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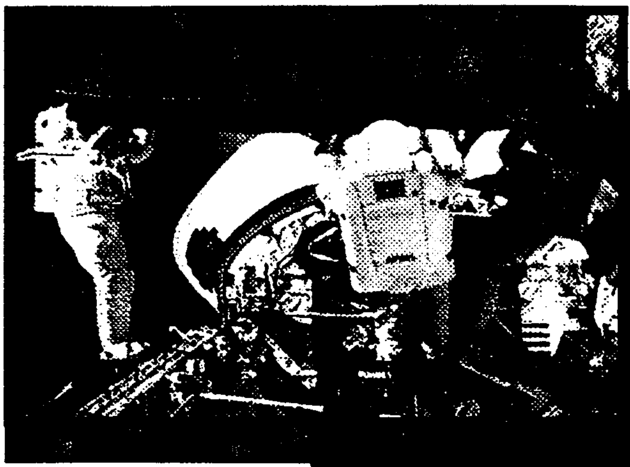
REPORT OF THE GROUP TASK FORCE ON



SATELLITE RESCUE AND REPAIR

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ON SATELLITE RESCUE AND REPAIR
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A Task Force of the
NASA Advisory Council

REPORT
OF THE
GROUP TASK FORCE
ON
SATELLITE RESCUE AND REPAIR

Washington, DC
29 September 1992

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1.0 PROLOGUE

The Group Task Force on Satellite Rescue and Repair was formed as a task force of the National Aeronautics and Space Administration (NASA) Advisory Council to review policies, pricing, and implementation for undertaking unanticipated satellite rescue and repair missions utilizing the Space Shuttle. In the course of this review, the Group became concerned about the execution and public perception of such missions. This Prologue discusses these concerns.

Rescue missions of any kind, whether on land, at sea, or in space, have many common characteristics. One of the most important of these characteristics is uncertainty. The necessity for rescue implies all is not well. It follows that in planning the rescue, a number of contingency actions must be kept in mind. Even in more common rescue attempts on land or at sea, the initial approach does not always succeed. The more extreme the situation, the more likely that several attempts at rescue will be needed before final success is achieved or final failure admitted.

With respect to the use of the Space Shuttle for unanticipated satellite rescue and repair missions, it is clear that the satellite involved must not only be in an orbit reachable by the Shuttle, but that the orbit must be stable for an extended period. On past attempts, the time required has ranged from four to 30 months. This specific time interval is mission-dependent and is determined by the duration of the planning, engineering, and training cycle required to verify safety and increase the likelihood of success as much as is practical. A virtue of this external cycle is that this "experience" enhances the possibility that the "*ad hoc*" activities usually required in successful missions can be evolved as needed. Historically, such "*ad hoc*" activities are needed to complete rescue and repair missions successfully.

Thus the success of satellite rescue and repair missions must be based on the final outcome. Anticipation of success must be tempered by the real possibility of failure; the failure of a particular attempt is just that. To offer judgement prior to either successful completion or admitted failure of the entire mission suggests a naive and an unrealistic point of view. The Group Task Force on Satellite Rescue and Repair came to fully appreciate this subtlety only after it studied the issue. We feel strongly that if nothing else comes from this study but recognition of this definition of mission success or failure, then an important contribution has been made by calling this definition to the world at large.

2.0 INTRODUCTION

The Group Task Force was chartered by the Administrator of NASA to recommend "a policy outlining the criteria, the design standards and the pricing model to guide NASA in assessing the responsibilities for government and nongovernment Satellite Rescue and Repair Missions." Criteria for accepting such missions, risks and benefits to all sectors of our economy involved in satellite services, adequacy of planning and training, and the impact on NASA's primary missions were reviewed.

The Group began by asking a more fundamental question; is satellite rescue and repair a logical element of NASA's mission? Factors considered were:

- The probability of rescue or repair opportunities arising
- The economic justification for such attempts
- The benefits to NASA, both from such *ad hoc* learning experiences in space operations and the impact on the public perception of NASA
- The effect of such unanticipated missions on NASA's scheduled activities
- Any potential effect on NASA's technical capability to work in space
- Any potential effect on U.S. economic competitiveness

2.1 Background

After the decision to develop the Space Shuttle was made in the early 1970s, national space policy evolved to take advantage of the initial Shuttle projected launch rate capability of up to 60 missions per year, and a low cost of less than $20 million per launch. A high payload traffic model was projected and, to assure maximum use of the Shuttle, the Administration mandated that virtually all U.S. satellites -- NASA, Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA) and commercial -- be launched by the Shuttle. The family of Expendable Launch Vehicles (ELVs) -- Atlas, Delta, and Titan -- was to be phased out.

NASA envisioned that extra vehicular operations in space would become routine. Selected NASA satellites (e.g., the Hubble Space Telescope (HST)) were designed to be serviced on-orbit for both scheduled and unanticipated maintenance. Rescuing satellites appeared a logical mission for the Shuttle.

But reality did not follow policy. Projected launch rates were not realized - 12 missions per year is the current Shuttle launch capability. The early traffic model also proved to be optimistic - 10 to 20 satellite launches per year is a more realistic projection of requirements for the foreseeable future. Shuttle costs have proven to be significantly higher than anticipated by the original costing model. At the same time, foreign ELVs (Ariane, Long March, etc.) have become more competitive with U.S. ELVs.

In terms of policy, the range of missions considered for flight on Shuttle was significantly impacted by the fundamental evaluation of National Space Policy which occurred following the Challenger accident. The policy which emerged from that process limited the Shuttle to missions which require human presence, other unique Shuttle capabilities, or which require Shuttle use for national security, foreign policy, or other compelling reasons. Unless they meet these criteria, no DoD or commercial payloads are flown on the Shuttle. This shift led to the reemphasis on U.S. ELVs to launch these satellites.

Four rescue/repair missions have been conducted to date. Three of the five satellites involved in these missions were launched by the Shuttle (one mission rescued two satellites). The most recent satellite to be rescued, an Intelsat VI, was launched on a Titan. It was later maneuvered into a Shuttle-compatible orbit using propellant available aboard the satellite. Four of the five rescues required real-time replanning due to difficulties encountered during the rescue operation. All five satellites were ultimately rescued.

By the end of this decade, the needs of Space Station *Freedom* will take priority on the Shuttle manifest, essentially dominating the schedule. The prioritization of satellite rescue and repair must be addressed within this new environment.

2.2 Present Trends

Today, commercial and DoD satellites are launched on ELVs, either domestic or foreign. This fact calls attention to certain technical issues that define the limits of a satellite rescue by a manned Shuttle mission. These issues are:

1. The Low Earth Orbit (LEO) parking orbits achieved by satellites launched on ELVs must be compatible with Shuttle orbits or the satellites must be maneuverable into a Shuttle orbit.

