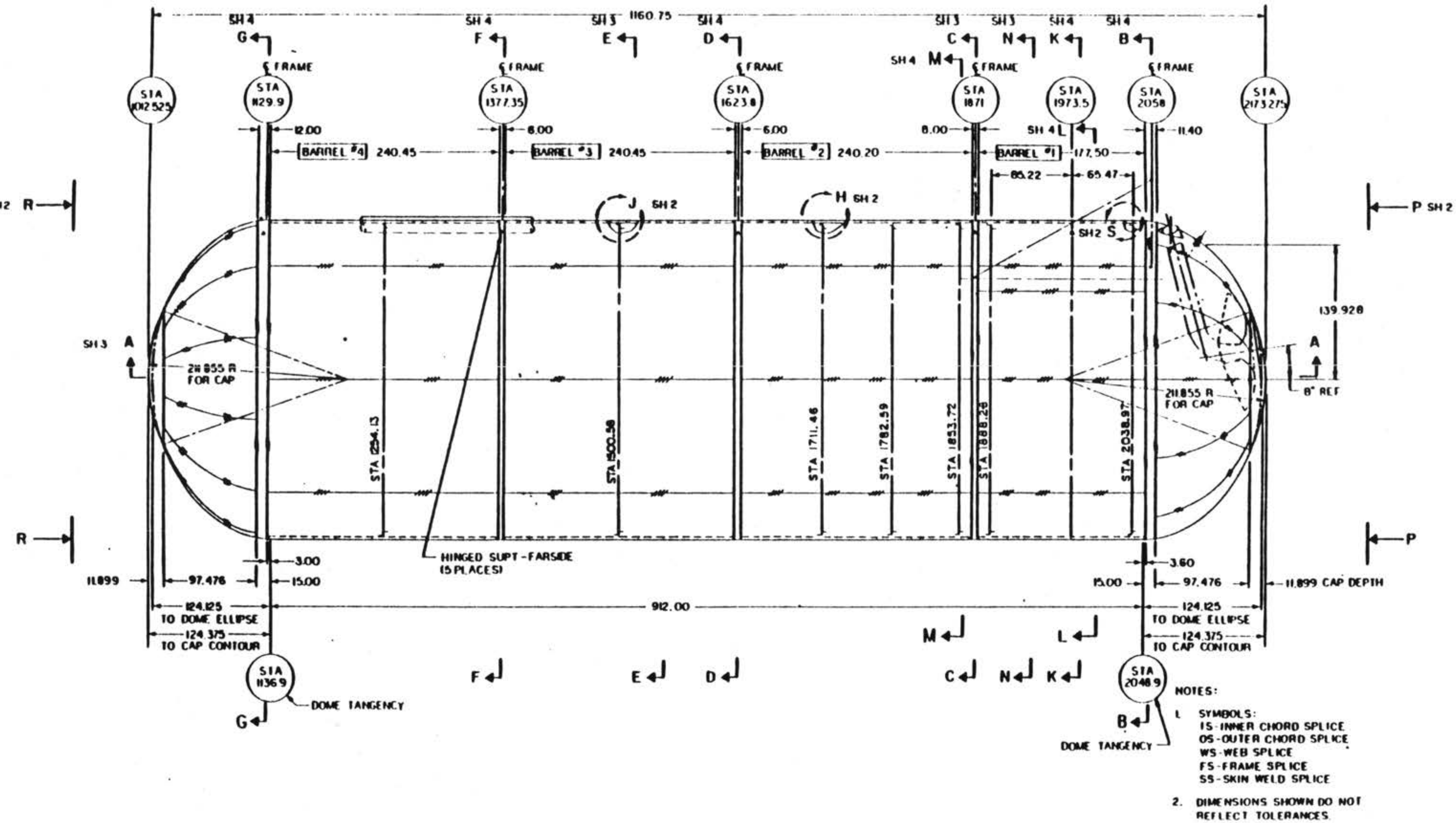
A. SOFI

Any operation which proposes the structural use of the ET needs to remove the SOFI from the ET exterior. The SOFI is sprayed on the ET over an adhesive base. The adhesive is extremely effective, so much so that the removal of the SOFI from the tank sections on the ground is done with fiberglass scrapers in a very dirty, labor intensive job (48). This type operation will be unacceptable in flight. Work on the subject by the California Space Institute has proposed several methods which should work well in orbit (15, 56, 95).

The best choice for removal appears to be the space equivalent of a hot wire 'cheese slicer'. Tests indicate cutting rates better than 33 feet per hour (15, 56). The problem with this technique is that there remains a thin layer of SOFI after the operation. The tradeoff here is how much contamination can the cutting, melting, or construction operation tolerate (92)? If the layer needs to be removed there are several removal methods. It can be stripped over the space of a month or two by molecular oxygen impact (14). It can be removed by a 'Weed Eater' type rotary device or wire brush. This operation would tend to dirty up the vicinity of the station quickly with small bits of debris. It can also be removed thermally by use of a solar furnance or an electron beam gun (56).



EXTERNAL TANK DETAILS



HYDROGEN TANK DETAILS

External Tank

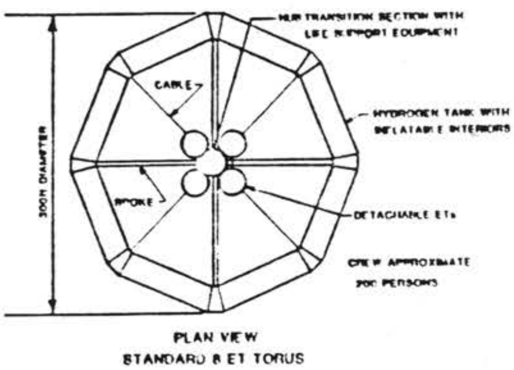
	WT. lbs.	% of Dry Wt.	
Forward tank	12,352	17.9	
Inter tank	12,080	17.5	
Aft tank, LH_2	28,900	41.9	
Separation Hardware	4,743	6.86	
Propulsion lines	3,760	5.45	Wt. metals
Miscellaneous	1,000	1.45	less misc.
			61,835
	62,835	91.06	
Insulation	6,190	8.94	
	69,025	100.00	

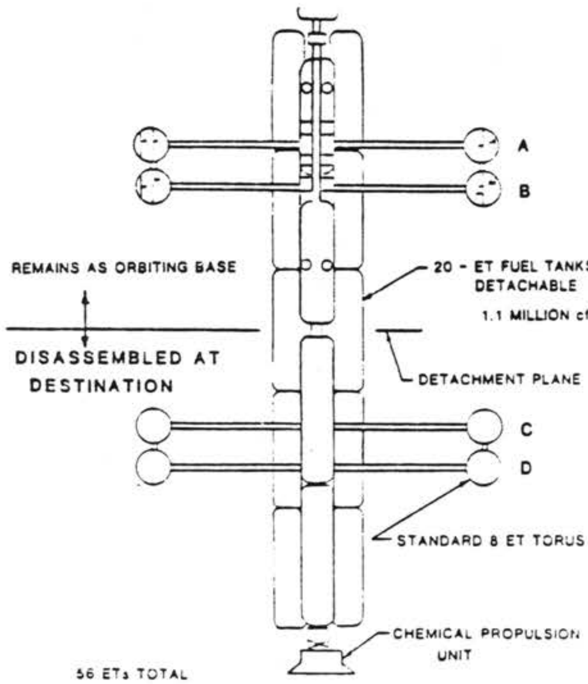
	% of total wt.	# of Material
Alloy 2219	64.44	44,480
2024	19.34	13,349
7050	3.3	2,278
7075	0.87	601
21-6-9	0.93	642
Inconel 718	0.44	304
Ti 6-4	0.31	214
	89.63	
Polyurethanes	5.54	3,824
Silicone Resin & Ablatives	2.37	1,636
Foams & Adhesives	1.03	711
Miscellaneous	1.45	1,001
	10.39	69,[illegible]

69,025

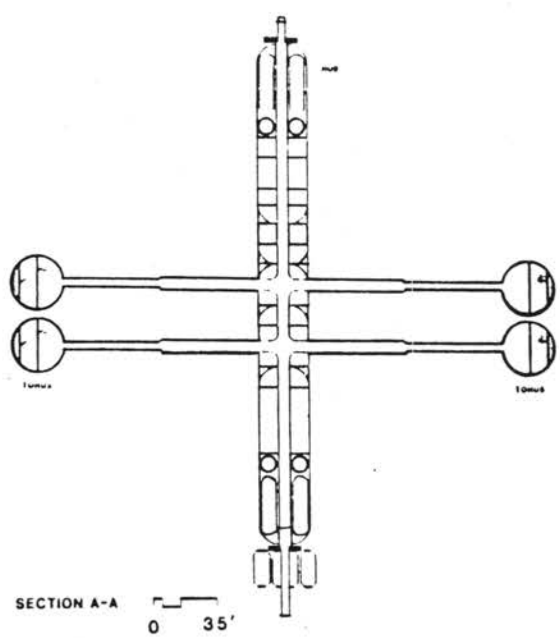
Al	=	56,490#	
Cu	=	3,450	
C	=	2,760	
O	=	1,725	
Si	=	690	
Fe	=	415	13 elements
Mg	=	268	from 200 to
Zn	=	173	35,000#
Ni	=	200	C, H, O, N
Ti	=	220	9 metallic or
Cr	=	188	metalloid
H	=	466	
N	=	246	
Others	=	1,807	(Co, Mo, V, etc)
		69,022	

Interplanetary Vehicle

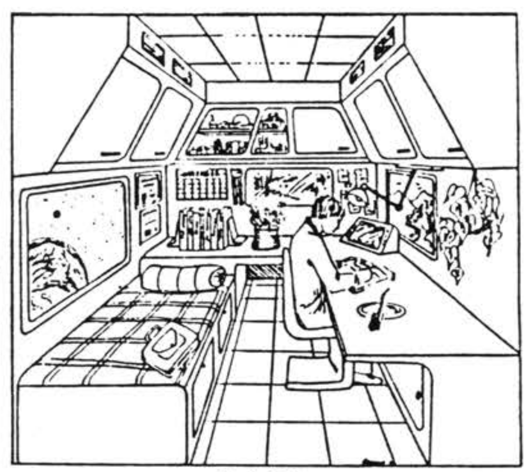




Four-Torus Vehicle



Mars Orbiting Support Base



Single Cabin

Interior Cabin

B. Major Pieces

Partial disassembly of the ET is a relatively simple repetitive operation (25). The major operation is the removal of the bolts that connect the Oxygen tank to the Intertank and the Intertank to the Hydrogen tank. Once taken apart, the interiors of the oxygen tank and the intertank sections become far more accessable for future use. The intertank also carries an extremely strong compression member called the SRB Beam which can be removed for use on-orbit. The tank domes can also be removed from the respective tanks for use as reflectors, hatch covers, antennas, or similar items.

C. Minor Pieces

In addition to the major parts mentioned above, there are several minor parts which can be removed for orbital use (63). There is the SRB and Orbiter attach hardware. These are large strong parts carried on the SRB Beam and the aft end of the ET. This attach hardware can be removed and used as attach hardware for other constructs in orbit. Another type of part is the feedline. The feedlines are insulated, inspected, and tested 17 inch diameter lines which can be used in other ways on a space station when removed. There are electrical lines, electrical connections, sensors, minor hardware, and range safety devices also mounted on the tank for use during launch. All of these can be removed and utilized in a properly designed space operation (25).

II. Large Rigid Constructs

The partially disassembled ET sections can be reassembled into extremely rigid structures of almost any size. Taylor has proposed a rigid torus constructed out of the ET and segments carried aloft as part of an ACC (82). The concept is to partially disassemble the ET and reconnect the hydrogen tank sections into an eight sided torus which would be spun for artificial gravity. The angled sections are either cut from intertank sections or carried aloft as ACC payloads. The torus is about 300 feet in diameter and can house up to 200 people comfortably.

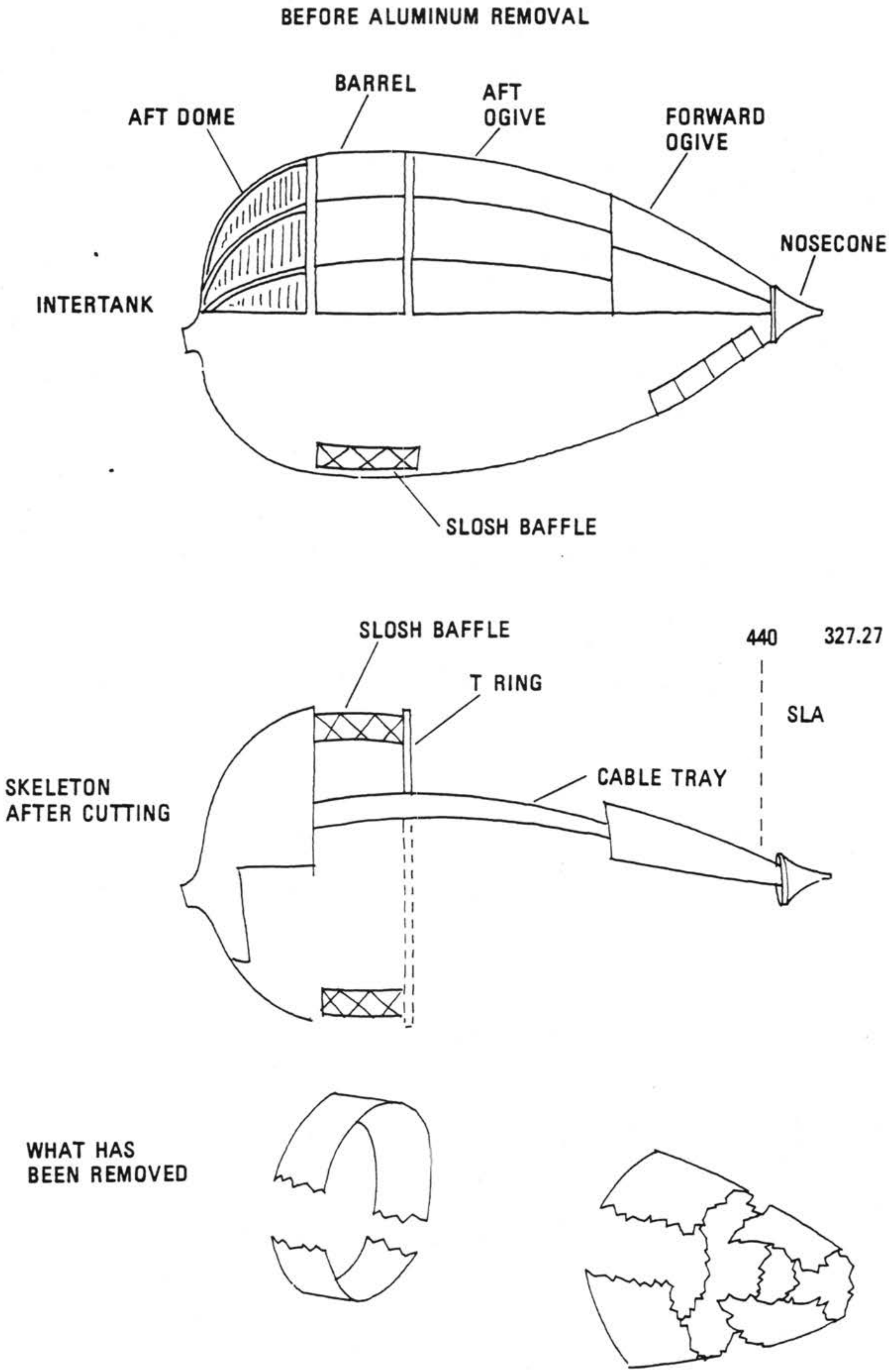
This torus concept was proposed as the basis for a manned mission to Mars (82). The ship was constructed out of ET hydrogen tanks, fueled, and launched out of earth orbit with the help of the OTVs. The tanks were to be used on site as a permanent manned space station in orbit around Mars after the mission was complete. The large size and available 'elbow room' of this concept are very attractive to anybody faced with the prospect of spending several years in a VERY small room during a manned planetary mission. The torus would also be a way to fly the recently propsed 'Space Castle' concept of large interplanetary stations.

In addition to the proposed torus, the partially disassembled ET can be reconnected into almost any size and shape appropriate to the mission at hand. Several hydrogen tank barrels can be attached lenghtwise into a long tube which can be used for an electrical catapult (25). A pressurized hydrogen tank could be used as a strength member due to its increased strength under pressure. Several ET domes can be attached in an array to provide solar thermal power. ET domes (properly mirrored and shaped) can be used to concentrate sunlight on Stirling cycle heat engines for onboard power. As with any other ET application discussed in this report, the only limitations of partial disassembly and reconstruction are in the mind of the planner.

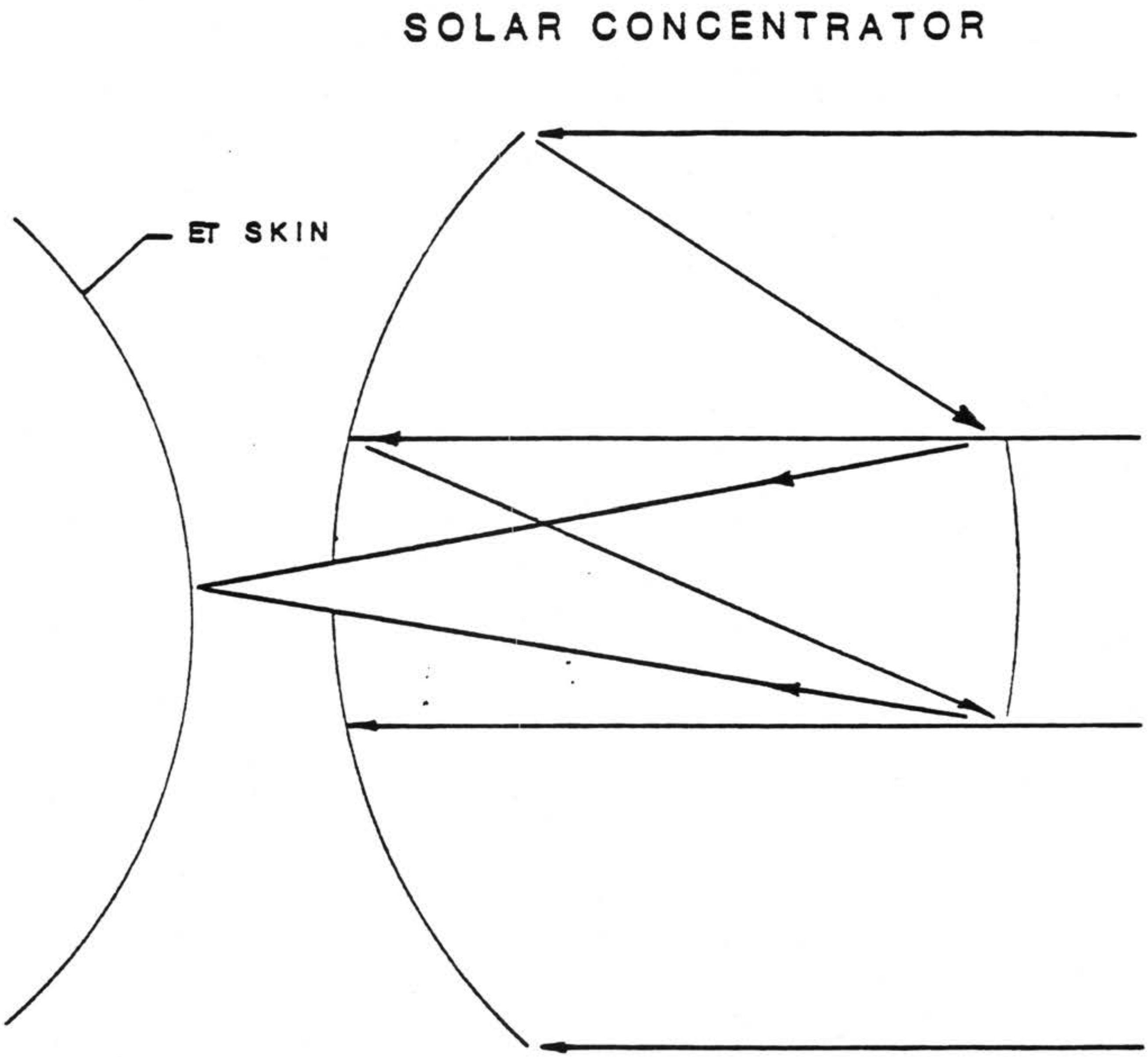
III. Cutting the ET

There are several plans for cutting, sectioning, and welding of the ET. One proposal uses conventional cutting and welding techniques under space conditions (20, 92). An important point to this is that conventional cutting and welding are known technologies involving known equipment being conducted under space conditions. We are very familiar with cutting and welding. There have been experiments involving welding and cutting conducted in both the US and Soviet space programs. The experiments have been successful and have warranted further study. There are welding studies being conducted in association with the construction and operation of the space station. If you can cut and weld a space station, you can also cut and weld any desired structure out of the ET. We are very familiar with the performance of aluminium being welded and cut on the earth. There is no obstacle today that prevents conventional cutting and welding in space (92).

There are two other techniques for cutting the ET. The first is the use of an Electron Gun and the second is the use of reflected sunlight by a small solar furnance (56). Both methods work by heating the aluminium until it



OXYGEN TANK CUTTING



SOLAR ET CUTTING

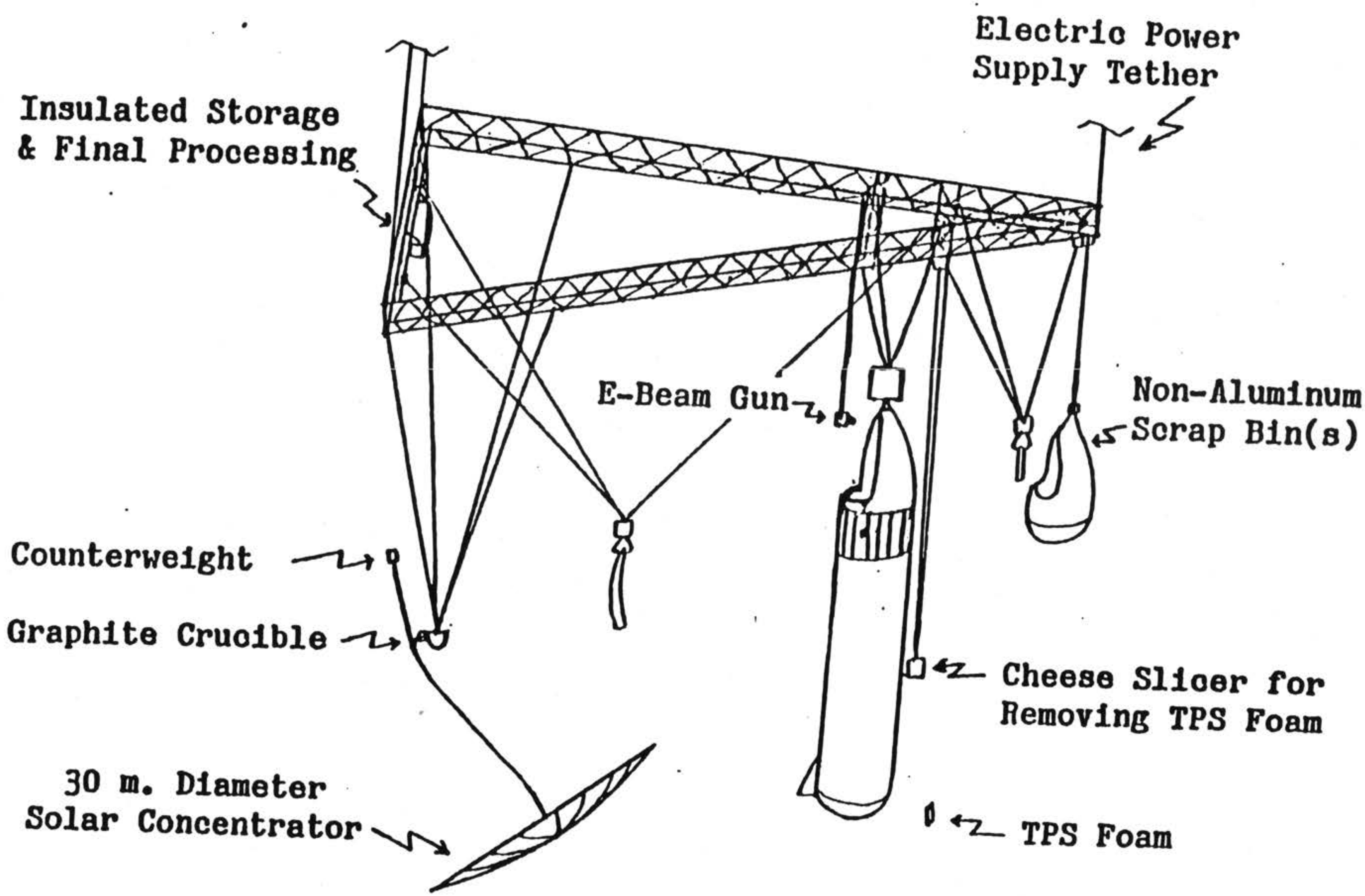
melts. The solar furnace does not require additional power for operation however. Both of these techniques are not as familiar to metal processing as conventional techniques. This will involve additional experimentation in space before being selected for use.

