INTRODUCTION

This paper summarizes worked conducted by OCST to analyze the effects and public risk sensitivities to destruct or flight termination actions taken on ballistic reentry vehicles (See Source Materials). Flight termination systems have been used to effectively limit vehicle deviations during powered flight regimes but are not commonly employed for risk control with un-powered reentering vehicles. This memorandum provides an overview of the capabilities, limitations and effectiveness of using destruct systems to control or minimize public risks from such reentry vehicles.

Using certain example assumptions, Section 1 of this paper provides a parametric risk analysis of the effect of various parameters on casualty expectancy.

Section 2 analyzes examines risks as a result of factors associated with a specific landing-site. The analysis identifies and discusses those factors or interrelationships that would affect a decision to destroy a reentry vehicle known to be endangering a populated area. The research will concentrate on factors affecting public risks, differences in associated public risks, information and support systems necessary to make a decision to destroy, and other risks associated with incorporating destruct systems on reentry vehicles.

SECTION 1: PARAMETRIC RISK ANALYSIS

This analysis is based on a number of assumptions and conditions specified by OCST. The basic parameters used were:

1. The vehicle reenters from altitudes of 100 to 300 nautical miles.

2. The trajectory for an orbital vehicle is such that impact occurs 90 degrees in longitude from de-orbit boost.

3. The vehicle is defined as a sphere of 48 inches, weighing 1000 pounds.

4. The vehicle is on an anomalous flight path and is exposing a populated area having a uniform population density of 10 persons per square mile.

5. No control of the vehicle is possible until after reentry and the vehicle has no lift and only drag and gravity forces act upon the vehicle.

These parameters result in a vehicle that reenters with a ballistic coefficient of approximately 133 pounds per square foot and a terminal impact velocity condition of approximately 334 feet per second (approximately 228 MPH).

The probable average number of casualties, called casualty expectancy (Ec), is determined using the following equation:

Ec = Probability of Impact (P_i x Lethal Fragment Area, LA) x Population Density (P_D)

Since the reentry vehicle will impact with a probability of unity and the population density is given as 10 persons per square mile, the primary effect on public risk will be determined by the lethal area of the reentering vehicle.

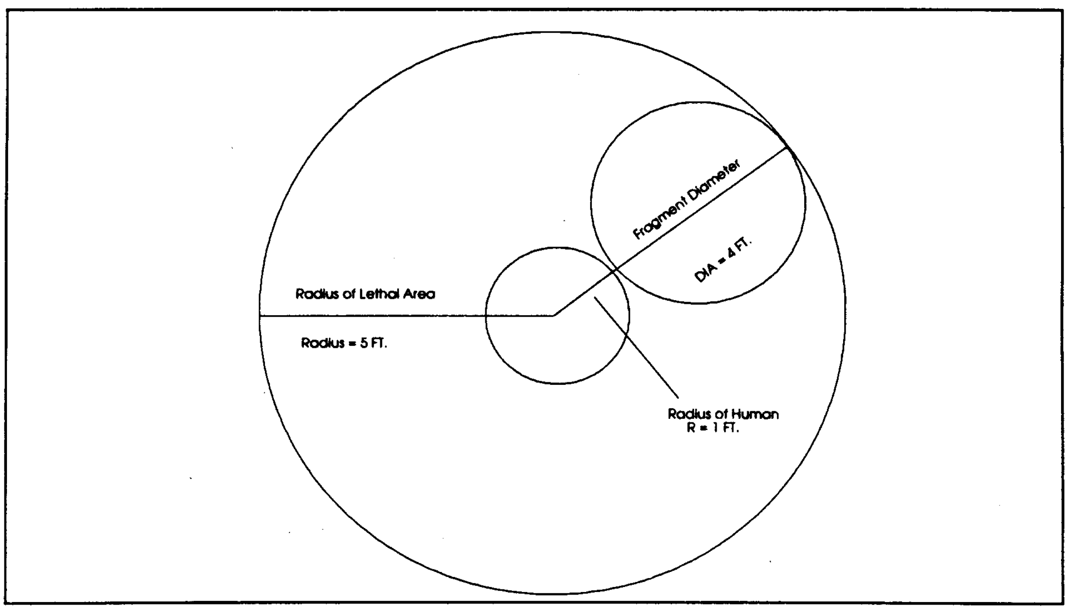
Shown in Figure 1 is a graphical illustration depicting the method used for determining the lethal area of a single fragment. A human has a radius of approximately 1 foot and for this case the reentry vehicle has a diameter of 4 feet. This produces a radius for the lethal area of 5 feet and an area of 78.5 square feet. The casualty expectancy for the intact vehicle is then:

