U.S. Special Operations Command

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This report summarizes the 1990 JASON Summer Study examination of a number of technical questions raised by the Special Operations Command.

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Introduction and Summary

With the help of LTC James Glock, we selected a wide range of technical subjects for Jason to review during the summer study. In this section we give a brief description of these topics, and a summary of our results. For convenience we subdivide these topics into two categories, "Show Stoppers" and "Technical Analyses and Inventions."

(A) Show Stoppers

These topics were speculative ideas for new systems, and Jason was asked to make a "sanity check", i.e. we were asked to see if there were any physical principles that would ultimately prevent the system from working as intended before major resources were expended.

(1) Cavitating Vortex Bubble Rings ("CVBRs"). CVBRs are underwater analogs to smoke rings. They can carry energy (in the form of circulating water) over long distances. We concluded that they could not be used as weapons, since the the rings become unstable for velocities $v^2 > 2gd$, where d is the depth, and g is the acceleration of gravity. Stable velocities are too low to make useful weapons, and it is highly unlikely that the unstable high velocity rings would last long enough to be useful under real conditions.

(2) Detection of very shallow mines using nuclear methods.

Some modern mines have no magnetic signature, and nuclear methods have been suggested to detect the nitrogen in the explosives. We reviewed all relevant nuclear techniques, and concluded that in each of them the range of the nuclear radiations is too short to permit a useful system. We recommend that no further work be done in nuclear mine detection. We do suggest alternative electromagnetic methods; these are described in section (B) below.

(3) Mathematization of human metabolism.

Are there mathematical techniques that could aid in the prediction of human response in a wide range of conditions? No, largely because of inadequacies in the data.

(B) Technical analyses and inventions

We were introduced to several technical problems being faced by USSOC personnel, and we searched to see if new or overlooked technologies could be used to solve some of these.

(1) Thermal control for Seals.

Suits worn by Navy Seals must provide warmth during periods of inactivity underwater, and yet cooling during periods of exertion. The ideal material would have high conductivity when the skin is warm, and low conductivity when the skin is cool. Could liquid crystals provide such thermal control? We did not have the expertise to find suitable materials, however we did suggest an alternative that we are sure would perform the same task: a well-known device called a "heat pipe" could be incorporated into a suit. It would provide high cooling when the human was hot, and low cooling otherwise.

(2) Trajectory Generation and Terrain Avoidance

Aircraft flight paths must sometimes be updated in real-time to take into account new information (e.g. SAM sites destroyed, or recently moved). To enhance the mission effectiveness, this trajectory generation is often done on a computer.

Newly developed mathematical techniques are far superior to the standard "dynamic programming" methods that are currently used. These include "simulated annealing" and "wavelets". These techniques should allow real-time calculation aboard the aircraft.

(3) Low observable boats.

Low observable boats can be constructed, like the B-2 bomber, from scratch. However because of the clutter of nearby sea surface, we believe that adequate cover can often be achieved by much simpler methods, and therefore existing boats can be retrofitted at relatively low expense.

(4) Shallow water mine detection.

Non-conducting mines can be detected in a seawater environment by the very fact that they are non-conducting, and therefore present a non-uniformity to an electric field.

(5) Directed IR Countermeasures

We suggest several technologies that could help the DIRCM problem, including the use of batteries for short-term power supplies, and the use of stabilized optics for tracking and shooting. In certain circumstances RF weapons might be used against surface-to-air missiles.

(6) Comments on Seal Operations

We were told that Navy Seals do not consume food or other nourishment while working, and we recommend that this practice be reinvestigated.

(7) Infiltration/Exfiltration

We studied the "Fulton" system of exfiltration, and although we found the effort to be excellent, we did have several recommendations of ideas that we thought could receive additional attention. Most systems are designed for a maximum of 8 g's, although a person suitably protected (e.g. wearing a g-suit) can be fully functional after a brief period of much higher acceleration; we recommend that future systems consider such higher g domains.

A1. Cavitating Vortex Bubble Rings (CVBRs)

We considered the possible use of cavitating vortex bubble rings (CVBRs) as underwater standoff weapons. According to an unclassified memo one wishes to form vortices of diameter of order 15 cm with energy density 100 J/cm^2 which would deliver an overpressure of 10,000 psi for a period of 1 millisecond. The main interest is in stationary targets but use against torpedoes or the creation of a cluster of CVBRs to spoof the opposition have been considered.

Small scale tests at Tracor Hydronautics have already been performed. They are considering large scale tests next summer and hope to achieve vortex velocities of 0.1 – 0.6 c ("c" is the speed of sound in water, ≈ 1500 m/sec) and to demonstrate damage of sample targets consisting of a pair of steel plates with target ranges up to 100-1000 yards. We should decide whether these large scale tests are reasonably based on theory and the small scale tests already performed.

A non-cavitating vortex ring can be modeled as an inner circle of radius a and vorticity κ surrounded by a flow field of radius R. In a fluid of density ρ and pressure P the vortex energy will be

$$T \approx \frac{1}{2}\rho R \kappa^2 \log(R/a)$$

and the vortex will have a forward velocity of

$$v \approx \frac{\kappa}{4\pi R}\log(R/a)$$

It is possible to vary log(R/a) to some degree by different choices of vortex generators, but it cannot be be varied substantially and we will take it to be of order 1. If v_a is the velocity at the inner radius a then the vorticity is $\kappa = 2\pi a v_a$. In order to achieve an energy density of 10^9 erg/cm^2 we require an inner velocity of

$$v_a \approx (4.5 \times 10^3 \text{ cm/sec})(R/a) = 0.03\text{ c } (R/a)$$

The actual velocity of propagation of the vortex will be somewhat smaller than this by geometrical factors. We estimate that in order to achieve energy densities of the type required we will need an inner velocity $v_a \approx 0.1$ c.

The analysis of CVBRs can be usefully be divided into three areas, the production mechanism, their subsequent propagation, and their interaction with the target. The latter two areas seem to be the weakest points. The main limitation arises due to a natural limit on the velocity for stable propagation. At the velocities of interest the inner pressure of the CVBR will drop below the vapor pressure leading to cavitation. Approximate the pressure inside the cavitating region by zero and the outside pressure by $\rho g h$ with h the depth and $g = 32$ ft/sec^2. If v_a is the velocity outside the cavitating region then hydrodynamics requires that $v_a^2/2 \approx \Delta P/\rho \approx gh$. At a depth of 30 ft the limiting stable velocity v_a is thus 31 ft/sec or 0.01 c Stable velocities of order 0.1c could be achieved only at operating depths of order 3000 ft or 1 km!