The cutting of the ET into segments is attractive for several reasons. The first is that the cutting of the hydrogen tank into strips can supply many pieces of aerospace grade weldable 2219 aluminium measuring 5 feet wide by 60 - 80 feet long. We also have all the engineering drawings for these strips (20). Almost any space structure is possible if the technology of cutting and welding is proven in space. The point in the cutting and welding process is that we are very familiar with the behavior of these pieces in ground based applications and can transfer this experience to orbital operations. Another reason for the orbital cutting is the isolation for future use of several aluminium alloys which make up the overall tank. The behavior of the alloys by themselves is well known. The different alloys that make up particular portions of the ET can be isolated from one another by carefully planned and executed cutting for future welding, melting, and forming into the desired structures (92).

In a space-based operation, the cutting and welding of structures will be an early desired (if not required) activity. Because of the use of known technologies, the cutting and welding of the ET sections will be a valuable addition to the space construction 'bag of tricks'. It is not particularly complex and does not require a particularly expensive R&D investment. The challenge is what to do with an essentially unlimited supply of potential structural segments at the rate of 30 - 35,000 pounds per delivered ET. Clearly, some sort of market study needs to be made in this regard (20).

IV. Complete Melting and Refining

Another structural technique is the complete melting of the ET and the on-orbit fabrication of structural members such as thin shells, beams, rods, channel sections, or other controlled extrusion processes. There are a large number of proposed facilities for the melting of the ET in orbit and the future use of the melted aluminium from the melt. This is a somewhat more complex activity than the cutting and welding and will require additional R&D and training. The fabrication of structural members will require the



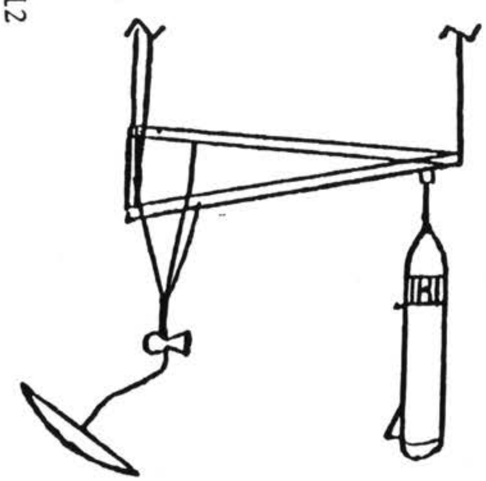
TETHERED ET RECYCLING FACILITY

Vapor Deposition

1 mm: day to month

"Spill" gives thrust

Slow, in wind → Al203



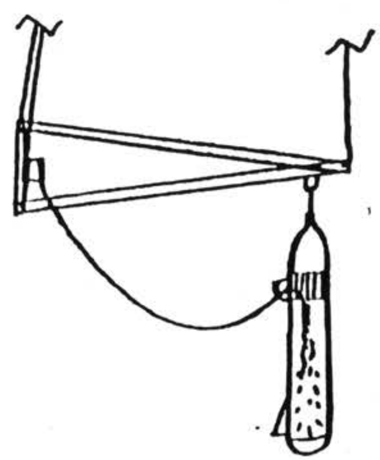
Molten Spray

Paint-sprayer hardware

Rapid solidification

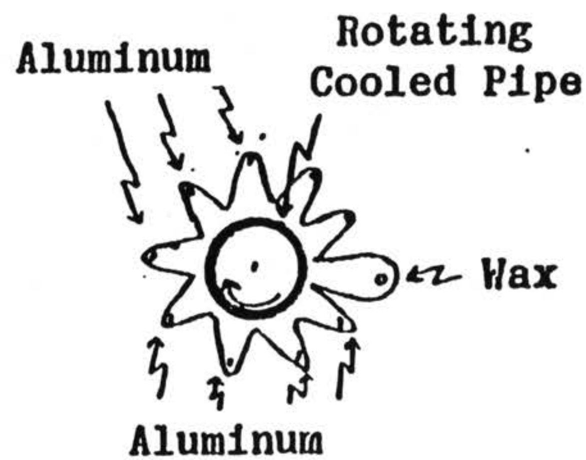
Lithium alloys?

Frozen-in stresses?

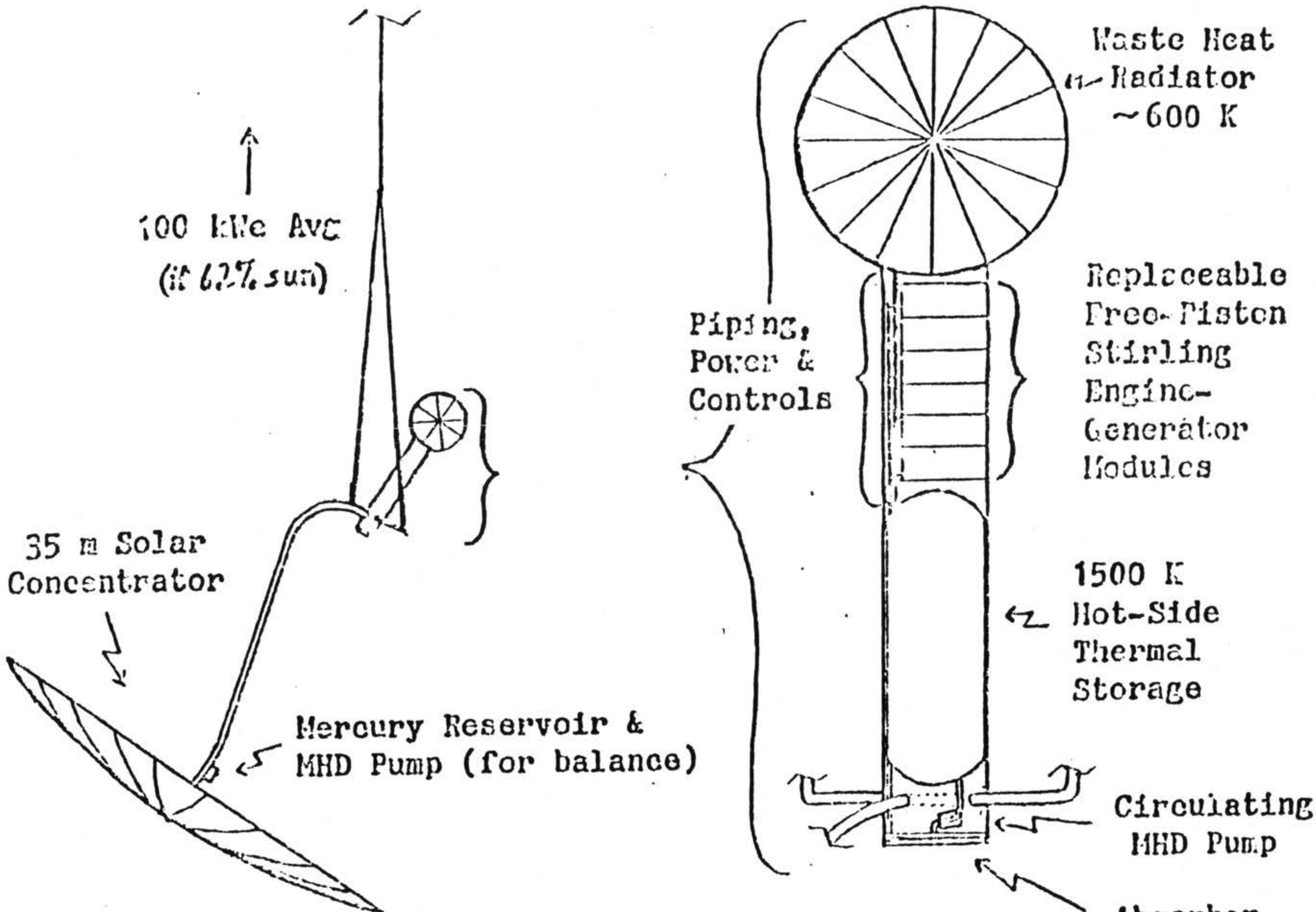


Possible Uses

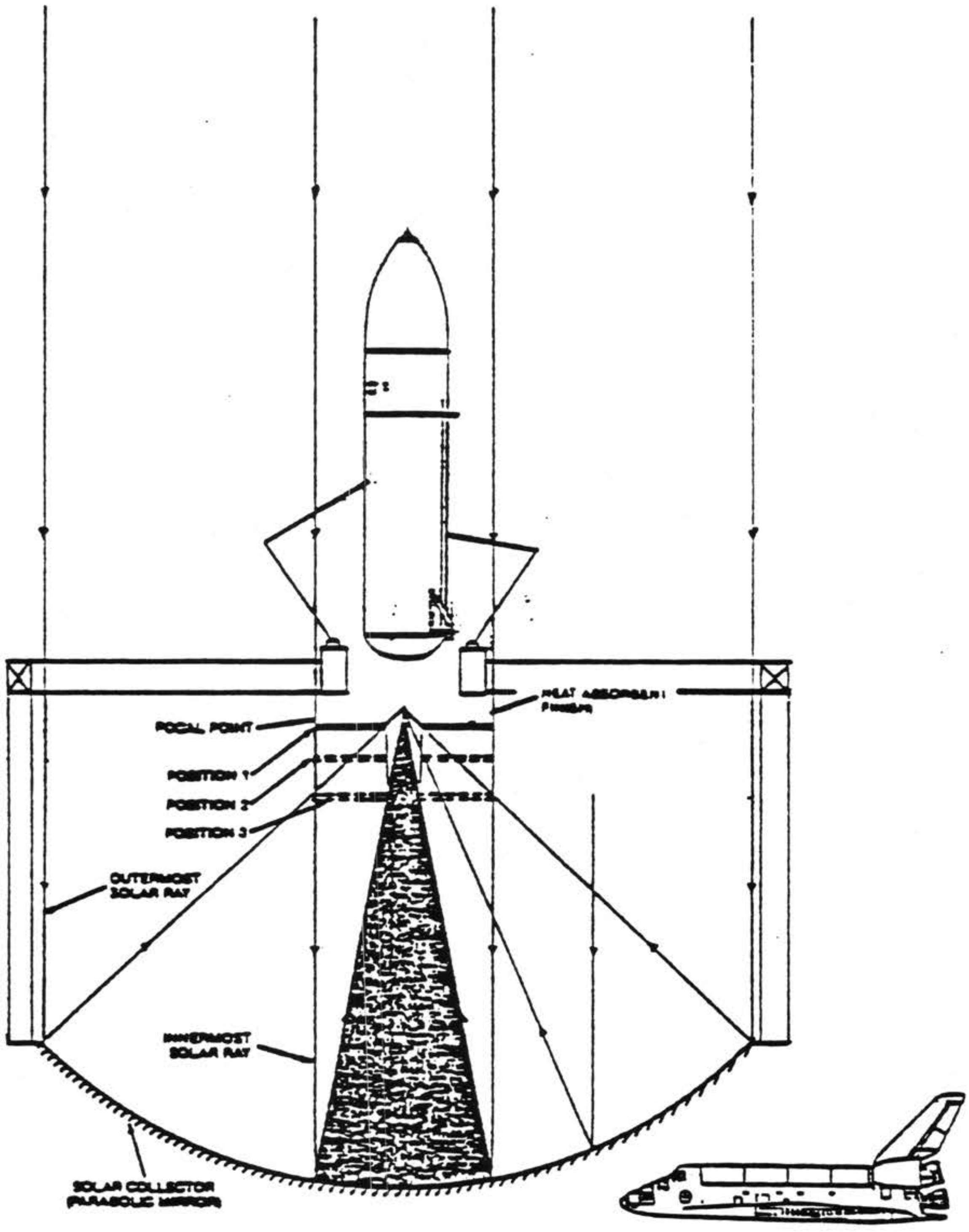
- Overcoat ETs:
  Alumina: protect TPS
  Aluminum: outgassing
  Alumina: thermal coat
- Beef up thin-wall forms launched collapsed
- Build up beams on reusable forms
- Make rolls of foil:



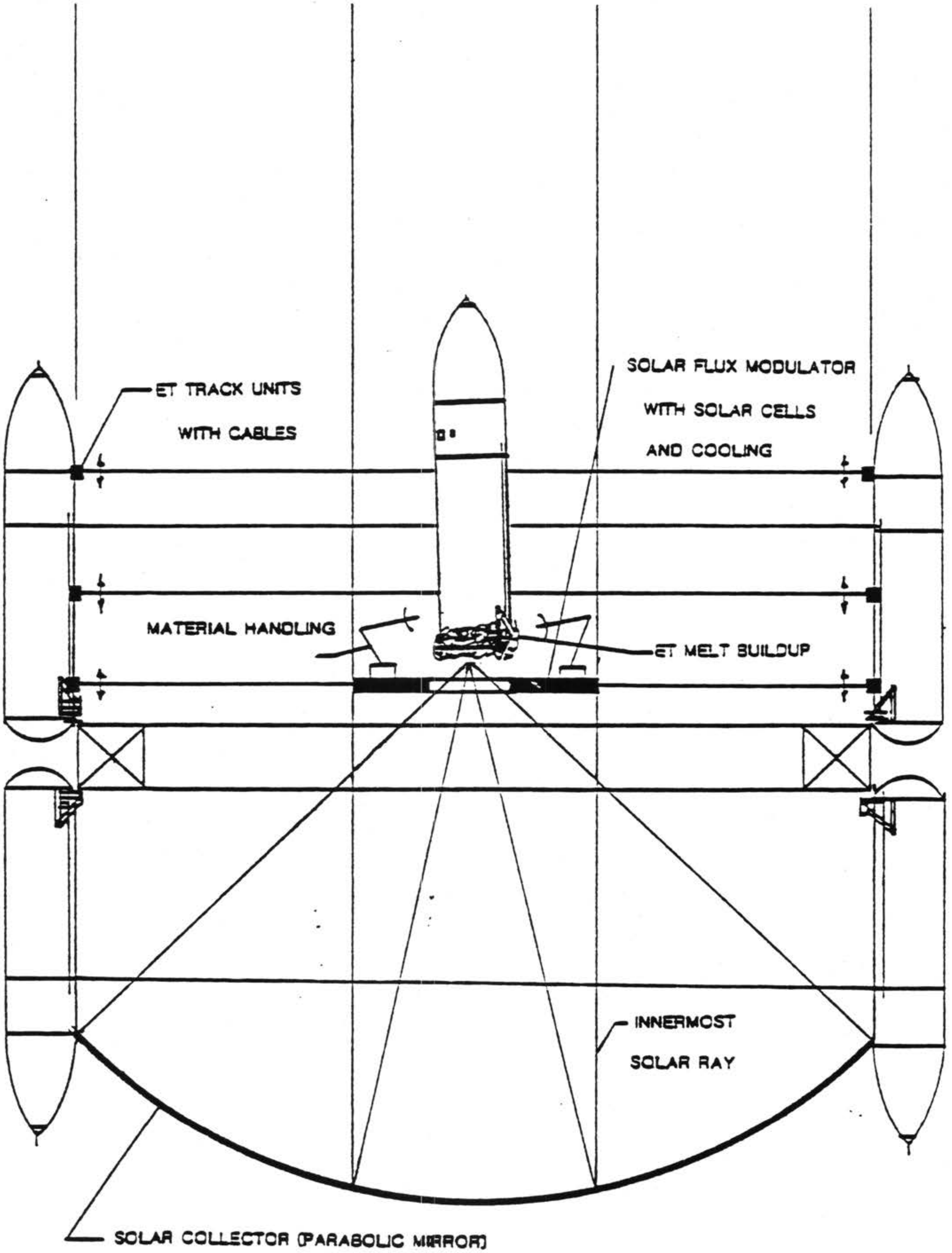
STRUCTURAL FABRICATION BY DEPOSITION



SOLAR THERMAL POWER WITH HEAT STORAGE



PARABOLIC ORBITAL FURNACE



ET MELT DOWN FACILITY

equivalent of a factory to be flown in orbit. The energy for this factory will likely be from a solar reflector (15). Other sources require additional mass to be launched to the factory and are therefore more expensive.

A. Melting Facilities

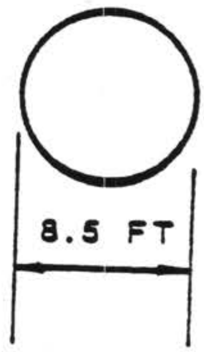
There are several proposed facilities for the melting and processing of the ET. Three different types will be described in the following sections. They are a tether based facility proposed by Dr. Joe Carroll of CALSPACE (15), a combination ET storage rack and melting facility proposed by Tom Taylor (25), and the materials processing facility proposed by Dave Christensen of Wyle Labs (17).

The Carroll facility sections the ET by the use of an Electron beam gun and then uses a 30 - 40 meter (about 115 feet) diameter solar mirror to melt them into a graphite crucible for storage or future use (14, 15). The A-Frame is used for structural strength of the facility. The tether is used for tank storage and the stabilization of the crucible. If the melt (on the order of five tons) is heated sufficiently in the graphite crucible and stored with either a layer of slag or a lid, keeping it molten will not be a large problem. The way that this particular system works is that once the melt is up to temperature, the total energy contained in the melt is so high and the surface area is so small that the losses due to radiation are not significant. The liquid can be drawn off and fabricated to any desired form such as metal flakes or powder for propulsion, metal vapor deposition for thin reflective surfaces, metal for extrusions, metals for metal crystal growth experiments, and metal rope or braided metal rope for tether or construction purposes (56). The Carroll facility is very attractive in that it is relatively simple to set up and operate and does not require a large amount of heavy industrial equipment to be flown.

A second type facility would be the combination ET storage rack and melting facility (25). The illustration above proposes a large diameter thin mirror working on an ET. The concept is to melt the entire ET into a molten ball. This would enhance the drag characteristics of the ET on-orbit. For example, 36 ETs could be stored in a ball of about 27 feet in diameter (25). This ball would have two layers. The outer layer would be a crust of slag which includes the remaining SOFI and the miscellaneous metallic portions.

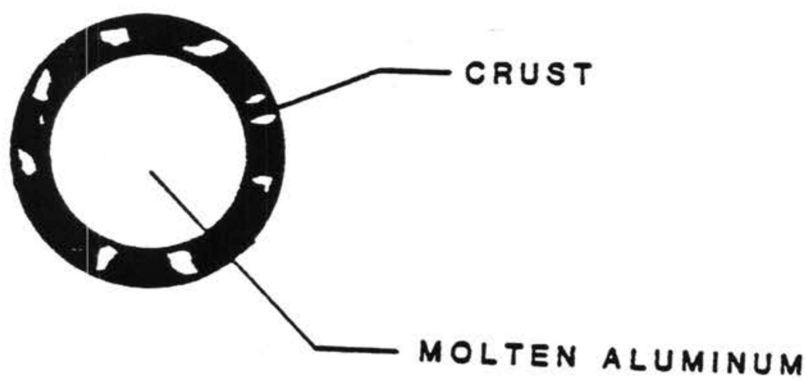
MOLTEN

ALUMINUM SPHERE

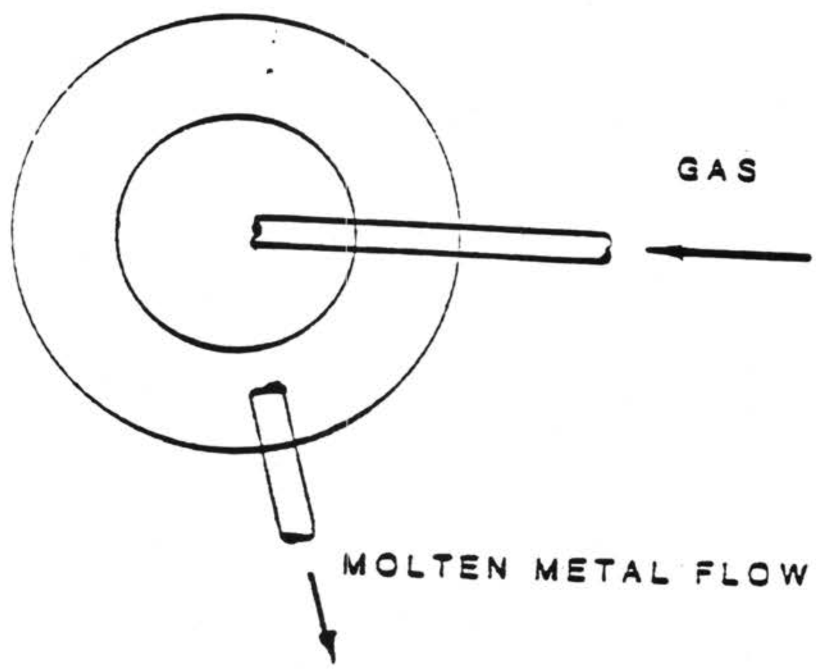


68,110 LBS ET

55,400 LBS ALUMINUM

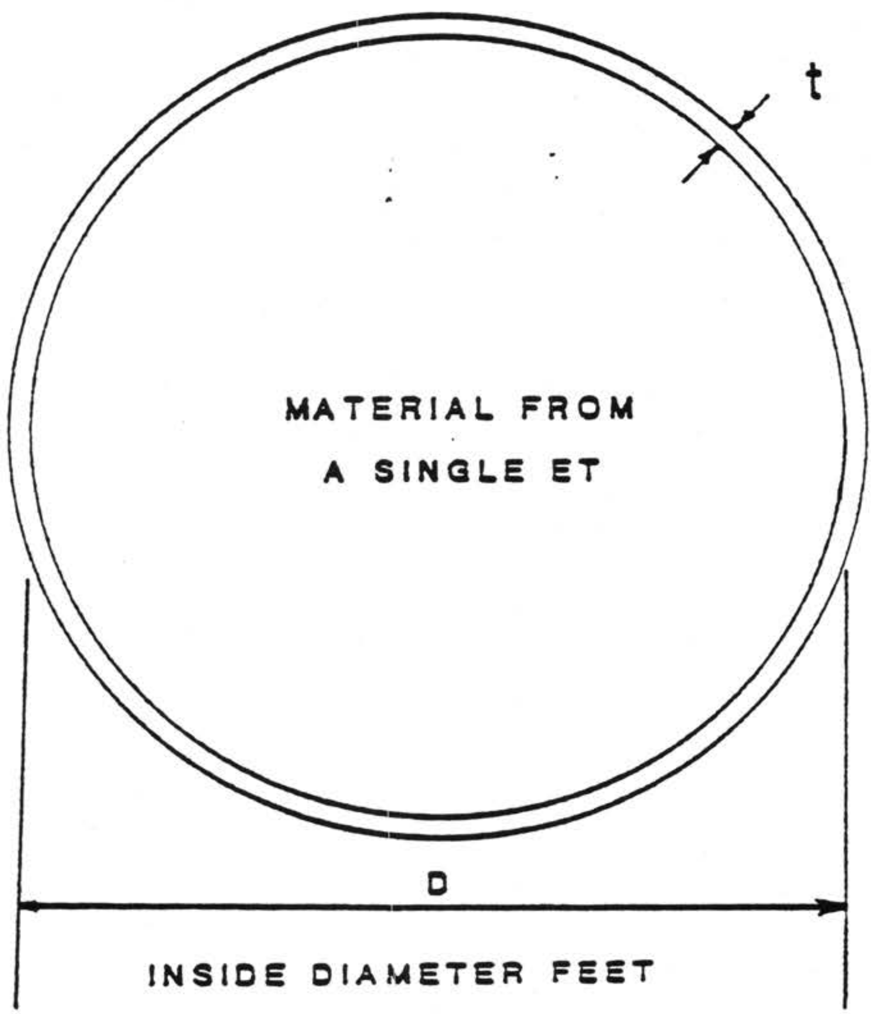


SINGLE TANK ALUMINUM IN MOLTEN STATE



MOLTEN METAL HANDLING

METERS t	METERS D	FEET t	FEET D
3.524	3	1.645	10
.055	10	.211	30
.002	50 .2 cm	1/8 inch .019	100



