Statement of

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Introduction

Mr. Chairman and members of the Science Committee:

Thank you for the invitation to come before you and participate in this hearing on the Future of Human Space Flight. I am honored by your request.

Like many Americans, I sat riveted to the television that Saturday morning when the shuttle *Columbia* and her crew failed to come home safely. I was both stunned and saddened as I sat and watched and wondered, "How could this have happened?"

As a scientist, I have participated in research experiments that flew on three of *Columbia's* previous flights (STS-62 in 1994, STS-75 in 1996, and STS-87 in 1997), and thus I felt a special kinship to the *Columbia* and her crew. In a curious way, I felt that the *Columbia* was *my* shuttle. I had briefed and spoken with the crews of the three *Columbia* missions that I had worked on, and in doing so I had met Kalpana Chawla one of *Columbia's* crewmembers who had just perished. I felt great sadness and sympathy for the families of the astronauts who died.

As I continued to watch the news coverage of the unfolding tragedy, I began to feel growing remorse and personal responsibility. STS-107 was a dedicated science mission, much like those in which I had participated. I asked myself if I, as a participating scientist in prior dedicated science missions, was in any way responsible for what had just occurred.

I thought back to my own time at the Marshall Space Flight Center in Huntsville, Alabama. While monitoring and controlling my experiments, my colleagues and I spoke often of the extraordinary risks that the shuttle astronauts took each time they flew a mission. We knew that the astronauts understood the risks and accepted them willingly. As scientists, we believed we understood the risks, and we debated whether or not we bore any responsibility for the acceptance of those risks. Even though our experiments were part of the payload brought to orbit by the crew, and served as partial justification for the mission, we confidently concluded that we were not responsible for any of the risk. We reasoned that NASA created and maintains the shuttle program in support of NASA's larger mission for the human exploration and development of space and not solely for the performance of laboratory science on orbit. Therefore, we concluded that we could not be responsible for the risks assumed.

Although our reasoning then may have been correct technically, our confident conclusion now seems utterly feckless and shamefully inadequate. That convenient, yet obviously hollow reasoning came crashing down to earth with the *Columbia* last February. As I sat and I watched, I realized that I must bear my share of the responsibility for the *Columbia* accident.

Unlike the astronauts who either conduct or bring these experiments to orbit, scientists like me, with the exception of a few Payload Specialists, never put their own lives on the line for the work that they do or the rewards that can follow a successful experiment. Is this then the source of the scientist's culpability that we reap the rewards while standing on the shoulders of others who assume the risks? No, I think not. The scientist's culpability stems from a conceit that we have long acknowledged privately but have not expressed publicly:

> **The vast majority of physical science experiments conducted in orbit simply do <u>not</u> require on-board human intervention or assistance.**

As penance for quietly accepting the benefits of on-orbit experiments without sharing the risks or expressing the alternatives, I need to say publicly that the cost of using astronauts to perform science experiments in space is too high both in dollars spent and in lives lost. At the risk of incurring my colleagues' wrath, I feel compelled to say that I, and the other scientists who reveled in the glory of conducting experiments aboard the shuttle, are not blameless. In that spirit, I wrote an article that subsequently appeared as an op-ed in the *New York Times* on Sunday, June 29, 2003 (see Exhibit 1, attached hereto).

Since the publication of that article, I have heard from many of my colleagues, both within and outside of NASA. Most of my fellow scientists who responded expressed their support and agreement with my article, but not all. I have engaged in lively discussions with many who have disagreed with the opinions I expressed in my article, and through those discussions, we are finding and forging common ground. My testimony here today has benefited from these discussions.

Answers To Specific Questions Submitted By The Chair

- **How necessary is it to have the participation of people in space for successful research in materials science?**

There are two types of on-orbit laboratory science experiments performed on the shuttle: (1) payload experiments and (2) laboratory experiments. Payload experiments are self-contained packages mounted in the payload bay of the shuttle. They run autonomously or are controlled remotely from the ground by the scientists and engineers who designed and built them. No human intervention is required for payload experiments. By contrast, laboratory experiments are conducted in the mid-deck or Spacelab module, and were generally operated by astronauts with teleoperational assistance from scientists on the ground.

