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Subcommittee on Space
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Chair, Technical Panel
NRC Committee on Human Spaceflight

Chairman Babin, Ranking Member Edwards, and distinguished members of the Subcommittee, thank you for the opportunity to discuss the options for architectures and intermediate steps to develop the capabilities and skills necessary to land humans on Mars, while maintaining constancy of purpose through the next, and *necessarily, many subsequent* administrations.

I had the privilege of chairing the Technical Panel of the congressionally mandated National Research Council (NRC[1]) Committee on Human Spaceflight, and I am here to represent some of the salient features of that Panel's conclusions about the possible pathways to Mars, as well as some of my own views. The first, and by far most significant conclusion is that while sending humans to Mars, and returning them safely to the Earth, may be technically feasible, it is an extraordinarily challenging goal, from physiological, technical, and programmatic standpoints. Because of this extreme difficulty, it is only with unprecedented cumulative investment, and, frankly, unprecedented discipline in development, testing, execution, and leadership, that this enterprise is likely to be successful.

To be explicit and to set the scale of the problem, the Technical Panel, aided by independent cost estimation contractors, and using an innovative process that respected the importance of development risks based on technical challenges, capability gaps, regulatory challenges, and programmatic factors, and the need to retain a reasonable operational tempo, concluded that the first crewed Mars landing might be possible 20-40 years from now, after a cumulative expenditure of on the order of half a trillion dollars (constant FY2013 dollars). The actual time frame and cost will depend greatly on the pathway chosen to achieve the goal, and candidly, the fastest and least expensive pathway that we examined comes with enormous risks to both the success of the missions and the lives of the astronauts conducting them.

Let me briefly (and superficially) review the most significant risks of attempting to send humans exploring in deep space.

Human Physiology and Psychology
We know that prolonged exposure of astronauts to the space environment has the potential to harm them. Astronauts on long missions (such as on the ISS and Mir) have experienced potentially debilitating effects caused by the microgravity environment. Musculoskeletal deterioration has been best studied, and while exercise has the potential to mitigate its impact, the regimen needed over the long duration of a human mission to Mars may not be realistic. Much more recently, ocular damage and negative effects on the development of the endothelial cells lining blood vessels have also been discovered.

The radiation environment in space, especially deep space beyond the protection of the Earth's magnetic field, has been quantified largely in terms of increased cancer risk due to galactic cosmic rays, against which shielding is ineffective without prohibitive mass penalties. The non-

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[1] The National Research Council is now known as the National Academies of Sciences, Engineering, and Medicine.

carcinogenic risks due to radiation, such as cumulative neural degeneration, are much less well understood and may well prove to be more limiting than carcinogenic effects. It appears that, with existing architectures for Mars missions, which include greater-than-one-year stays on the Martian surface (which itself poses unquantified health risks due to perchlorates and other chemical hazards) physiological limits may not be prohibitive, although risks to the astronauts would be very high. Long duration orbital missions at Mars, or on Mars' moons, may not be feasible at all, because of radiation. And finally, the psycho-social limits on a small group of astronauts confined to extremely tight quarters for multiyear periods, without possibility of real-time interaction with family and friends, pose another poorly understood threat to crew safety and mission success.

Technological Challenges

The NRC Technical Panel included a vast pool of experience in virtually all areas of space technology, and members who were deeply involved in earlier efforts going back to the Apollo, Gemini, and Mercury programs, and others involved in helping to define NASA's current technology roadmaps. Few of the technological challenges of a crewed Mars mission are insurmountable, but cumulatively, they represent a huge gap relative to our current capabilities, and our currently available resources. The Committee's final report includes a list of 15 high-priority technical capabilities needed to get humans to Mars, each assessed against the difficulty of developing the technical capability, the gap between what is needed and current capability, regulatory challenges, and cost & schedule challenges. One can summarize the situation by considering a matrix of the 15 capabilities indexed by the four different types of challenge, resulting in 60 assessments. Eighteen of those intersections are rated "green," meaning that progress can be expected with minimal risk. Twenty-four intersections are rated "yellow," indicating significantly higher risk. Finally, 18 of the intersections are rated "red," indicating such hurdles as "no technical solution known," "no such systems have ever been developed at the necessary scale," "current regulations impose significant challenges and will be difficult to change," and "development to operational capability is on the order of previous large, national programs." In short, there is an awful lot of technical work to do.