THIN SHELL CONSTRUCTION

THIN WALL SPHERES

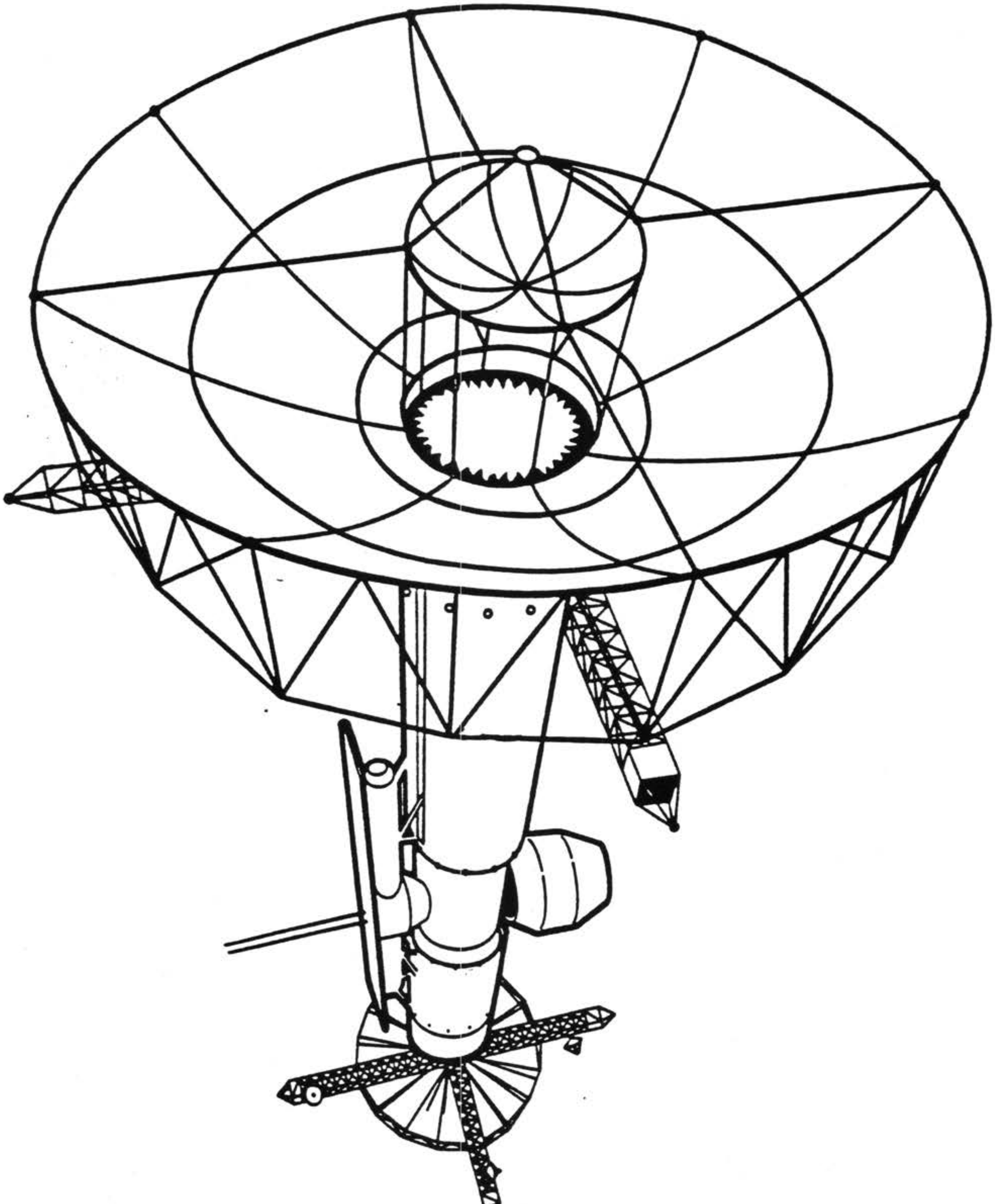
The interior would be almost pure aluminium alloy. The primary forces on this body would be the surface tension of the slag and aluminium. A possible application of this molten ball would be to introduce low pressure gas into the center of the molten ball and inflate it like a balloon. A non-rotating blob of metal could be inflated and cooled to yield thin walled metallic shells. The thickness of the shells would be dependent on the purity of the aluminium being worked, the rate of inflation, and the ability to control the cooling rate. Rotating the blobs would produce complex curved shells with controlled thicknesses. It would also be possible to construct thermally sensitive aluminium springs out of this type rotating melt and cooling operation.

In addition to the structural shells, there is also the possibility of making foamed metal for use as lightweight structural members (25). This would work like nondirectional honeycomb in high performance aircraft wings. Additional uses would be to form powdered or foamed metal into structural members for the construction of large space platforms and perhaps Solar Power Satellites (73).

The third example of an orbital facility was concieved by Dave Christensen of Wyle Labs (17). It consists of two ETs connected end to end with associated ACC shrouds and payloads. The mirror on the end is the proposed Carroll 115 foot diameter solar collector capable of generating up to 300 kilowatts (kw) thermal or 100 kw electrical energy. This facility would conduct materials processing, energy generation, ET melting, and related missions. Excess electricity generated by the reflector would be transmitted to the sister space station. The materials processing conducted would be to melt the ET and prepare the aluminium for future storage or use. Once again, this is a utilization of the orbital resources for future needs. Early missions of this facility would be to conduct orbital testing of large structures. This is an example of an actual private facility that is being planned for flight with corporate funding that will utilize ETs as components, products, and working media.

B. Factory Machinery

Another device that would be of interest in the handling of molten aluminium is the Induction Furnace. If an induction furnace is assymetrically wound with heating coils, it is possible to feed in stock to be melted on one



WYLE LAB ORBITAL FACILITY CONCEPT

end and force the melt out the other end (92). It may be possible to use this furnace to form extrusions directly without the use of a press. This furnace would solve some of the mass problems inherent in handling liquid metals in a weightless environment. Dr. Andrew Cutler of CALSPACE feels that this type facility can be flyable for under 15,000 pounds mass (18, 20, 92). This furnace could use gravity gradient stabilization to help stabilize long slender extrusions.

Early studies of chemical processing of the ET indicate that it is more expensive in terms of energy (30 - 40 times) and launch mass than when using a thermal (reflected solar) furnace (56). For this reason, operations that discuss chemical manipulation of the SOFI and other ET minor parts have been addressed only in a minor way in this report. Undoubtedly, this will happen in the future. However, thermal materials processing will be the starting choice of near future operations due to lower energy and launch mass requirements.

The barrel of the ET has also been proposed as the base for a solar furnace (56). It is pictured below. Film deposition on the ET exterior may be used to retard SOFI outgassing. Finally, the ET itself could be used as very large diameter spool for extruded wire or cable.

V. Strongback

The use of the ET as a strongback takes advantage of the strength build into it as a base for construction. This has been referred to as a bedplate, a strongback, a base, or a station itself (56, 95). This concept provides mass and rigidity for operations such as space stations, satellite retrieval and repair, space antenna and reflector construction and flight, and pilot plants for goods and services. The recent evolution of the space station structural design from the Power Tower to the Dual Keel shows that structural strength and safety are very important to future planners (8). Once again, the ET can provide a very large strong object on-orbit for a minimal cost.

An early proposal by General Dynamics/Convair recommends the use of the Enterprise and an ET/ACC as an initial relatively inexpensive space station (56). The rationale here is that the Enterprise will never fly without massive reconstruction. In order to get some operational use out of it, the

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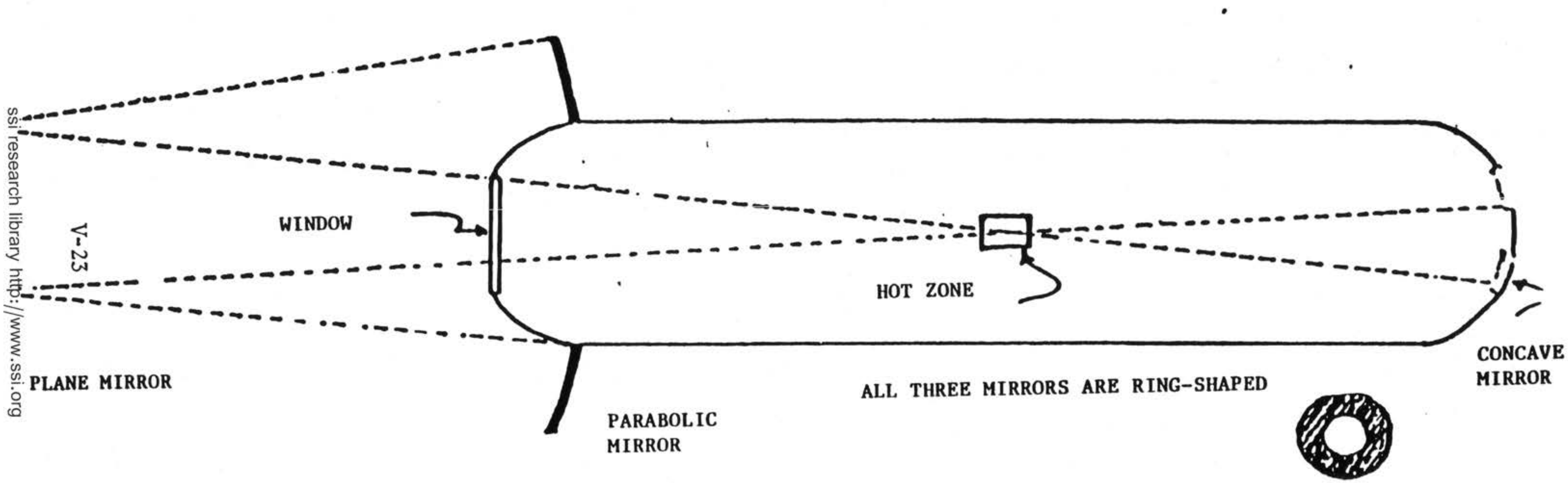


NOMINAL TASK - PREPARING ABOUT 50 kg Al_2O_3/hr

HOT ZONE TEMPERATURE - GREATER THAN 2300 ^oK

THERMAL POWER AT HOT ZONE - 80 kw

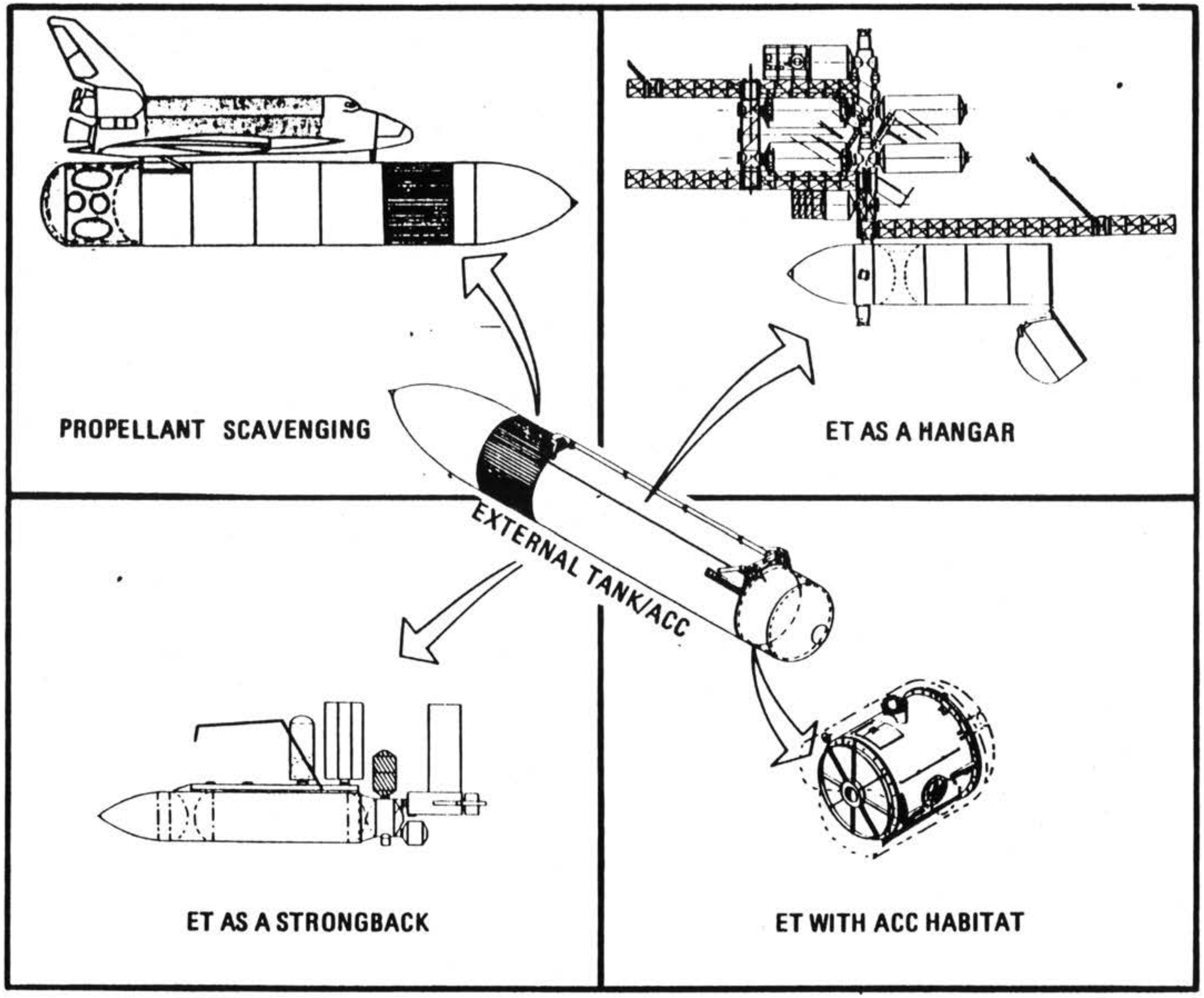
COLLECTOR AREA - ~100 M^2

VOLUME OF HOT Al_2O_3 - ONE LITER

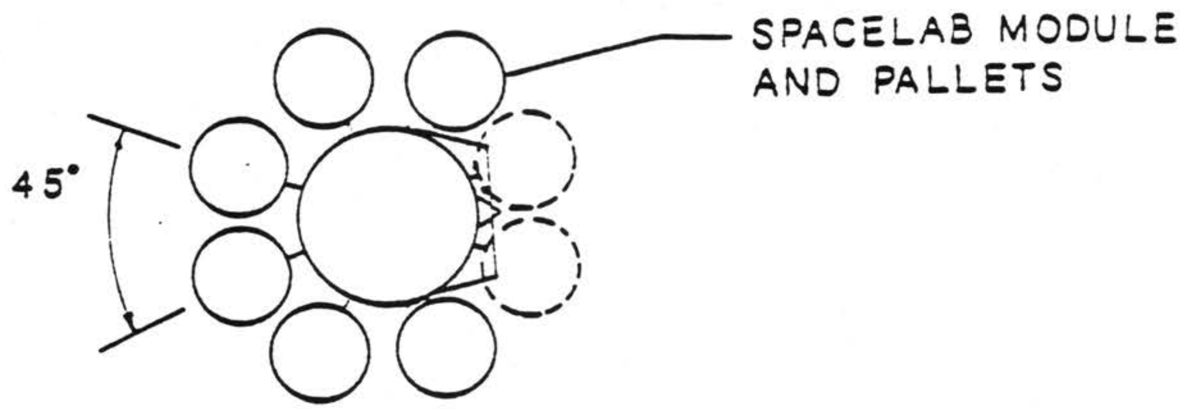
TANK WALL (770 M^2) SERVES AS WASTE HEAT RADIATOR

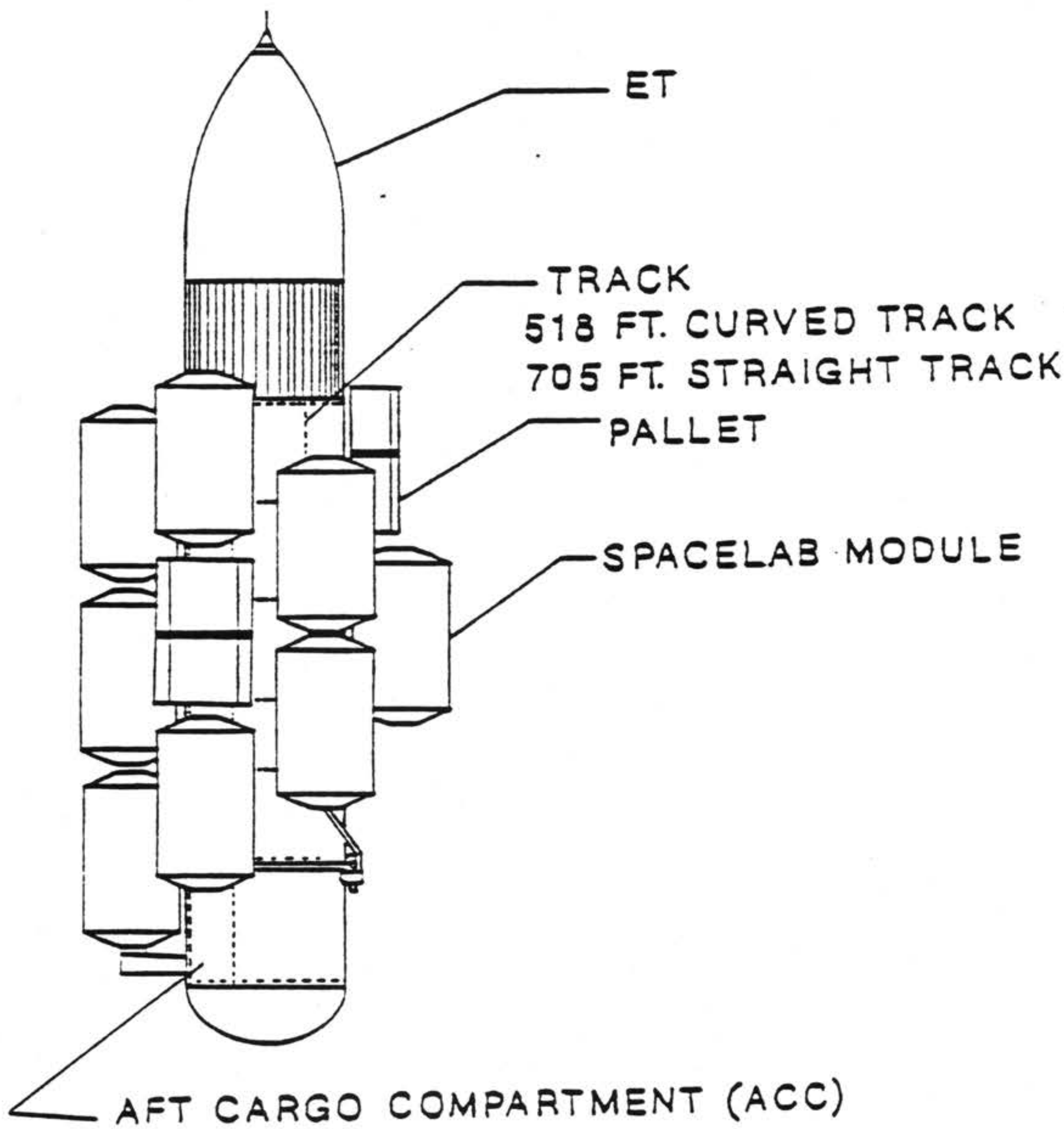
TANK MAY BE EVACUATED OR GAS-FILLED, AS DESIRED

SOLAR FURNACE IN MODIFIED LH2 TANK

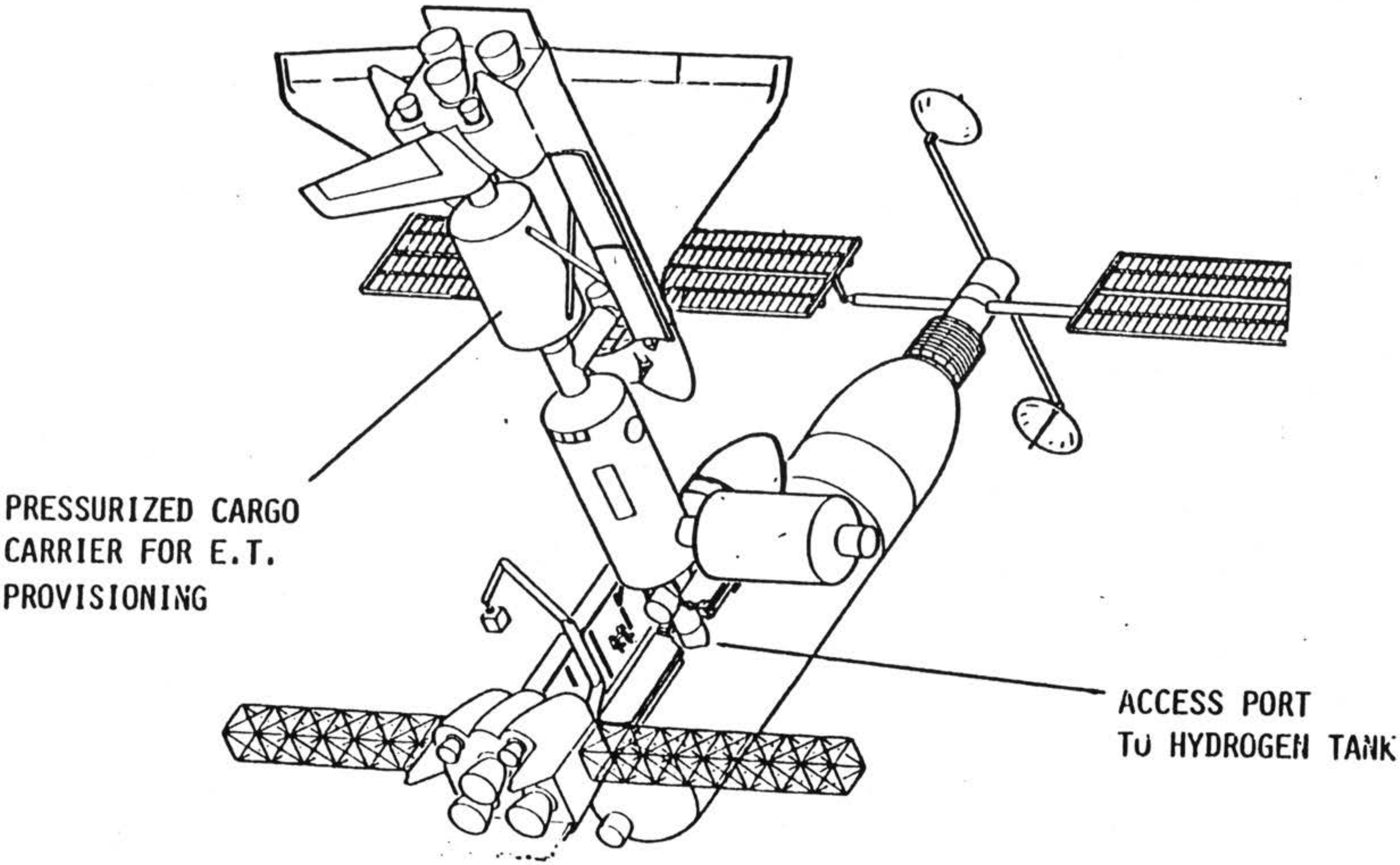


VARIED ET APPLICATIONS





SPACELAB TRACK APPLICATIONS



GENERAL DYNAMICS CONVAIR ENTERPRISE BASED ET FACILITY proposal is to remove the wings and other reentry and landing systems, stretch the cargo bay, mount it permanently on an ET and launch it directly into orbit. The station could be visited for startup or it could be launched manned with another orbiter ready for a quick servicing or resupply. The advantages are shuttle compatible hardware throughout, standard shuttle in orbit, the addition of the ET and ACC as part of the station, and a base for an RMS arm to operate. Once again, this is an ET based system that utilizes already purchased equipment for uses other than what was originally envisioned. This would be somewhat more expensive than launching and flying the basic ET/ACC station, but the potential for orbiter based operations should be extremely attractive to a buyer.