2. The launch failure must occur at insertion from LEO to the desired orbit or, if after insertion, the spacecraft must have enough expendable on-board propellant to achieve a Shuttle- compatible orbit.

3. Unmanned spacecraft are not required to be man-rated unless launched from the Shuttle. Safety interlocks, hand holds, and maintainability features appear to be an unacceptable overhead for unmanned payloads.

As a result, the demand and opportunity for satellite rescue and repair is anticipated to be quite limited. We estimate only one percent of the total satellites to be launched will become candidates for rescue and repair.

Scientific payloads have also reflected a shift in policy. After a decade of "bigger is better," the trend is toward a larger number of smaller satellites. These smaller satellites are designed to require no on-orbit maintenance. Experience has shown that a spacecraft designed for on-orbit maintenance is roughly 20 percent more expensive to develop and the cost of maintaining a logistic capability for the life of the satellite becomes significant. Some scientists believe that for this emerging class of payloads, the probability that adequate data can be collected over the life of a scientific satellite is high enough to accept the risk of a maintenance-free life. In addition, launching on ELVs can provide greater schedule flexibility while the elimination of a maintenance requirement offers a broader range of possible orbits.

Nevertheless, the Shuttle should continue to support those science payloads, such as the HST, designed to be serviced to prolong life, enable mission enhancement, or recover space experiments for detailed study on earth.

2.3 Other Considerations

If the full cost of a Shuttle mission were charged for a rescue, the economic benefit to either the manufacturer, the owner, or the insurer would be greatly diminished. It should also be noted that, to date, the availability of satellite rescue has had virtually no effect on the satellite or insurance industries which have balanced risk of failure against insurance cost.

As noted above, the Shuttle manifest will become dominated by Space Station *Freedom*. Any required rescue missions would need to be inserted into the manifest, involve additional crew training, and, potentially, displace planned payloads. In addition, rescue mission experience illustrates a continuing problem in ground-based simulations and analysis of on-orbit activities.

The case has been made that the lessons learned from the rescue missions have significantly contributed to our understanding of how to operate in space. Properly documented and communicated, these lessons can be valuable resources. Future satellite rescue and repair missions will add incrementally to this body of knowledge. NASA must also take full advantage of the lessons learned to date. Nevertheless, displacing well-planned extravehicular activity (EVA) experiments by *ad hoc* EVA activities associated with the satellite rescue or repair will usually result in a net loss in understanding operations in space.

A final consideration is the effect on the public perception of NASA and, therefore, national support for its mission. In the case of the previous five rescues, the pre-mission publicity that defined "success" committed NASA, and the Shuttle crew, to capture the satellite and either repair it or return it to Earth. As mentioned above, four of the rescues encountered significant obstacles. Although the ultimate success of each of these missions did provide a short-term boost to NASA's public image, the negative publicity which would have resulted from an unsuccessful rescue attempt must not be discounted. Had the Intelsat VI rescue not succeeded despite repeated attempts, NASA would certainly have been subjected to considerable criticism. A concerted effort should be made to educate the public to both the difficulties involved in conducting such a mission and the knowledge that can be gained even if the rescue and repair operation is not completed.

3.0 EVOLUTION OF SHUTTLE USE

In July of 1969 the Apollo Space Program successfully achieved its goal of landing men on the Moon and returning them safely to Earth. America was looking toward its future in space. In the same year, Vice President Spiro Agnew appointed a Space Task Group to define a post-Apollo Space Program for the United States. The committee issued the following recommendation: "The next logical step for us to take in space will be to create permanent space stations in Earth and lunar orbits with low-cost access by reusable chemical and nuclear rocket transportation systems in assembling our capacity to explore the planet Mars with men thereby initiating man's permanent occupancy of outer space."

At the time, budget constraints prevented the United States from pursuing the proposed plan: concurrent development of the Shuttle, a space station, and human planetary exploration. However, a reusable space transportation system which could meet all of NASA's launch requirements as well as those of the DoD, commercial and possibly international customers at a reduced cost (due to the reusability of the system) would make economic sense in light of the perceived high cost of expendable launch systems. In addition, the 12 different types of expendable launchers available at that time made the idea of one reusable system to meet all needs attractive. NASA contracted with Mathematica[1] to assess the cost effectiveness of such a reusable space transportation system. The report stated that the principal objectives of the Space Shuttle system were:

1. A new capability of meeting all foreseeable space missions in NASA, DoD and elsewhere, including manned space flight capabilities.

2. Reduction of space program costs (manned, unmanned, NASA, DoD, commercial users) over the present expendable space transportation costs through reuse, refurbishment, maintenance, and updating of payloads.

3. Reduction of space transportation costs for all missions (low energy, high energy, manned)

4. Option of later transition to a fully reusable system.

5. A low non-recurring cost to meet funding constraints.

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[1] *Economic Analysis of the Space Shuttle System*, Mathematica, Inc., NASW-2081, January 1972

6. Assurance of a low cost per launch of below $10 million and if possible $5 million -- justifiable when payload costs and effects are considered.

It should be noted that a reusable space tug was considered to be part of the program as a system for delivering payloads to and from a Shuttle-achievable orbit.

Projected high development costs forced NASA to abandon initial design concepts which featured fully reusable vehicles. The decision was made to dispose of the giant external fuel tank with each mission -- this is the Shuttle configuration flying today.

In April 1981 the Shuttle *Columbia* flew the Space Shuttle Program's maiden flight. Prior to the *Challenger* accident in January 1986, the Shuttle flew 24 successful missions. These missions exercised the broad range of Shuttle capabilities, including the deployment of commercial communications satellites and the rescue and repair of both scientific and communications satellites. In this period, NASA vigorously pursued the national policy of replacing ELV launches with the Shuttle.

It was decided to replace the *Challenger* vehicle and to maintain a fleet of four Shuttles. Henceforth the Shuttle would only fly missions requiring human presence, unique capabilities of the Shuttle, or to meet national security and foreign policy goals. Post-*Challenger* reviews drove numerous changes to procedures for preparing Shuttles for flight and for determining flight readiness. These new procedures, coupled with existing launch preparation facilities, the Shuttle fleet size, and routine planned maintenance led to a steady state launch capacity of no more than twelve missions per year. Subsequent budget decisions have reduced the planned launch rate to between six and eight per year.

