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2.0 PLANETARY IMPACT EXPERIMENTATION

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2.1 Introduction

Impact processes have operated in the Solar System from the time of formation to the present, at all scales, and on every solid body. Evidence of its effects are apparent in virtually every lunar sample and meteorite, and contributions to the cosmic-dust complex by impact are not unlikely. One of the most dominant influences on the final outcome of an impact event is the magnitude of the local gravitational acceleration (g). Furthermore, a variety of target configurations are possible across the wide range in g existing throughout the Solar System. Most experiments intended to examine the role of gravity in impact processes and to simulate some of the important target configurations in the Solar System have been severely limited or rendered only partially successful by the 1-g environment in which they have been attempted. The advent of the Space Station has provided the potential foundation upon which an impact facility could be constructed to resolve many persistent and critical questions. Specifically, by supporting laboratory studies that would address outstanding problems in accretion dynamics, asteroid evolution, cratering at very low g-levels, and regolith processes on small bodies, the Space Station would permit experimentation that is virtually impossible to perform anywhere else.

The Role of Gravity in the Impact Process

A short review of the effects of gravity on the impact process will be presented in order to establish the context for subsequent discussions. The bulk of our understanding as it is presented here reflects the results of theoretical work (particularly computer-based models and analytical approximations), laboratory experimentation (predominantly at 1-g and higher accelerations), and planetary observations.

Except for its influence on the final velocity of early ejecta, gravity has little effect on phenomena that occur during the initial stages of projectile contact and penetration: the stress field and material properties are the dominant factors at these early times. As the shock front propagates from the impact area, it encompasses a growing volume of material and, because of conservation of energy, decreases in intensity. Except for minor effects such as self-compression of the target, the rate of stress decay is essentially independent of g. When gravitational forces acting over distances similar to the dimensions of the final crater are greater than those due to the target's material strength, gravity assumes a major role in governing subsequent events. Gravity constrains the motions acquired by the shock-mobilized material, and dominates other factors in determining the volume of material removed from the cavity via ejection as opposed to that simply displaced from its initial location by compression. (The degree to which g must be reduced before "low-level" forces -- such as electrostatic attraction -- begin to control crater dimensions is unknown.) It is likely that gravity readjusts the shape of the crater even as the cavity is growing. When the gravitational acceleration is sufficiently high relative to material properties, these modifications become manifested in large craters as terraced walls, flat floors, and central uplifts. The strength of the gravity field also determines the ballistic range of ejecta. If the velocity of ejection were high enough, a reimpacting fragment would begin the formation of a secondary crater, during which the basic process would be repeated, albeit at a reduced intensity and a smaller scale. At lower velocities, simple mixing and deposition would be the rule.

Additional consideration must be given to the small bodies of the Solar System. Initially coherent objects could be severely fragmented by a single large impact or through repetitive pounding by smaller events. Such bodies would be held together not by material strength, but by their own gravitational fields. If no such effect were to occur, it is likely that many members of the present asteroid population would not exist today, due to their dispersal during major collisions. It is possible that an unconsolidated object could be disrupted by an impact below some threshold, only to be "reconstituted" by virtue of its own gravitational field.

Gravity and Impact Phenomena: Geological Aspects

While the masses of ejected and displaced material are controlled by g, the final geometry of the stress field is not. Insofar as the initial locations of shock-metamorphosed material are strongly tied to the geometry of the stress field, they are also independent of g. Thus, the dispersal of shock-metamorphosed material (impact melt, for example) might depend on gravity; if g were very low, highly shocked material might escape from the target body completely. This combination of effects might cause deficiencies of impact-melted material in regoliths on small bodies. If these fragments were ejected at speeds above the target's escape velocity, they could become meteorites or part of the cosmic-dust population. At lower speeds, the ejecta would return and comprise the crater's ejecta "blanket." The relationship between ejection velocity and g is critical in determining whether a regolith on a small body can persist, whether it would be removed by repetitive impacts, and how the shock-levels recorded in its components would compare to those in its lunar counterpart.

The rate and depth of regolith mixing is dependent on the volume of ejecta represented by the total volume of craters formed in the regolith. The volume of ejecta and the manner in which it translates into ejecta-blanket thicknesses is important in shielding samples from the solar wind, as well as from solar-flare and cosmic radiation. (These particles and their effects are used to decipher the evolution of the regoliths which they have affected as well as to probe the histories of the radiation sources themselves.) Autochthonous displacement during cavity formation in a porous regolith results in compaction and therefore a net increase in density. Not only will this alter the characteristics of subsequent cratering, but it will also encourage more effective shielding by increasing the amount of mass in a given column of material.