$Ec = P_I \times LA \times P_D$

$Ec = 1 \times 78.5 \times 10/(5280)^2$

$Ec = 2.8 \times 10^{-5}$

FIGURE 1: LETHAL AREA



The destruct of a reentry vehicle would generate multiple fragments. The public risk sensitivity to such destruct action is directly proportional to the total lethal area produced by these fragments. Shown in Table 1 below is the lethal areas produced by destructing the reentry vehicle into various numbers of fragments and the corresponding casualty expectancy.

TABLE 1. PUBLIC RISK VERSUS NUMBER OF FRAGMENTS

NUMBER OF FRAGMENTS	FRAGMENT DIAMETER (Ft.)	LETHAL AREA (Sq. Ft.)	CASUALTY EXPECTANCY
1	4	78.5	2.8×10^{-5}
2	4	157	5.6×10^{-5}
5	3.58	330	1.2×10^{-4}
10	2.53	392	1.4×10^{-4}
15	2.07	444	1.6×10^{-4}
20	1.8	493	1.8×10^{-4}
25	1.6	531	1.9×10^{-4}
30	1.46	570	2.0×10^{-4}

Shown in Figure 2 is a plot of the casualty expectancy versus the number and size fragments determined in Table 1 above. This figure indicates the rapid rise in casualty expectancy as the number of fragments are initially increased and then a leveling effect as the fragment size decrease offsets the increasing number of fragments.

The effects of other parameters specified for examination for their effect on public risk were:

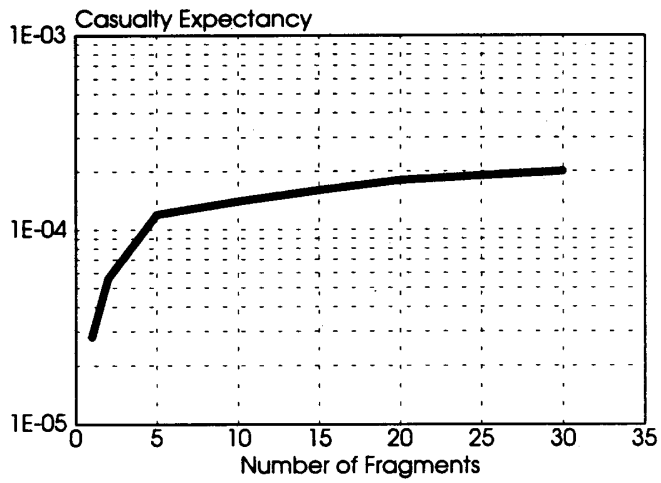
1. Destruct Altitude from 20,000 to 500,000 feet.

The altitude of destruct will not change the public risk levels so long as the impact region has a uniform population density. The impact location of the fragments will vary with destruct altitude, change in ballistic coefficient and due to the effect of winds on the falling fragments.

2. Fraction of fragments surviving reentry from 10% to 100%.

The casualty expectancy is directly proportional to the number of fragments surviving reentry. For example if 30 fragments are generated and only 10% survive, the casualty expectancy would be reduced by 10% from 2.0×10^{-4} to 2.0×10^{-5}. Such destruct action would have to be initiated prior to the vehicles entry into dense atmosphere at attitudes above 300,000 feet.

FIGURE 2: CASUALTY EXPECTANCY



3. Imparted velocity from destruct action.

There would be no direct effect on casualty expectancy from the velocities imparted to the fragments as long as the impact area had a uniform population density and they survived reentry. The main effect of imparted velocity will be to increase the size of the area being exposed. If destruct occurs before reentry and imparted velocities are large, the fragments can be spread over areas of hundreds of miles. Destruct action taken at lower altitudes after reentry will tend to limit the impact area size due to the drag effects.