Subsequent to a limited distribution of this section of the report in draft form we received a commentary on this draft by Dr. D. W. Sallet and Mr. J. A. Thywissen of Obert Assoc. Inc.. In their commentary they mention a *Redirection of Work* and *Summary Proposal of Work* which we have not been given. They agree with the limitation on stable propagation velocity discussed in our original draft, but suggests that rapid depressurization may result in non-cavitating non-equilibrium vortex rings which would persist for of order 0.4 seconds. Such a possibility is difficult to assess theoretically. We would mention however that even if such non-equilibrium conditions could be achieved in the laboratory, under realistic conditions the presence of impurities, ambient air bubbles, fish, etc. are likely to lead to much shorter delay times for the onset of cavitation. Thus even if CVBRs showed this kind of metastability in laboratory experiments, they are not likely to be stable in a practical situation.

We also feel that the possible damage done by CVBRs to a stationary target is uncertain. The experiments done to date were performed at very short distances to the target and have not clearly separated the damage done by the CVBR from the damage done by the slug of water which is emitted from the generator. For example the plots of force vs. distance in Figure 5.12 of the report from Tracor Hydronautics show a steep fall off at short distances as would be expected from the effects of a slug of water. A more accurate estimate of the damage done solely by the CVBR would require experiments at larger distances that can cleanly separate the two effects.

From a theoretical perspective the mechanism by which a CVBR would damage a target is not completely clear. The CVBR may exert some overpressure on the target which would depend on the velocity of the CVBR. This overpressure is limited by the limit on the velocity of propagation described above. As the core of the CVBR approaches the target the CVBR should exert suction on the target since the pressure in the core of the CVBR is below ambient pressure. The magnitude of this suction is limited by depth. To achieve 10,000 psi would require operating at a depth of 6 km. It should be possible to obtain a better theoretical estimate of the pressure exerted by a CVBR by solving the scattering problem for a line vortex ring interacting with a fixed plane. The analogous problem for the scattering of a pair of vortex lines suggests that the distance of closest approach for the CVBR will be of order its diameter. Thus the suction exerted by the CVBR is likely to be substantially less than the pressure differential between the inside and outside of the CVBR.

In conclusion, while the physics of CVBRs is undoubtedly fascinating, there are fundamental physics reasons why the proposed use as a standoff weapon are unlikely to work, and we do not believe that large scale tests are justified.

A2. Mine detection using nuclear methods

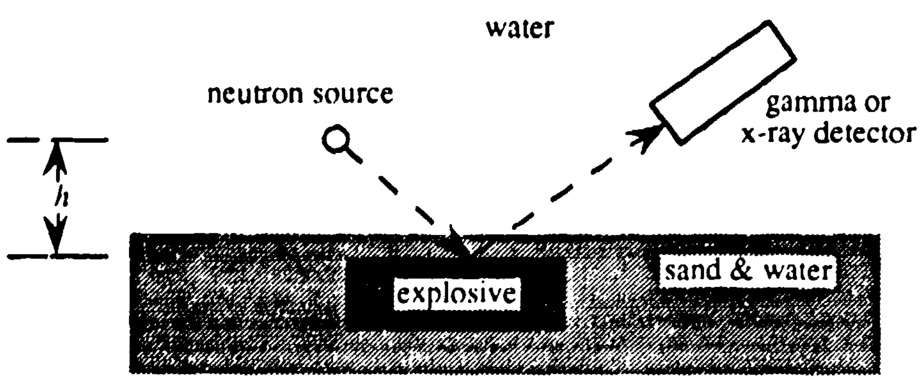
The reduced acoustic and magnetic signatures of mines buried in several inches of sand under water make it difficult to detect and localize these targets by conventional techniques. It has been suggested that nuclear phenomena might be used to identify the nitrogen invariably present in the mines' explosive. We investigate this possibility in the following.

In a typical nuclear detection method, a source (radioactive isotope or accelerator) generates interrogating radiation. When this radiation strikes the target material (Nitrogen, in this case), a characteristic responding radiation is produced. A detector of some kind signals the presence of this characteristic radiation, and hence the target material.

The ranges of both the interrogating and characteristic radiation in water determine the range of any given detection scheme. Energy loss by ionization severely limits the range of charged particles (protons, electrons, and alpha particles, having characteristic nuclear energies up to 10 MeV), so that neutral particles must be used. As the ranges of the relevant neutral particles in water are a fraction of a meter (see Table 1 below), nuclear phenomena cannot be used for mine detection, where ranges up to 10 meters must be probed.

Radiation	Energy	Range (cm)
gamma ray	2 MeV	40
	10 MeV	60
	20 MeV	80
neutrons	thermal	3 (diffusion length)
	2 MeV	0.5 (scattering mean-free path)

In contrast to mine detection, nuclear techniques might be applied to mine localization. Nitrogen emits a characteristic high-energy (about 10 MeV) photon when exposed to thermal neutrons. This is the phenomenon exploited in the Thermal Neutron Analysis (TNA) explosives detectors used in airports. For a point neutron source (e.g., a fission source) in water separated from the explosive by a distance h (as in the figure below), a fraction $0.5\exp(-h/L)$ of the neutrons will reach the explosive and be available to produce the high-energy photon (we ignore the intervening sand).



This fraction could be increased by geometrical tailoring of the source. As L is roughly 3 cm, sand thicknesses of several inches could be probed. The photon detector can stand off from the source by several 10's of centimeters to avoid interacting directly with the neutrons. Detection of the high-energy photons must take place in the background of low-energy 2.2 MeV photons produced when neutrons are captured by the hydrogen in water, but detectors with sufficient energy and time resolution are available.

We close with some comments on specific schemes that have been proposed for the easier problem of land-mine detection. One proposal is to use high-energy (30-60 MeV) photons to induce a (gamma, 2p) reaction on ^{14}N to produce ^{12}B. This latter nucleus has a lifetime of 20 ms and the continuum bremsstrahlung and characteristic (4.4 and 3.2 MeV) radiation it produces upon decay could be detected. As previously noted, the limited range in H_2O of the photons involved makes this scheme inapplicable for mine detection in water. Further, sources of 30-60 MeV photons are unlikely to be swimmer-portable. Even if one ignores the problem of supplying power and liquid helium, the best superconducting rf cavities can accelerate electrons at 25 MeV per meter, implying at least a 2 meter device.

A second proposal is to exploit characteristic elastic neutron resonances in the light elements to identify nitrogen. As the mean-free path for MeV neutrons in H_2O is only a fraction of a centimeter, this technique cannot be applied in the water.