Having been disrupted by an impact with insufficient energy to disperse it completely, an initially differentiated asteroid would "reaccrete." During reaggregation, once differentiated layers would be mixed. A reflectance spectrum of such an object would not be representative of a single meteorite type, and potential meteorites derived from its "new" surface would probably be unusually polymict.

2.2 The Space Station and Impact Experimentation

As will be discussed in a subsequent section, it is possible to perform low and microgravity experiments with existing facilities and aircraft. Invariably, however, these capabilities fall short of those required for high-quality investigation of most of the processes and problems described above. Drop towers provide zero-g, but only for a short period of time; not only is the duration of possible experiments limited, but constraints are placed on the types of targets that could be employed. The NASA KC-135 Reduced-Gravity Aircraft can provide longer time in which to work, but atmospheric turbulence typically causes "noisy" accelerations, particularly at the lower g-levels. The Space Station, however, would provide a unique platform for experiments of extended duration at different g-levels. This exciting potential is due to three basic factors: (1) free-floating targets could be impacted to study their disruption and subsequent motions; (2) targets with more realistic or more appropriate structures than those employed in the 1-g laboratory could be fabricated and used in a variety of microgravity experiments; and (3) the actual environments on small planets, asteroids, and satellites could be simulated with high fidelity. Points (1) and (2) could be accommodated on the IOC Space Station at a simple level, while point (3) will require a means of generating "artificial gravity", more than likely through centrifugal methods. In no realistically conceivable case would all three capabilities exist in any other single facility, and none of the three could be supported to yield the requisite level of quality anywhere else.

Potential Experimentation: Selected Examples

A wide range of experiments that might be conducted with an impact facility on the Space Station has been proposed, debated, and discussed over the last few years. In the interest of brevity, however, only a few examples will be presented here.

Late-Stage Accretion Processes -- During the period between the beginning of accretion in the presolar nebula and the late stages of planet formation, an evolutionary trend between constructive and destructive processes occurred. As more of the dust and gas was absorbed by growing planetesimals, average encounter velocities grew in response to the increasingly concentrated gravitational sources, and relatively gentle coagulation was gradually replaced by high-velocity impacts.

Representative Questions: At what velocity measured relative to typical encounter velocities did the transition between net accretion and disruption occur? What factors controlled the transition between the two competing processes? Do relics of this period remain and, if so, what might be their observable characteristics? Previous Experimentation: Hartmann [1978] has performed relatively low-velocity experiments using rock, H_2O-ice, and "dirt clod" projectiles and both rock and particulate targets to map the potential for accretion vs. encounter velocity. Numerous experiments at higher velocities have been conducted to study the destructive aspect [see the review of Fujiwara, 1986]. Schultz and Gault [1986a] have impacted particulate "clouds" into particulate targets and found relatively large, "fairy-castle" structures hitherto unobserved with any other projectile-target combination. Potential Space Station Experiments: The difficulty in constructing low-density targets and projectiles in a 1-g field precludes studies using a type of configuration that might have been abundant during accretion. Indeed, the bulk of probable cosmic-dust grains collected by aircraft are porous aggregates [e.g., Brownlee, 1978]. The Space Station environment would encourage the use of similar assemblages in both low- and high- velocity experiments. Particulate "clouds" also could be employed.