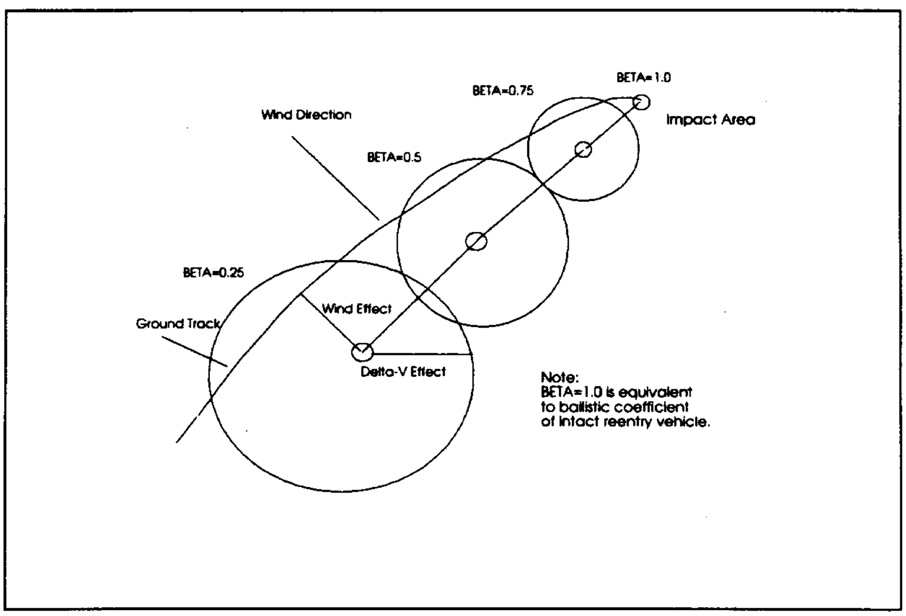
4. Ballistic coefficient of reentering fragments.

As with imparted velocity, the ballistic coefficient of the reentering fragments will have a more significant impact on the location of the impact area's but may have little effect on public risk. Destruct action on any vehicle tends to produce fragments with ballistic coefficients lower than that of the original vehicle. The effect of this is a decrease in impact range depending on the altitude of destruct. One effect on public risk that does occur as the ballistic coefficients become small is a decrease in the potential severity of the fragment impacts and their potential for penetrating structures.

The analysis above was conducted for persons in the open, however if various sheltering is considered, casualty expectancies will decrease proportional to the penetration energy of the fragments. These effects have not been evaluated in this study, however, they can significantly effect public risks if cities are exposed or areas where uniform density assumptions are invalid.

The typical envelope for fragments of various ballistic coefficient ratios (Beta) and for typical imparted velocities are shown in Figure 3. In general, destruct action shortens the impact range of the various fragments because their ballistic coefficient is less than the original vehicle. Shown in Figure 3 are illustrations of how both wind and ballistic coefficient effect the impact location and impact area size. Destruct action on a reentering vehicle typically shorten the impact range proportional to the ballistic coefficient reduction achieved and spread debris over larger areas. It must be noted, that destruct of a vehicle normally will produce fragments having significant variation and uncertainties in the ballistic coefficients. In most cases the fragments will also have some lift as well. The cumulative effects of destroying the vehicle will tend to produce a number of debris classes rather than a uniform ballistic category and debris will be spread over several of the beta circles rather than being confined to just one of the areas.

FIGURE 3: TYPICAL IMPACT AREAS



In summary, the public risk levels will generally be increased by increasing the number of reentering fragments and larger areas will be exposed to the debris threat. It is unlikely that uniform population densities can be achieved as the debris areas grow and population centers are likely to be included, thereby further increasing public risks.

SECTION 2: LANDING SITE FACTORS ANALYSIS

In order to understand how factors associated with the landing site, this analysis examines three aspects to be covered:

A. Factors affecting a decision to destroy or not, when the impact area is highly populated

B. Operator ability to make a destruct decision based on impact point being outside of the landing area

C. Risks associated with having a destruct system

Each of these will be discussed individually in the sections which follow. Each begins with a specific description of a situation and then explores the associated issues affecting risks.

A. To Destroy or Not, When the Impact Area Is Highly Populated

Given that a vehicle falls into a highly populated area (100% probability), this analysis discusses the differences in risks to the public between destroying and not destroying the vehicle. It further discusses the factors involved in considering the differences in public risk, such as population distribution, type of shelters, potential use of other safety devices (e.g., parachutes and controls) (note: this section may be primarily qualitative). In approaching this analysis, OCST focussed on various factors and interrelationships that can influence the risks in different scenarios, rather than numerical solutions to a casualty expectation problem.