Of the two varieties of experiments, payload experiments tend to be larger, more ambitious and robust, and historically delivered more useful data and results. Astronauts have limited time and capabilities to conduct elaborate experiments in space.

Although rarely the subject of popular media, most of the experiments in materials science conducted on orbit were payload experiments. This simple and irrefutable fact demonstrates that it is not necessary to have human participation to conduct orbital research in materials science.

While I do not profess to be an expert in fields other than my own, it follows that human participation has not been and is not essential to conduct orbital research in Fundamental Physics, as the majority of those experiments were conducted as payload experiments. In addition, and despite that the majority of experiments in both Fluids and Combustion were not conducted as payload experiments, I believe that the participation of people in space is not strictly necessary to conduct orbital research in either of these disciplines.

- **What proportion, if any, of the experiments now conducted on the Space Shuttle or Space Station unmanned probes could conduct autonomously?**

There are very few science experiments, save those on human themselves, that were conducted on the Space Shuttle or Space Station that could not have been conducted autonomously or remotely. At the outset, making on-orbit experiments fully autonomous or remote controlled will require more development time, and the experiment design would most likely need to be more complicated and involved, but it can most certainly be accomplished. Speaking immodestly, scientists and engineers are a creative and gifted bunch and are more than up to the task of finding new ways to conduct orbital research without on-site human assistance.

Nonetheless, with apologies to the Committee, I respectfully submit that we are asking the wrong question. The *Columbia* Accident Investigation Board concluded that the burden of proof must be reversed on any future shuttle missions. Instead of awaiting evidence that the shuttle might be unsafe to fly, on any future missions, NASA must instead affirmatively demonstrate that the shuttle is safe to fly. Given the grave risk to human life orbital research involves, scientific experiments ought to meet that same exacting standard. If a scientist proposes an orbital experiment to be conducted by astronauts aboard the Shuttle or the Space Station, he or she must demonstrate by a preponderance of evidence that human assistance is only reasonable way to conduct the given experiment.

Although some may believe me audacious for making such a sweeping statement, I submit here today that almost all the physical science experiments now conducted on the Space Shuttle or Space Station could be conducted autonomously or remotely. In addition, I believe that many life science experiments, save those using human themselves as subjects, could be conducted autonomously or remotely as well.

I have made a broad and bold assertion, and one that requires some additional explanation. To do that, let's imagine a hypothetical "experiment" where we want to compare how water and milk freeze in ice cube trays. The easiest way to proceed is to get a freezer, some ice cube trays, a camera, some thermometers, and a computer. Then, one after another, fill the ice-cube trays, place them in the freezer, and record what happens. This is simple, fast, and completely human dependent. If we were to repeat this experiment in a dangerous environment, the needs and requirements of the human operator to exchange the ice-cube trays would be a major concern and complicating factor. If we were to repeat this imaginary experiment on orbit, the human operator is placed at extreme risk, and at a minimum requires significant infrastructure and support. In this imaginary experiment, the ease of conducting the experiment via human operators is clearly offset by the complexities and risk of getting the operators safely to orbit and back, and of sustaining them while in orbit. The added complexities, development time, expertise and effort to automate or remotely control the exchange ice cube trays and the recording of data is quite obviously the best way to proceed. This is very much the situation we are in with respect to human enabled experiments on the space shuttle or space station.

In the case of the Space Shuttle and Space Station, the infrastructure and facilities to support humans on orbit is already there. So it is certainly easier to design smaller experiments to operate in the laboratory mode with astronauts running experiments that are important and compelling. However, this is an efficacy and not a requirement. With sufficient development time, funding, and expertise, virtually all physical science experiments now conducted on orbit could be done either autonomously or remotely. In addition, doing so would be consistent with the *Columbia* Accident Investigation Board's recommendation to separate humans from cargo.

It is easy to imagine the criticisms to this analysis from those who believe that direct on board human engagement is required. They might say that intelligent response is required to deal with unanticipated phenomena, or that a particular instrumental dexterity is required, or that humans are needed to troubleshoot and repair instruments and equipment, or that we need human involvement to realize serendipitous discoveries. To be sure, all of these criticisms have an element of truth, but in the end, they do not withstand detailed scrutiny.