As these policy changes were evolving and being implemented, significant changes occurred in the scientific community concerning the design of satellites for compatibility with different launch vehicles. Due to the decline in the number of Shuttle launch opportunities, it was now more difficult to manifest a payload on the Shuttle. This caused a shift away from satellite designs which require launch on the Shuttle. In addition, technological advances in satellite miniaturization led to a gradual decline in size and weight of satellites. Missions which may have required Shuttle launches in the past are now designed to fly on smaller, less expensive ELVs.

The strategy of building a single, very large platform to carry out complex missions is being gradually replaced by a strategy to use smaller, less expensive platforms which can be launched on ELVs. With less expensive satellites, modern sensors and data handling equipment, and lower launch costs, it has become more cost effective to build a satellite without the redundancy required to assure long life. Thus, a replacement satellite can be launched to continue the mission if needed rather than repairing an orbiting satellite using the Shuttle.

The Shuttle will remain a critical part of America's space program for many years to come. It will be the only means for the United States to place humans in orbit at least through the year 2005. As such, it will continue to be an integral part of NASA's program. By the year 1996, a preponderance of Shuttle missions will be devoted to construction and maintenance of Space Station *Freedom*. The missions required by Space Station *Freedom* could impact the opportunities for unanticipated missions, such as rescue and repair of deployed payloads.

4.0 SURVEY OF SATELLITE RESCUE/REPAIR OPPORTUNITIES

Several factors must be considered in evaluating opportunities for Shuttle-based satellite rescue and repair:

- The projected launch rate for satellites over the coming years determines the pool of candidates for rescue.
- The satellite's orbital inclination must be one attainable by the Shuttle.
- The vehicle or satellite system failure, which created the need for on-orbit rescue, must have occurred while the satellite was in low Earth orbit at an altitude within the capabilities of the Shuttle.
- The satellite itself must not violate NASA Shuttle safety requirements.
- The satellite cannot be damaged to the point where repair or rescue costs preclude any attempts.

These factors act to severely constrain the potential need for satellite rescue and repair missions in the future.

Most government and private sector near-term estimates of the U.S. and international commercial launch markets indicate an average of 15-20 satellites available for launch annually through the year 1996, tapering off to approximately 10-15 spacecraft annually thereafter. These estimates take into consideration current technological trends toward larger, more powerful geosynchronous spacecraft and longer on-orbit service life, as well as improvements in terrestrial communications such as fiber optics. However, future technological developments could significantly impact these estimates.

Today, four NASA scientific satellites could be repaired on-orbit: the HST, the Compton Gamma Ray Observatory, the Extreme Ultraviolet Explorer, and the Upper Atmosphere Research Satellite. Periodic servicing missions are already planned for the HST, but no servicing missions are planned for the other three spacecraft. Any known HST repairs are planned to be accomplished during its servicing missions and were not addressed by the Group Task Force.

Commercial communications satellites are most often launched into inclinations nearly due east of the launch site. This approach allows the maximum payload to be placed into a geosynchronous transfer orbit. The inclinations for scientific payload launches are largely determined by mission requirements. To become a candidate for rescue or repair, these satellites must have been launched into transfer or operational orbits with inclinations compatible with the possible Shuttle orbits or capable of being moved to such orbits. From the Kennedy Space Center (KSC), the Shuttle is capable of attaining orbital inclinations from 28.5° to 57.0°.

In identifying candidate missions for rescue and repair, the possible inclinations for satellite launches and the most likely inclination selected from this range must both be examined. Table 4.1 shows that this range of inclinations is compatible with portions of the ranges for most launches of vehicles in use today. The exceptions are launches into high inclination polar orbits. Excluding these polar orbits, the Shuttle is capable of reaching the most frequently selected inclinations for all vehicles except the Titan III and the Ariane. This is particularly significant as over 60 percent of all commercial satellites are currently launched aboard Ariane boosters.

There are three basic types of failures which prevent a satellite from accomplishing its mission. First, there are launch vehicle failures which prevent the satellite from reaching the proper transfer orbit. Second are insertion failures where the satellite reaches transfer orbit but fails to reach its operational orbit (geosynchronous orbit for virtually all communications satellites). Third are on-orbit failures where the satellite reaches its operational orbit, but fails to function or fails soon afterward.

The operational orbits of communications satellites are far beyond the capability of the Shuttle. A small group of scientific satellites remain candidates after an on-orbit failure because their operational orbits are within the Shuttle's inclination and altitude limitations or they can be moved to proper orbits.

Two additional technical factors must be considered. The recent trend away from Perigee Kick Motors (PKMs) to satellites with integral liquid propulsion systems could reduce the number of failures which occur in Shuttle compatible orbits. The second factor is the transition of many satellite requirements away from satellites using spin stabilization for attitude control to satellites using a 3-axis control system. "Spinners" can maintain thermal equilibrium in low-Earth orbit while receiving the critical power necessary to survive until a rescue/repair mission can be mounted. Satellites using 3-axis control present greater difficulties. The satellite must either have a built-in safe hold mode which consumes little or no power, or the solar arrays must be deployed prematurely to maintain satellite health.

A summary of launch vehicle and spacecraft failures from 1970 to 1992 is shown in Table 4.2. The 42 total failures represent approximately 10 percent of the 406 launches which occurred during this 22-year period. While the 10 insertion failures represent approximately 24 percent of the 42 failures, they represent only 2.5 percent of the total launches. This number is reduced to approximately one percent if the satellites launched aboard Ariane to its primary inclination are excluded.

Candidates for rescue must also meet the standard safety policies and requirements for payloads using the Shuttle. These requirements identify potential hazards and establish requirements for their control. These requirements must be satisfied before a rescue mission will be accepted for further consideration.

TABLE 4.1 -- LAUNCH AZIMUTHS AND ORBITAL INCLINATIONS
SELECTED U.S. AND INTERNATIONAL EXPENDABLE LAUNCH VEHICLES

Vehicle	Launch Site	Launch Azimuth	Orbital Inclination (Most Frequent)
Shuttle	KSC	44°-110°	28.5°-57.0° (28.5°)
Delta	Cape Canaveral Air Force Station (CCAFS)	57°-112°	28.7°-51.0° (28.7°)
	Vandenberg Air Force Base (VAFB)	185°-270°	70.0°-100.0° (99.0°)
Atlas/ Centaur	CCAFS	90°-108°	17.0°-44.0° (25.0°)
Titan III	CCAFS	93°-108°	N/A (26.5°)
Titan IV	CCAFS	93°-108°	N/A (28.4°)
	VAFB	147°-210°	N/A (approx. 90°-99°)
Ariane	Kourou, French Guiana	0°-108°	5.2°-100.5° (7.0°)
H-2	Tanegashima, Japan	85°-135°	31°-???
Proton	Baikonur, Belorus	N/A	51°-72° (51.6°)