1. *Assumptions*. For this analysis, the reentering body is assumed to be a spherical mass of 1000 lbs, 4 feet in diameter. Such a device will have a ballistic coefficient of approximately 133 lb_f/ft^2, and will impact at a terminal velocity of about 334 ft/sec or 228 mi/hr. Kinetic energy of this mass at impact (1.7×10^6 ft-lbs) is sufficient to penetrate approximately 24 inches of high strength, reinforced concrete--the equivalent of three to four floors of modern offices, condos, or apartments. It would crater about 11 feet in sandy loam.

The degree of the threat from a reentering device is generally related to it's size and kinetic energy. Size and kinetic energy interact with the impact environment (type of structure hit vs. an open area impact) to define a lethal area. For example, a small fragment will generally have a small lethal area even if it is entering a very high speed. A large device will have a larger lethal area due to it's size alone, but may also produce extraordinary effects if its size and speed results in a structural collapse, substantial "splatter," or both. Splatter is the ejecta from the impact point, consisting of matter from both the impacting unit and the ground/structure receiving the impact.

2. *City vs. Rural Factors.* Population densities of less than 10 people per square mile are normally considered rural. This type of environment is characterized predominately by single family dwellings. Potential worst case casualties in such an environment is approximately four to five.

Cities, on the other hand, have average densities of 3000-4000 per square mile, with peak densities in certain complexes of 10,000-20,000 per square mile. Even though the size is small, casualty expectancy from a hit are orders of magnitude higher simply because of population density. Lethal area increases because of possible roof failure in multistory facilities, splatter, etc. This can add at least another order of magnitude to casualty expectancy. Consequently, potential worst case casualties rise into the hundreds of dead and injured.

3. *Number of Pieces Generated By Destruct.* A destruct may be a severe event (explosion) or a benign, designed severance of parts, producing a planned number of pieces with known sizes. In either case, resulting pieces may have ballistic coefficients as high as the original reentry body. Smaller pieces hitting within a population center may produce less damage due to the reduced likelihood of major structural failure. Impact point(s) for pieces will generally be short (uprange) of the non-destruct impact point. Some cross-range movement may occur depending on imparted velocities to the pieces at destruct time, ballistic coefficients of the pieces, and wind direction and speed.

4. *Destruct Methods and Effectiveness for Ballistic Reentry Vehicles.* The risks associated with the flight termination depends upon the method employed. The following examines the potential options for terminating flight and associated issues that must be considered:

a. Explosion

- o Generates large number of small high velocity fragments (depending on amount of explosive).
- o Ballistic coefficients of resulting pieces are hard to predict and depends on sphere construction and internal parts.
- o Imparted velocities to the pieces at destruct time will spread the impact footprint over a larger area.

- o Casualty expectancy may not change because of large numbers of fragments, even if resulting impact area has a lower average population density. Severity will be less.

- o Most effective if done before reentry heating. Most fragments consumed when they are small.

b. Shaped-charge Disassembly

- o Generates a quantifiable number of pieces.

- o Ballistic coefficients are more predictable.

- o Larger pieces--not as susceptible to burn up during reentry if initiated before reentry.

- o Very small imparted velocities to pieces--reduced dispersion and more exposure control at impact.

c. Destruction of Reentry Thermal Protection

- o Vehicle breaks up due to reentry heat.

- o Depending on structure, may be completely consumed.

- o Number of pieces surviving may be small and will land short of normal impact point.

- o May be an effective method but may be difficult to design and implement mechanically.

In addition to destruct-type flight termination systems, the following describes other alternatives for terminating or modifying the flight path of the vehicle:

a. Parachutes, Drogues, Parafoils, etc.

- o Will reduce terminal velocity, accident severity.

- o May move impact location depending on when deployed.

- o Deploying at higher speeds and altitudes typically requires stronger parachutes or more drogue and reefing stages.

- o Increases wind drift distances. For example, a device deployed at

100K feet and producing an average descent speed of 20 ft/sec would lead to a total descent time of 83 minutes. If average wind were 25 mph, this would produce a 35 mile drift.

- The device would have to be designed for all possible opening environments (speed, altitude, etc.) for maximum flexibility.

- High altitude parachute opening would enable intercept by aircraft and additional control actions if necessary.

- Parafoils have high lift-to-drag ratios and can move a substantial lateral distance for each unit of altitude lost. These can be used to move the impact point, with the distance proportional to altitude of deployment. By "flaring" just prior to landing, vertical velocity can be reduced to near zero. Depending on relative wind direction, horizontal motion still may be present. Radio control, either by an interceptor or by tracking, would be required.

b. On-board Emergency Propulsion

- Could be used to boost the vehicle beyond or bring it in short of a population center.