Asteroid Evolution -- The rotational characteristics of observed asteroids are well documented, but the factors involved in initiating these spin rates are not fully understood. Even if these objects had formed with residual rotations, the spin angular-momentum vectors almost undoubtedly would have changed as a result of subsequent impacts. The probable existence of highly disaggregated asteroids and planetary satellites (as described in an earlier section) implies targets with little or no cohesive strength. Impacts into such bodies will result in a transfer of momentum and will generate severe stresses that would lead to further fragmentation and possibly destruction of the object as an entity. Representative Questions: How does the thickness of a fragmental layer affect momentum transfer during a major collision? Can the angular momentum gained during this type of event be sufficient to rip away that layer, or can this be accomplished only by shock-induced spallation? How does a weakly-bound asteroid break up catastrophically, and what are the relative velocities of the fragments? What is the size of the largest crater that can form on one of these "rubble piles" without destroying it? Knowing this, what does the crater Stickney reveal about the internal strength and structure of Phobos? Would a small, fast projectile be as efficient as a large, slow impactor in disrupting one of these bodies? Previous Experimentation: A variety of experiments treating collisional disruption have been performed with solid target materials [see the review of Fujiwara, 1986]. Some work into the transfer of momentum in solid [Gault and Heitowit, 1963] and particulate targets [Davis and Weidenschilling, 1982; Gault and Schultz, 1986; Schultz and Gault, 1986b] has also been performed with ballistic pendulums. Interpretation of experiments using ballistic pendulums is often made difficult by the large pendulum masses and reimpacting ejecta that contribute to the total momentum transfer. Generally, only two components of momentum can be examined in a given experiment. Potential Space Station Experiments: The ability to employ free- floating targets of widely differing compositions and structures would permit experimentation across the spectrum of possible target configurations, including noncohesive or even liquid targets that are impossible to use on the ground. Six degrees of freedom (three each in rotation and translation) would allow documentation of all momentum components in each experiment. Ejecta would not return to the target in microgravity experiments, and the extended time during which the target could be observed would permit detailed observations of its motion following the impact.

Dynamics of Crater Ejecta -- Predictions of the role of g in influencing ejection velocities have been made on the basis of dimensional analysis [Housen et al., 1983], but little data exist for testing and calibrating the theory. Regolith evolution on and loss from small bodies are highly dependent on ejection velocities which, in turn, should be dependent on g. In addition, the relationship between the stress field and the final volume and velocities of ejected material is related in no small way to the amount of highly-shocked material that can be retained in asteroidal regoliths. Representative Questions: How are ejection velocities affected by g, especially during impacts into small objects? How large must an asteroid be to retain most of the material melted in a cratering event? Would there be a general relationship between g and trends in spectral reflectance? What fraction of the cosmic- dust population can be attributed to ejecta from craters on asteroids? How much ejecta from a given crater escapes Phobos and Deimos to undergo subsequent reimpact via Soter's [1971] mechanism? Previous Experimentation: Ejecta velocities for small craters in rock [e.g., Gault et al., 1963] and sand [Oberbeck and Morrison, 1976] have been measured in the laboratory; only the sand case would be affected by g at this scale. A variety of studies has also been performed on ejecta from explosion craters, but because of significant mechanical differences between explosions and impacts, their applicability to the impact process is not complete. Potential Space

Station Experiments: Ejecta dissectors or slit-illumination techniques would be employed at different g-levels to segregate planar segments of ejecta plumes for photography and subsequent analysis. The initial points of origin of individual fragments of ejecta could be traced using established methods, such as layered targets, columnar markers, and/or individual "tracer" particles embedded in the target. Ejecta catchers could be used to measure ejecta mass as a function of range to evaluate "blanket" thicknesses and the contribution from each layer at a given range.

Regolith Processes on Small Bodies -- Most stony meteorites appear to be samples of very complex regoliths. Lunar samples have provided fundamental information about regolith evolution on a relatively large body, but important differences exist between the two sample types. Meteoritic breccias possess features common to their lunar counterparts. The meteorites, however, appear to be derived from coarser regoliths, are generally more weakly shocked, have lower solar-gas abundances by orders of magnitude, and were exposed at the surfaces of their respective parent bodies for much shorter periods. Nontrivial differences in their original environments are indicated. While much remains to be learned about the impact process on the Moon, even less is understood about the effects of impact in asteroidal environments. Because of this circumstance, the questions to be answered seem simplistic in comparison to those posed above. Relevant Questions: How small must g be before "low-level", non-gravitational forces begin to dominate cratering phenomena? Is this even a realistic consideration? Will fine-grained material be retained in sufficient quantities on small bodies to generate a regolith remotely similar to that on the Moon? If so, what are the relative fractions of excavated and compressed material during a given cratering event? Would such a regolith undergo net compression due to repetitive impact, or would it actually become more porous during the emplacement of low-velocity ejecta? Will gravitationally-retained impact melt on an asteroid or satellite be dispersed over greater areas than on the Moon? What are the potential effects of these phenomena on reflectance spectra? Previous Experiments: A large number of experiments have been performed with existing facilities, leading to much of our current practical knowledge of cratering processes; they are too numerous to be cited here. Very few have been conducted at reduced-g. Although it is possible to perform reduced-g experiments with existing facilities, as has been done with the Ames Vertical Gun [Gault and Wedekind, 1977], the durations of the lowest g-levels are very limited. Low-velocity experiments also have been conducted on the NASA KC-135 Reduced-Gravity Aircraft [Cintala et al., this volume] at relatively high atmospheric pressures. Potential Space Station Experiments: Assuming that the desired range of g-levels would be available, an exploratory series of impacts would be performed at accelerations of 0.1 to 0.01 g. In addition to those listed in the Ejecta Dynamics section, parameters such as crater dimensions, subsurface displacements, distribution of shocked material, target grain-size effects, and density changes in the target will be analyzed. Should gravity continue to dominate the process at the lowest g-level employed in the series, further reductions in g would be applied in an effort to determine the limits of influence.