Finally, we comment on the impossibility of using neutrino beams for this problem. It is true that neutrinos have a very long range in water (effectively infinite in the present context) and so one might be tempted to use them in the detection problem. However, the very fact of their long range makes neutrinos exceedingly difficult to detect. Sophisticated multi-ton detectors and months of counting time are required just to detect a few neutrinos. Neutrinos are entirely inappropriate for the problem at hand.

A3 Mathematization of metabolic rates

The Naval Coastal Systems Center representative, Dr. Rudolf Wiley, presented us with the following problem, ``to devise a rational approach to understanding how nutritionally induced metabolic changes enhance cognitive performance, so as to devise countermeasures to decrease high attrition within the Base Underwater Demolition School." In particular, he asked us to examine two possible solutions:

1. "Mathematicize linear and non-linear rate kinetics"
2. "Devise a metric which describes cognitive performance as a function of reaction rate parameters."

We claim no special expertise in the areas of human metabolism and human cognitive performance; our response to this problem is based on knowledge of mathematics and data analysis. We do not believe that the present data set is adequate to allow a useful mathematization of the problem along the lines suggested.

We believe that the most appropriate source of expertise to advise the Basic Underwater Demolition School about human performance problems would be the sports medicine community. Professional sports medicine experts are accustomed to dealing in a practical way with the interactions of nutrition with physiology and psychology. They also have real-world experience in the art of extracting high performance from human beings under conditions of high stress. We believe that the practical experience of sports-medicine doctors is far more relevant to the problems of the Basic Underwater Demolition School than any mathematical theory can hope to be. In particular, our limited knowledge of mathematical theories of rate kinetics and cognitive performance does not give us any reason to think that these theories could be useful in the context of the Naval Special Warfare program.

We note that according to one of our briefings, that Navy Seals have no means of consuming nourishment during an operation. Based on our own limited experiences, we believe this is something that could and should be rectified.

B1. Thermal Control for Seals

Navy Seals have a difficult insulation problem: they must wear thick suits to protect them from the near zero Centigrade water environment for periods of inactivity that may last hours, and then be able to dump heat at a rapid rate when they are swimming hard. Suits that have variable thermal conductivity are under development. We were asked if we could find materials whose thermal conductivity depended on temperature. Such a material would provide additional cooling when the swimmer's skin is warm from heavy exertion, and reduced cooling during periods of inactivity.

We are not aware of a suitable material (although we don't know that they *don't* exist), however we suggest another approach. A device commonly called a "heat pipe" provides the required property, and has been high developed. We believe that heat pipes can be incorporated in the suit worn by the Seals without interfering with the other requirements (flexibility, etc) of the suit.

Two books that we found useful were:

Heat Pipe Theory and Practice, A Sourcebook by S. W. Chi, George Washington Univ., McGraw-Hill Book Company

The Heat Pipe by D. Chisholm, M&B Technical Library TL/ME/2, Mills & Boon Limited, London.

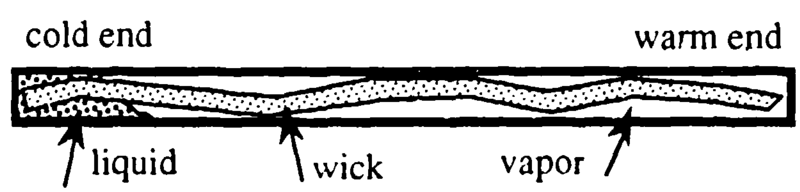
A heat pipe has two three essential parts:

(1) a working fluid (refrigerant) that vaporizes rapidly when heated

(2) a hollow region (not necessarily in the form of a pipe) in which the vapor can flow

(3) a wick or other material that will draw the liquid from the cool region to the hot region.

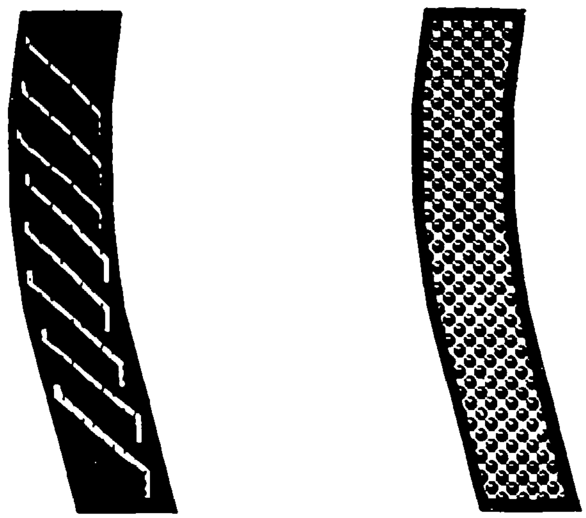
These components are shown in the following figure, which shows a "classical" heat pipe:



The basic operation in a Seal Suit would be as follows. Small flexible (but not collapsible) tubes in the jacket bring the fluid close to the skin of the diver. As long as the skin is relatively cool, the fluid remains fluid, but if the temperature of the skin rises then the fluid rapidly vaporized, absorbing heat in the process. The vapor flows toward the cool end of the pipe, near the water surface. Up to this point, the fluid is doing the same job that is normally done by perspiration. At the cool end, the fluid condenses, giving up its heat to the water. The wick then draws the water back to the hot end. Thus heat provides the pumping and circulation power to draw the working fluid in its circular path.

The heat pipe provides, in a sense, an artificial "sweat" in the underwater environment. It is a very natural environment for the heat pipe since the water provides a very good thermal sink for removing heat. Heat pipes would not work nearly as well in heavy protective suiting used in the air (CBW suits, for example) where there is no good fluid on the outside comparable to water for removing the heat.

Two possible configurations for heat pipes in suits are shown in the following figures.



discrete heat pipes — open interior (but non-collapsable)

A quick search through a list of possible working fluids produced two candidates. These were trichloromonofluoromethane (usually known by its brand name, *Freon-11*) and water. It is not surprising that water would appear on this list, since it is the material whose vaporization at skin temperatures is the primary method the body uses for cooling; however the variation of vapor pressure of water over the interesting temperature range (90°F to 100°F) is probably insuficient to make it practical. Although Freon-11 is considered an environmental hazard when used in large commercial quantities, we feel we should point out that in the small quantities needed for the suits proposed here, the environmental impact is completely negligible. Neither water nor freon may be optimum; further research and design is necessary to find the best fluid.