TABLE 4.2 -- HISTORY OF LAUNCH/SATELLITE FAILURES 1970-1992

Type of Failure:

1: Launch failure - vehicle failed during ascent phase and/or spacecraft failed to reach proper transfer orbit
2: Insertion failure - spacecraft reached transfer orbit but failed to reach proper geosynchronous Earth orbit - (GEO)
3: On-orbit failure - spacecraft reached GEO but did not become operational or failed soon thereafter

LAUNCH DATE	SATELLITE NAME	LAUNCH VEHICLE	TYPE OF FAIL.	COULD BE RESCUED BY SHUTTLE	DESCRIPTION OF FAILURE
1970					
07/23	Intelsat III F8	Delta	2	No	Apogee Kick Motor (AKM) failure
08/19	Skynet 1B	Delta	2	No	AKM failure
11/06	IMEWS 2	Titan 3c	2	No	Premature transtage shutdown
11/30	OAO B	Atlas/Centaur	1	Yes	Centaur failure
1971					
05/08	Mariner-H	Atlas/Centaur	1	Yes	Centaur failure
10/21	ITOS B	Delta	1	Yes	2nd stage malfunction
1972					
1973					
07/16	ITOS E	Delta	1	Yes	2nd stage malfunction
1974					
01/19	Skynet 2A	Delta	1	Yes	2nd stage malfunction

LAUNCH DATE	SATELLITE NAME	LAUNCH VEHICLE	TYPE OF FAIL.	COULD BE RESCUED BY SHUTTLE	DESCRIPTION OF FAILURE
02/11	Viking/Sphinx	Titan 3E	1	No	Centaur ignition failure
1975					
02/20	Intelsat IV F6	Atlas/Centaur	1	Yes	1st stage malfunction
05/20	DSCS 5/6	Titan 3C	1	Yes	Booster malfunction left spacecraft (S/C) in too-low orbit
1976					
1977					
04/20	GEOS 1	Delta	1	No	3rd stage spin-up malfunction placed S/C in subnormal transfer orbit
09/13	OTS 1	Delta	1	No	1st stage explosion
09/29	Intelsat IVA F5	Atlas/Centaur	1	No	1st stage malfunction
1978					
03/25	DSCS 9/10	Titan 3C	1	No	Centaur failure; destroyed by Range Safety
1979					
12/07	RCA Satcom 3	Delta	2	No	AKM malfunction

LAUNCH DATE	SATELLITE NAME	LAUNCH VEHICLE	TYPE OF FAIL.	COULD BE RESCUED BY SHUTTLE	DESCRIPTION OF FAILURE
		1980			
04/14	Solar Max	Delta	3	Yes	Malfunctioned on orbit (repaired by STS-41C on 04/09/84)
05/23	Oscar 9	Ariane 1	1	No	Booster failure
08/06	FLTSATCOM 5	Atlas/Centaur	3	No	S/C achieved GEO but not operational status
		1981			
		1982			
04/10	Insat 1A	Delta	3	No	S/C achieved GEO but not operational status
09/10	Marecs-B/Sirio-2	Ariane 1	1	No	Booster failure
		1983			
04/04	TDRS-A	Shuttle	2	No	Inertial Upper Stage failure (but S/C got to GEO using thrusters)
		1984			
02/03	Westar 6	Shuttle	2	Yes	Perigee Kick Motor (PKM) failure (retrieved by STS-51A)

LAUNCH DATE	SATELLITE NAME	LAUNCH VEHICLE	TYPE OF FAIL.	COULD BE RESCUED BY SHUTTLE	DESCRIPTION OF FAILURE
02/03	Palapa B-2	Shuttle	2	Yes	PKM failure (retrieved by STS-51A)
06/09	Intelsat V F9	Atlas/Centaur	1	Yes	Centaur early shutdown left S/C in low orbit
		1985			
04/12	Leasat 3	Shuttle	2	Yes	PKM failure (later repaired by STS-51I)
08/27	Leasat 4	Shuttle	3	No	Failed on-orbit 09/06/85
08/28	KH-11 7	Titan 34D	1	Yes	Premature 1st stage shutdown
09/12	Spacenet F3/ECS-3	Ariane 3	1	No	Booster failure
		1986			
01/28	TDRS-B	Shuttle	1	No	Catastrophic explosion
04/18	Big Bird	Titan 34D	1	No	1st stage explosion
05/03	GOES-G	Delta	1	No	Premature 1st stage shutdown
05/31	Intelsat V F14	Ariane 2	1	No	No 3rd stage ignition
		1987			
03/26	FLTSATCOM 6	Atlas/Centaur	1	No	Triggered lightning; destroyed by Range Safety

LAUNCH DATE	SATELLITE NAME	LAUNCH VEHICLE	TYPE OF FAIL.	COULD BE RESCUED BY SHUTTLE	DESCRIPTION OF FAILURE
11/21	TVSat-1	Ariane 1	3	No	S/C solar panels failed to deploy
		1988			
09/02	VORTEX	Titan 34D	2	Yes	Transtage failed to ignite for 2nd burn
		1989			
08/09	Hipparcos	Ariane 44LP	2	No	AKM failure left S/C in transfer orbit (partial scientific return)
06/05	Superbird A	Ariane 44LP	3	No	Thruster stuck open in 12/90; dumped all S/C GEO station-keeping fuel
		1990			
02/22	Superbird B/BS-2X	Ariane 44L	1	No	1st stage explosion
03/14	Intelsat VI F3	Titan 3	1	Yes	Wiring error left S/C in sub-transfer orbit (later retrieved and reboosted by STS-49)

LAUNCH DATE	SATELLITE NAME	LAUNCH VEHICLE	TYPE OF FAIL.	COULD BE RESCUED BY SHUTTLE	DESCRIPTION OF FAILURE
08/28	BS-3A	H-1	3	No	Solar panels damaged in deployment; insufficient power to operate fully 6 months out of the year
		1991			
04/18	BS-3H	Atlas/Centaur	1	No	Centaur ignition failure

Summary of Failures

1 (Launch)	**25**
2 (Insertion)	**10**
3 (On-orbit)	**7**
Total	**42**

Candidates for Rescue

15 Eight of these failures occurred prior to the first Shuttle launch in April 1981; one of the eight was the Solar Max satellite which was repaired in 1984. Please note that the determination of which satellites could be rescued by the Shuttle is based on the best estimates of the Group Task Force.