In listing the types of experiments that could be performed with a Space Station facility, it is natural to recall previous activities in ground-based laboratories. In doing so, however, one rapidly comes to the realization that, had a similar exercise been attempted in justifying the proposed construction of the NASA Ames Vertical Gun, for instance, foresight would not have made a strong showing. That facility, built to evaluate impact cratering as a potentially important process active on the lunar surface, has since been used in a myriad of studies that could not have been predicted at the time. Instead of listing those investigations, it will simply be suggested that the use of a Space Station facility would be analogous to that of the Ames and other guns in the sense that many, and probably most, of the experiments that could be performed in the microgravity laboratory have not even been imagined yet.

2.3 Experimentation in Reduced Gravity: Practical Considerations

A low-level effort has been underway since the latter part of 1984 to evaluate the requirements of performing experimentation at reduced-g. These studies have been made possible by the availability of the NASA KC-135 Reduced-Gravity Aircraft, which is the responsibility of the Johnson Space Center and based at Ellington Field in Houston.

The NASA KC-135 Reduced-Gravity Aircraft

The NASA KC-135 Reduced-Gravity Aircraft is a Boeing 707, specially modified to support zero-gravity flight. With only a few passenger seats in the rear of the aircraft, it presents a large volume to the experimenter for hardware and its operation. A typical "zero-g" parabola has a duration of ~23 seconds, while lunar- and martian-g maneuvers can last up to ~35 and 45 seconds, respectively. Due to atmospheric turbulence and density variations, winds, and other factors, a given g-level can be held to within roughly 0.05g; thus, lower g-levels become relatively "noisier" in terms of the targeted accelerations, with the result that the higher g-levels are generally "smoother." Should very low accelerations be required, relatively short periods (on the order of 5-10 seconds) of nearly zero-g can be obtained by detaching the necessary hardware from the airframe and "free-floating" it in the cabin. The desired sequence of maneuvers is determined before flight, although considerable flexibility exists in terms of real-time changes.

The Experimental Hardware

Details regarding the experimental apparatus can be found elsewhere [Cintala et al., this volume]; an abbreviated summary will be presented here to establish a context for the following discussion and comments. The low-velocity impact facility consists of a glass-walled, aluminum-framework box (52 cm x 52 cm x 48 cm) on the top of which is mounted a vertically-oriented Sheridan pellet pistol, modified to be fired electronically. A microcomputer controls event sequencing, which includes camera operation, recording of acceleration and atmospheric pressure data, firing the gun, and recording detector information for determination of projectile velocities. This facility, intended to be flown again in 1986, is limited in terms of impact velocity (maximum of ~130 m/s with lead pellets), lack of a vacuum system (meaning that all impacts take place at cabin-atmosphere pressure, ~0.85 atm), and container size. Nevertheless, a good deal of practical information has been collected thus far. Trends in crater scaling were found to be similar to those found through 1-g and centrifuge studies, with some variations whose causes are not yet established. Crater growth-times tentatively appear to be at variance with both theoretical predictions and extrapolations from ground-based data; this latter observation, however, will require more data before any claims can be made with confidence.

Practical Lessons Taught by the KC-135

Due to the rapid changes in acceleration, activities performed on the KC-135 can be extrapolated to the orbital environment only with some caution. Even so, the aircraft provides information that would be impossible to obtain otherwise. A few points will be presented here.