ALTERNATIVE TO HEAT PIPES

There is a concept that is even simpler than a heat pipe which may have advantages in many situations. Since the swimmer is surrounded by coolant (water), all we need to do is to have a suit that provides enough thermal insulation to handle cold water and long periods of inactivity, and we accommodate the need for cooling under warm-water conditions and periods of intense activity by allowing controlled access of water through the suit to the skin. In this way we take advantage of the fact that there is available free coolant, for the asking, that need not be conserved or recycled -- different from almost all other cooling problems. People are accustomed to putting on a sweater when they get cold or taking off some clothing when they get warm. In similar fashion, if part of the suit were made porous, it could be covered with a patch that could be closed by zipper, in order to prevent water circulation. Alternatively, slits in the fabric could be held closed by a draw string that would go back and forth in a certain region.

One would like to avoid having intensely cold water impinge on a portion of the body, which could lead to cramps and to impaired performance of muscle or even brain. A substantial portion of the body might be provided with a mesh undergarment, to which water would have access, but the water would come through a valved dual heat exchanger. In this way, water at ocean temperature would enter a tube in the rubber heat exchanger, move about ten inches along this tube and then have access to the space between skin and suit. Near the distant region of this space, another tube would allow the water to exit through the second parallel channel of the counterflow heat exchanger, and thence to the ocean. If the heat exchanger were perfect, exchanging heat between the two streams without any temperature drop, no matter how much water flowed, there would be no heat loss. Water would enter at body temperature, having already been warmed to that temperature by the outflowing water in the counterflow heat exchanger.

Of course, we don't want exactly that, so the heat exchanger can be smaller and less perfect. We suppose the water flow might need to remove as much as 300 watts or some 260 Cal per hour (food calories). This would be achieved by warming only about 150 cc per minute of water, so one does not need to have a large tube or a big flow. If water enters at something like 10 C below body temperature (having been warmed in the heat exchanger) and leaves at body temperature, about 500 cc/min of water flow is required. This is a very modest technical and operational problem and could be available sooner and more cheaply than the heat pipe solution.

B2. Trajectory Generation and Terrain Avoidance

We were briefed by Lt Col Brian Maher (USSOCOM) and Mr. Aivars Smitchens (WRDC/FIGX, Wright Patterson AFB) on several of the problems associated with improving air infil/exfil. The problems are many and they are complex, and unfortunately we did not have the time or resources to make the detailed study of this problem that we had intended. However we do have some suggestions on one particular subtopic, that of trajectory generation and terrain avoidance (TGTA).

Aircraft flight paths must sometimes be updated in real-time to take into account new information (e.g. SAM sites destroyed or recently moved) or changes in the mission. Given an aircraft's current location and state (attitude, etc.) TGTA algorithms are used in a computer in an attempt to find the ``best'' trajectory towards a distant objective. The problem is essentially one of maximizing a complicated utility function by suitable choice among a large number of possible waypoints. Present TGTA algorithms use some combination of pure gradient searches, dynamic programming, and brute-force tree searches.

We are aware of two new areas of applied mathematics which, taken together, should provide a completely new methodology.

The first is *simulated annealing*. Based on the physical analogy of removing a material's defects by slowly cooling it, simulated annealing is a procedure for finding approximate *global*,, not just local, maxima of complicated functions. In real time applications, like TGTA, it has the very distinct advantage over techniques based on dynamical programming, that at any time -- even before it's calculation has run to completion -- it is able to give ``best-so-far" complete results. In fact, its best-so-far answers are often extremely good. Simulated annealing is therefore able to use real time very efficiently, achieving near-optimal solutions when there is time for it to do so, and fairly good solutions when there is not time. One can imagine that Special Operations could benefit from this flexibility, and the accompanying ability to re-optimize missions taking into account new facts as they become known. For a further description of simulated annealing, we recommend the text "Numerical Recipes" by W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, Section 10.9. (This book comes in separate editions for different programming languages, Fortran, Pascal, & C; any one of these will do.)

The second technique is the expansion of functions in *wavelets*. A trajectory can be represented not as a series of waypoints, but rather as the sum of a set of basis functions. Wavelets provide a natural basis that is hierarchical in scale: a few big wavelets can ``rough in" the overall path, while smaller scale wavelets refine the path to avoid local obstacles, threats, etc. With this natural decomposition by scale, the performance of any maximization algorithm (e.g. gradient search) can be considerably increased over the waypoint basis; simulated annealing algorithms can play particularly well with such a decomposition. For further reading on wavelets, we recommend the Jason report which is in preparation for DARPA. To obtain a copy contact Robert Henderson of the Jason Program Office, telephone (703) 883-6997.

B3. Low Observable Boats

Radar cross-section reduction for small boats would be an important enhancement for special operations. We point out that relatively simple measures can be taken to provide stealth against commercial ship radar.

Commercial ships normally use relatively unsophisticated S band (10 cm) or X band (3 cm) radars. The detectable range will be determined by the clutter background, which is typically $\sigma_0 \sim 0.01$ m^2 per m^2 of beamwidth. The area of the radar resolution cell will depend on the azimuthal beamwidth. For an antenna of length L, the resolution is $\theta \approx \lambda/L$. For $\lambda \approx 3$ cm and $L = 3$ meters, $\theta = 0.01$ radians. We take the range resolution to be $\Delta R \approx 15$ meters (typical for these radars). The clutter area will be $A_C = \Delta R\ \theta\ R$, and the clutter cross-section is

$$\begin{aligned} \sigma_C &= \sigma_0 A_C \\ &= 0.01\ \Delta R\ \theta\ R \\ &= (1.5 \times 10^{-3})\ R \end{aligned}$$

where R is in meters, and σ_C is in m^2. Thus for various ranges, the clutter cross-sections are typically:

Range	Cross-section of clutter
10. km	15.0 m^2
1. km	1.5 m^2
100. m	0.15 m^2

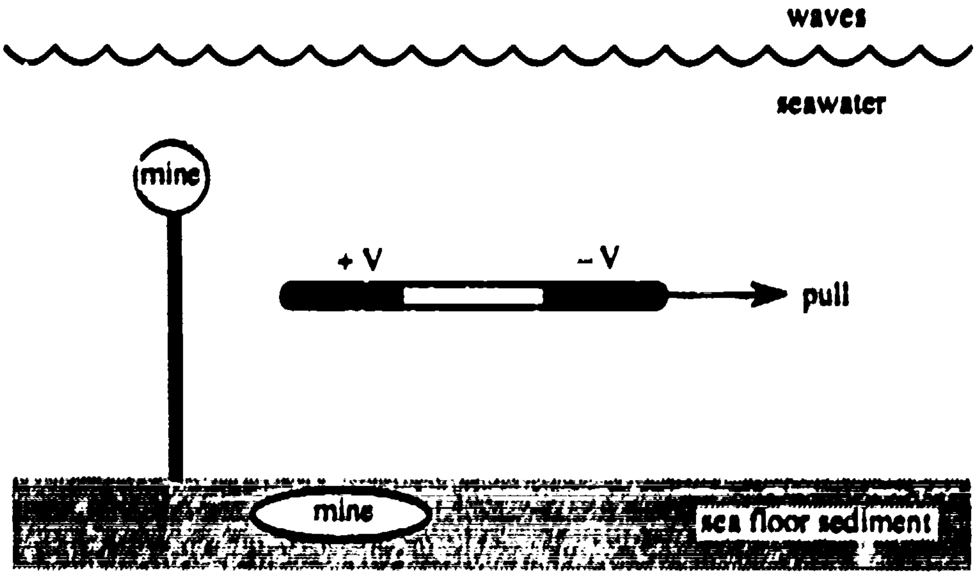
However for reliable detection the signal to clutter ratio must be about 10. At a range of 100 meters, this means the target cross-section must be $\sigma_t > 1.5\ m^2$. Thus if the boat cross-section can be reduced below 1 m^2 the boat will not be detected above clutter for distances as near as 100 meters.