Rescues Accomplished

5

5.0 ECONOMICS OF SATELLITE RESCUE MISSIONS

5.1 Introduction

Public policy with respect to satellite rescue missions cannot be adopted without consideration of the costs and benefits associated with such missions. Several categories of costs must be considered:

- Capital costs
- Avoidable costs
- Opportunity costs
- Mission-specific costs
- Social costs

These costs are defined in Appendix 5.A

5.2 Cost Allocation

In many cost categories, the matter of the allocation of joint or common costs can be critical. While there are accounting guidelines for the allocation of common costs, there is often more art in it than science. This is especially true for activities which are not continuous and have a substantial fixed cost component associated with them. The Shuttle meets these criteria and thus the allocation of costs becomes one more of policy than of accounting. Nevertheless, the proper proportion of joint or common costs should be included in any calculation of costs associated with a rescue.

Table 5.1 summarizes the categories of cost relevant to satellite rescue attempts; it also indicates the locus of the impact of such costs. These costs can spread across a broad spectrum of parties, underscoring the widespread interest in everything related to the Shuttle and the space program. It also explains why space-related decisions are, inevitably, political decisions.

5.3 Benefits

The benefits of a satellite rescue can accrue to the public (including NASA) or to private parties (e.g., the satellite-owners or insurers). It is said, for example, that the recent Intelsat VI rescue mission provided NASA with insights and experience that are proving especially valuable in the context of the space station program. This is particularly noteworthy because reliable simulations of conditions in space have been elusive. Successful satellite rescues foster popular and political support for its Shuttle program. Successful satellite rescues mean that space satellites are being saved, together with at least part of their anticipated value. Anything that avoids or ameliorates the financial loss encourages future investment in space endeavors.

Table 5.1 Satellite Rescue Mission Costs and Allocation

	NASA	Other U.S. Govt	U.S. Public	U.S. Industries or Firms	Non-U.S. Industries or Firms
Overall Capital Costs or Investment (Sunk Costs)	X	X			
Mission-Specific Investments				X*	X*
Avoidable Costs				X*	X*
Mission-Specific Costs				X*	X*
Social Costs			X		

*Depends on Satellite Ownership

5.4 Costs Relevant to Shuttle Rescue Missions

The avoidable cost related to an entire Shuttle mission represents the appropriate base from which to cost (although not necessarily to price) Shuttle rescue missions. The use of avoidable cost eliminates from consideration many sunk costs, including those related to Shuttle and launch systems development, investment made in the total Shuttle fleet and in the entire range of launch and recovery facilities.

To the extent that other activities carried out during the same launch and recovery sequence can appropriately bear some of the total launch costs, the gross avoidable cost borne by NASA should be reduced. For non-U.S. Government customers any reduction must be calculated conservatively.

If there is doubt about the avoidability of any cost element or how to allocate genuinely common costs, it is the satellite rescue that should bear the brunt, given the rescues being contemplated by the Group Task Force and given the relatively modest benefits accruing to the U.S. government and the U.S. public as a result of such rescues. Every element of costs that would be avoided if the rescue attempt were not undertaken at all should be added to the overall mission cost.

Rescue attempts clearly add to the risk associated with any Shuttle launch and recovery. Not only is the risk increased, but the costing of such risk is a difficult proposition.

Table 5.2 summarizes the discussion as to the elements of cost that need to be considered before committing to rescues together with suggestions as to how to allocate those cost elements.

Table 5.2 Cost Elements Appropriate for Pricing Satellite Rescue Missions

Elements	Proportion of Cost Allocable to the Rescue Mission
Full, Long-Run Avoidable Costs of Shuttle Launch and Recovery	That proportion not reasonably allocable to other activities of the overall Shuttle mission
Rescue-Specific Avoidable Cost	100%
Opportunity Cost Associated with Displaced Activity	100%
Incremental Risk-Associated Cost	100%

5.5 Pricing Satellite Rescues

It should be recognized at the outset that there is no "automatic" reason why satellite rescue attempts should be priced strictly on the basis of the cost incurred in carrying them out. Cost is bedrock; it is not necessarily the only basis for establishing a price for a rescue. NASA should determine the value of the attempt to a customer and to society as closely as it can prior to taking any positive action with respect to such a prospective attempt, including pricing it.

Satellite rescue pricing policy should be broad enough to accommodate U.S. Government agencies and commercial enterprises as well as international governments and commercial clients. A pricing policy option that should be considered would involve the sharing of risks between the various customers and

NASA. U.S. Government agencies would pay marginal Shuttle costs for rescue missions. The commercial and international customers would pay the marginal costs and all other mission direct cost up front and then upon success of the mission the customer would then pay a negotiated portion of revenues until the full cost was paid. This type of pricing policy would provide flexibility to the Administrator and also enable the customer to make sound business decisions based on known factors.

6.0 MISSION PLANNING AND TRAINING

The planning and training phase for a human mission has evolved from the Mercury, Gemini, and Apollo programs and the earlier Shuttle missions to the present. The duration of this planning period was significantly extended following the *Challenger* accident although the accident was unrelated to the planning and processing requirements. Currently, NASA has a program to reduce the planning and processing period while maintaining the safety and integrity of the current processing.

Planning is typically initiated with the signing of a formal customer contract 32 months before launch. The first major milestone is the development of the Payload Integration Plan (PIP) and its annexes, which define the payload and Space Shuttle roles and responsibilities, the integration tasks and schedules, and annexes with specific technical details. This baseline PIP milestone is currently scheduled 22 months before launch. This is followed by the Interface Control Document (ICD) baseline which, for a standard mission, is scheduled 21 months before launch. These two requirements are established early in the schedule to provide adequate time to develop the required technical details, including the physical, electrical, trajectory design, command, training, and extra vehicular activities. Each Shuttle mission requires the complete reprogramming of the ascent trajectories due to the variations in orbital inclination, orbital altitude, and payload constraints. The PIP annexes, which are produced through working group meetings between the customer and NASA, are scheduled to be completed between 18 and six months prior to flight. The six-month date is critical since the flight crew as well as the launch and mission control teams require this period to complete training for the mission, including malfunctions, contingencies, and aborts.

Training of an EVA mission specialist covers a similar time period; however, this type of training is much more mission-specific. Alternate back-up procedures are developed for each EVA operation. In addition, during the flight, the ground facilities at Johnson Space Center (JSC) are prepared to test any modified or new procedures that are required by situations that develop in real time. These facilities include the Weightless Environment Training Facility (WETF) and the five degree of freedom simulator, each of which can simulate most, but not all, of the zero-g space operations.