- Stable platform or attitude control required to achieve a known thrust vector direction.

- Most efficient if done before reentry; becomes less and less effective as time to impact becomes smaller.

- Weight and operational complexity penalties are associated with this option.

- Recovery hazard is increased if the device is unused, and there ia a possible increase in impact lethal area unless used in conjunction with a parachute.

c. Mechanical Lift or Drag Devices

- Pop-out panels/wings/flaps could provide directional stability, lift and drag modulation.

- Would require thermal protection if deployed during heating phase of reentry.

- o Could be used later if sufficient lift/drag obtained.
- o Penalties are weight and mechanical control complexities.

B. Operator Ability to Make a Destruct Decision Based on Impact Point Being outside of Landing Area

This analysis discusses the ability of an operator to make a determination to destroy based on where the estimated impact point is outside the range (i.e., not destroy if impact is in unpopulated area versus destroy if in a higher populated area)? Included in this discussion, the analysis will address the factors that affect the operator's ability to make such determinations and how such a strategy might affect risk.

Before addressing the ability of an operator to make a destruct determination, the elements that make up such an ability should be determined. In other words, what is essential to an ability to make such a decision?

Before looking at that question, it is important to note the distinction between an ability to make a determination and an ability to execute the decision. As described in the tasking above, this analysis is concerned with factors affecting an operator's "ability to make a determination." Factors relating to execution of a destruct decision, such as the existence of command facilities and on-board ordnance, are not part of an ability to make a decision and are not discussed here.

What, then, are the elements of an ability to make a destruct determination? or what conditions must exist to make a supportable decision to destroy? The following are suggested as appropriate elements:

- o The operator must have sufficient timely information, presented in forms for quick assimilation, to determine
  - \- Impact point if no action is taken.
  - \- Predicted impact point(s) of debris, and estimated public risk, if action is taken at various times during the reentry.
- o The operator must have individual expertise to properly interpret the available information

There is a lot of detail summarized in these two general statements. An examination of a typical reentry scenario, from an operator's viewpoint, will reveal the multiple factors which make up the summarized elements.

1. *Scenario.* A "range" exists and is the planned landing area for a reentering payload which has been in orbit for some number of days. Actually, a specific point within the range is the planned landing point. The range itself is very sparsely populated; only a small number of mission essential personnel and observers are within miles of the planned landing point. Outside the immediate boundaries of the range, the population is also sparse, although with a slightly higher population density than within the range. Some few miles from the range boundary along a certain direction, population begins to increase at the suburban extremities of a large city. Inside the suburban ring is a several square mile, high-density metropolitan area.

2. *Assumptions.* The inbound vehicle is carrying a destruct package, and the "operator" has available the facilities to initiate the destruct. There is no other control of the vehicle.

3. *Analysis.* How will the operator know whether to use the destruct system or not? First, he/she must know where the vehicle is going to land. If it is headed toward the planned landing site, obviously no action is needed. But he/she must be able to know this. If it is headed "out of bounds," but into a sparsely populated area, destruct may be initiated or not, depending on previously established mission rules for the operation. If impact is predicted near or in the city, the operator will still want to know where the debris is likely to fall. The operator must see and assess the changing state of the situation from moment to moment, and predict ahead, so as to initiate the action before consequences progress to an unacceptable level, or when a minimum risk level is achieved.

Several things can now be concluded about factors affecting the operator's ability to make a destruct decision.

o <u>Information and Its Presentation</u>. Perhaps the most obvious factors affecting the operator's ability to make the decision are preplanning and knowledge about what's happening with the inbound vehicle where it's going. Absent such knowledge, no rational decision either to continue flight or to destruct the vehicle could be made. This is fundamental and essential.

  Several things are implied by this. First, some form of sensors must provide the raw data (position, direction, speed, etc.) which can be processed into a useable form. The processing capability to convert the data must exist. For example, estimated impact predictions for the intact vehicle and debris area if the vehicle were destroyed must be computed. The debris impact area and its size vary with time of destruct action. The data must be displayed in a form the operator can easily use. And all of it must be accurate and timely so that if action is required, it can be done soon enough to prevent or minimize serious consequences. The combinations of reentry off-nominal conditions and population areas may be so numerous and so complex that only the real-time computers can determine the optimum course of action.