It should not be difficult to reduce the radar cross-section of a small boat below this level. This can be done by measuring the boat with an inverse synthetic aperture radar (ISAR) to determine the spots of most intense backscatter. Major reflection can be expected from the front of the boat (where the jutting edge forms a corner--reflector with the water; a sharp V-shaped front can deflect the radar to the sides), from the cockpit (which can be protected by a metalized windshield, which would deflect the radar upwards and to the sides), and from faceting, ducts, inlets, and metal parts on the outside surface (which can be eliminated by removal or by covering with radar-absorbing materials).

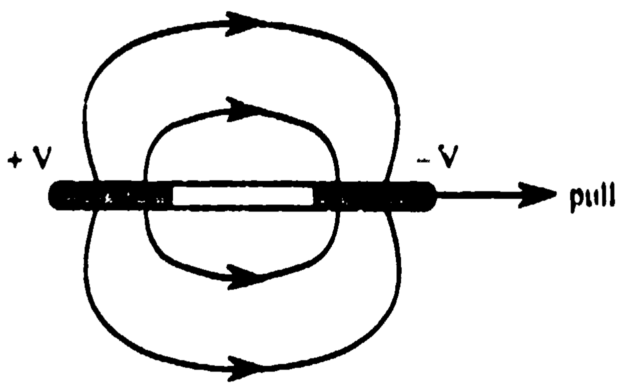
B4. Shallow Water Mine Detection

Mines can be located by their magnetic signature if they contain a magnetic material such as iron, by their anomalously high conductivity (using a metal detector) or by sonar or sonic imaging. Some newer mines are immune to these techniques; they are made of non-conductors, and covered with material that renders them acoustically invisible. We were asked to consider the use of nuclear materials to detect such mines, and we concluded that they are not practical (Section A2). In this section we will argue that such a mine can be located by the very fact that it is *not* a conductor, whereas the material surrounding the mine (seawater) does conduct electricity. The method should work both for buried shallow water mines and for suspended mines (perhaps invisible due to murky water).

A non-metallic mine in seawater, or in a sand bed that is saturated with seawater, provides as much electrical contrast as a good conductor (traditional metal mine) in the same location. Unless the electrical conductivity of the mine is matched to that of the sea bed, we observe this contrast by sending electric currents through the sea bed. Put another way, we can measure the *resistance* of the seabed to the flow of current. If the mine is present, then the resistance of that region will be higher. The detection can be done remotely by using two or more electrodes to send current through the water and the sea bed. The geometry should be optimized to arrange that most of the current would flow through the region where the mine might be. One possible geometry is shown in the following diagram:



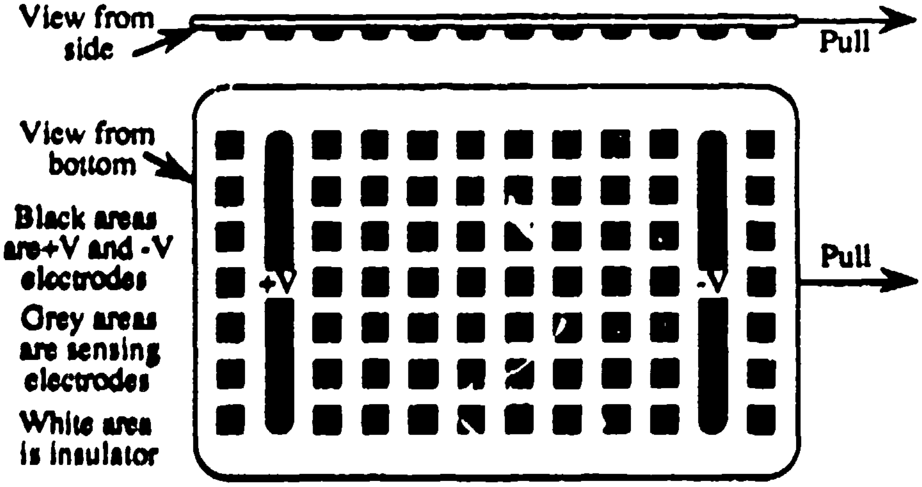
The detector here consists of two electrodes, and the current between them is monitored. The current will extend into the seawater a distance equal to several times the separation of the electrodes, as is shown in the following diagram:



Thus if the electrodes are a meter apart, then we expect to be able to detect mines that are several meters away. The system should be equally effective at detecting metallic mines, since they would increase the conductivity between the electrodes.

The biggest problem with such a detector is probably clutter from rocks on the bottom and from surface waves. If the depth of the detector varies as it is pulled, so that the distance between the electrodes and the sea floor changes, then the current will change; additional sets of electrodes can compensate for this effect. For buried mines it could prove invaluable to place an insulator over the electrodes, to force the current through the bottom region. This would not only increase the signal level, but it would cut down on clutter from waves.

Given the above considerations, and the availability of a modest amount of computation power, we can significantly improve the design by substantially increasing the number of electrodes. An advanced design might have two current-carrying electrodes, a two dimensional array of sensing electrodes, and a flat "blanket" of insulator that sits above everything else. This concept is illustrated in the following figure:



In this layout, the sensing electrodes do not carry current; they are high impedance and only serve to map the local voltage. With the layout shown there is sufficient information in the pattern for the system to be able to determine the distance to the bottom, the tilt (if any) of the electrode array, and the nearby presence of lumps of non-conductors or conductors.

This diagrams are meant to be schematic; a realistic system will have to balance the desirability of many electrodes and insulators with the difficulty of dragging complex system through the water. A very simple system could be carried by a single diver, but its range is fundamentally limited by the separation of the electrodes; in addition, the diver must not be too close to the system lest it detect him.