The piloting functions for the Space Shuttle are thoroughly simulated and developed in several facilities. They are rehearsed in the months prior to launch with the teams at the KSC and JSC, plus in very precise spacecraft simulators at JSC. These simulate real flight circumstances very accurately, and draw on decades of experience in simulation from civil and military aircraft as well as on prior space programs such as Gemini and Apollo. Major investments have been made to make the powered flight simulations as realistic as possible, including many types of anomalous behavior. The same degree of fidelity, however, has not been achieved for EVA simulations. One reason is the impossibility of simulating zero-g for more than about 30 seconds coupled with the infrequency of EVAs.

However, several of the Earth-based facilities can simulate certain aspects of space extra vehicular activities. WETF activities allow the astronauts to train in a free floating mode, but the density and viscosity of water creates different responses to movement and utilization of equipment. Therefore, another facility is used in which the astronaut is suspended in air and free-floating satellites are supported on air bearings to simulate five of the six degrees of freedom. However, it is difficult to simulate both the mass and the mass moment of inertia about all three axes. In addition, the air bearing support system for the satellite is not friction free, which will invalidate some of the training.

Since none of the facilities can duplicate the zero-g space conditions completely, NASA has had to break up the training for some operations into short sequences that are tested at different facilities. As each of these facilities afford training in part of the overall task, they are called "part task trainers". There is no end-to-end high fidelity simulation with mission control, EVA astronauts, and pilot astronauts rehearsing the planned and emergency procedures as there is for flight portions of the missions.

Due to the complexity of the mission planning and training, rescue missions require more than a year to plan and conduct. This was the case for the Intelsat VI rescue mission which was initiated in March of 1990 and completed in May 1992. The PIP baseline data was not finalized until 17 months before launch and the ICD baseline was established 14 months before launch, both seven months later than standard. The late definition of the interfaces resulted in extensive overtime to meet the schedule launch date. There was no evidence that this led to any reduction in the training for the mission.

Training for the Intelsat VI capture operation was conducted in the air bearing facility rather than the WETF because it provided a better simulation of the dynamics of capture. The satellite mock-up was mounted on the air bearing floor with the combined mass and the mass moments of inertia about two axes equal to those of the satellite, but the mass moment of inertia about the third axis was much greater than the actual satellite. The dynamics of the Shuttle orbiter and the pilot astronaut were not included in this simulation. This test set up was used to develop and validate the capture bar design and the capture procedures. Post flight analysis of the test identified a five pound break out friction in the air bearing simulator. The five pound breakout friction was sufficient to prevent the satellite from drifting away during ground training with the capture bar. In space, the small forces created by trying to put the capture bar in place resulted in accelerations of the satellite of a few hundredths of a foot per second per second and thus caused the satellite to drift away from the astronaut in both capture attempts. In orbit, even five pounds of force acting on a large satellite for a few seconds can impart linear and angular velocities large enough to make use of the capture bar difficult or impossible.

The EVA astronauts practiced extensively in the WETF facility at JSC. However, the principal benefit of these tests is to physically condition the astronauts in a neutral buoyancy facility. The muscles used under neutral buoyancy are essentially the same as those used in space, but because of the water resistance, the effort is much greater. Initially, the water resists movements of both the satellite and the astronaut and can provide assistance to the astronaut in positioning himself. This phenomena is called virtual or apparent mass which can be determined because "the kinetic energy of the solid plus the kinetic energy of the fluid exceeds the kinetic energy of the solid by a well defined amount."[2]

The only anomalies that occurred during the Intelsat VI rescue mission EVAs were in the satellite capture phase. Once the satellite was captured and secured in the payload bay all EVA activities proceeded as planned. A second anomaly occurred in the release of the satellite from the payload bay by an astronaut inside the Shuttle cabin. The problems encountered in capturing the Intelsat VI satellite arose, in our opinion, from the inability to adequately simulate the dynamics in the facilities used to train for EVA. None of the these training facilities are capable of a realistic simulation of space operations. Another issue was the failure to make a dynamic analysis of the process. Adequate training facilities or dynamic analyses would have uncovered the deficiencies in the capture technique that was used.

It also appeared that EVA experiences from earlier missions had not been adequately considered in the design of the Intelsat VI capture technique. These experiences have, however, produced a better understanding of space simulation facilities, as well as the problems encountered during space operations, especially when astronauts and satellite are not both firmly attached to the same structure. Furthermore, even if more representative facilities are not developed, the phenomena, once understood, can most likely be avoided by different design approaches to the capture. In the case of the Intelsat VI rescue mission, the capture options were severely limited by the satellite designer's concern that only the thrust ring at its base could be used to capture and attach it to the Shuttle. When that approach was not successful, three

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[2] See Appendix 6.A.

astronauts were allowed to grasp the satellite at three points and "muscle" it into the payload bay.

NASA's ability to perform satellite on-orbit rescue and repair could be significantly enhanced through the development of improved standard tools, procedures and training programs. One approach involves the attachment of a special plate to the orbiting satellite which would be attracted to a magnetic device mounted on the end of the manipulator arm. Another approach involves the development of a routine training program for astronauts in rendezvous techniques, remote manipulator system operations, and EVA operations who would be available to plan and undertake rescue and repair missions.

The Group Task Force would like to point out that some important lessons were learned from this mission that could be important in developing Space Station *Freedom,* but would note that the rescue mission took time that was planned for more orderly experimentation designed to support space station development. Ground simulations of EVA must account for the fact that even very small forces can cause relative movements in space; thus simulations must be of extreme dynamic fidelity for two bodies drifting independently in space.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. The opportunities for performing unanticipated satellite rescue or repair in the future are likely to be rare.

2. The actual time required to prepare for a satellite rescue or repair attempt is mission dependent and, in the past, has varied from approximately four months to 2.5 years.

3. Previous experience suggests it is difficult to establish a routine approach to accomplishing these satellite rescue and repair missions.

4. The operational uncertainties associated with unanticipated satellite rescue and repair missions are such that it is unreasonable to expect that every rescue attempt will succeed on the first attempt, or at all.

5. Previous satellite rescue missions have contributed to the overall knowledge of extravehicular activities and the associated mission operations. However, this experience is mission-specific, not easily generalized, and is being lost as experienced people leave NASA.

6. Satellite rescue mission training requirements exceed the existing capability to conduct integrated training (mission specialist and Shuttle commander combined) and are limited by the lack of high fidelity simulations and by a lack of training facilities for each sub-element of the overall activity.

7. Representatives of the insurance industry indicate that the small number of rescue missions, both in the past and forecast, has virtually no impact on the cost of satellite insurance.

8. NASA's past public statements have not adequately communicated the difficulty of satellite rescue missions, the missions' contributions to accomplishing the overall NASA mission, or that failure to accomplish specific mission goals does not necessarily equate to mission failure.