The creative input of human intelligence to deal with unanticipated phenomena is a hallmark and a necessity of experimental science. Indeed in many experiments there will be contingencies that were not preprogrammed into an automated system. However the remote control of orbital experiments provides the necessary human intervention. The scientists on the ground who are most expert in the phenomena and the experimental apparatus are the most qualified to recognize the need for change, and to make that change. If a hardware or equipment modification is now called for, then a re-flight is the best way to make that modification.

For the issue of instrumental dexterity, clearly humans are better at some tasks while computer or technology is better at others. However in experimental science there is no single correct way to accomplish a particular task. There are many ways that work and the job of the experiment designer is to find a way that works. That way may require the unique abilities or advantage of a human operator and may indeed be the simplest and most straightforward way to accomplish a particular task. However it is extraordinarily unlikely that it is the only way. The challenge of the design team is to figure out a way to accomplish the task that does not require human dexterity.

Troubleshooting or repair of apparatus and equipment is most definitely an area where humans excel as compared to autonomous or remote control systems. However I know of no experiment so important that it is required that it be successful on the particular flight it is manifested. It seems to me that in such cases where repair is necessary, that the repairs could take place post flight and the experiment could be re-manifested and flown in due course.

Advocates for an on board human role in physical science experiments often claim that the serendipitous discoveries that are vital to the continuing advancement of science require a human being with all five senses activity involved in the experiment. I certainly agree that serendipitous discoveries are vital to a healthy science. Today's directed research questions often came from yesterday's serendipitous discovery. However the key to these discoveries lies in the mind of the scientist and not in the sense instruments. In addition, who is more likely to make a serendipitous discovery? The astronaut, who no matter how extraordinary, or well trained, has many experiments and tasks to monitor and is not an expert in the particular experiment. Or the science team on the ground comprised of the experts who designed the experiment and are engaged with the tele-metered data full time? Clearly the scientists on the ground are better prepared to make serendipitous discoveries.

In addition, of the five human senses, only taste and smell cannot be bettered via instruments. We certainly don't want astronauts using their sense of taste or smell in performing experiments on orbit. To protect the astronauts, we rightly require that every experiment be carefully contained and confined to ensure no breeches or leaks that could be inhaled or ingested. Furthermore, the apparent weightless environment affects the astronaut's sense of smell and taste and serendipitous discoveries come from the superior sensitivity of cameras and sensors that record precise data at high data rates. Thus, many of the subsequent unanticipated discoveries come later, and these discoveries are made by the science teams who even years later are still studying and analyzing the data from a flight experiment.

To be sure, with a broad and sweeping statement such as "almost all the physical science experiments now conducted on the Space Shuttle or Space Station could be conducted autonomously or remotely" there will be exceptions. I thank the many scientists who took the time to discuss their concerns with me following the publication of my article. However, because I believe these situations will be the exception rather than the rule, it goes without saying that we need a well-designed rubric to determine when an exception is warranted even if it has been demonstrated with a preponderance of evidence that human tending is absolutely required.

First, is there sufficient probable value in the results of the given experiment? If it were probable, or even reasonable possible, that the human tending of a given experiment would yield key or irreplaceable results on the path to curing cancer then that experiment would be worth the established costs and risks. For such a seminal experiment even I would be able to overcome my fear of flight to participate in such an endeavor. However, revolutionary results of that dimension are extraordinarily rare in science and should not be the basis of policy. Science grows and develops by innumerable small and hesitant steps, and its power comes from, as the great philosopher of science Alfred North Whitehead said, "…the entire transformation of human habits and human mentality produced by the long line of men of thought from Thales to the present day, men individually powerless, but ultimately the rulers of the world."

Second, as discussed above, scientists must be made to demonstrate that human tending of their experiment is vital to the success of their experiment. Put bluntly, the experiments of scientists who are unwilling or unable to state why their experiment could not be designed to run autonomously or remotely ought to not receive access to precious orbital research time, money, and space. Or alternately they affirm that the flight and the risk are bourn for other reasons and the human tended science experiment is a valuable add on. As the *Challenger* and *Columbia* tragedies have made all too apparent, science must be accountable for the high costs and substantial risks human-tended experiments entail. We scientists should no longer be given a free ride on these issues.