Scale -- For a given set of impact conditions, a crater will be larger in a lower g-field than a crater formed in a higher g-field. In designing a facility for cratering experiments in reduced gravity, this phenomenon is the cause of what is perhaps the principal experimental concern. Even at the low projectile energies employed in the KC-135 experiments, it is apparent that a larger target chamber and target container is necessary for serious investigations. Craters take so long to grow at the low g-levels that the first -- and fastest -- ejecta to leave the crater has sufficient time to rebound off the chamber walls and impact in the vicinity of the growing cavity. This could become a significant problem in serious attempts to perform cratering investigations. Two independent suggestions have been made, and the ideal solution would employ both. The first is obvious, but the most expensive in terms of volume: make the impact chamber and target containers large. The absolute dimensions, however, are difficult to suggest in the absence of data at low g-levels; conversely, it is entirely possible that the final dimensions of the physical apparatus will dictate the minimum g-level for which meaningful experiments could be conducted.

Employing the second solution would result in an impact chamber lined with mechanical ejecta catchers or deflectors; a sort of "monoclinic honeycomb" would be an example of the kind of device envisioned.

The question of scale persists, however, when the actual growth of the crater is considered. The longer it takes a crater to grow, the more time exists for stress waves to reflect from the container and interfere with the expanding cavity. Again, the lack of data at the low g-levels precludes a meaningful treatment of the problem. Obviously, the ejecta catchers/deflectors would be of little help in this case. These topics will be considered further in a subsequent section.

Experiments employing free-floating targets will require sufficient free space to permit unconstrained motion for a few seconds following impact. Since collisions with rebounding ejecta also would complicate matters, some of the same considerations described above remain applicable in these studies. An additional factor involved in both areas of experimentation is the effect due to muzzle blast from the projectile accelerator. While this point would be academic if an electromagnetic or other "clean" accelerator were used, the use of either a powder or light-gas gun would require both active blast-deflection measures and some distance between the accelerator's muzzle and the impact region. Such techniques exist, and their incorporation is not considered to be a problem.

Free-Floating Targets -- This topic is somewhat more difficult to address specifically, since experiments involving free-floating targets have not yet been attempted. On the other hand, many impromptu experiments using cameras, film canisters, pens, and other assorted objects have been performed during "zero-g" portions of KC-135 flights. These trials have shown that it is difficult to release an object by hand without imparting undesired motions, and there is widespread agreement between those who have been involved in this sort of activity that a relatively motionless release will require a special target-holding and release mechanism. It is intended to attempt experiments with free-floating targets on the KC-135 in the relatively near future; more specific information regarding release methods and other idiosyncrasies inherent in the technique should then be forthcoming.

Time -- Once one is accustomed to the peculiarities, working in the low-g environment is no more difficult than in the 1-g laboratory. Indeed, when it comes to moving massive objects, the low-g case is much less exhausting, and activities can generally be performed at a faster pace. On the other hand, more time must usually be spent overall during a complete experiment in low- or "zero-g" than in the ground-based laboratory. On the ground, the small items necessary in experiment operations (nuts and bolts, film canisters, pencils, tools, etc) can be and usually are left on a workbench or table. For obvious reasons, this cannot be done in zero-g, and stowing each piece of equipment after its use takes time. By the same token, cleanup after each experiment is somewhat more tedious, since dirt and debris do not fall to the floor or a corner of the chamber, but must be removed from what is typically a very hectic three-dimensional volume. The addition of a sensible gravity field, however, alleviates many of these small but irksome problems.

Overall, the tasks requiring more time tend to be offset by those taking less, but the net result still leans toward a longer period of time to perform a given experiment. Nevertheless, the difference is not dramatic. Impact experimentation in a reduced or microgravity environment is by no means an overwhelming proposition; indeed, with a modicum of experience, it is no more difficult than its ground-based counterpart.

2.4 The Road to the Space Station

A variety of studies, discussions, experiments, and workshops over the past two years [see Appendix A] has led to the realization that the planetary impact community cannot claim vast experience in microgravity experimentation. This has resulted in the recommendation that a phased approach toward impact experimentation on the Space Station be adopted in order to gain some of that experience; simultaneously, a base of fundamental scientific knowledge would be obtained. This approach can be divided into four distinct stages which, in the ideal case, would overlap in a temporal sense: (1) "pathfinder" experimentation, both ground-based and on the KC-135; (2) STS experiments; (3) a relatively simple IOC Space Station facility; and (4) a post-IOC, dedicated Space Station Impact Facility. Each stage will provide engineering and other technical information to support the next step in hardware complexity, and also will raise the level of sophistication of the scientific data. It is likely that the first three stages will be undertaken by a few research groups. Although it is probable that a KC-135 facility would be open to interested scientists, the dedicated Space Station impact laboratory would be a national or international facility, for use by all qualified investigators.