B5. Directed IR Countermeasures

We found that we were able to devote only limited time to the issue of Directed IR countermeasures. This was in part because the issue is large and complex, and we did not have the time or resources to familiarize ourselves with the entire problem. We found, for example, that some of the ideas that we came up with were already under development. Therefore we shall in this section give only a few unrelated contributions to specific DIRCM issues. These are RF defense, stabilized optics, and IR power supplies.

(1) RF defense.

Through briefings unrelated to USSOC, we learned that some of the SAMs that we wish to defend against may be vulnerable to certain types of RF pulses. This should be explored further to see if there is a possible defense that could be developed using an RF generator. For further information on this issue we suggest that USSOC contact the following people:

Herbert W. Head, Col, GS, Director
Department of the Army
Headquarters, U.S. Army Laboratory Command

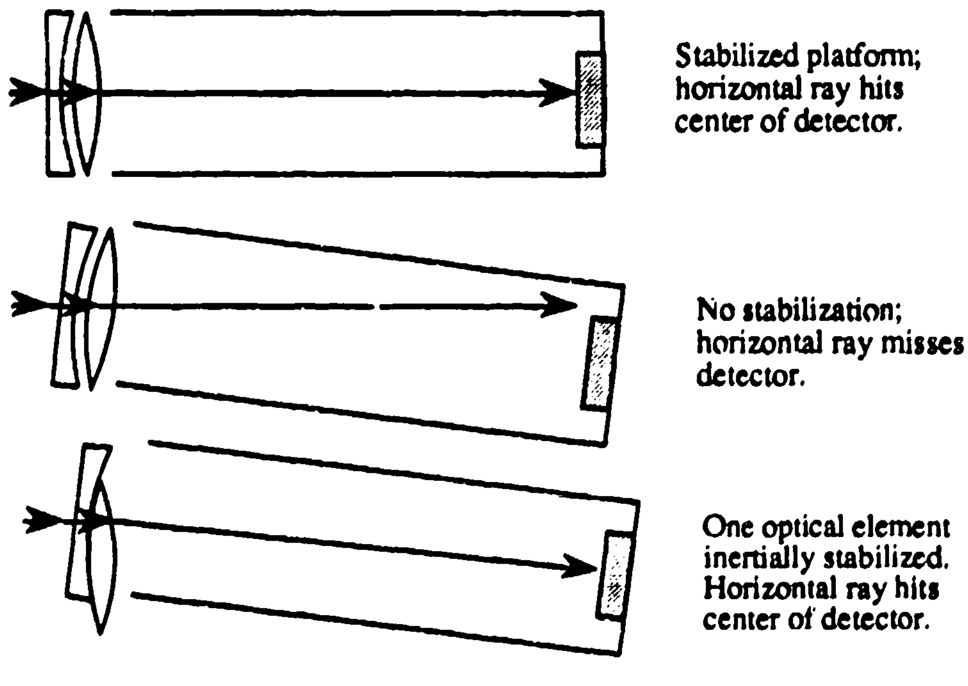
2800 Powder Mill Rd, Adelphi, Md 20783-1145
also

Donald J. Sullivan & Gary R. Hess
Mission Research Corp
1720 Randolph Road, S.E.
Albuquerque, New Mexico 87106
(505) 768-7600

(2) Stabilized optics

We learned from Capt. Rich Snyder (Air Force Logistics Command Combat Talon Program) that laser DIRCM systems have difficulty pointing because of aircraft shaking. The "standard" solution to this problem is to put the optics on a stabilized platform, but this solution is heavy , or can require considerable power. There is an alternative approach called "stabilized optics" in which just one optical element is stabilized. This can be done electronically, or (more elegantly) with an inertially-supported optical element. The stabilized optics could be attached to the end of the laser weapon. The emerging beam would then not reflect the jitter or shaking of the aircraft. If the pointing and tracking is optical and done through the same optical system, then the stabilization will work for it as well.

A diagram illustrating inertially-stabilized optics is shown below:



These diagrams illustrate the incoming light hitting the detector. The same optics would stabilize a laser beam moving out from the detector region.

As far as we know, the only company developing stabilized optics is Schwem Technologies in Pleasant Hill California. We spoke to the president, Jan Alvarez, telephone (415) 935-1226. They have developed stabilized optics for pointing lasers and for imaging. Their optics are inertially stabilized, with some electromagnetic coupling for low frequencies to allow scanning. (Completely stabilized optics would always point to the same place on the sky!) They expressed interest in the DIRCM problem.

Stabilized optics have many other applications beside DIRCM, and it is worth mentioning those here. In particular, for IFF (Identify Friend or Foe) it is sometimes necessary to obtain visual confirmation. In an airplane, helicopter, moving vehicle, or even on the ground, stabilized optics can enormously increase the effective resolution of optics. In situations where the stabilization must be light weight or low power, inertial stabilization is probably best.

NOTE: One of the authors of this report have a financial interest in Schwem Instruments, so he did not take part in the writing of this section or in the decision to include it in the report.

(3) IR Power supplies

We were told that certain of our aircraft do not have adequate auxiliary power supplies to operate an IR countermeasures system. We were told that what was needed was 54 kW for 10 seconds. This is a total energy of only 0.54 megajoule.

We suggest that this power can be supplied by a storage battery. Many batteries are available, but we will suggest an ordinary Lead-Acid automobile battery since these are familiar, well-behaved, and most of us know (from personal experience in trying to start a balky car) that they can be safely drained of their energy in a short time. A phone-call to a local Firestone dealer produced the following numbers: their best battery has a "cold cranking capacity" of 850 Amp, and a reserve of 115 Ampere-hours at 12 volts. This represents a total stored energy of

$$\text{Energy} = (115 \text{ A-hr})(3600 \text{ sec/hr})(12 \text{ volts}) = 5 \text{ megajoules}$$

This is about 10 times the energy we need. Let us assume that at its full cranking capacity its voltage drops to 6V; then it can deliver a power of (6V)(850A) = 5.1 kW. 54 kW would require 11 of these batteries, and they would run for 8 minutes, much greater than the 10 sec specification. Thus they could be used many times without a recharge.

We cite automobile batteries as proof of concept; other batteries are certainly better. What is desired is high energy capacity (lead-acid is relatively poor for this) and low internal resistance (high cranking capacity) so the batteries can deliver their power quickly.