ET Project - Tethers

Tethers are essentially long flexible 'ropes' which connect two bodies. They have been suggested for a number of future space applications which are meaningful when discussing External Tank uses in space. The following section will detail possible tether enhancements of space shuttle, space station, and ET based missions.

I. Introduction

Tethers are important to future operations in space for several reasons. These include momentum transfer and storage, energy storage, stabilization and control enhancements, controllable microgravity environments, structural strength of a tether based rotating station, and electrical power generation and/or propulsion. Any operation that can take advantage of tethers for these applications will expand capabilities significantly. Enhancements of the energy and momentum storage, structural strength, and attitude control translate directly to increased capabilities without the increased launch costs (13, 56, 84).

The basic tether makes use of the dynamics of long flexible bodies in orbit. Typically, two bodies are connected by a tether of some length (on the order of miles in some proposals) and either swung around one another or left to dangle in a gravity gradient stabilized mode. Tether based stabilization can be accomplished in a gravity gradient mode, a swinging or rotating (librating) mode, or in a drag stabilized mode. The more massive that the body is on either end of the tether, the more energy it takes to move it and disturb the structure. The ET is ideally suited for tethers due to its large inexpensive mass on-orbit. This allows it to be used as a counterweight or momentum storage device for either static or librating tethers. It also is suited to tethers because it is the strong structural member of the STS stack. In an ET based tether application, tethers can be attached to the SRB attach points and the Orbiter attach points and the ET can be spun up (50, 56). Tensile loads on the ET are far lower than those during launch. This allows a substantial safety margin without tank modifications.

II. Tether History

The tether has been flown on manned missions in the past (13, 50). There were tether experiments carried out on the last two Gemini missions. Gemini XI used a 100 foot long tether between it and the Agena to conduct artificial gravity experiments at two different rotation rates. Gemini XII used a similar tether to conduct gravity gradient stabilization experiments. Both sets of experiments were extremely successful and the results warrant further study.

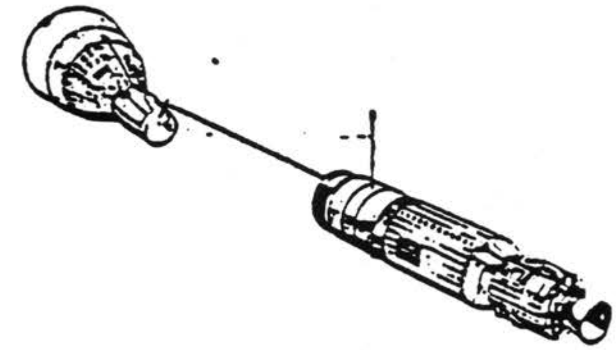
The next planned tether experiment is a proposed Italian subsatellite designed to investigate the upper atmosphere from LEO. The concept is to deploy the satellite from the orbiter on the end of a 50 km (over 30 nautical mile) long tether and sample the upper atmosphere. Engineering objectives include the behavior of a very long tether in space, dynamics of the mass-tether combination, and the testing and operation of a winch in space. This is an important proof of concept experiment that should lead to increased emphasis on tethers in the future (56).

III. Tether Physics

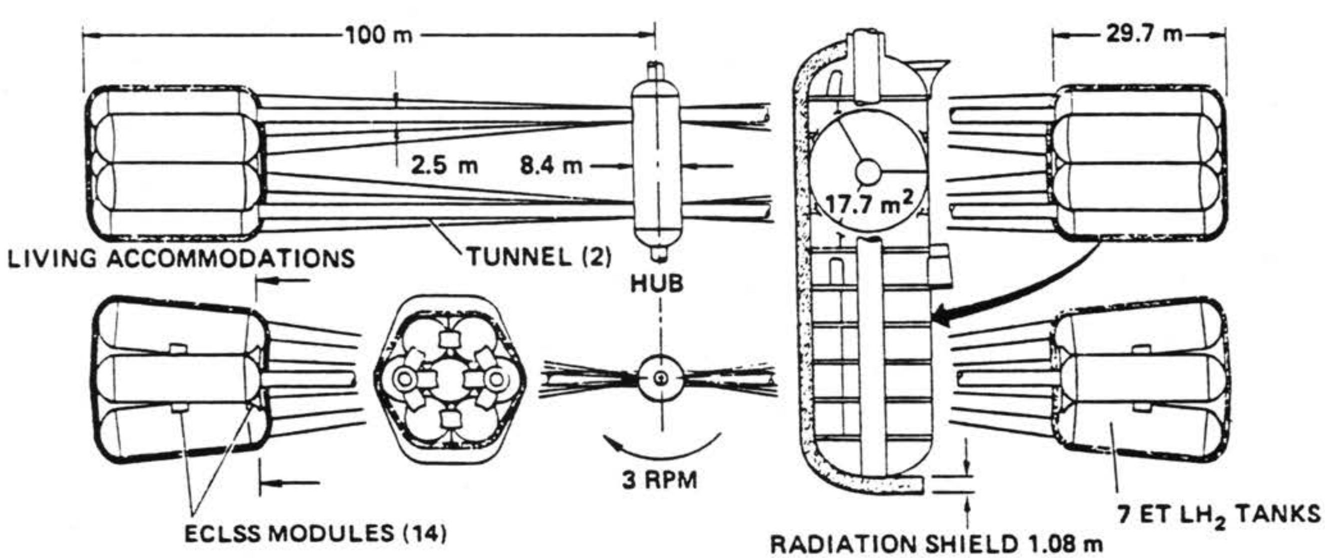
A. Gravity - Actual and Artificial

A long object will tend to stabilize with its long axis pointing at the center of the earth. The combination of forces will lead to small artificial gravitational forces on either end of a stable platform. This artificial gravity is equal to 1.5 times the change of gravity gradient in LEO at about .0004 g per km. The extra third is due to centrifugal force gradients induced by the end masses attempting to pull into different orbits away from the center of mass. The presence of these forces also causes a tension on the tether. This force doubles as the length of the tether doubles (13, 56).

In addition to a stationary tether, artificial gravity can also be induced by rotating the mass-tether combination. This has been proposed in several space station applications including Dr. Gerard K. O'Neill's original High Frontier proposal (13, 37, 56, 84, 89). This proposed using rotating hydrogen tanks in a tethered facility 200 meters in diameter at a rotation rate of 3 rpm to induce internal gravity for habitation from .7 - 1.0G.

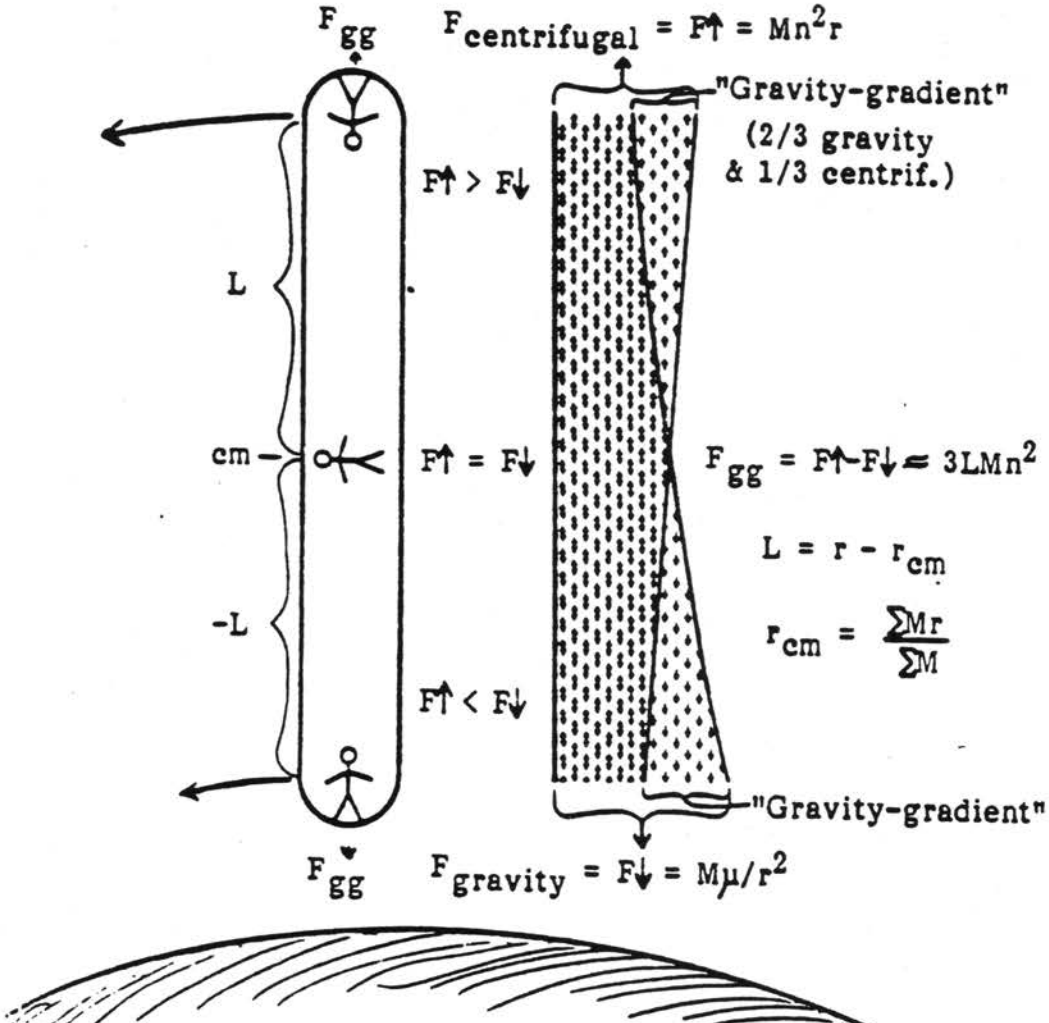


GEMINI SPACECRAFT/TARGET VEHICLE TETHERED CONFIGURATION

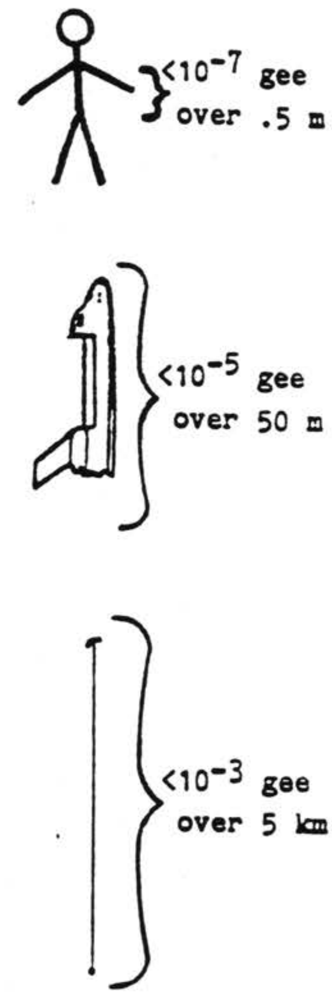


SMF HABITAT

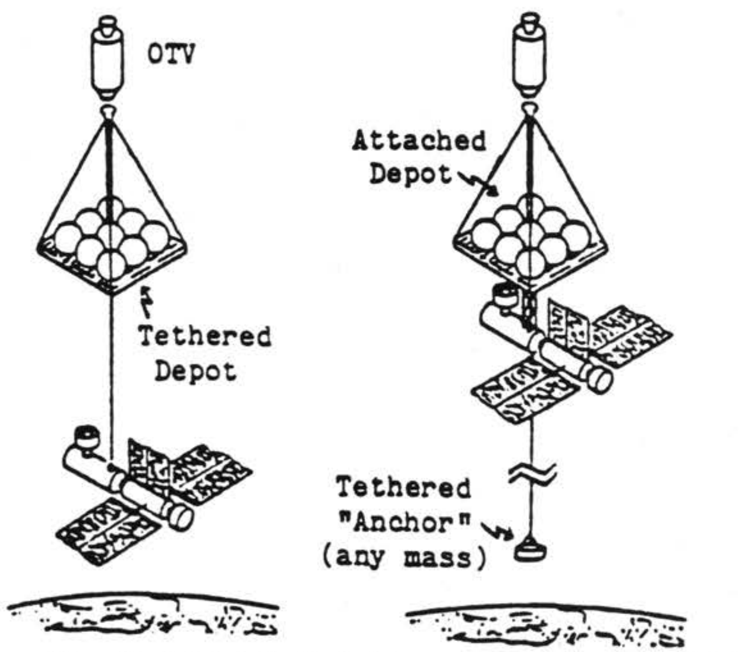
Gravity Gradient Effects



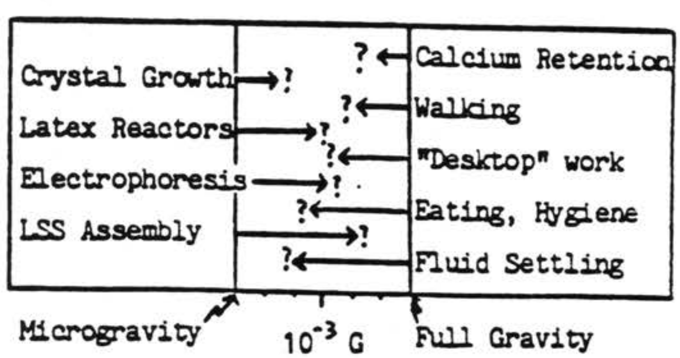
Origin of "Gravity-Gradient" Forces



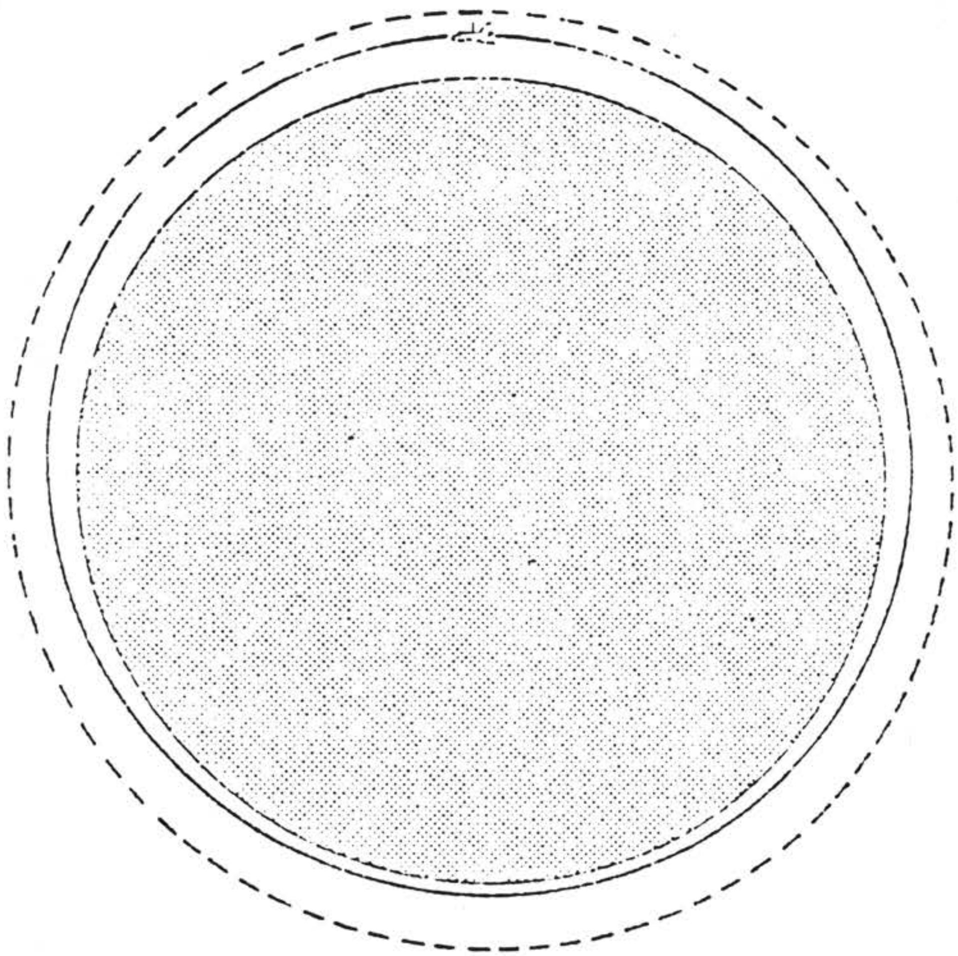
Magnitude of Gravity Gradient Effects in LEO



Two Propellant-Settling Options



Potential Overlap of Regions for Low-Gee & Gee-Dependent Operations



Deployment of an External Tank using a Pallet Mounted Deployer and Retriever. While the Shuttle is at apogee of a 220-417 km eccentric orbit, the release of the External Tank automatically injects the External Tank into a circular orbit 450 km altitude.

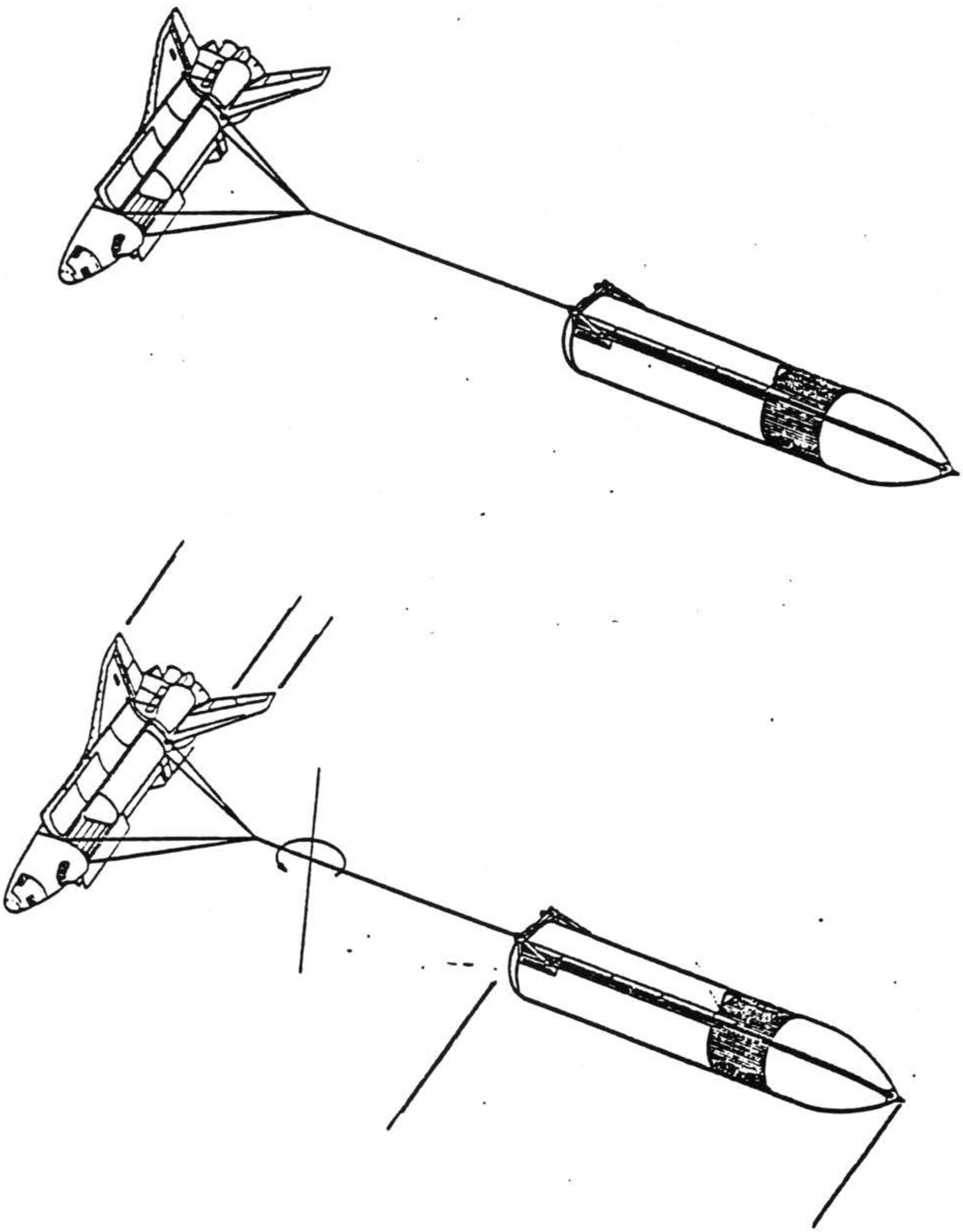
ET TETHER RELEASE

There are several items of interest with a rotating station. The first is that there are indications that the body cannot tolerate rotation rates much greater than 1 - 3 rpm (89). Thus the station should be kept large enough to keep the rotation rates small. The second concern is to minimize coriolis forces (13). This is also accomplished by keeping the station large. The third concern is operational. There are docking problems associated with arriving at and leaving a rotating station. The typical proposal is to make the center of rotation the docking port. This is feasable and should work. The last concern is with the very real problem associated with adaptation to zero 'G' by visiting crews. If a station is designed for habitation which includes living quarters with artificial gravity, there may be problems when the crew transitions to zero 'G' for the 'workday'. This may or may not be a problem. However, the unhealthy effects of long-term weightlessness on the human body are serious enough that this solution should seriously be studied.