This very change in philosophy of on-orbit scientific pursuits has already begun in the field of astronomy. NASA has chartered a panel to review agency plans for the phase out of the Hubble Space Telescope to the transition to James Webb Space Telescope. The Hubble Space Telescope however could still be further enhanced and its life extended by Space Shuttle servicing missions. Naturally such missions are both risky and expensive. Not being an astronomer, I take it as axiomatic that such missions would significantly contribute to astronomy, and that in any reasonable near term such a mission could not be conducted robotically or remotely. The question then that the panel must answer and take ownership of is "is the further enhancement and use of the Hubble Space telescope worth the risk and the expense of a shuttle servicing mission?"

- **If researchers no longer had access the Space Shuttle or Space Station how would advancement in the material sciences be affected?**

If researchers no longer had access the Space Shuttle or Space Station, then a vital research area in the advancement in the materials sciences would be halted.

With the indulgence of the Committee, I would like to briefly discuss my field of expertise and how orbital research has played a key role in promoting understanding of our physical world. One of the major thematic elements in the research and manufacturing of materials is what is termed the *microstructure*. The understanding and control of microstructure is one of the ultimate goals of both the materials scientist and materials engineer. A material's microstructure includes not only what atoms make up a material (composition), but also *how* are those atoms arranged (structure).What is the geometry of these atomic arrangements and what patterns emerge? Microstructure is a vital theme in materials science because it appears in both major paradigms of material science. That is, the way a material is formed determines its microstructure, and a material's microstructure determines how it behaves. This then, of course, determines whether or not a material is useful for a given engineering purpose.

Historically, during the emergence and development of materials science, scientists were most interested in the two microstructures that could be completely described, perfect single crystals and completely disordered glasses. Nonetheless, important aspects of a specimen's properties depend on a range of complex microstructures that exist between these two extremes. They could not be addressed from a general scientific or engineering methodology until the description and behavior of those complex microstructures were better understood. For most materials, this analysis requires the understanding of how solids form from their melts. For metals and alloys, such an analysis further requires an understanding of what we call dendritic solidification.

During the past fourteen years my research activities have concentrated in the examination of microstructure as it concerns dendritic solidification. Dendritic solidification is the transformation of a molten liquid into a complex, tree-like branching crystalline microstructure. Dendrites are known to appear in the freezing of water, molten salts, ceramic materials, organic materials, and most importantly in the solidification of metals and alloys. I have been personally involved in the experimental investigation of the growth of thermal dendrites. With the aid of NASA's orbital facilities and programs we have made substantial progress because the effective reduction in gravitational body forces on orbit enabled us to understand details of the process that we were not able to accomplish otherwise.

The NASA materials science program has also made substantial gains in the understanding of microstructure. Currently, through its flight programs, NASA is the leading governmental agency in promoting and enabling the understanding of microstructure.

With respect to dendritic solidification in particular, despite the recent advances, the following quote from 1999's National Research Council's (NRC's) report on *Condensed Matter and Materials Physics* makes clear there is more to be done. The report states,

> Very significant progress has been made in the last decade in understanding dendritic pattern formation in crystal growth. That progress, however, has yet to have a major impact on efforts to predict and control solidification microstructures in industrially important materials. In part, the difficulty is that there remain some challenging scientific problems to be solved, such as the 'mushy zone'. Another part of the difficulty is that there is relatively little effort in this area in the United States, especially in industrial laboratories.

Work remains to be done both in understanding additional details about dendritic growth, and in bridging the gap between our understanding of an isolated isothermal dendrite and the final, as-cast microstructure of metals and alloys. The "mushy zone" during dendritic solidification processes is the region where solidification is actively occurring, and the material is part liquid and part solid (hence the term "mushy zone"). This zone consists of many dendrites, each growing in a complicated manner, interacting with their neighboring dendrites. The ultimate scientific goal is to understand this process in its entirety. But to reach this goal, it is necessary to first understand how individual dendrites grow, both isolated from and subject to external influences. This is the substance of several NASA funded projects.