B6. Comments on Seal Operations

We were briefed on Combat Swimmer Operations by CDR Bert Calland (USSOCOM). One of the facts we heard is that Navy Seals do not consume nourishment while on a mission. If this practice is the result of a research program, or even based on carefully-reasoned medical judgement, then we are not going to dispute it. We fear, however, that it is more the result of tradition than either of the above. Sports medicine physicians have in recent years changed their practice concerning nourishment during vigorous work. It is commonplace to see GatorAide being consumed in between football plays. We do not know whether a simple sugar liquid such as this is ideal, or whether one should take advantage of the more complex and complete nutrition available from liquid foods designed for dieters. Certainly it would not be hard to devise simple methods for delivering food during a mission; one might even be able to adapt the devices that were invented to feed astronauts in space. We would urge a moderate and inexpensive research program be started to determine if there is merit in this idea.

B7. Infiltration/Exfiltration

We were briefed on personnel extraction and delivery systems by Mr. Bob Underwood and Ken Oliver of Lockheed.

SOC would like to extract groups of up to 6 people by an aircraft flying at 250 kt at 250 ft above terrain. The capsule or harness might weigh 3000-6000 lbs, fully loaded.

The Fulton Skyhook system is a reasonable basis for such a capability, since the aircraft exist and have adequate space and load capacity. Questions remain as to the optimization of structure and fabrication of the capsule, whether it is delivered and occupied in the hour before extraction or whether it is pre-emplaced and hidden, etc. We rehearse the basics of the Fulton Skyhook to provide a basis for further comment and suggestion.

The individual to be extracted may find a clearing with 100 ft distance upwind to an obstacle less than 100 ft high. He or she then inflates a balloon that suspends the extraction line attached to the harness, with the balloon floating somewhat above the extraction flight path. The C-130 grabs the line below the balloon, by means of a Y-like probe projecting ahead of the aircraft nose; the slack line drapes back under the aircraft, whence it is scooped manually to attach to a winch inside the aircraft.

Straight and level flight of the aircraft would lift the individual surprisingly gently and (initially) vertically. It is worth restating the simplest case. Begin with a non-stretchable line of length L buoyed vertically by a helium-filled balloon. An aircraft at altitude L above the terrain and moving at velocity V is assumed to snag the line. Looking at the action from the reference frame moving with the aircraft, the motion of the load is that which would ensue from a body moving aft at velocity V, suddenly attaching to the bottom end of the line hanging from the aircraft.

For small V, in the (unrealistic) absence of air drag and lift, the load would move as a pendulum -- first aft, then swinging down through vertical, then forward, etc. But for "high" velocity V, the load would swing aft, through the horizontal, up through the vertical, forward and down -- in a circular arc of almost constant speed. More quantitatively, there is a characteristic speed determined by the acceleration due to gravity g and the line length, such that $v^2 = 2gL$, where v is the V which will just carry the load to the horizontal.

For L=250 ft, and for $g=32.2$ ft/s^2, v = 127 ft/s or 75 knots. For the interesting case of V=250 kt (422.5 fps), the load could swing to the top of the arc and retain a (forward) speed with respect to the aircraft of 226 kt (382 fps). The nearly constant speed along the circular arc allows one to approximate the G-forces acting on the load. The centripetal force supplied by the line is v^2/L or 22 g. To this is added initially the 1-g gravity load that must also be provided by the vertical line. Note that at current parameters of 130 KIAS and L=500 ft, the g-load is 1+3 or about 4 g, with a line that does not stretch at all. Normal g-loads for personnel recovery have averaged on the order of 6 g, with some as high as 10 g, perhaps because of delay in applying load to the line.

Quite generally, if the initial g-load on a non-stretching line is G (including the one-g of gravity), the line tension when the load has swung to the horizontal is G-3, and when the line has swung to the top is G-6 times the mass of the load times the acceleration of gravity.

The Fulton Skyhook system is credited with "a near-vertical trajectory for the first 100 feet of pickup..." How does this come about? First a strictly numerical example. For a 500-ft line at 130 kt, the time to coast up the arc to 100-ft altitude is about 1.5 s.

In this time, the aircraft has moved forward at 220 fps a distance of 323 ft, while the load has swung 323 ft along the arc. The net horizontal motion of the load is 300 ft back in the aircraft frame of reference, hence 323-300 or 23 ft forward altogether.

If aircraft and load were sufficiently sturdy, the 250-ft/250-kt case would require 0.55 s to have the load rise to 100 ft, moving 232 feet along the circular arc and 200 ft horizontally in the frame of the aircraft. The net forward motion at 100 ft altitude would be 232-200 or some 32 feet, all assuming no air drag on the load to that point. In fact, the load at 100 ft altitude would be moving with a vertical component of velocity of 338 fps and a horizontal component of 169 fps.

The Fulton sky-hook system provides a truly remarkable capability. The challenge is to perfect a practical system of mitigating the g-load to about 8 g, under 250-ft/250-kt conditions. Imagine a line that truly limits g-load to 8; the acceleration of the load of mass m is $a=F/m$ for $F < 8gm$ and is then limited to 8 g by extension of the line. We later discuss several approaches to such g limitation. The vertical line immediately develops 8-g pull, with initial vertical acceleration of the load. The line extends to maintain constant tension at 8-g as the aircraft proceeds on its path. After 0.1 s, for instance, the vertical velocity is approximately 22 fps, and Vh is only about 2 fps. During the next 0.1 s, the vertical velocity reaches about 44 fps and the horizontal about 8 fps. As the aircraft proceeds at 422 fps, the line becomes more nearly horizontal, so that after 0.4 s the aircraft has travelled 169 ft, the load has been lifted some 17 feet and moved horizontally about 4 feet. But after 1.05 s, the line is just 22 degrees below the horizontal, the load has cleared the 100-ft obstacle and is accelerating horizontally at 7.2 g, and has a vertical rate of rise of 160 fps.

The characteristic benefit of the Fulton sky-hook system has not been lost, since the 100-ft obstacle-clearance distance has been extended only to 64 ft from the load start point.

We calculated the trajectory of the 250-ft/250-kt case for a no-stretch line. The g-load is clearly unacceptable at a pretty constant 23 g. The load clears a 100-ft obstacle in 0.56 s with 33 ft of horizontal motion. A calculation for an "8-g" extensible line case, with the 100-ft obstacle cleared in 1.05 s, with 64 ft of horizontal motion shows the line load falls suddenly from 8 g to 1.56 g at 2.10 s, at which time the 250-ft line is 512 ft long.