9. NASA's pricing has not recovered the full cost of satellite rescue missions.

10. The Intelsat VI rescue mission lacked an overall mission manager

11. The ability to conduct unanticipated satellite rescue and repair missions is a valuable and unique national asset. As a unique national asset, the national command authority may decide an unanticipated satellite rescue and repair mission is necessary to meet a national or foreign policy objective.

7.2 Recommendations

Policy

1. The unique ability to accomplish satellite rescue and repair should not be forfeited.

2. Satellite rescue and repair missions should comply with one or more of the following criteria:
   a. the satellite requiring rescue or repair is a NASA or NASA cooperative mission.
   b. the mission is required to meet national security objectives.
   c. the mission is required to meet foreign policy objectives.
   d. the mission enables NASA to accomplish U.S. and/or NASA objectives in a manner which benefits the United States and/or NASA.

3. Only those unanticipated satellite rescue and repair missions that produce genuine benefits to U.S. interests should be considered in view of the inherent risks to the Shuttle and its crew. These risks include those faced in the rescue process as well as the intrinsic risk associated with a Shuttle flight.

4. The authority to employ this capability should rest solely with the NASA Administrator.

Pricing

1. NASA should determine the full cost of Space Shuttle missions in so far as possible.

2. NASA should charge for unanticipated satellite rescue missions as follows:

   a. For non-NASA U.S. Government missions, customers should pay marginal costs

   b. For reimbursable missions (i.e., commercial and international), customers should pay marginal costs and all other direct mission costs up-front. If the mission is successful, the customer would then pay a negotiated portion of revenues until the full cost of the rescue is paid. The price should not include Shuttle replacement, NASA facilities costs, or facility amortization costs.

   c. If the rescue provides significant benefit to NASA or the U.S. Government, consideration should be given to sharing costs with the customer.

Implementation

1. NASA should continue to ensure that safety requirements are met for all satellite rescue and repair missions.
2. Mission managers should be assigned upon acceptance of a mission. The mission manager should be responsible for all aspects of pre-flight mission execution.
3. Mission integrated training is essential for all aspects of Shuttle training.
4. NASA should adequately communicate the inherent complexity of rescue missions to the public.
5. NASA should commit to the maximum use of individuals with previous experience (both internal and external to NASA) and past lessons learned to help ensure mission safety and success.
6. NASA should upgrade its EVA capability, including the use of state-of-the-art EVA tools and training methods.

APPENDICES

APPENDIX A
GROUP TASK FORCE MEMBERS

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Lt. Gen. Thomas P. Stafford, USAF (Ret.), Co-Chairman

Dr. Joseph P. Allen

Gerald D. Burns

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Doyle McDonald

Norman Ryker

Prof. Joseph Shea

Maj. Paul M. Stipe, USAF

Dr. Jerry Waylan

Dr. Albert D. Wheelon

Capt. John Young, USN (Ret.)

APPENDIX 5.A
DEFINITION OF COST CATEGORIES

Capital Costs

The capital costs associated with a rescue grow out of investments which have been made, often long before the need for the specific rescue arose. Capital costs directly and uniquely related to the rescue must clearly be booked against that rescue. For example, in the recent Intelsat VI rescue, the capture bars uniquely designed to deal with Intelsat VI seem to have been fully costed and charged to Intelsat, as was entirely proper.

Avoidable Costs

Costs incurred by NASA which would have been avoided but for a rescue attempt should be assessed against that attempt. For example, if additional EVA time to that which was planned when the launch was manifested is required solely because of the rescue, the full cost of that incremental EVA time must be a charge to the rescue effort.

Opportunity Costs

In some instances it appears that another cost of a rescue is that related to the opportunities foregone on the overall mission, precisely as a result of substituting the rescue for other work. The value (opportunity cost) of the foregone efforts should properly be charged against the rescue; such costs can be extremely high, depending entirely on the nature of what is foregone to accommodate the rescue. Opportunity costs seem not to have been a consideration heretofore when NASA has priced satellite rescue.

Rescue-Specific Costs

All rescue-specific costs should be booked against the rescue. Such costs fall into two categories: those which clearly could have been avoided but for the rescue attempt, and that portion of total Shuttle launch and recovery costs which is directly attributable to incorporation of the rescue attempt in the total objectives of the overall mission. An example of rescue-specific costs would be those incurred in providing astronauts with training which was required only because of the rescue to be undertaken.

Social Costs

The social costs of the rescue attempt, apart from opportunity costs associated with opportunities not pursued precisely because of the rescue, are very difficult to identify prior to the attempt. If the rescue fails, however, there are social costs associated with the bad light in which the space program, NASA and the United States are cast. Such costs are borne by society because of the risk inherent in any rescue attempt. They are difficult, if not impossible to quantify.

APPENDIX 6.A

COMMENTS ON THE USE OF NEUTRAL BUOYANCY CHAMBERS TO SIMULATE ORBITAL PHENOMENA

Comments on the Use of Neutral Buoyancy Chambers to Simulate Orbital Phenomena

Introduction

The use of neutral buoyancy chambers to simulate on orbit extra-vehicular-activities (EVA) has been a subject of some discussion. All parties seem to agree that it is possible for a balance of forces to exist. In this case the object is suspended and looks like a free floating object as observed in orbit. The discussion is related to the dynamics of the situation and seems to have been centered about the influence of fluid mechanical drag on the simulation. This is a matter that is resolvable through analysis, though some ambiguity may possibly exist in terms of the appropriate representation of the drag coefficient as a function of Reynolds number. This effect will be discussed in more detail below.

An additional dynamical consideration does not seem to have been discussed at all. This point relates to the mass and inertial properties of an object suspended in a neutral buoyancy chamber. Simulation of these properties is more subtle as will be shown now.