The fact that NASA has been funding research on dendrites since the mid 1970's, both in ground and flight programs, and that the research is now so varied and so vibrant, is evidence of the success of NASA physical science in space program. Using the orbital environment to continue this progress in understanding dendrites is vital. If the access to orbit were eliminated, then the most fruitful avenue of advancement on this important topic will be halted. While orbital research is vital, I content that human tended scientific missions are not absolutely necessary to continued progress in our quest to understand more about microstructure.

And while I have mentioned research on dendrites specifically, I am mindful that the research in which I participate is but one of many examples of productive lines of research in materials science. There are many additional examples of important research being done in the fields of Fluids, Combustion, Fundamental Physics, and Biotechnology. Since I cannot speak authoritatively on these fields, I refer the Committee to experts in those scientific fields.

- **What alternatives exist to carry to orbit micro-gravity experiments that could be conducted autonomously if the Space Shuttle or Space Station were not available for whatever reason?**

To the best of my knowledge, at this time, there are no alternatives for autonomous or remote operations of on orbit experiments if the Space Shuttle or Space Station were unavailable. NASA has extensive ground programs that use drop tubes, drop towers, and parabolic airplane flights to provide from 2 to 25 seconds of apparent weightlessness. These are valuable and productive programs in their own right, but they are not a substitute for long duration orbital flight experiments.

I believe that the Office of Biological and Physical Research in Space has begun to discuss an autonomous or remote platform, but no action or commitment to such a program has been made.

- **If none, how much would it cost NASA to provide researchers such an alternative?**

I do not have the necessary expertise to make a specific financial estimate of what a free flying, on orbit, autonomous or remote controlled facility would cost. However, I can detail the tradeoffs between an autonomous/remote facility versus that of continued human enabled facilities. In my view, these trade-offs favor the autonomous/remote facility.

NASA already has the appropriate expertise at the Office of Biological and Physical Research in Space and at the various field centers to design, built, launch, operate, and recover an autonomous/remotely controlled payload platforms. The only new feature would be the newly designed and built space flight hardware for these operations.

If experiments had to be designed for an autonomous/remotely controlled facility, there would be both cost increases and savings. The cost increases would be to design and built autonomous or remotely controlled experiments in place of those that were formerly designed for astronaut operation. Similarly, those experiments that were built to operate autonomously or remotely could be scaled back some because of the relaxation of constraints necessary for flight aboard a human tended spacecraft.

The greater cost savings would occur because there would be no need to launch and operate shuttles dedicated to physical science experiments. There would be significantly less upmass to the International Space Station for physical science experiments. The Space Station itself could be scaled back as there would be no need for laboratory space dedicated to physical science experiments, and there would be no requirements for astronauts to be trained or travel to orbit to conduct these physical science experiments.

In addition, there would be some secondary cost savings as well. Currently, payload experiments are designed and built to exacting standards so as to certify that a given experiment has a greater than 90% chance of success. This high standard is necessary since the cost and risk of bringing that payload to orbit is so high. If a new unmanned autonomous or remote facility could be brought online and made operational at a lower cost per launch, the probability of success standards could be relaxed to, say, 75%, with a much greater percentage reduction is design, construction, testing, certification, and operating costs. This is so because if a given experiment were not successful, it could be modified and re-launched on a future flight quickly and inexpensively. In other words, a whole new design and operating philosophy would occur with significant cost savings.

Lastly, with an autonomous or remote facility as described above, it would be significantly easier and more likely to maintain launch and operating schedules. The reliability of scheduling would also result in a cost savings and would give the program a consistency that would benefit all current investigators and help attract graduate students and post doctoral associates into the program.

- **To what extent, if any, would a more ambitious mission for NASA, such as sending people back to the moon or to Mars, be likely to provide materials science researchers with unique opportunities for experimentation?**

It is very unlikely that a more ambitious mission for NASA, such as sending people back to the moon or to Mars, would be likely to provide materials science researchers with unique opportunities for experimentation. Materials science is a laboratory science aimed at understanding and controlling the inner workings of materials. Unlike like observational sciences and planetary geology, the moon and Mars have little or nothing to offer to the physical laboratory sciences.