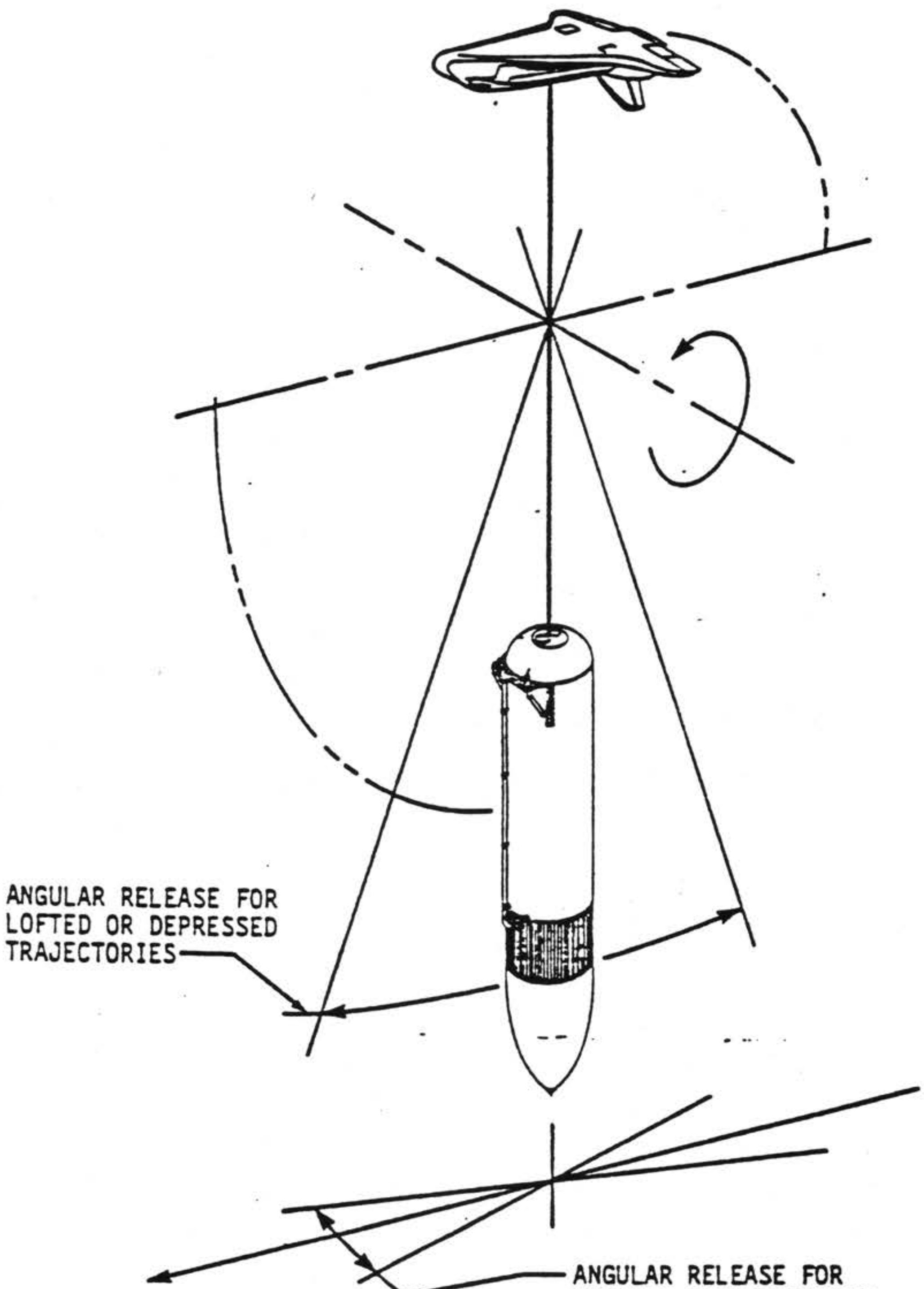
B. Momentum Exchange

Momentum storage and exchange are related in this context to the raising and lowering of orbits. Due to the forces discussed above, if a tethered mass is released from a stationary orbiting station, it and what it was released from will assume stable orbits with the closest approach seven times the length of the tether. If the release was from rotating tether, the closest approach of the final orbits would be as much as 14 times the length of the tether (13, 56). The equation for mass and orbital radius is also on the diagram.

The orbit of any facility or structure can be raised or lowered by momentum exchange procedures alone. If the operation is conducted with enough planning, the station may not require thrusters to keep it in orbit. For example, if an orbiter arrives at a space station, it uses a certain amount of OMS fuel to get there. If the orbiter meets a tether tens of miles below that same station and is winched up into the station that same OMS fuel becomes excess and can be transfered to the station for OTV refueling (16, 37). When the orbiter leaves, it can be winched down to the capture altitude or even lower and released. If is is released far enough away from the station, no OMS burn will be necessary for reentry. The net gain in this operation is the OMS fuel excess delivered to the station. The net loss is the time that the station spends in the lower net orbit due to the winching up of the orbiter.



SWINGING OR ROTATING ATTITUDE



INITAL CONDITIONS FOR TETHER RELEASE

The use of momentum transfer by the space station, orbiter, or the orbiter/ET combination would result in overall savings in onboard fuels, possible opening up of higher orbits to the orbiter, and insertion of the ET into a high orbit without expenditure of any residual cryogenics. If the ET and orbiter are tethered together, spun up to an appropriate rate, and released at the correct time and attitude, the ET orbit could be raised 40 x 560 km and the orbiter could have its orbit lowered 10 x 130 km, or low enough to deorbit. Loads on a tether in this case are less than 4,000 lbs tension. This is well within existing tether material capabilities today (50, 56).

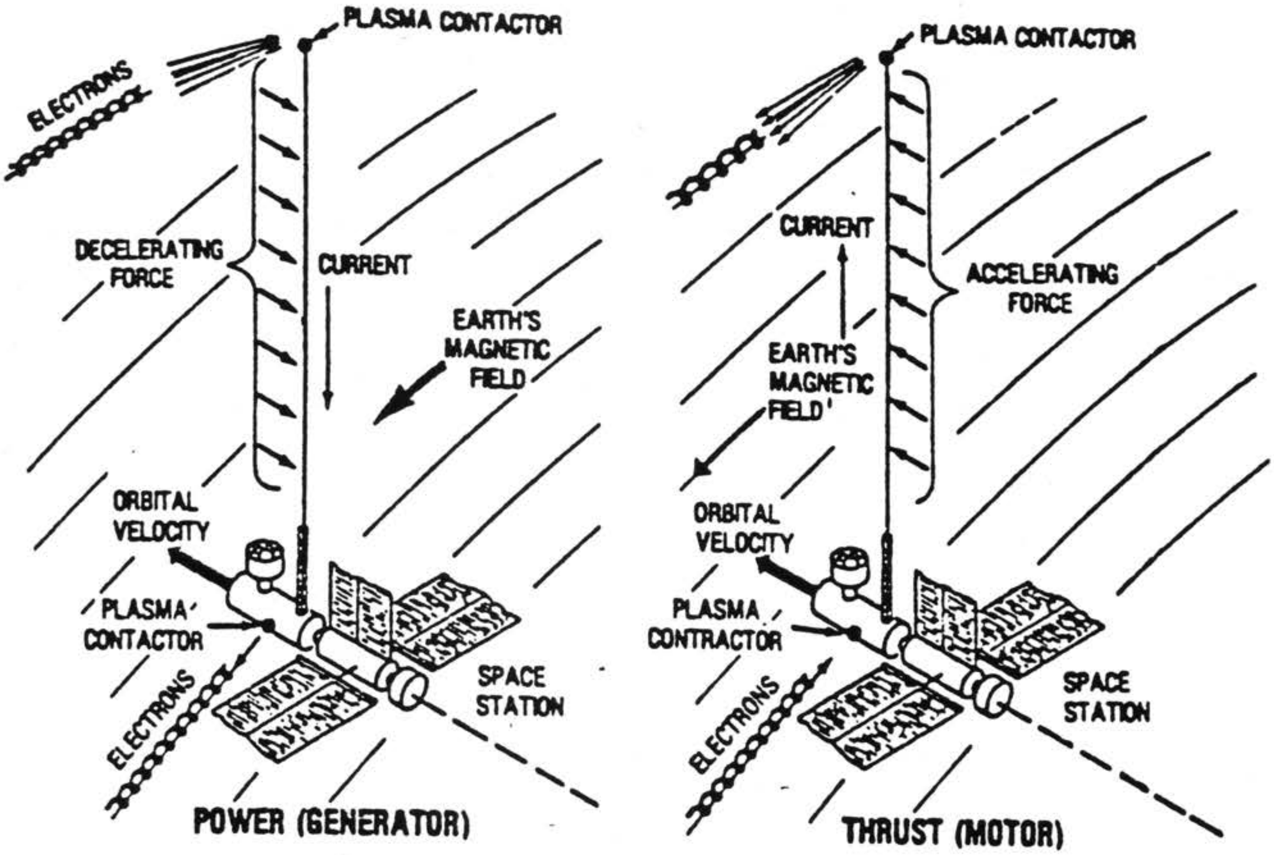
C. Electromagnetic Effects

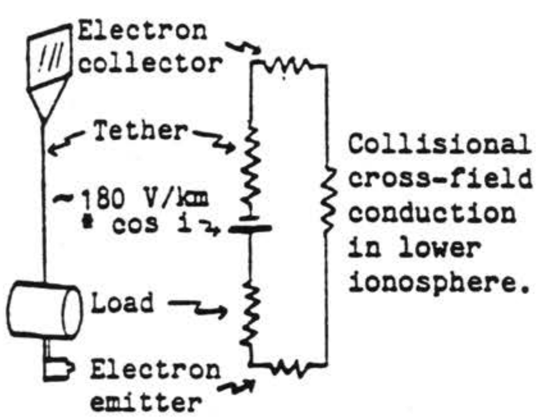
The final possible application discussed here involves the use of a tether as an electrical device. In addition to moving through space, bodies in LEO are also moving through a plasma in a magnetic field. As a result of these effects, there is a net potential difference between the bodies on either end on the order of 200 volts/km. If the tether is made of a conducting material and properly connected, a substantial current could be drawn for onboard power. A proposed design for power has been made that will deliver between 5 - 65 kilowatts continuously (13, 56, 84).

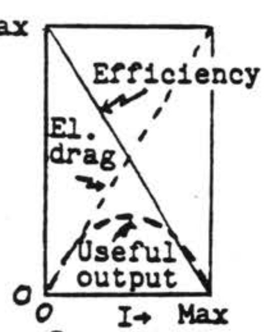
As with any other application, there is a tradeoff with this form of electrical power generation. It induces additional drag on the station by interaction with the magnetic field during power generation. This means that the momentum of a tethered station becomes an electrical energy storage device. As electrical power is generated, the station's orbit decays. Any method of supplying additional mass to be released below the station thereby becomes a method of supplying future electrical requirements. Calculations of a station that will lower and then release a visiting orbiter 150 km below the station will generate over 9,000 kilowatt hours (kwh) of electricity without orbital decay (56).

There is a reverse application to this power generation scheme. The Alfven Engine has been proposed by Drell et al. as a method of orbit maintenance, plane changing, orbit raising, manuvering, and excess energy conversion (13, 56, 84). If excess electrical power exists, a current flow could be forced against the potential work against the magnetic field. Theoretical efficiencies of 50% have been suggested. If this proves feasable,

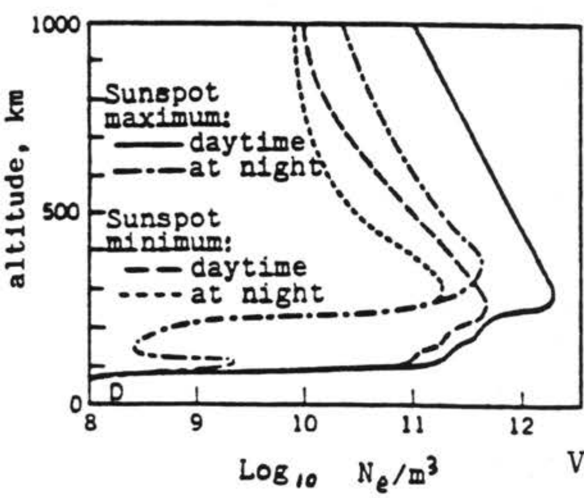
Electrodynamic Tether Principles

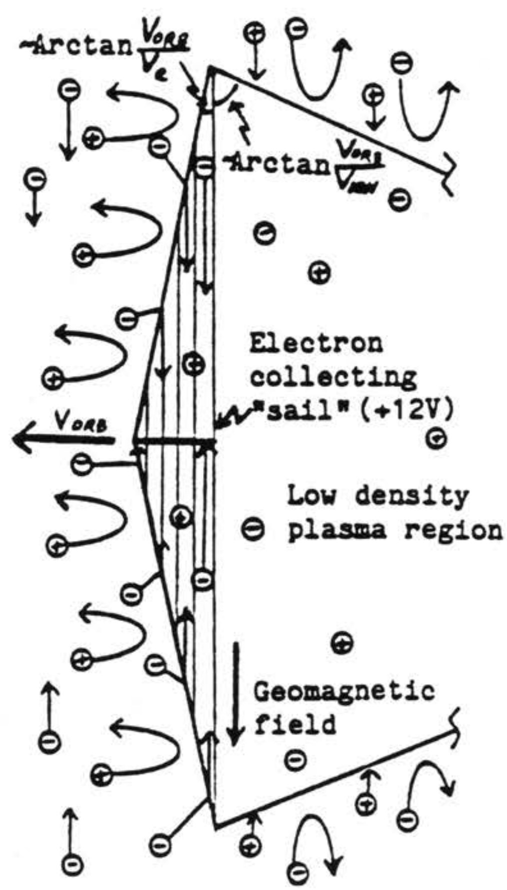






Generator Performance





Top View of Electron Collection

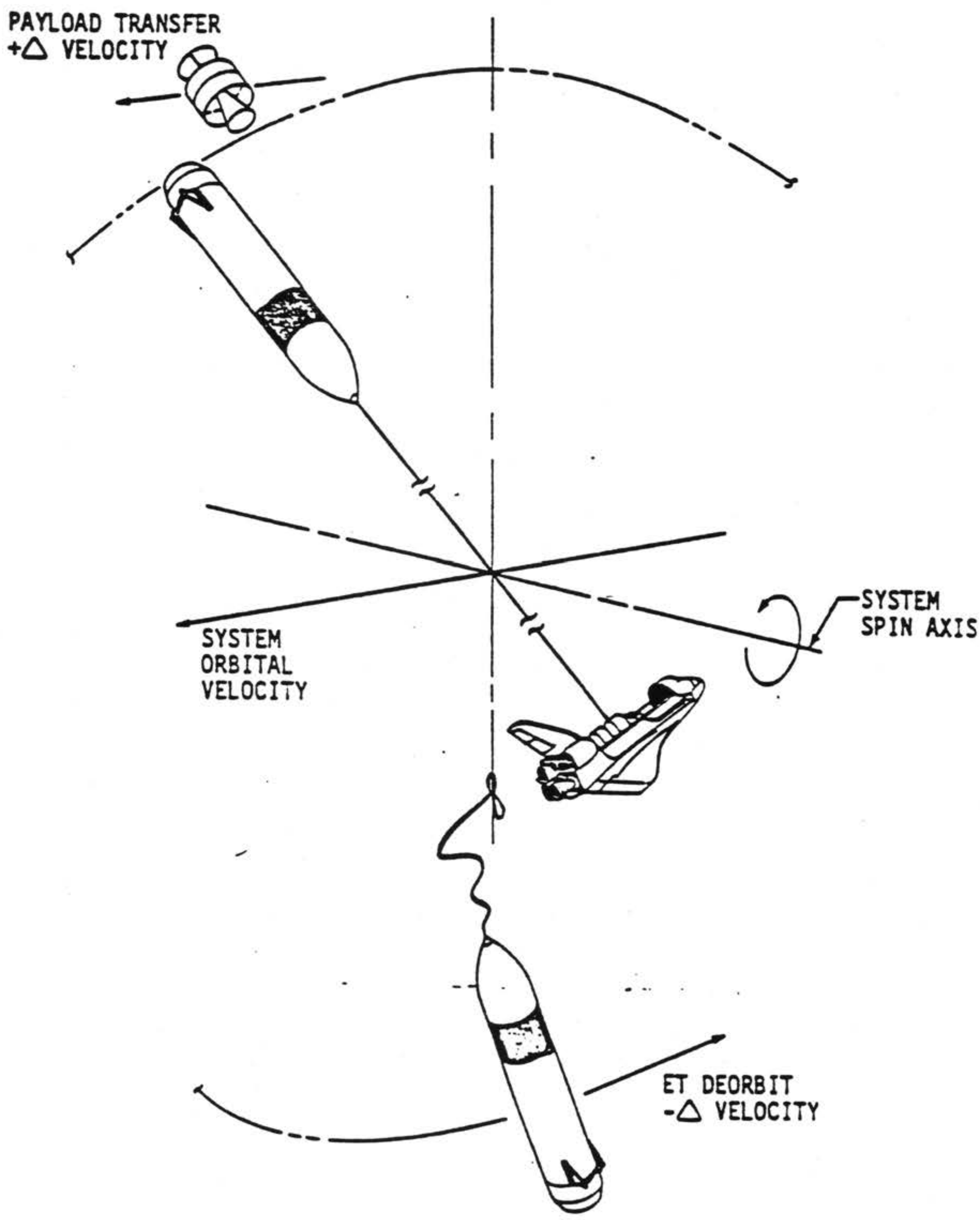
there exists an orbital engine with a better power to thrust efficiency than present ion engines. Another technique would be to store excess photovoltaic energy by raising altitude through the Alfven Engine during daylight periods of the orbit and use the excess to power the station during periods of darkness in the orbit.

IV. Shuttle Mission Enhancements

There are significant tether related enhancements of the basic shuttle mission. As had been mentioned in earlier sections, the momentum exchange technique is clearly the most attractive when combined with the ET. There are several variations to this theme that are of interest when applied to shuttle missions.

A. Orbit Raising and Lowering With the ET

As mentioned previously, the timed released of the ET into the proper orbit can be used to transfer the orbiter and/or its payloads into orbits unreachable with current techniques (50, 56). There are several choices in this regard. The first is the reentry of the orbiter from altitude while lofting the ET into an orbit which will not decay in a short period of time. The second choice is to loft the orbiter into a higher orbit by the controlled release of the ET from a rotating ET/Orbiter which will not decay in a short period of time. The second choice is to loft the orbiter into a higher orbit by the controlled release of the ET from a rotating ET/Orbiter system and deorbit the ET after release. This is a possible use of the ET, but may not be the best choice for actual applications. A third choice would be to release the ET in either direction from a non-rotating system. A fourth possible use would be to release a payload from the orbiter itself while the orbiter is still connected to the ET. The advantage of this technique is in two areas. The first is that a swinging release coupled with a burn by the payload at release is even more effective than a swinging release. The second advantage is that the combined mass of the Orbiter/ET is more than that of the Orbiter itself and therefore allows more energy to be put in the loft of the payload.

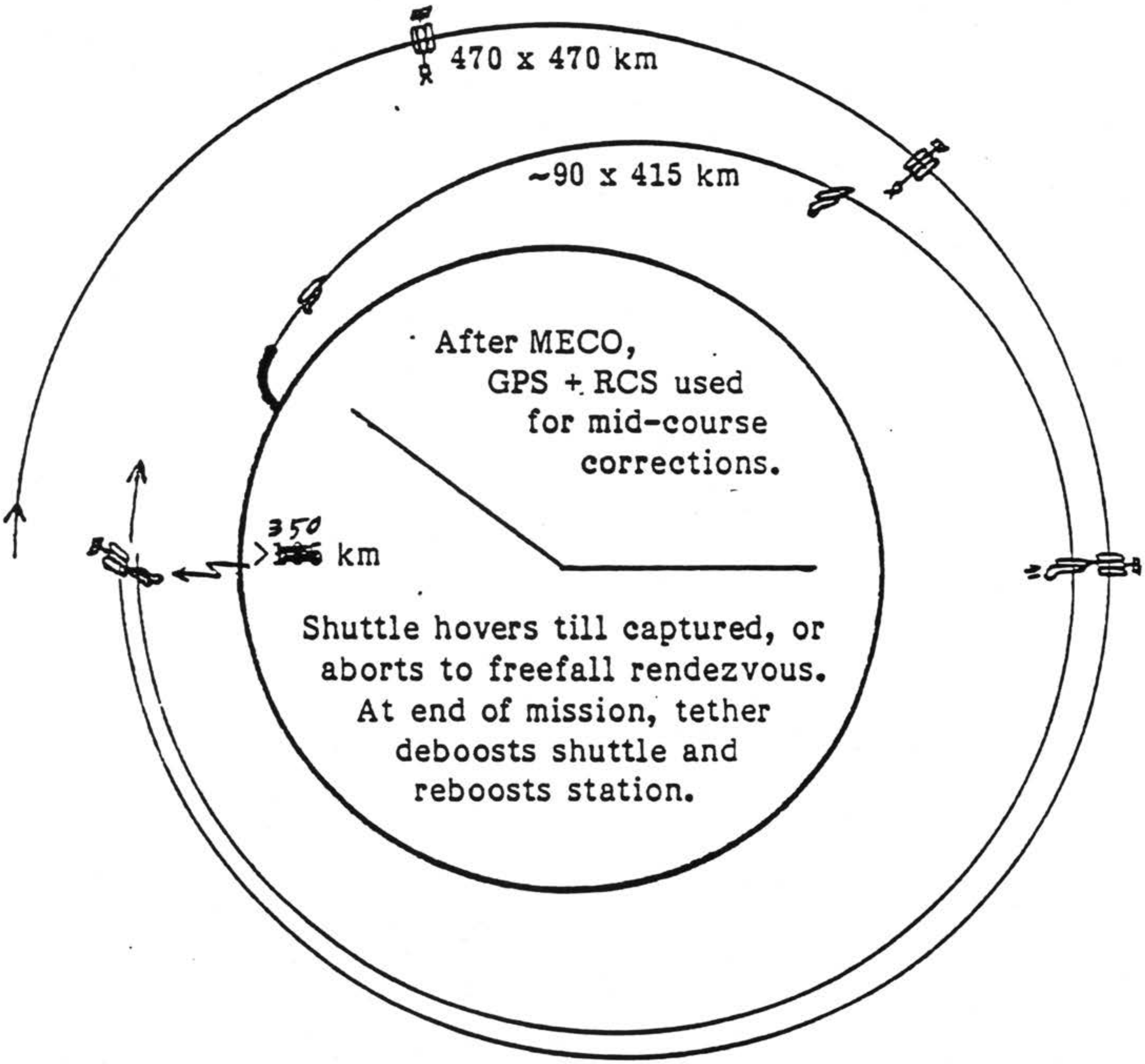


SEQUENTIAL RELEASE OPERATIONS

B. Shuttle to Station Advantages

There are significant advantages in placing the tether in a space station and only launching the orbiter partway to the altitude of the station. This is refered to as Tether Mediated Rendezvous (16). The basic idea is to launch the STS to a highly elliptical orbit that intersects that of the end of a space station mounted tether 41 - 47 minutes after launch. The orbiter will rendezvous with the tip of the tether using the ET nose itself as a docking probe for the Orbiter/ET. After the docking is complete, the stack is winched the remaining 40 - 55 km up to the station. The advantages include the delivery of several tons of OMS fuel to the space station holding tanks for future use in OTV operations, the delivery of the ET and Orbiter to the station, the settling of the residual cryogenics and possible scavenging of them during the winching procedure into tether mounted holding tanks. All of these advantages translate directly into fuels delivered to the station. There is also an additional safety factor in the use of the ET as the docking probe. The ET nose will protect the nose and windows of the orbiter from possible impact with the tether tip by being 50 feet closer to the tip than the orbiter itself.

This appears at first glance to be a procedure that requires precise timing. This is partially true in that it does inflict another constraint on the launch timing itself and continue to narrow the launch window. The arrival at the tether is timed based on midcourse corrections flown enroute and the venting of residuals as they slowly boil off for thrust through cold-gas engines. The orbiter arrives at the tip of the tether with sufficient OMS fuel to conduct several abort scenarios. The mission rules should always allow the orbiter to carry enough OMS fuel to complete the rendezvous in case the tether technique does not work for whatever reason. The strategy also allows the orbiter to 'brute force' the departure and reentry by the use of the OMS engines. It is important to point out that there are three levels of success in this plan. The most successful mission would be one that allows the orbiter to dock with the tether tip with a minimum of hovering, delay, or the requirement to 'wave off' the docking for another orbit. This delivers the maximum OMS fuel to the station in the minimum time. An intermediate success would be an OMS burn for rendezvous with the station and a tethered release for departure. This allows the scavenging of the OMS fuel necessary for an unaided release for the station



TETHER MEDIATED RENDEZVOUS

reboost. The most unsuccessful mission would be precisely what is planned for current shuttle to station missions - unaided arrival and departures (16).