The Pathfinder Activities

As discussed above, an array of topics must be addressed before sophisticated experimentation at very low g-levels can be conducted effectively and efficiently; principal among these is the persistent issue of experiment scale. Due to the many questions remaining unanswered with respect to crater scaling, it is likely that the first IOC experiments which will probably be done in a facility of limited size would involve free-floating targets. It is essential, then, that experience be gained not only in assessing the dimensional constraints for the cratering experiments, but also in performing investigations with the free-floating targets. This sort of background information can be obtained only through experimentation, using existing NASA facilities such as the Ames Vertical Gun Range, the Johnson Space Center Vertical Impact Facility, the NASA KC-135 Reduced-Gravity Aircraft, and the various drop towers. The latter two will also be instrumental in providing initial information for the IOC concept.

The STS Experiment Package

Existing drop towers provide a relatively stable zero-g, which is limited in duration to only about 10 seconds; delicate instrumentation would likely be destroyed or heavily damaged upon impact of the experiment chamber. The KC-135, on the other hand, can supply more time but a "noisier" g-level, especially at accelerations approaching zero-g. While they would be very useful for the early development efforts, the next major advance would require investigations on Space Shuttle orbiters. In addition to the greater volume and other support necessary for experimentation, Shuttle orbiters can provide a low-g environment for extended periods of time. Valuable experience would be gained in the areas of handling target materials, target fabrication, testing preliminary versions of the IOC experiment package, and general housekeeping. High-quality data could be expected from these experiments.

The IOC Space Station Impact Facility

As indicated above, this first phase of experimentation on the Space Station will probably concentrate on impacts of free-floating targets for both operational and scientific reasons. Available volume will be limited in the initial stages of Space Station operations. Variable-g capabilities are highly unlikely, and the studies utilizing the free-floating targets would provide an early information return.

The hardware necessary for these experiments could be relatively compact, taking perhaps the space of a double rack (approximately 100 cm x 100 cm x 200 cm); the accelerator might require some small volume in addition to this. In order to minimize the undesirable muzzle-blast complications cited earlier, some distance would be required between the target and the accelerator. This might be effected by pivoting the gun outside the laboratory module via an airlock mechanism, or by mounting it radially outward in the module, perpendicular to its major axis. Should advances in limiting muzzle-blast have been made in the meantime, however, it is entirely possible that the accelerator could be included within the double-rack volume.

This experiment package will possess a vacuum-capable impact chamber, an accelerator able to launch projectiles to velocities between 0.1 and 2.5 km/s, diagnostic instrumentation, and data-collection equipment such as film and video cameras and digital recording devices. It is anticipated that this facility will be a direct outgrowth of the STS package, with improvements made on the basis of that experience.

2.5 The Space Station Impact Facility

The ultimate configuration of the post-IOC Space Station facility is certainly not established and will undoubtedly evolve from that currently envisioned. Nevertheless, the flavor of its desired characteristics can be conveyed by a description of the preliminary view obtained over the past three-years' effort. Generally speaking, five key requirements have emerged: (1) variable-g capability; (2) a large impact chamber; (3) ability to launch a variety of projectile types and sizes over a wide range of velocities; (4) flexibility in fabricating targets of different compositions, structures, geometries, and physical states; and (5) "hands-on" experiment operation.

Variable-g Capability

The ability to subject the target(s) to a preselected g-level is a principal reason for suggesting this facility. The undesired accelerations suffered by the KC-135 at very low g-levels make it extremely desirable to attain and sustain levels between ~10^{-5} to 0.2g. This range will permit experiments involving free-floating targets as well as those overlapping the capabilities of the KC-135. The source of the variable g-levels is problematic at present, although it almost certainly will involve the application of centrifugal acceleration. The prevailing view has assumed the undocking and spinup of a habitable module for general low-g operations, a capability which might benefit other user groups. The details of this operation remain to be defined.