The key element of the on orbit free fall environment for materials science researchers is the effective elimination, or great reduction, in gravitational body forces. This reduction effectively eliminates the hydrostatic pressure in fluids, and thereby effectively eliminates buoyancy, sedimentation, and natural convection while giving greater reign to other convective processes and surface effects. This allows a materials scientist to try to understand fundamental phenomena in how materials are formed and function in a way that is simply not possible on an Earth based, or other planetary, laboratory.

Naturally, if NASA had a more ambitious mission, such as sending people back to the moon or to Mars, materials science would be one of the enabling technologies, much like the present NASA sponsorship in materials for radiation shielding. The need for such enabling technologies would benefit materials science as there would be increased funding for certain lines of research. However that research work would be the more traditional Earth-based laboratory materials research and is not really different that that which is taking place in academic, national, and industrial laboratories today.

<u>Additional Comments Related to the Specific Questions Submitted by the Chair</u>

In addition to my statement directly addressing the specific questions posed by the Chair, I have a number of comments that indirectly address those questions.

Several of the questions addresses to me were specifically directed to my professional experience in condensed matter and materials physics. I answered these questions to the best of my ability. In addition, when I believed my knowledge to be up to the task, I inserted comments about other of the disciplines under the auspices of the Office of Biological and Physical Research in Space.

When colleagues heard that I was testifying here today, one said something like "Don't say anything bad about Fundamental Physics." Well I won't. But I would like to do one better. I affirm the tremendous value of the research in combustion, fluids, fundamental physics, and materials science that has been done by brilliant and talented scientists, and it remains my fervent hope that this fundamental research will continue to take place on orbit. I cannot make, and will not attempt to make any value judgment that places one of these disciplines, even my own, above another.

I say this for the real fraternity I belong to is science, and when one science is diminished in competition with another, all are diminished. It is crucial that all sciences have a path to the future. A while back when the crisis in science funding occurred in the Office of Biological or Physical Research, a fellow materials scientist advised me to get out there and lobby for materials the way other scientists are doing for their discipline. To the extent that this was true, it was deleterious to all the so named "microgravity" sciences, and other sciences as well. I will not engage in that. Despite any criticisms I have expressed, I am a committed advocate of the on-orbit environment as one of many vital national resources for scientific advancement across the disciplinary boundaries.

Lest my advocacy for an autonomously or remotely operated facility for the physical laboratory sciences in low earth orbit be misinterpreted, I also favor a continued human presence in space. We may always need astronauts to assume certain risks human exploration and development of space. I agree with NASA when they say that "exploration is what great nations do" and "exploration is part of the human fabric." Space shuttles and space stations may indeed be necessary to fulfill that need to explore. I am only advocating that a better balance be found for autonomous, remote and human enabled programs. I fully support NASA and the country in looking for a grand overarching mission, including that of the future of human space flight. However, the time has come to decouple the human exploration and development of space from the needs and benefits of conducting basic research in the laboratory physical sciences in low earth orbit.

I think that many scientists fear that if this decoupling takes place, that the basic laboratory physical sciences would disappear from NASA's portfolio in favor of the more dramatic and compelling future of human space flight. I share that fear, and if that came to pass it would be a great shame. However, the cost of using astronauts to perform science experiments to gain public support of science in space is not justified. All the orbital experiments that can be conducted autonomously or remotely should be done in that mode. The Office of Biological and Physical Research portfolio is a vibrant and vital program. I truly believe that moving the physical science research program, and as much of the biological research program as possible, to a fully autonomous or remote facility would benefit both the program itself and be a great complement to NASA's larger mission.

Conclusion

As stated earlier, NASA already has the appropriate expertise at the Office of Biological and Physical Research in Space and at the various field centers to design, built, launch, operate, and recover an autonomous/remote controlled payload platform. I believe, based on the way NASA has created and cultivated such a robust, professional and productive laboratory science program on orbit, that they could assuredly manage a tremendously productive autonomous/remote facility as a vital national resource, and do so at a reasonable and reduced cost and at greatly reduced risk.

Again, thank you for the opportunity to address you here today.