Some of the information necessary for an operator to make a decision must be developed before the real time reentry event. For example, the operator should not have to make determinations of what areas are acceptable for landing during the actual event. Even more basic, any required layouts of the populated areas on plot charts or computer displays should be prepared beforehand. In other words, a major factor affecting the operator's ability to make a decision is preparation.

A sub-factor of the information issue is the magnitude of reentry errors that the operator attempts to accommodate. Miss distances of several hundred miles are possible with only small errors in deorbit conditions. As the miss distance increases, the ability to acquire data from the reentry vehicle diminished due to acquisition problems and possibly reduced reaction computation times. Additionally, the computational complexity increases proportional to the square of the radial distance within which the operator attempts to control risks. When miss distances exceed several hundred miles, control capability is probably unattainable.

o Operator Preparation, Training, and Expertise. Another aspect of preparation, or at least one related to it, is individual expertise. An operator performing a function such as this needs a basic aptitude for assimilating complex information rapidly and being able to make a decision under pressure. This relates to both innate abilities and to the individual.

The operator must be well trained in this specific function. He/she must know the mission rules; there will not be time to look them up. Because not every situation can be pre-conceived, the operator must understand the displays and systems that are presenting data to him, instantly comprehend it, and be able to recognize when portions of it may not be valid.

This scenario and walk-through analysis has focused on the minimum set of factors affecting an operator's ability to make a destruct determination, based on whether a reentering vehicle may impact outside the planned landing range.

C. Risks Associated With Having a Destruct System

This analysis qualitatively discuss the risks uniquely associated with a destruct system being part of the vehicle (i.e., regardless of whether the system is used or not), e.g., ordnance handling issues.

Several issues are raised in examining the safety of vehicles with on-board destruct systems:

1. Installing a destruct system (ordnance, safe and arm device(s), receivers, antennas) on a reentry vehicle increases certain risks. The destruct system, containing ordnance elements, is itself a hazardous system that can endanger personnel during ground processing of the payload. However, there are procedures for safe handling and testing of these systems. Such procedures are well-established within the companies that manufacture or launch vehicles carrying ordnance. Companies not having an already developed base of expertise in destruct systems would have to develop such a base.

2. Ground processing of a vehicle carrying a destruct system will be different than for one that does not, simply because it is an ordnance carrying vehicle. Special technician certifications are needed. Facility requirements are different. Transportation requirements are different. A vehicle otherwise considered non-hazardous can be processed and tested almost anywhere. An ordnance carrying vehicle cannot. The addition of ordnance requires observation of quantity-distance separation criteria between the processing facility and the public. In short, processing such a vehicle is somewhat more complex, hazardous, time-consuming, and expensive.

3. The degree of increased risk caused by the addition of a destruct system varies from nearly insignificant to substantial, depending on the design of the destruct system and type/quantity of ordnance used. If safe designs are used, only cutting types of ordnance are used, installed late in the processing cycle, and the system is not armed until reentry is to occur, then the increased prelaunch risks are small.

4. Probably the greatest risk occurs after the reentry device has landed, and destruct was not necessary. In such an instance, there will exist a device on the ground, not necessarily under immediate secure protection. If the vehicle's destruct system were still armed, a hazardous situation would definitely exist. Presumably, procedures not yet defined would require the destruct system to either be commanded into a safe state or to be automatically de-armed during descent. Even so, there will remain an ordnance carrying vehicle to be located, secured, transported, and post-flight processed.

SUMMARY

This paper has provided a discussion of three specific topics relating to control of risks involved with a reentering payload. Specifically, the discussions address factors relating to employment of a destruct system on the reentering vehicle in order to reduce risks to the public.

Factors such as nature of the impact area (city/rural), number of pieces produced by a destruct, effects of various types of destruct, and use of other risk reduction methods were discussed in the context of factors affecting a decision to destruct an inbound vehicle.

The type of information and nature of its presentation to an operator were noted in the context of things affecting an operator's ability to make a destruct decision. The operator's innate abilities as well as preparation and training were also discussed as important factors.

Finally, risks and other considerations engendered by the addition of destruct ordnance to a reentry vehicle were presented.

SOURCE MATERIALS

1. "Flight Termination System Risk Sensitivity Analysis of Reentry Vehicles," DRAFT Technical Memorandum, Research Triangle Institute, August 6, 1991.

2. "Flight Termination System Risk Sensitivity Analysis of Reentry Vehicles, Subtask 3: Specific Landing Site Analysis," DRAFT Technical Memorandum, Research Triangle Institute, October 9, 1991.