V. Space Station Mission Enhancements

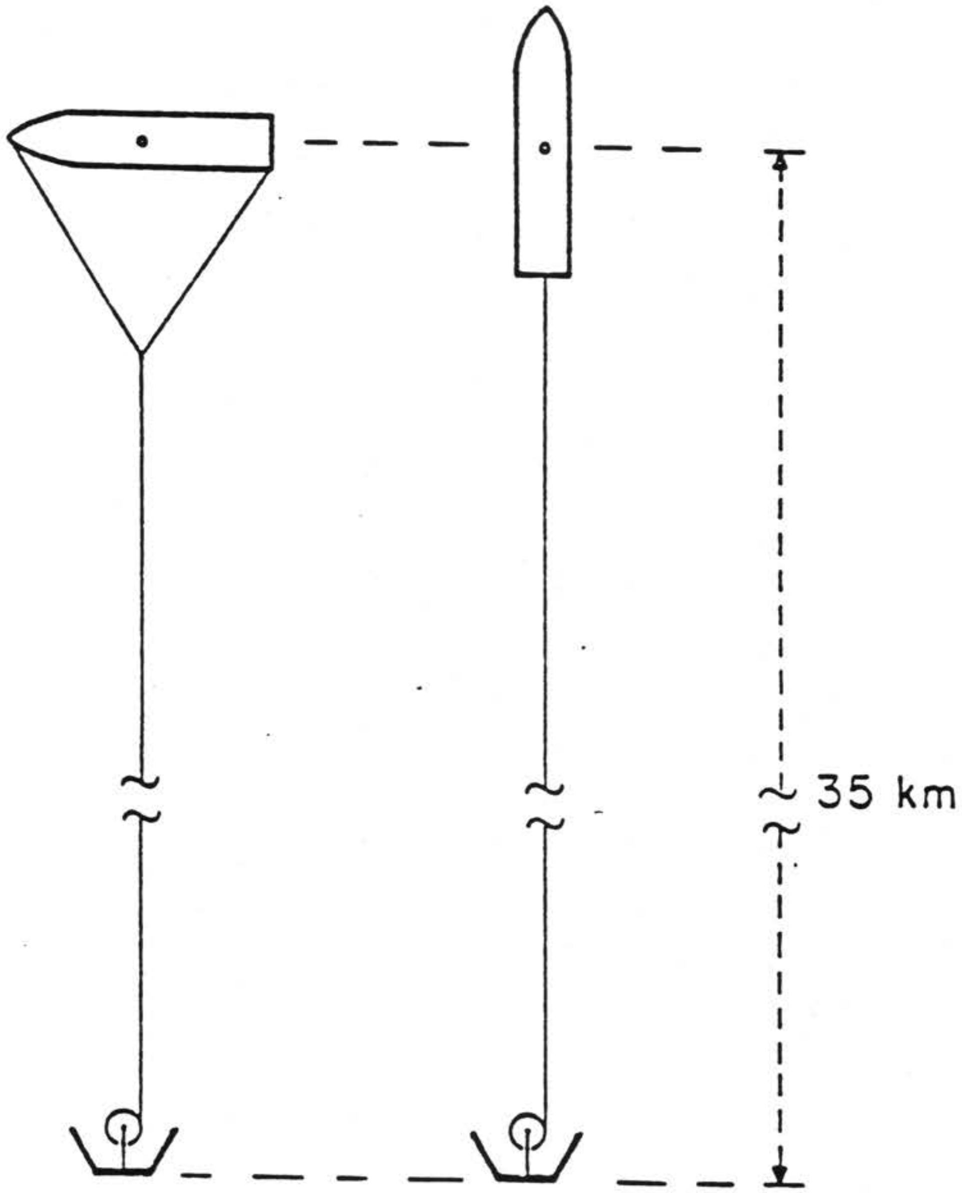
There are several tether and ET based applications that are possible in the design and operation of a space station. These are all combinations of previously mentioned applications that will enhance the operation of the space station.

A. Liquid Storage

The microgravity applications of bodies on tethers can be utilized to store liquids so they will be available for use. The problem with weightlessness is that normal liquid flows will not take place. It will likely be very important to store the cryogenics, scavenged OMS fuels, water, or any other liquid a certain distance above or below the station for use. This takes advantage of the combined effects of the gravity gradient and centrifugal forces to settle the liquids on one end of the storage facility where they can be normally pumped (13, 56).

B. Tank Storage

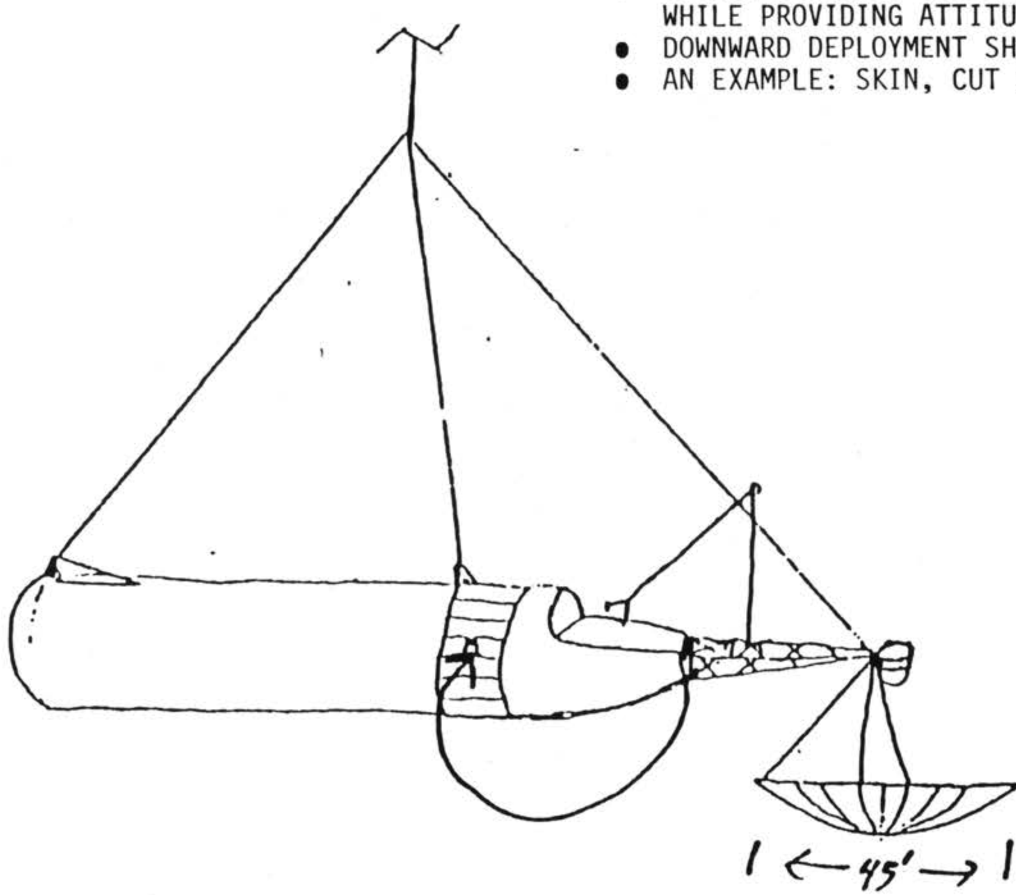
Tank storage on orbit can also be enhanced by the use of tethers to minimize the cross sectional area 'into the wind' (56). The intention is to hang a mass below the ET or the ET farm on the end of the longest possible tether. This serves several needs by putting the ETs in the best possible attitude relative to the 'wind' on orbit. It also puts them at the best possible altitude relative to the 'wind' by placing the ETs at the highest portion of the orbit above the atmosphere. It places a massive object in space for possible use by visiting orbiters. The orbiter can rendezvous and dock with the end of a tether carried on the tank farm and run the same momentum exchange as was discussed earlier for a space station. It can deposit the ET it carries at the 'tank farm' and winch itself to the lowest possible altitude for release into a reentry trajectory.



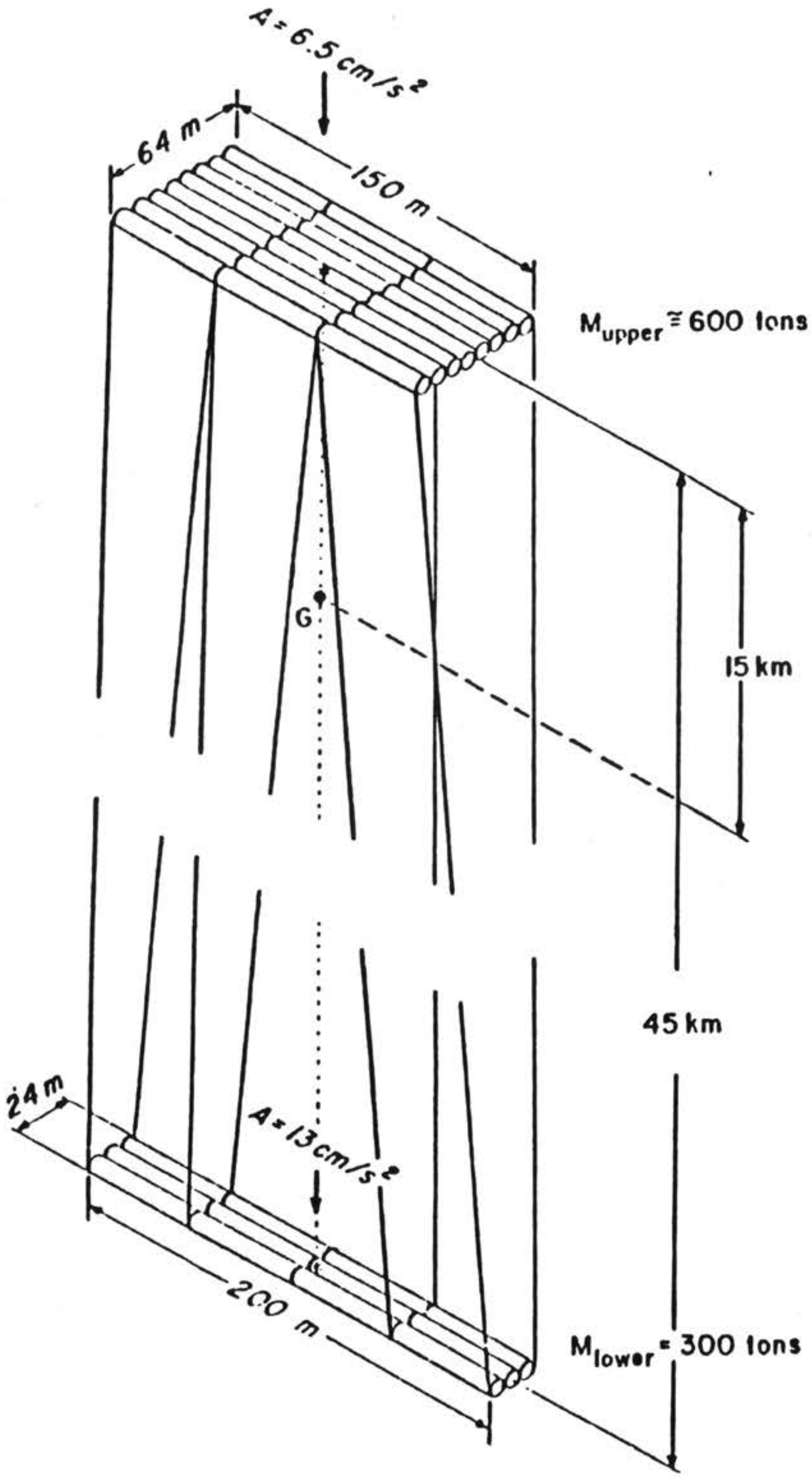
Two possible configurations of an External Tank plus PMDR (Pallet Mounted Deployer-Retriever). The left hand configuration is preferred because it has a lower A/M ratio than the right hand configuration.

HAZARDOUS OR CONTAMINATING OPERATIONS

- TETHER ISOLATES CONTAMINATING AND HAZARDOUS OPERATIONS WHILE PROVIDING ATTITUDE,POWER,STATIONKEEPING
- DOWNWARD DEPLOYMENT SHORTENS DEBRIS ORBITAL LIFE
- AN EXAMPLE: SKIN, CUT UP, AND MELT DOWN ETs



HAZARDOUS OR CONTAMENATING OPERATIONS



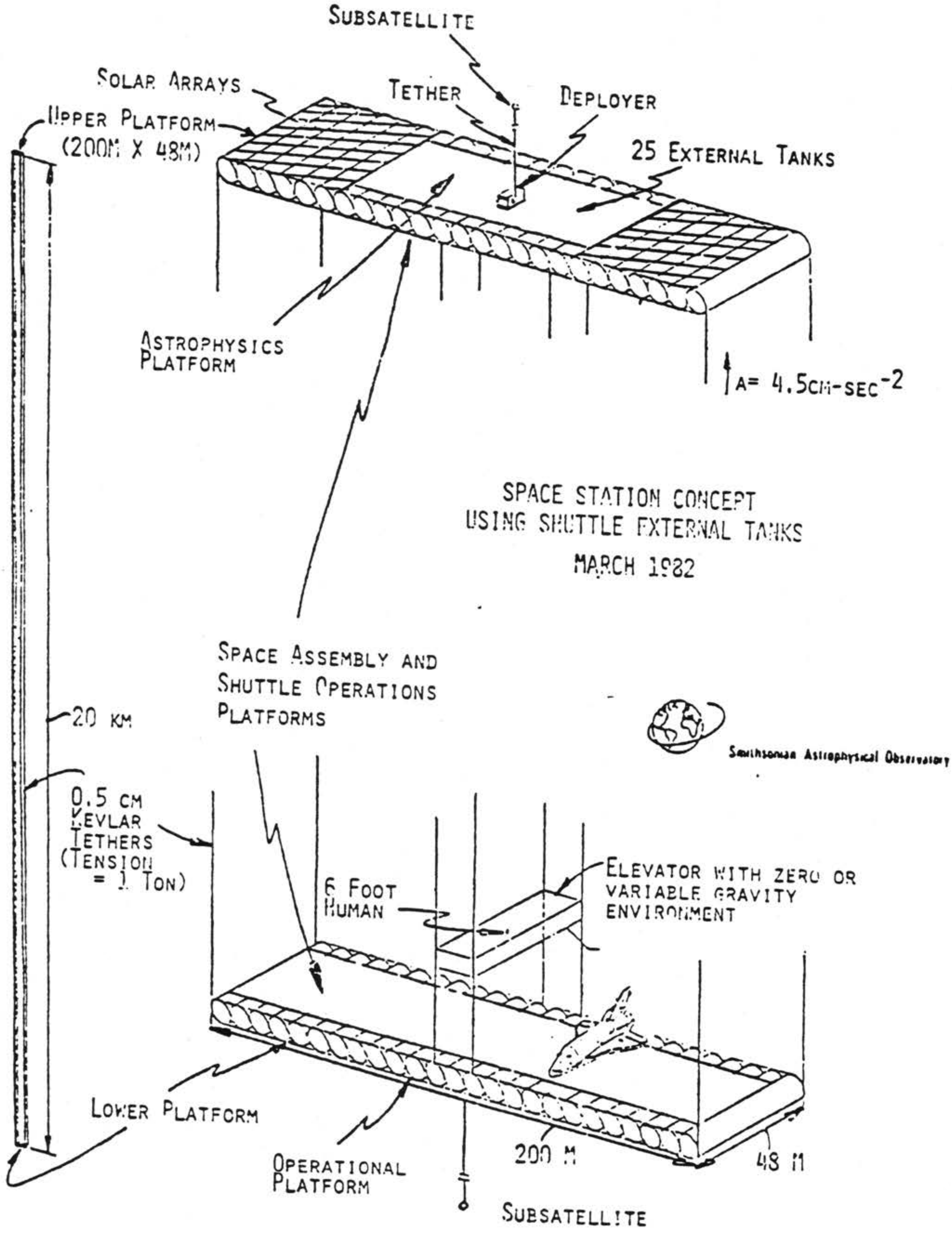
Example of an asymmetric platform. The total number of External Tanks used is 36; 24 of them are assembled to form the upper deck, 12 the lower deck. The two decks are linked by 8 cables, 0.5 cm diameter, of 45 km length. The system in circular orbit at 400-500 km has the mean motion of the center of mass of the system which lays roughly 15 km below the upper deck and 30 km above the lower deck. The total tension is of the order of 5 tons distributed in the 8 cables.

The asymmetric configuration has the following advantages:

a) The upper and lower platforms may be designed so that the atmospheric drag gives a zero torque with respect to G.

b) We have larger acceleration at both the upper and lower levels. In particular, at the lower deck it may be advantageous to have a larger acceleration for simplifying operations there.

c) The lower platform has lower velocity, much lower than the local circular velocity and the Shuttle may dock there with zero relative velocity from an eccentri[illegible] it with much lower perigee.



SYMMETRIC PLATFORM

- Long swinging tethers or short spinning ones?
- Three ranges of deltaV have utility:

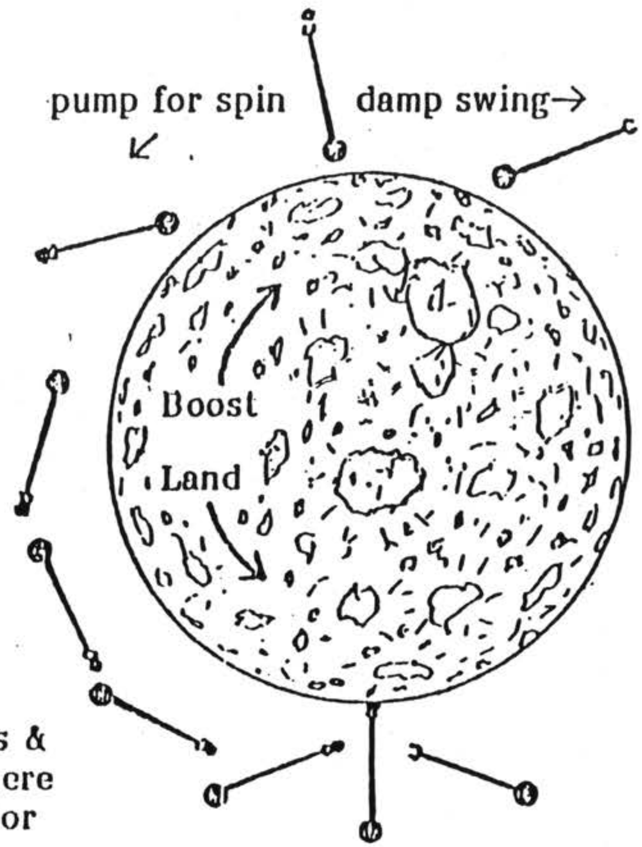
small, for capturing payloads in orbit (Mt $\ll$ Mp)
850 m/s, to get 2/3 of surface-TEI deltaV (Mt $\approx$ Mp)
1700 m/s, to pick up objects on surface (Mt$\approx$10Mp)

Required Technology:

Advanced tether controls
Powerful tether deployer
Maneuverable tether tip
Large power supply
High-Isp propulsion
Propellant extraction

Transport Capabilities:

Surface—Orbit—Escape
Handles large payloads
Max g-loads < .3 gee
Rocket backup if desired
Two-way mass flow is "free"
Net boosting costs ~25 MWH/tonne
Polar orbit: frequent access to poles & infrequent access everywhere
Equatorial: frequent access to equator



LUNAR - ORBITING TETHER FACILITY

C. Space Station Architecture

In a paper by Dr. Giuseppe Colombo et al., the use of multiple tethers and platforms made of connected tanks is suggested as a way to fly a space station (56). The suggestion is to construct massive platforms so as to minimize the cross sectional area into the 'wind'. The tasks performed on the different platforms can be designed to take advantage of the separation of the two units. For example, the top platform can fuel and service OTVs, launch satellites to higher orbits, conduct scientific observations higher above the atmosphere than the lower platform. The lower platform can conduct operations that tend to contaminate the environment around the station such as materials processing, tank stripping, disassembly, cutting, and melting.

Because it is lower in altitude and inside more of the upper atmosphere, emissions at this level will not pollute the upper level and will reenter the atmosphere sooner (15). A lower level would also be the location of a orbiter retrieval and payload reentry operation. The space equivalent of an elevator would operate between the two levels. There would be low gravity at both levels, so any applications that require zero gravity would need to be conducted at a separate station or at the center of mass of the station. A typical schematic is detailed below.

An additional space station architectural application would be to use a rotating station to induce artificial gravity for the station crew (14, 89). This would be advantageous in the preparing the crew for the gravities on the moon, Mars, or elsewhere. Additionally, the spinning ET based station is easy to construct, structurally sound, and capable of stopping the deterioration of the human body under weightlessness if the gravity level induced is high enough.

VI. Miscellaneous

There are additional tether related uses that are farther from realization. These include the use of the ET as a landing module deposited on the surface of the moon or Mars from the tip of a rotating tether (14). The concept is to use the momentum transfer to kill most or all of the velocity differential between the ET and the surface and load the ET with whatever is required for the lunar or Martian base. An additional tether use would be the

"Rotating Skyhook' (84). This uses a long tether for launch and landing of small (or not so small) payloads on the lunar or Martian surface. The ET application here would be as a counterweight for momentum storage.

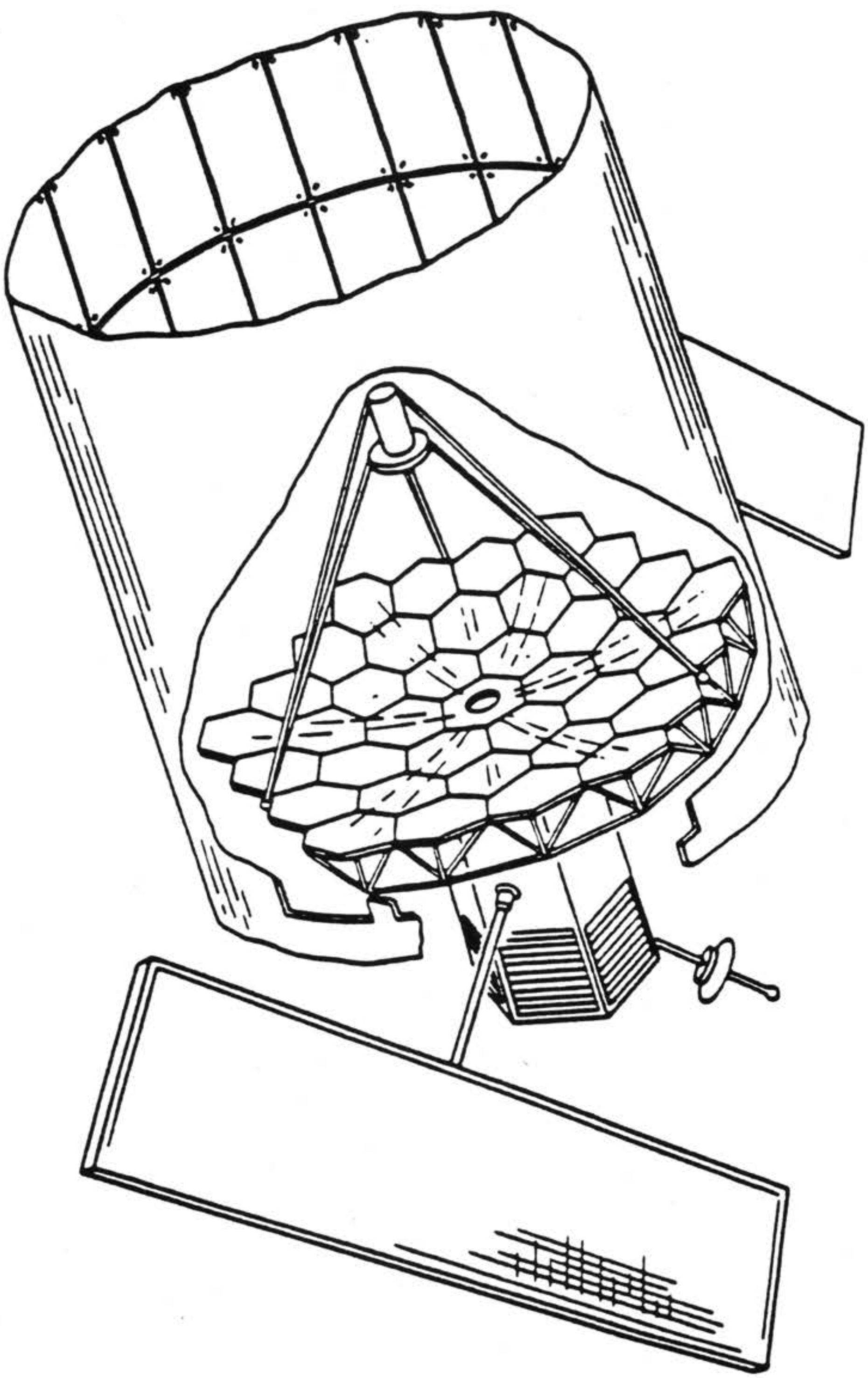
This section details a variety of external tank applications that are not readily matched with the previous categories. These applications are in no way less important or feasable. Indeed, the military and scientific applications may very well be the first use of the ET or the ET/ACC combination on orbit. The majority of the science applications were suggested in two workshops held at the California Space Institute in 1982 - 1983 (56, 95).