Mass Properties

For the purpose of this discussion we will consider only the initial motion of a solid from rest. The solid is immersed in an infinite mass of stationary fluid that is incompressible. We will consider only the initial motion of the fluid following an impulsive start to the body. By restricting ourselves to the initial motion we can assume that the motion of the fluid is derivable from a velocity potential. This can be shown from consideration of the fluid following the impulsive motion of the solid body[1-4], and the results given by Schlicting[5] which show the separation point(s) on cylinders form only after the body has moved a third or so of its radius. Thus for a short time following the impulsive start of a solid body immersed in a viscous fluid, the velocity distribution is approximated well by potential flow. At short times then the kinetic energy of the fluid can be calculated by integration the product of the perturbation velocity potential and its derivative normal to the solid's surface over that surface. The result is that the kinetic energy of the solid plus the kinetic energy of the fluid exceeds the kinetic energy of the solid by a well defined amount. This amount is the product of the density of the fluid, the volume of the body, and a numerical factor. The product is called the apparent mass. The numerical factor is thus determined from the additional kinetic energy. This factor is dependent upon the shape of the solid, and ranges in value from one for flow normal to an infinitely long circular cylinder, to zero for flow along the long axis of the cylinder. The factor is 0.5 for a sphere. The values of this factor are listed in Table 1 below for axially symmetric shapes. In Table 1 the factor k_1 applies for motion along the long axis of a slender cylinder and k_2 applies to the cross flow. The factor k^1 corresponds to the factor applied to the moment of inertial when the body is rotated about an axis that is normal to its long axis. Note the inertial factor is identically zero when the solid is rotating about its long axis. The apparent mass for a disk moving normal to itself is the product of the fluid density, the volume of a sphere whose radius equals the radius of the disk, and the number 0.63 (actually two divided by *pi*). Clearly the flow around sharp corners adds greatly to the apparent mass.

Table 1
Inertia Factors of Ellipsoids of Revolution for Axial Motion, Lateral Motion and Rotation.

a/b	k_1	k_2	k^1	a/b	k_1	k_2	k^1
1.00	0.500	0.500	0.000	6.01	0.045	0.918	0.764
1.50	0.305	0.621	0.094	6.97	0.036	0.933	0.805
2.00	0.209	0.702	0.240	8.01	0.029	0.945	0.840
2.51	0.156	0.763	0.367	9.02	0.024	0.954	0.865
2.99	0.122	0.803	0.465	9.97	0.021	0.960	0.883
3.99	0.082	0.860	0.608	∞	0.000	1.000	1.000
4.99	0.059	0.895	0.701				

To proceed further it is useful to show values of several mass parameters of satellites that have been retrieved during Space Shuttle missions. These properties are shown in Table 2.

Table 2
Satellite Mass and Volume Properties

Satellite	Weight pounds	Volume cu.ft.	Density slugs/cu.ft.	Specific Gravity	Reciprocal
Intelsat	08961	1607.2	0.173	0.089	11.24
Syncom	15316	2129.5	0.220	0.113	08.85
Westar	07307	0360.3	0.630	0.324	03.09
Palapa	07670	0353.0	0.675	0.675	02.87
Solar Max	04956	0363.3	0.420	0.216	04.63

The question from these results is clear. Is it possible to design a geometrically similar model of the solid body to simulate orbital dynamics in the neutral buoyancy chamber? The sum of the solid's mass and its apparent mass will exceed the mass encountered during the EVA. The mass of the satellite under neutral buoyancy ranges from 2.87 to 11.24 times its actual mass. If the mass factor is taken to be 0.5 then the total mass of the satellite model in the neutral buoyancy chamber ranges from 3.3 to 16.86 times the real mass of the satellite. The same kind of factor will be found for the moments of inertia. Thus one must work much harder in the neutral buoyancy chamber to both accelerate and decelerate the solid body than one would in an EVA if drag were not a factor. (This observation about the differences between the on orbit and the neutral buoyancy chamber was reported to members of the Group Task Force on Satellite Rescue and Repair by Astronaut David Leestma at Johnson Space Center on 6 July 1992)

The only way in which the mass plus the apparent mass can simulate reality is for the satellite to be much denser than the fluid in the neutral buoyancy chamber. One should note that the perception of the error will be less as the piece is smaller. Thus a one pound piece that would react as if it is 1.5 pounds presents virtually no problem. The same can not be said of a satellite that is six feet in diameter, and six feet long whose density is, say, one-third of water.

Effects of Fluid Mechanical Drag

To return to the issue of the effects of fluid mechanical drag. The kinetic energy possessed by the solid after it moves a distance x from its initial position in response to a constant force, F, is

$$KE=\frac{Fm}{\rho SC_D}(1-e^{-\frac{\rho SC_D}{m}x})$$

Note the mass, m, is the total, or actual plus the apparent mass of the solid. The density, ρ, is the density of the fluid in the neutral buoyancy chamber. It is easy to show that in the limit as the drag coefficient, assumed constant here, approaches zero the kinetic energy is just equal to the work done, i.e., Fx. The error in kinetic energy due to drag is just

$$\epsilon(\chi)=\sum_{n=1}^{\infty}(\frac{\rho SC_D}{m}x)^n\frac{(-1)^{n+1}}{(n+1)!}$$

so

$$\frac{\Delta KE}{KE}=\epsilon$$

It is easy to show that when the error is small, the fractional velocity error is

$$\frac{\partial V}{V}=\sqrt{\epsilon}$$

The position error due to drag is more difficult to calculate since it involves an apparently unexplored transcendental function,

$$\int_{o}^{\xi} \frac{\theta\xi}{\sqrt{1-e^{-\xi}}}$$

In this case

$$\xi = \frac{\rho S C_D x}{m}$$

If we take a two term approximation to the integrand, i.e., x is small, we find an approximate solution

$$\xi \approx 1 - \cos\left(\frac{\sqrt{F\rho S C_D}}{m} t\right)$$

This approximate solution is important for two reasons. First the proper non-dimensional time comes out naturally, and second the distance is measured in a scale determined by the loss in velocity due to drag. What actually happens is easy to describe. When the force is the same, at a given time the effect of drag is to cause the body to move a shorter distance than it would if the drag were zero. The fractional distance that is lost can be computed from a series expansion, namely

$$\frac{\Delta x}{x} = \frac{F\rho S C_D}{m^2} \frac{t^2}{3\cdot 4}\left(1 - \frac{F\rho S C_D}{m^2} \frac{t^2}{5\cdot 6} + ..\right)$$

This result is very interesting, for it shows that in a neutral buoyancy chamber, the effects of drag are partially balanced by the square of the (increased) mass of the satellite. Consequently, if one is simulating the properties of a low density satellite in a neutral buoyancy chamber, the trajectories could be surprisingly accurate due to the combination of the drag and the apparent mass for a timely interval near the start of the motion. However, the drag causes the body to slow more quickly than in orbit.

Summary

The dynamic scaling of solid bodies in a neutral buoyancy chamber to simulate the same object during EVA in orbit is only possible when the body has a density somewhat greater than the fluid in the neutral buoyancy chamber. The effects of apparent mass do in fact mitigate the loss in accuracy due to fluid mechanical drag. However, the amount of work done in accelerating, decelerating or moving an object in a neutral buoyancy chamber is excessive in comparison to that done in orbit while drag acts to slow a coasting body in water much work quickly than in air. Except for the physical conditioning achieved by full time task simulation, the technique developed in a neutral buoyancy chamber that are to be applied in on orbit activities may prove to be unreliable.

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