We have considered 5 options for the "stretchy line:"

(1) appropriate nylon-like material tailored to the job (105% stretch)

(2) a partially doubled inextensible line, with a friction clamp joining the two lines

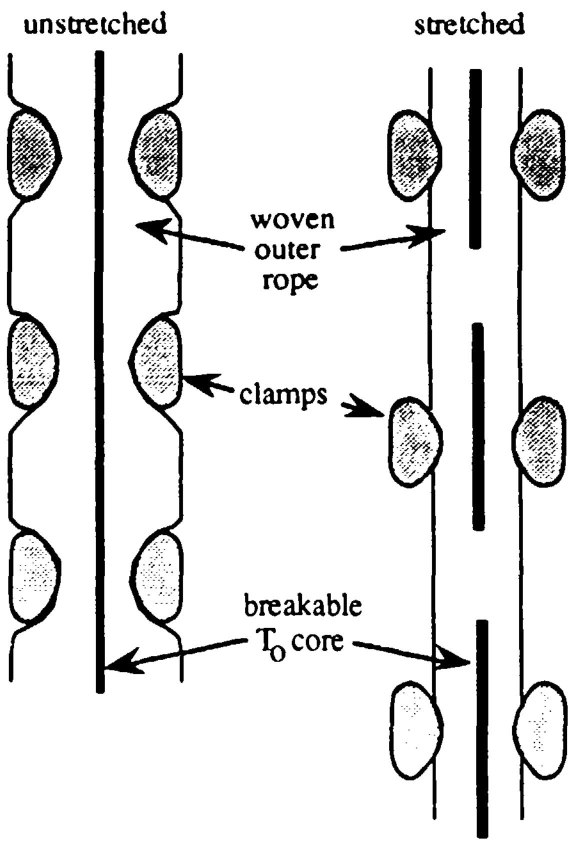
(3)providing constant-tension slack through an appropriate drag chute

(4) a tucked line with individual loops of inextensible line of strength greater than 8 g doubled by shorter snap lines of strength equal to 8 g

(5) a facility in the aircraft set to limit line load by paying out line.

We have no great knowledge of the availability of adequate mountaineering ropes, etc, so we make no further comment on the first possibility, even though it is the one used in the Fulton sky-hook system. The second approach presents a difficulty in heating of the friction clamp (through friction!) because of the 30 megajoules of dissipation required to bring a 3-ton load to aircraft velocity. This would heat to the boiling point some 100 kg of water, so it is a substantial problem to reckon with. The drag-chute approach avoids this problem -- heating free air imperceptibly -- but seems an unnecessary operational complication.

The tucked line would appear to transfer the shock energy pretty much uniformly along the load-bearing line. The following diagram illustrates the concept:



The idea is that the core would snap, allowing the rope to lengthen, whenever the tension exceeded the design value T_0. The unbreakable outer section would lengthen by a prescribed amount and then lengthen no more. (A woven rope could easily be designed to do this; the fibers don't stretch, but they pull into a more linear configuration.) As long as there were sections of the breakable core left, the tension in the rope would never exceed T_0.

The dynamics of snapping are not clear. With extension ratio of 2 to 1, it would appear to have a mass about 50% greater than that of a normal line capable of safely holding 8 g -- a penalty we would willingly pay. We were told that just such a line is used by mountaineers on glaciers, so there may be experience among the rope designers. It remains to be seen how the line design ensures against unzipping and how the 30 megajoules is safely accommodated in strain energy of the line. We must assure that a wave of snapping does not proceed down the line even when the average tension is less than T_0.

It seems that an aircraft disk brake attached to the winch as a clutch, and with access to 260 ft of slack line in the C-130 would be an adequately engineered and reliable way to limit the load and handle the dissipation in bringing the load up to aircraft speed. But if the tucked line were satisfactory, it would be a simpler and cheaper solution.

We urge that attention be paid to an automatic method of transferring the buoyed line from nose-catcher to winch line at the rear of the aircraft. The key point is to use a winch in the aircraft equipped with a clutch similar to (and probably made from) the brake of an aircraft landing gear, combined with an overrunning clutch. The capstan drum is connected to the aircraft frame by means of this clutch, so that the line can pay out at a preset load, taken here for example as 8-g. The winch itself would be clutched in after the line pay out ceased, just as a rod-and-reel fisherman may begin to reel in only after playing the fish with the brake. In particular, the power of the winch need only be enough to reel in the line at modest tension.

For instance, if the maneuver pays out enough line so that the load stabilizes in trail behind the aircraft, the winch need only pull the air drag of the load. In the 250 kt/250 ft example shown with an 8 g line, the winch must handle a force equal to 1.56 times the weight of the load. For a load of 3000 lb and a total line length of 550 ft, if one needs to reel in a tension of 5000 lbs for 550 ft in one minute, this is about 85 hp.

In the analysis that has preceded, we have not included air drag at all, but have included the small effect of the 1 g gravity field. Air drag is important, in order to keep the load from climbing the arc behind the aircraft, and to stabilize its motion. We could add in this analysis any isotropic air drag (the equivalent of a balloon or set of vanes, or could add a ram-air inflated combined lift and drag device, which seems the way to go. We leave this for future calculations, and for people more experienced in this

Nevertheless, it seems entirely feasible to perform the extraction from an aircraft in level flight at 250 kt, flying 250 ft above terrain, while subjecting the load to a maximum of 8-g, and without requiring significant new technology. The key is a simple clutch that pays out line at 8 g until the required tension falls below that level.

One may do even better by taking advantage of the maximum g tolerance for humans. The data was provided by Jim Brinkly Division Chief AAMRL, Armstrong Aerospace Medical Research Lab Wright Patterson AFB; phone (513) 255-3603,2:

Acceleration in direction parallel to spine: 12-14 g's for <1% chance of injury.

Acceleration in direction perpendicular to spine: 30-35 g's for <1% chance of injury.

Acceleration in direction perpendicular to spine: 46 g's give 50% chance of injury

The high g loads in these data undoubtedly take advantage of special "g suits" that minimize relative accelerations between parts of the body. According to Brinkley the maximum g loads for acceleration perpendicular to the spine, 12 to 14 g's, are true for both the "eyes up" and "eyes down" cases.

Thus with suitable packaging, humans can take considerably higher accelerations than the 8 g's that is now standard. It appears that in designing pods for future infil and exfil, that good advantage can be taken of these higher numbers.

Finally, for dead drops from *h* feet onto an airbag or other device providing constant deceleration in height d ft, the resultant body g's are h/d. One might carry an airbag to cushion the fall-- a 35-g cushion for a 250-ft fall would be 250/35 ≈ 7 ft deep. But 250 kt corresponds to some 2700 ft of fall, so in any case a drag chute would be needed to cut the forward speed in order to allow the air cushion or shock absorber to work. The shock absorber might be configured as a set of crushable foam stacks, or water-filled cylinders from which the water squirts through a check valve.

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