I. Ovservational Science

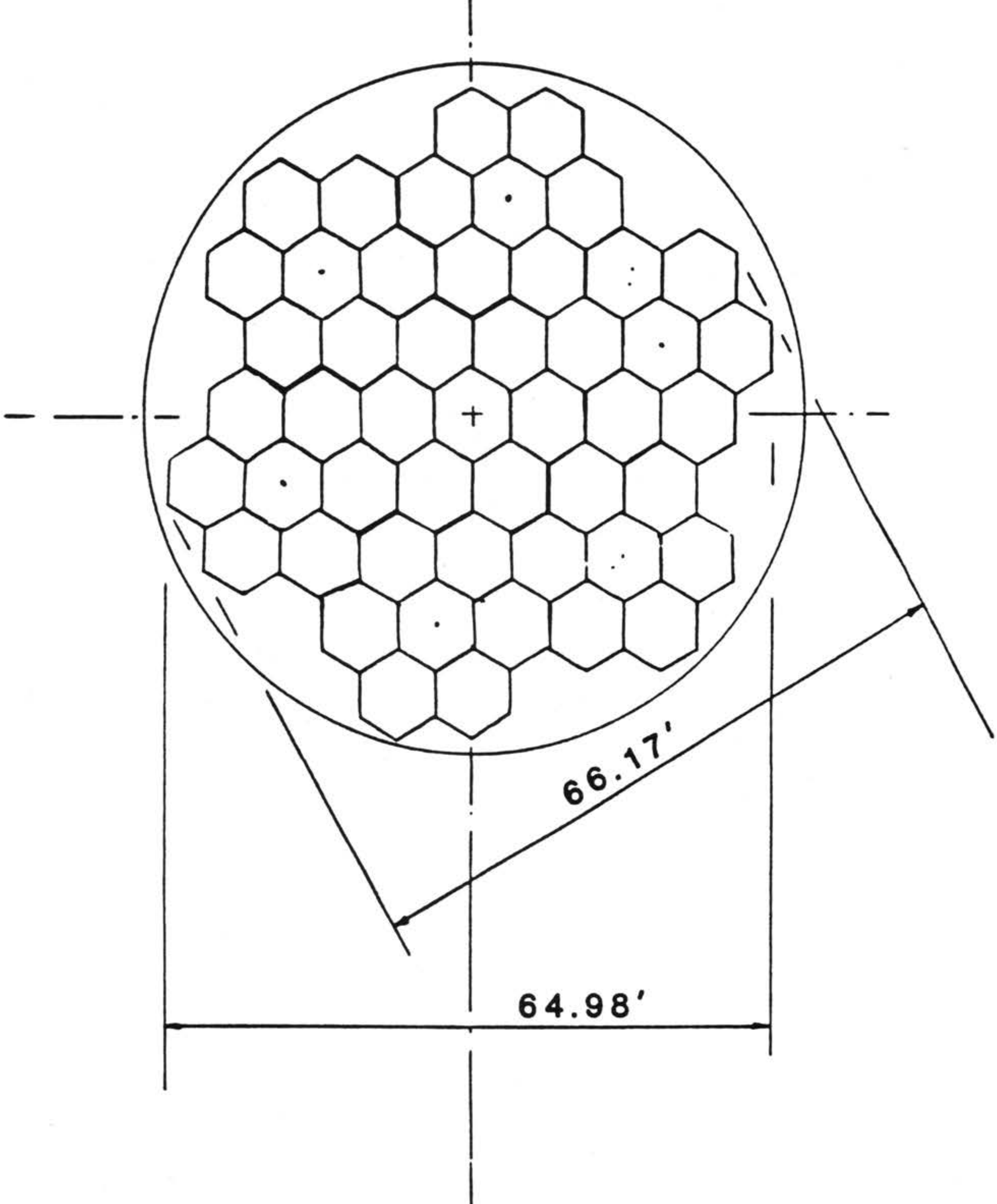
The External Tank has been proposed as the heart of a variety of telescopes for observations of the earth and space across majority of the electromagnetic spectrum. These include the use of the volume of the tank and the ET/ACC carrier as a way to carry large mirrors into orbit, the use of the tank itself as a strongback for the construction and stabilization of large structures, and the use of the interior of the tank itself as a telescope for high energy astronomy.

A. Large Deployable Reflector (LDR)

One of the early uses of the tank could be to carry mirror segments in the ACC for on orbit construction into a LDR (35, 81). This telescope is primarily intended for research in the infrared and submillimeter wavelengths. Its basic design would also serve nicely for a large diameter optical reflector. The basic plan is to carry seven panels composed of seven hexagonal segments stacked on top of one another in the ACC. Each panel is proposed to be 24.5 feet across. The panels are removed from the ACC and assembled on orbit into a rigid structure about 66 feet across. There are 18 edges to be connected on orbit in this plan. An alternate method would be to carry the smaller segments in the cargo bay and assemble them into the LDR on-orbit. This alternate method is not as attractive because it requires several more edges to be joined together. This leads to additional problems associated with pointing and mirror adjustment of 49 total segments.

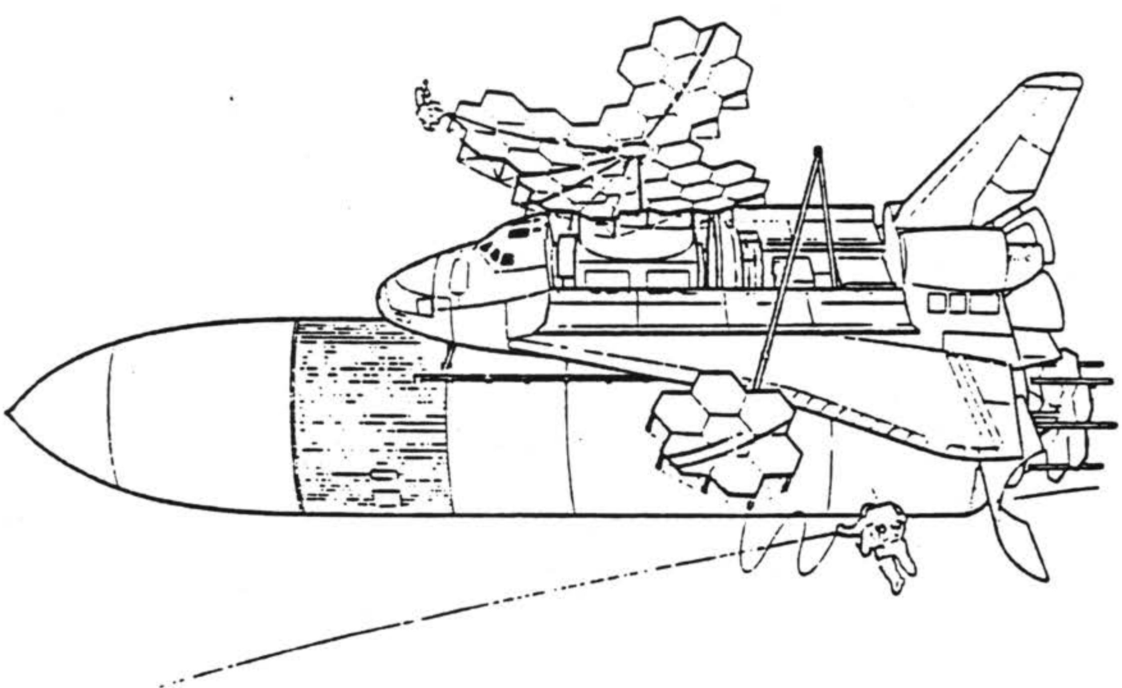


LARGE DEPLOYABLE REFLECTOR



LDR DIMENSIONS

Diameter	≥ 20 m
Shortest wavelength of diffraction-limited performance (λ_c)	30-50 μm
Light bucket blur circle	≤ 2 arcsec at 1-4 μm
Temperature and emissivity	Primary ≤ 200 K, $\epsilon = 0.01$ at $\lambda = 1$ mm, $\epsilon = 0.05$ for $\lambda \leq 1$ mm
Chopping	2 Hz, 1 arcmin (reactionless)
Sidelobes	Low near sidelobes
Scan	1° by 1° - Linear scan at 1°/min
Slew	≥ 50°/min
Field of view	≥ 3 arcmin
Absolute pointing, jitter	0.05 arcsec, 0.02 arcsec



SHUTTLE ASSEMBLY OF LDR

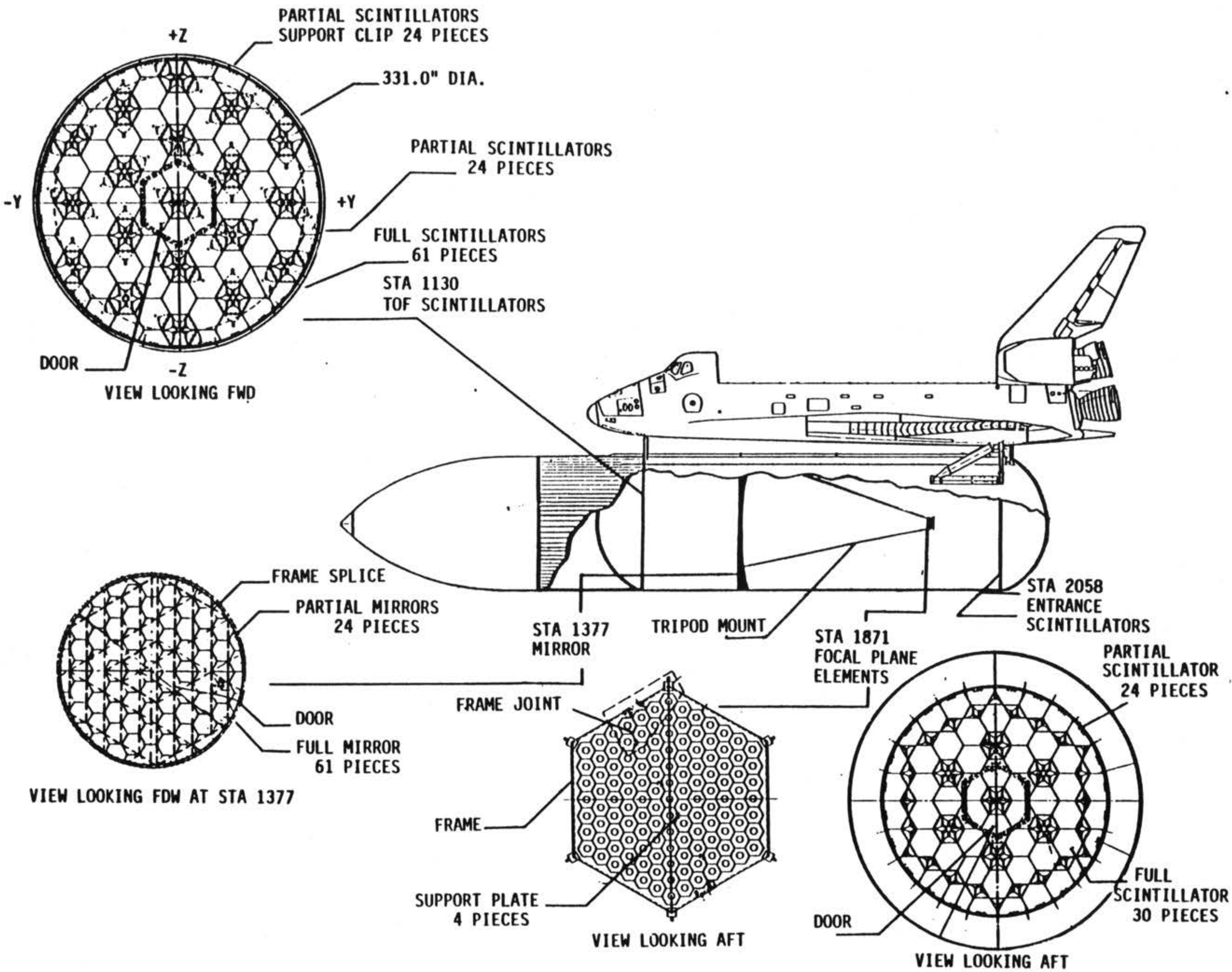
The astronomical advantages of this type telescope in the optical, infrared, and submillimeter wavelengths is enormous when compared with current and planned ground and space based telescopes. In the optical wavelengths, the 65 foot diamter compares nicely with the 200 inch (about 17 feet) Hale telescope and the 400 inch (over 33 feet) proposed Texas multiple mirror reflector. In the infrared, the pure dimensions of this telescope alone have the potential to improve upon the IRAS data by several order of magnitude. The advantages gained by the use of the ET and the ET/ACC are gained by the ability to launch a few large panels for construction rather than having to connect 49 small segments to one another during a 7 - 10 day shuttle sortie. The ET also can provide a very large gravity gradient stabilized base or an anchor to which the telescope can be attached to for operation.

B. High Energy Observations

The ET also has potential as the base for cosmic ray, gamma ray, and x-ray observations (40, 56, 91). A tank that is outfitted with proper detectors and stabilized in a gravity gradient mode could be turned into a gamma ray telescope as pictured below. The interior of the hydrogen tank could be turned into large orbiting Ion or Cherenkov chambers for detection of cosmic and gamma rays. The cost of these would be low enough due to the use of a tank, so that there is the possibility of flying more than one high energy observatory. This leads to the possibility of long baseline detections of activity and thus better, more comprehensive data. The tank is also large enough to mount large arrays of proportional counter systems to conduct x-ray astronomy of the heavens.

C. Low Energy Observations

As was mentioned with the LDR, there are advantages in using the ET in observing the longer wavelengths. The ACC itself is large enough to accommodate a very large deployable antenna. The diameter of the mirror can be increased by nesting panels and attaching them together in orbit. The obsrevation of the earth and planets by Synthetic Aperature Radar involve large antennas. The ET can serve as the structural base for a large antenna used for this purpose. It even has the capability of being cut in half lengthwise and turned into a long trough antenna for these purposes. Once again, size, mass, and structural strength are all advantages.



GAMMA RAY TELESCOPE

D. Additional Observations

The ET can serve to fill several other observational science needs (56, 95). It can be used as a space based occultor for ground and space based observations. Two tanks tethered together can be used as a low altitude gravity gradient detector. The tank can be used to study the interactions of large bodies and the upper atmosphere, plasmas, and magnetospheric effects of charged and uncharged bodies in space. Most of these are studies that are possible with large inexpensive bodies in orbit that would not be possible on near this scale in an operation that does not use the ET.

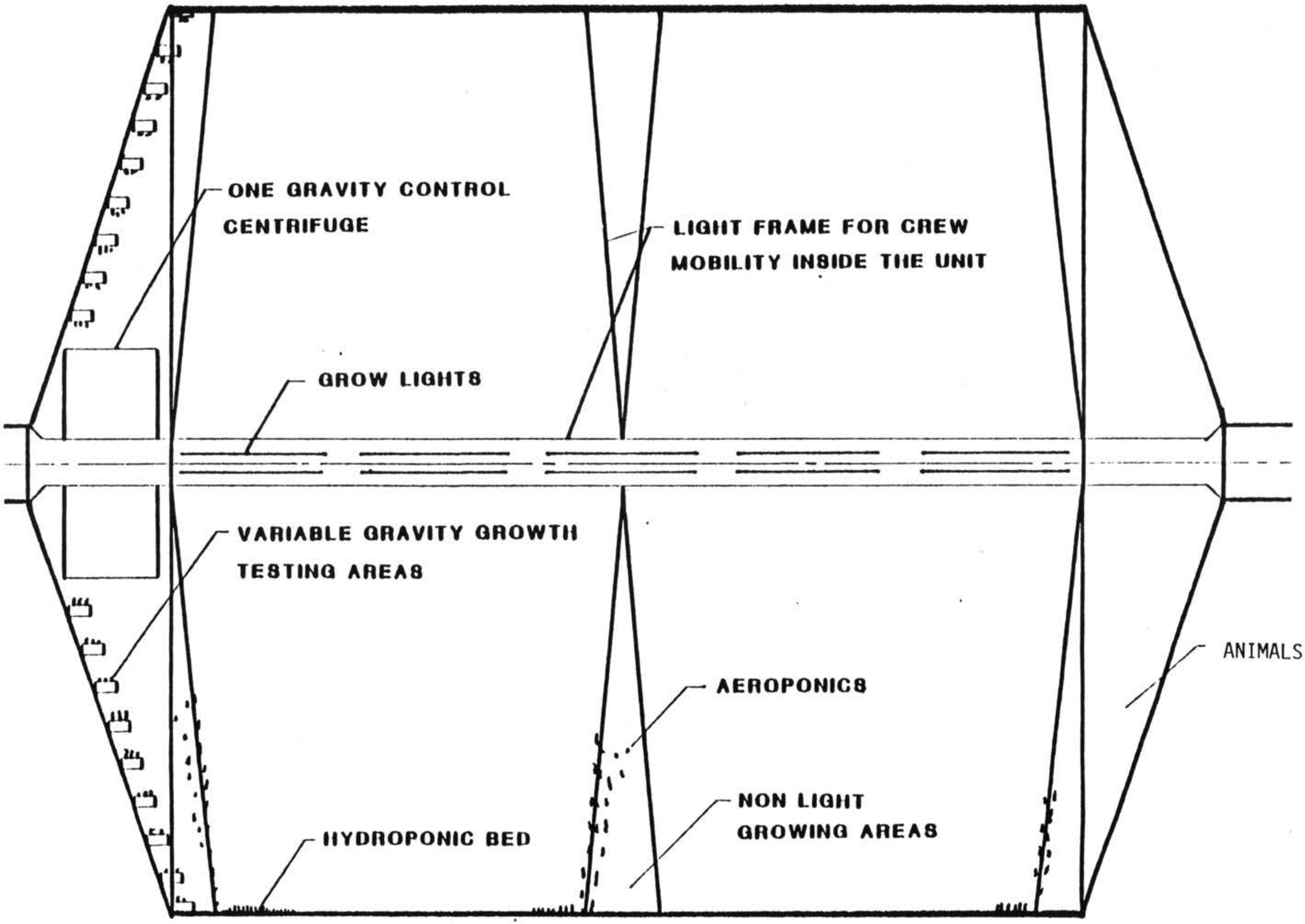
II. Biology and Life Sciences

A. Waste Management

The first class of application is to use the interior of either tank as a waste management facility (56, 95). If the waste is nonbiological, the interior of either tank is sufficient to store scraps and debris that would become a hazard if left in orbit. This debris could later be used as reaction mass or melted to serve structural needs. The second class of waste is biological (95). Any system containing living components will generate these wastes. In order to make a space based operation as self-sufficient as possible, it is in the interest of planners to recycle the maximum amount of consumables. This typically involves some sort of waste management. The tank can be turned into a very large microbiology lab which could conduct large experiments on waste recycling. The tank is large enough to partition into several portions and run several experiments. The advantage of large size is biological inertia. This means that any unwanted changes could be identified and dealt with before the experiment fails.

B. Biology

A large pressurized volume can be used to conduct experiments and development of those strains of plants and animals best suited to zero gravity. This would serve to develop living things that could be used to support living systems from within the space station. A large inflatable could be attached to the exterior of the ET and used as a farm as detailed



INFLATABLE FARM

below. The isolation of the tank in orbit could allow genetic experiments to be conducted in space that would not be possible on the surface (25, 56, 95).

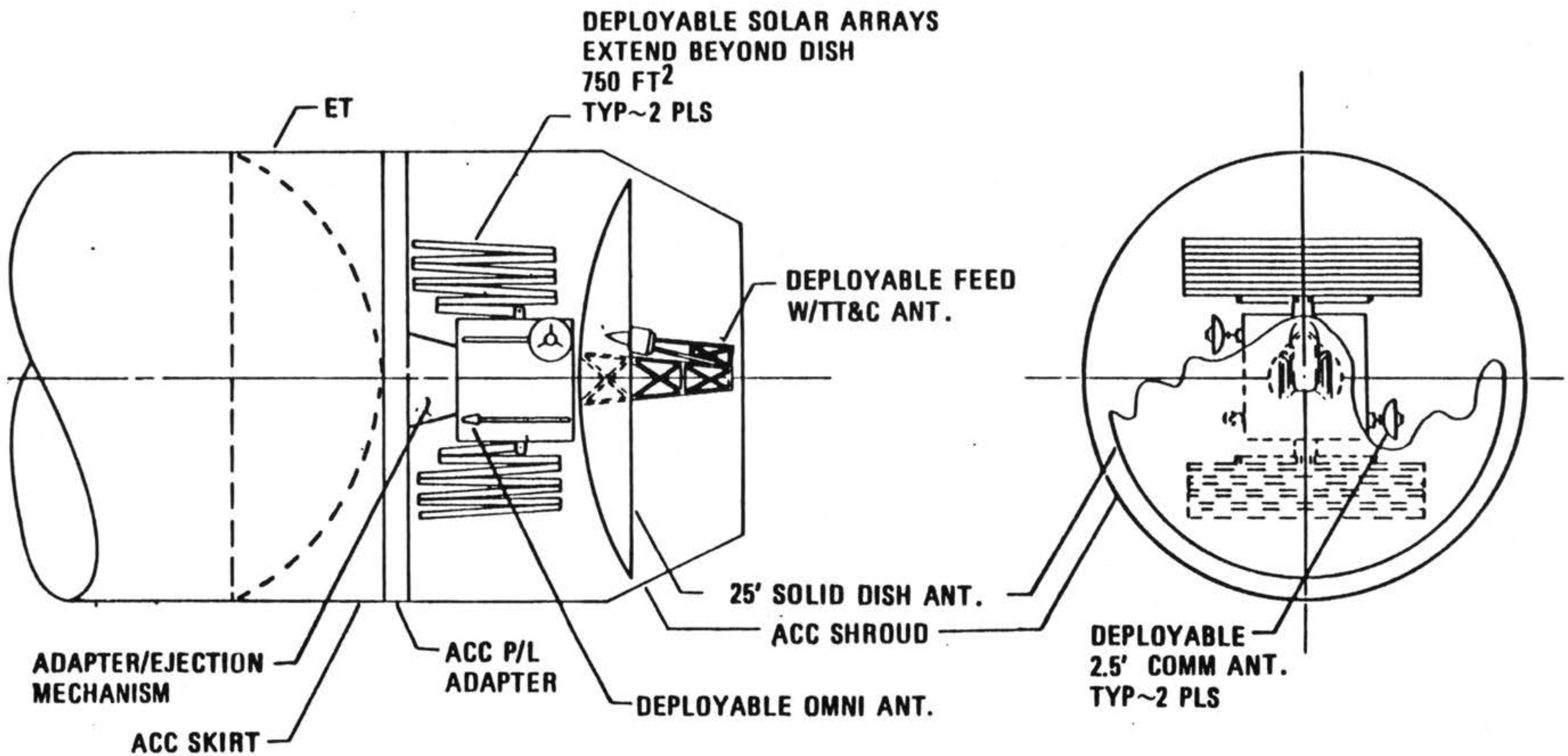
C. Life Support

The ET could also be used as an active or passive lifeboat (95). The oxygen or hydrogen tank that is being used for an experiment in waste management or farming would be pressurized. This provides a lifeboat available for use to a stranded crew or the crew of a station that is unable to provide normal life support due to problems or an emergency. The hydrogen tank is large enough to provide several man-months of activity before the CO_2 levels become dangerous (95). This is a passive life support system. Several tanks in several orbits could provide an excellent safety margin for a large space-based operation. All that is required is to fill the tanks with oxygen or a nitrogen - oxygen mixture at 14.7 psi and release them into the desired orbit.