Impact Chamber

As cited earlier, a variety of reasons lead to the requirement of a large impact chamber, among them being stress-wave reflections and rebounding ejecta. In addition, a fragment of ejecta can be tracked longer in its trajectory in a large chamber, free-floating targets could be monitored for a longer period of time after impact, more diagnostic instrumentation can be placed in a larger chamber, and more energetic events could be accommodated at lower g-levels. A chamber at least 4 meters in length by 4 meters in diameter would be sufficient to accommodate the potential experiments as currently envisioned. Although this might seem to be inordinately large, a useful analogy can be made with the Ames Vertical Gun's impact chamber, which is 2.5 meters in diameter. Craters formed with the light-gas gun in sand are typically 30-35 cm in diameter, which is one-eighth the diameter of the chamber; rebounding ejecta in this chamber at 1-g are seldom a problem. Identical projectiles at low g-levels, on the other hand, could easily form craters more than a meter in diameter in sand; the 4 meter space station chamber relative to a crater of this size, would be only half as large when compared to the Ames case above. Clearly, a more voluminous chamber would be highly desirable. The facility could conceivably be used in its earlier stages with a smaller chamber inside the laboratory module. It is more likely, however, that the final version will include an attachable chamber via a docking port or an airlock. With this in mind, it is strongly urged that hatches/airlocks at least 1 meter in diameter be included in the module containing the impact facility; a decision implementing the proposed 50- inch hatches would be welcome indeed by users of the impact facility. A suggestion with some potential employs an inflatable chamber fabricated with a tough composite or similar material. It would occupy a small volume when idle, and, with the proper materials and some ingenuity, could even be larger than the minimum size suggested above.

Projectile Accelerators

Not only will a wide range of impact velocities be required by users of the facility (~0.1 to at least 7 km/s), but a variety of projectile compositions (e.g., metal, plastic, glass, rock, etc.) and sizes (small "grains" to spheres or cylinders up to perhaps 2 cm in diameter) will also be employed. In light of present technology, this implies the use of air, powder, and light-gas guns. On the other hand, technological advances in attaining high velocities (rail guns, mass drivers, and electrothermal guns, for example) might well provide alternatives, in terms of efficiency, mass, and/or performance; it is important that the potential incorporation of such accelerators not be excluded from the final design by default. All of the non-induction accelerators produce exhaust gases and debris as by-products of their operation; not only must the contamination of the chamber be kept to a minimum, but the gases must be removed by venting or containment. Experiments involving low-yield explosives might also be performed.

Instrumentation and Support Hardware

Three general categories of instrumentation required will be used for (1) monitoring gun-firing and the chamber environment, (2) recording the impact event and subsequent phenomena, and (3) post-experiment analysis. The first group includes items such as computer-controlled and monitored gun operations and sequencing, flash x-ray generators and detectors, pressure and temperature gauges, and accelerometers. Event recording will be performed by various cameras, including both film and video, with lighting to support very high and relatively low framing rates; additional equipment should include devices such as pressure transducers, multichannel digital recorders, holographic systems, and spectrometers. It is likely that many of these instruments will be controlled and/or monitored by computers, which would also be used for scientific programming in tasks such as data reduction. Post-experiment analysis will require microscopes, various photographic and holographic systems, "scales" for mass determination, and sieves.

Target Preparation and Housekeeping

Additional, more mundane hardware will be required for target preparation, facility maintenance, projectile construction, and the other activities necessary for successful impact experimentation. A brief representative listing in this important area includes a small machine shop, a "workbench," target containers, microwave and thermal ovens, vacuum systems, a freezer, an ice crusher, an oscilloscope, and various temperature and pressure transducers. This sort of equipment would almost certainly be needed by other research groups, and could be part of a shared equipment pool.

Personnel

A minimum of two experimenters equivalent to STS payload specialists will be required for efficient operation of the facility, with two backup specialists on the ground.

2.6 Summary

An understanding of impact processes in low- and microgravity environments would be advanced significantly by the construction and use of an impact facility on the Space Station. It is proposed that initial studies begin as soon as possible in ground-based impact laboratories, on the NASA KC-135 Reduced-Gravity Aircraft, and in existing drop towers. The resulting experience and information base could then be applied toward an experiment package designed for use on Shuttle orbiters to support pilot studies in orbital environments. These experiments, as well as the first efforts made on the IOC Space Station, should involve the impact of various free-floating targets; such studies would yield a substantial scientific return while providing valuable experience and engineering information for use in refining the design of the dedicated Space Station Impact Facility. The dedicated facility should be designed to support impact experimentation, including but not limited to cratering, asteroid and ring-particle dynamics, and accretional processes.

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