Additionally, the SOFI can provide some radiation protection. The aluminium shell also provides some protection from radiation (95). An additional possible ET life support contribution is gravity. According to NASA scientists, the human body does not tolerate long periods of weightlessness without serious deteoriation of bones and muscles (55). Two ETs can be attached by a tether and swung around each other to create gravity for crews living inside. They can also be attached end to end in the form of a torus and spun up to provide gravity. The ET is structurally strong enough to tolerate the loads imposed by both of these proposals (48). It is even stronger if it is pressurized. The only requirement is to make the rotating facility large enough that coriolis effects are minimized. A rotation rate of 1 - 3 revolutions per minute seems tolerable at this time but would require experimentation with a crew to find out. This rotation rate also requires either a long tether or a very large diameter torus.

III. Military Applications

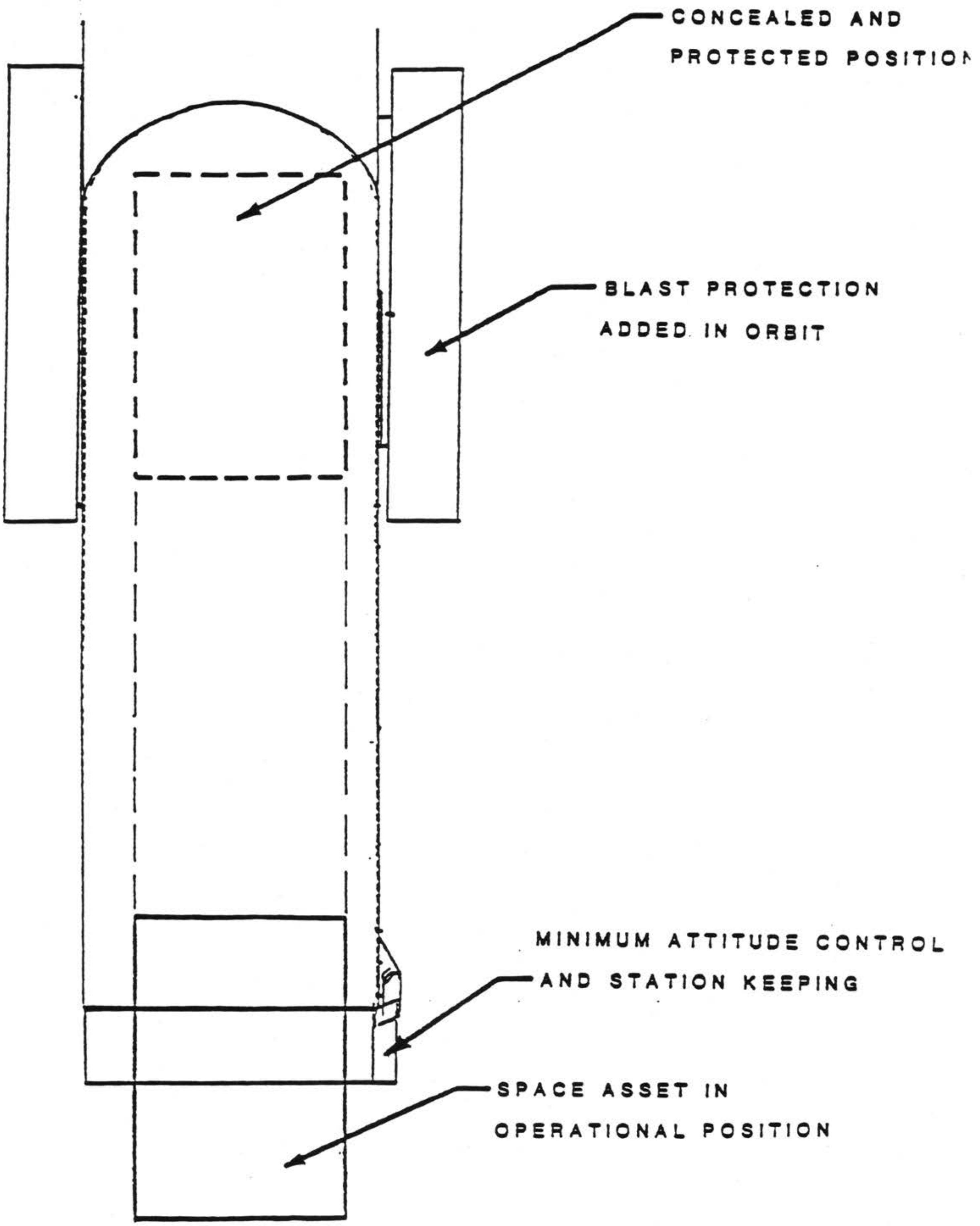
There are also significant military applications possible with the ET and the ET/ACC combination (25, 56). Like the applications mentioned previously, these take advantage of the low cost, large size, and large mass available with an ET. There will be no attempt made here to sell or hide possible



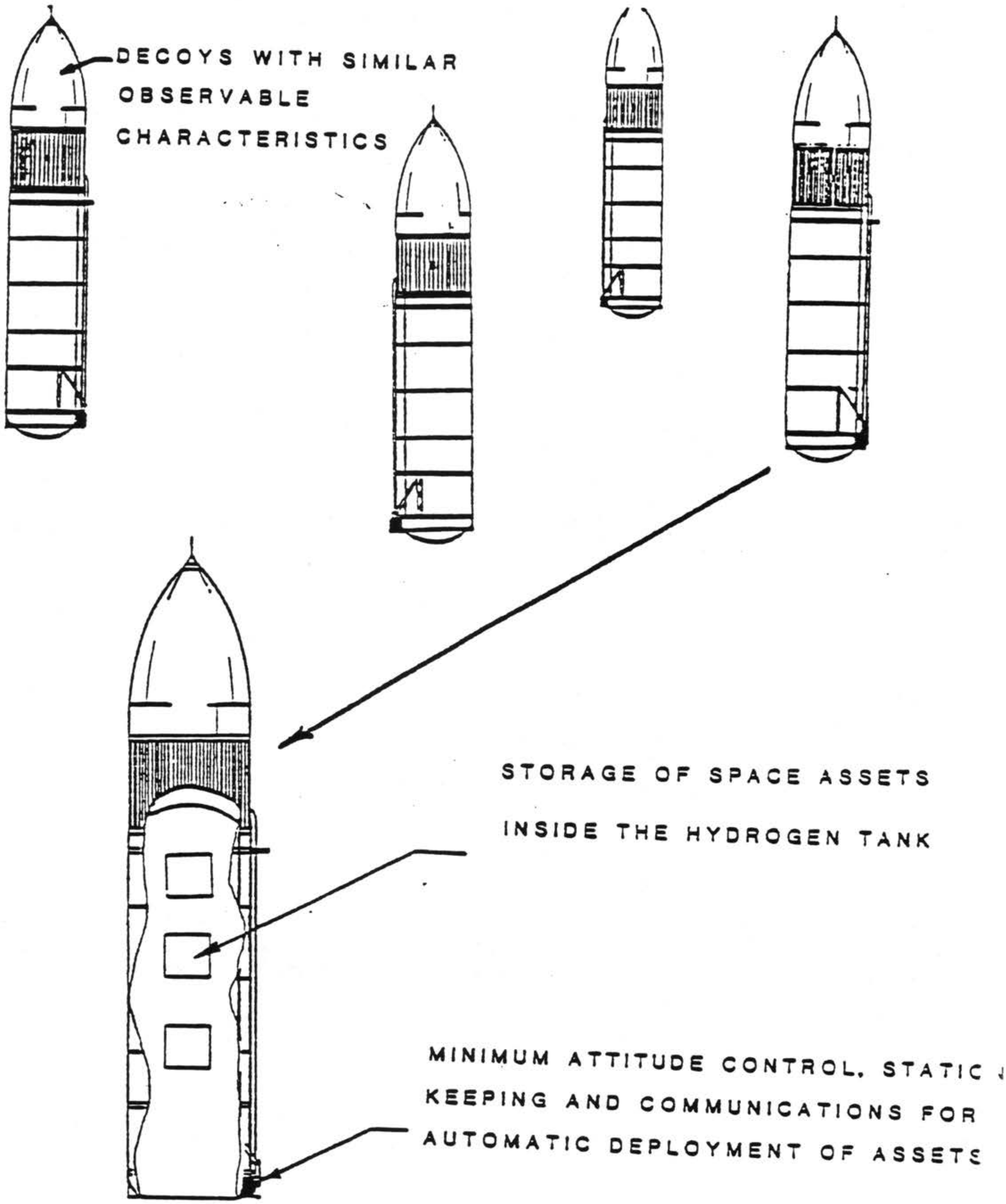
<u>DOD PAYLOAD FOR ACC</u>

MAIN ANTENNA RADAR~11,000 LB
MAIN ANTENNA COMM ~ 7,000 LB
SCALE 1" = 10' (=120")

DOD GENERIC PAYLOAD



PROSPECTIVE PAYLOAD VEHICLE



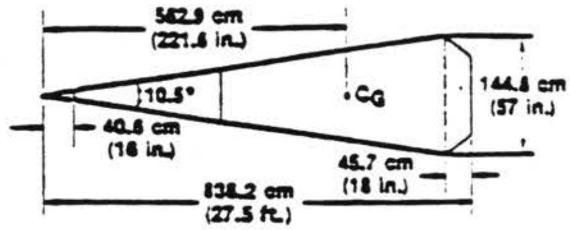
STORAGE FOR SPACE ASSETS IN THE ET

military applications. Like any other space based activity, the use of the ET is available for both civilian and military uses. Both activities will likely take place in the near future.

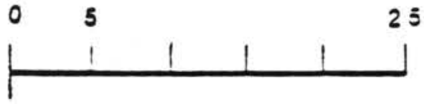
A. Military Space Station

Several advantages exist in the use of the ET as a military space station. The primary advantages being large size, easy expandability, and low cost. The same capabilities mentioned in previous sections of low cost commercial space stations apply equally well to military stations. These stations can serve as separate bases from which DOD satellites can be launched, retrieved, repaired, or deactivated. The previously mentioned possible on-orbit storage of spares also allows a military operator to quickly replace a satellite that has stopped functioning for whatever reason. This response time advantage will be a military advantage in future conflicts. The possible use of the ET as a hangar or a battle station allows concealment and suprise in the use of military assets on orbit. The ACC also provides a space for the launching of large diameter mirrors which could be used as space based high energy weapons (25, 56). These would also take advantage of the ease of launching an ACC payload and therefore be more responsive to future needs.

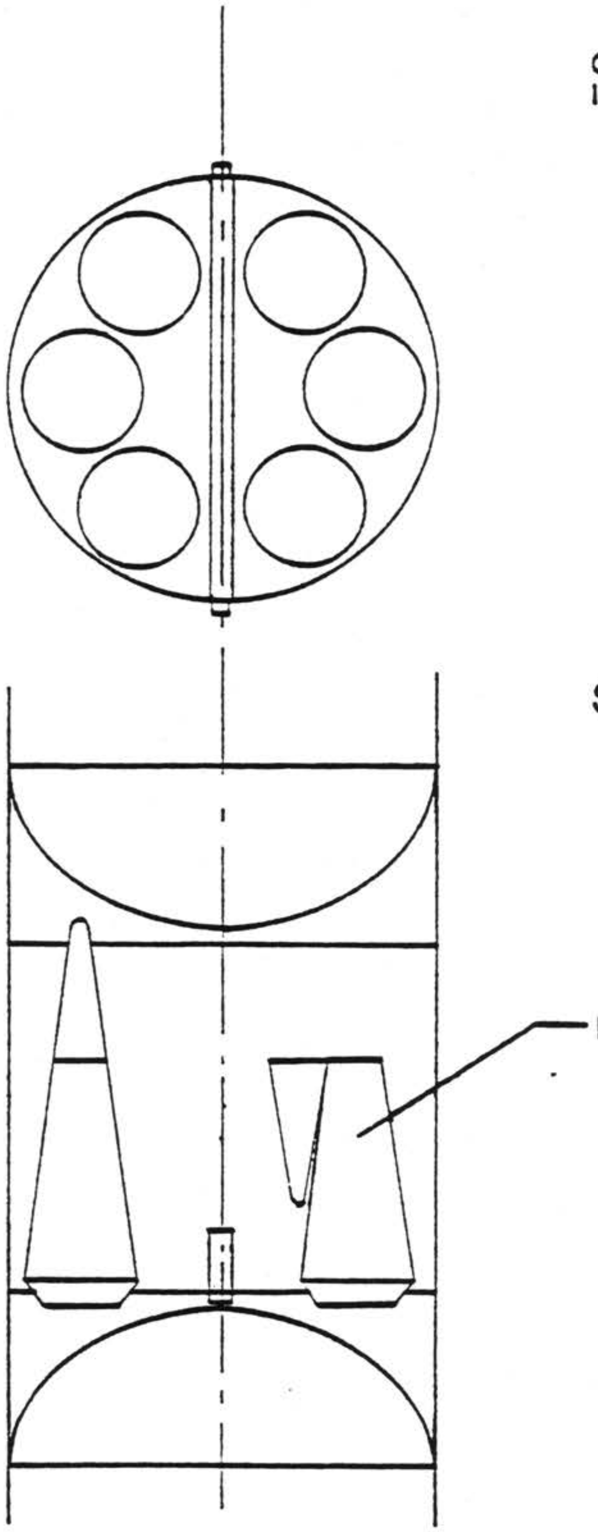
There are other possible military uses for a ET based space station. The first one is a space-borne equivalent of the Coast Guard. The search and rescue aspects of the coast guard mission are well known and similar type role can be filled by a military station. An important consideration may be based on international military activities. The Soviet Union and the United States are involved in the SARSAT program which includes five active spacecraft so far. There is no reason why this could not be extended to manned military (or civilian) systems as well. The second concerns on-orbit inspection and deactivation of other satellites. There has been a proposed spaceplane that can serve this mission (25). The spaceplane could be based out of an ET adapted station. It makes far more sense to do this with a small manned spacecraft than it does with an orbiter. Another use of a manned station could be the military conduct of orbital surveillance, photography, communications, and new systems experimentation and development. For example, the military roles and missions currently practiced on the Salyut can be practiced on a ET based military station.



Overall length — 792.5 cm (26 ft.)
Included cone angle — 10.5 deg



SCALE



SPACEPLANE STOWAGE

B. Miscellaneous

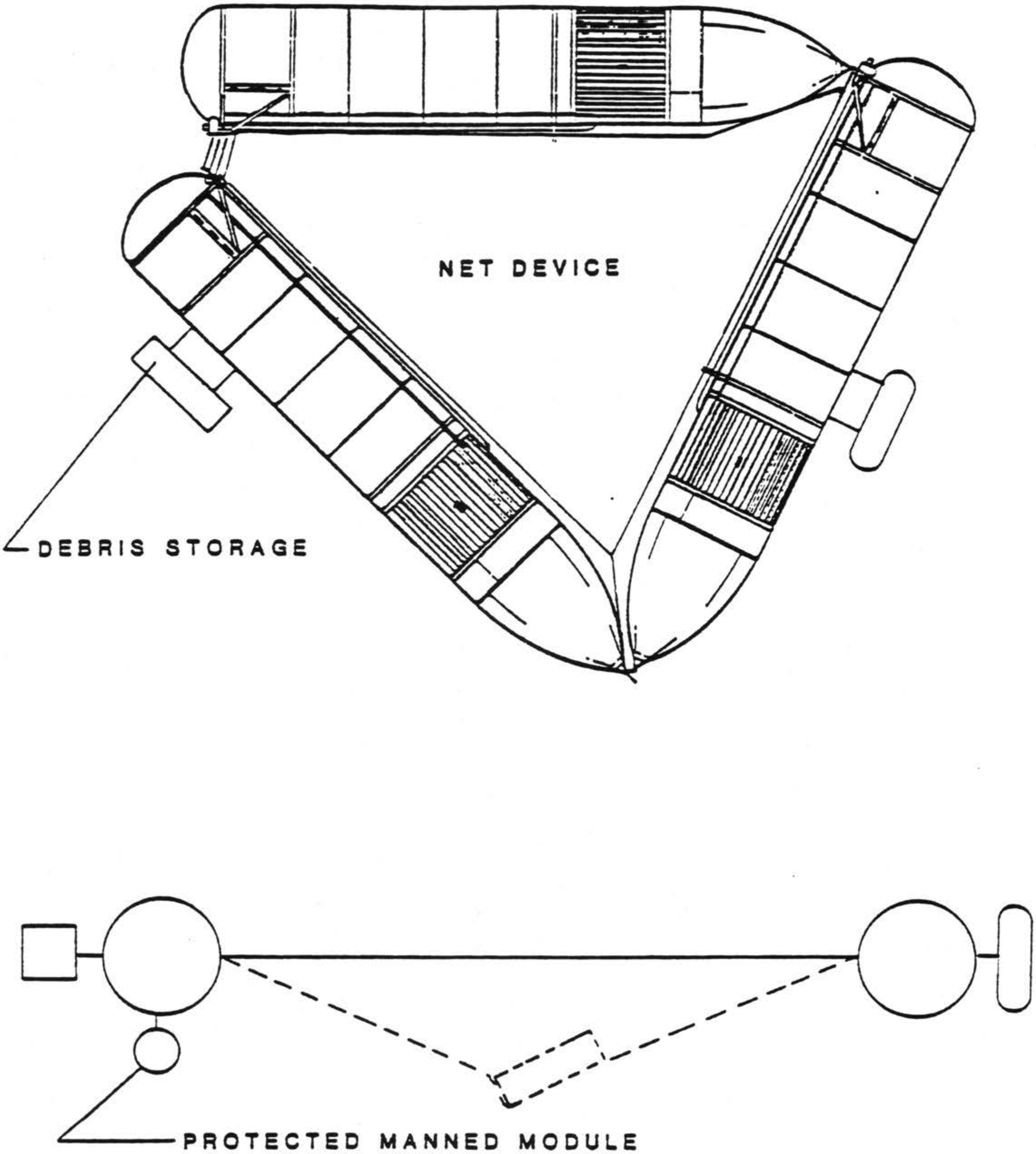
The ET could also be used for a number of additional orbital tests, missions, and roles (25). For example, a number of identically configured empty tanks could serve as orbital decoys. A tank could be used as a 'Junk ASAT'. The ET could be manuvered into the flightpath of a target satellite and destroy it on impact. The tank could be melted and foamed on-orbit. This metallic foam could serve as a blast and impact shield. The ET can also be used as a target for SDI R&D experiments or demonstrations. The idea here is to deorbit the ET and shoot it on the way down. The tank is large enough to take more damage than conventional satellites and thus may be an advantage to the military use of space. The real advantage in using the ET as the basis of a military space station is that it keeps military activities seperate from the civilian activities. This is politically a very important advantage.

IV. Orbital Cleanup

An ET based OTV could clean out each individual orbit of space junk and debris over a period of time (25). This could be done by two methods. The first one would use a soft rendezvous with a minimal Delta-V and could use tethers or a very precise rendezvous to clear the required altitudes of debris. The retrieval would be slow and controlled and likely very fuel intensive. The second could be somewhat larger and more massive and be used as a hard target with the appropriate use of foamed metals, netting, or nested cylinders and capture the debris by impact. This is an idea worth consideration that has not had anything more than very preliminary work done on it.

V. Future Resource

The ET is also a potential resource for a wide variety of presently unknown, wildly speculative, and unanticipated applications. As has been demonstrated by a number of other space based activities in the past, the present discussions of ET and ET/ACC applications will likely serve as a starting point and nothing more. There have been several less than mundane or 'far out' proposals for the ET that may be of great importance in the near or not so near future. One proposal is to use the STS or an STS derived vehicle to eliminate nuclear waste by launching it from the surface and storing it in



LOW ORBIT DEBRIS CATCHER

deep space or sending it out of the solar system. The author then suggests using the jettisoned tanks as a starting structural base for setting up large industrial operations in orbit (43). Another author proposes deorbiting the tanks and selling the remaining aluminium at the going rates for scrap aluminium (39). A third author proposes using tanks as landing vehicles for large cargos to be deposited on the moon (or possibly Mars). The cargo is carried in one of the tanks and the landing (or controlled crash) is conducted in such a way that the impact and crushing of the tank absorbs the excess energy in landing and thus cuts the energy requirements necessary for a soft landing of cargo.

The point in this discussion is this. The ET presents an enormous possibility in the expansion of operations into space. The ET is an item that is very flexible to a broad range of user applications (25). It is simply capable of an enormous range of possible uses, most likely yet to be concieved. We do not yet know what is the best way to use the tank. What we do know is that the more investigators look at the tank and tank applications, the more possible applications are proposed.

Two important decisions need to be made quickly. The first decision that needs to be made is the early insertion and on orbit storage of the ET. The second decision concerns ownership and identification of possible markets for the tank. We are in the position at this time to start planning for the future of this nation in space. If this resource is inserted into orbit and made available for sale to interested parties either before or after launch, the possibilities for the future of this nation in space are far greater for far less money.

As has been discussed in the previous pages, the External Tank is a very large, very inexpensive enhancement of the American space effort. For almost no additional cost, the STS can deliver an ET complete with residual cryogenics to a space station orbit. This 69,000 pound object could become a multi-billion dollar investment in the future of our space program. Typical figures for aluminium mass alone a yield net worth over $20 billion after 250 launches. This does not include the previously discussed economic advantages of cryogenics scavenging, aluminium fueled rockets, ACC additional volume, and the resulting elimination of the volume limit for STS launches.

With the external tank, we have the potential for achieving an extremely high return if the tanks are taken to orbit today and stored for later use. This is something that can be used to leverage the growth, national preeminence in space utilization, jobs, and tax revenues. It is also an enabling technology that will enhance the safety in potentially dangerous research in genetics, pharmaceuticals, and industrial chemicals by stationing the 'lab' in orbit. The existence of large inexpensive space platforms opens the field for space based research on more risky and less well known subjects. This widens the possible avenues of both commercial and governmental research and allows additional approaches to be made with the corresponding potential increase in new discoveries.

The space station can be enhanced by flying literally a fleet of additional stations in close proximity. The multiple stations could include DOD, Corporate, and Foreign platforms both manned and unmanned. The actual enhancements of the station itself include elbow room, storm shelters, experimental volumes, fuels scavenging and storage, to name just a few. The addition of the ET or the ET/ACC to the space station will be a welcome answer to those critics of the space program that want low costs and high returns on investments.

As with any other suggestion that paints a very rosy picture, the use of the ET does have its problems. These include the lack of a current market for a large number of tanks, the maintenance of the tanks in an orbit high enough not to decay to an uncontrolled reentry, and the problems of SOFI outgassing. The information used by the author in this report indicates that none of these problems are insoluble. Indeed, the most difficult question to answer is the one concerning the present or future market for the ET. It has been demonstrated that there are myriad uses of the ET in almost every area of space endeavor. All that remains is the decision to use the tank or to allow it to be used.

Recommendations for the use of the ET are:

1. Quickly fly the ET and store it in a permanent storage facility in relatively high earth orbit.

2. Arrive at a pricing policy that covers the cost orbital storage and maintenance of the tank. Sales should be based only on average storage costs. If a tank is purchased for orbital use, the purchase cost and agreement can be determined prior to launch. The only stipulation should be that the buyer be able to physically do something with the ET in a specified period of time.

3. Design and offer the ACC as an enhancement of the STS itself. The ACC is initially thought of as a secondary cargo carrier. This need not be the case if the ACC payload is the primary payload for that flight.

The External Tank is simply too flexible and valuable a resource to continue throwing away in the upper atmosphere. We as a nation are fortunate that such a great opportunity for program advancement exists at so little cost. The use of the ET is well within our current capabilities and would be a welcome addition to the future of the United States in space. We recommend that the tank be flown early and often.

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