Having spent my life as a technologist, I can say that a large job list is not altogether a bad thing. But it does require a great deal of discipline, and a certain ruthlessness in pruning efforts that are not making needed progress. I applaud the fact that, with this Committee's and the Appropriators' help, NASA finally has a Space Technology Mission Directorate, which has recently made some significant contributions to the capabilities that my Panel identified as "highest priority." One of those areas, essential to landing humans on Mars, is "Entry, Descent, and Landing," where the technology developed for the NASA Curiosity robotic rover currently exploring Mars will not scale to the capabilities needed to land astronauts. STMD in 2015 successfully tested the Low Density Supersonic Decelerator, using the Earth's upper atmosphere as a surrogate for Mars' thin atmosphere to investigate one of many possible approaches to decelerate astronauts to a safe landing on Mars.

However, in other areas that the Panel identified as "highest priority," such as "In-space Power and Propulsion," NASA appears to be maintaining the entire trade-space of possible propulsion technology in a diffuse, subcritical approach to one of the chief challenges. Certainly, the SLS is a big-ticket item that is one of many chemical propulsion concepts that could launch components of a Mars mission for assembly in Low Earth Orbit. There are also much smaller efforts consuming resources on Nuclear Thermal Propulsion (viewed by many members of our Panel as essential to getting to Mars), long-term cryogenic storage (suggesting that NASA intends Mars missions to be chemically propelled through deep space), and electric propulsion intended for use in the Asteroid Redirect Mission, which, in my opinion, serves no useful purpose in developing the capability to send humans to Mars. (A high-capability ion thruster, however, could be extremely enabling for robotic planetary exploration.) This leads to what is probably the most important conclusion of the Human Spaceflight Committee, the importance of establishing a Pathway for human exploration of deep space.

Pathways for Human Exploration

As context for this portion of my testimony, I wish to note for the Subcommittee that one of the Technical Panel's earliest, and foundational conclusions is that there is a very limited set of potential destinations for humans in the solar system, given what we know about technology, its likely future, and human physiology. (Most of us are science fiction fans, and optimists, so we don't mean to imply that people won't go farther, ever. But for this study, the ground rules were set by Congress in the 2010 NASA Authorization bill. We were to look toward a foreseeable future, where it made sense for the United States to have concrete plans. As it was, we exceeded the mandated time constraints, to make clear the extreme difficulty and expense of human missions to deep space.)

We've been to the Moon, so we know that's possible. We probably can go to some near-earth asteroids, and, as we've discussed earlier today, maybe we can get to Mars. That's it (ignoring some uninspiring missions to special "points in space" that in my view lack intrinsic interest). Given the relative simplicity of the field of regard, there are tremendous technical and programmatic advantages to deciding, once and for all, where we're going, and in what order. Each of these possible destinations has proponents to be "what's next," as we've already heard today. But, given the size of the job jar, it's not helpful to keep changing our minds. The NRC Committee advocated, and many of us still advocate, a defined "Pathway," with missions to the different possible destinations in a sequence that has some highly desirable properties, and not deviating from that Pathway unless we run into an insurmountable obstacle, such as new information on the space environment, the limits of human physiology, or national solvency. A desirable pathway has six critical attributes:

1) The final (horizon) and intermediate destinations have profound scientific, cultural, economic, inspirational, and/or geopolitical benefits that justify public investment.
2) The sequence of missions and destinations permits stakeholders, including taxpayers, to see progress and develop confidence in NASA's and national leadership's ability to execute the pathway.
3) The pathway has a logical feed-forward of technical capabilities.
4) The pathway minimizes the use of dead-end equipment and capabilities that do not contribute to later destinations on the pathway.
5) The pathway is affordable without incurring unacceptable development risk. And,
6) The pathway supports, in the context of the available budget, an operational tempo that ensures retention of critical technical capability, proficiency of operators, and effective use of infrastructure.

The NRC Committee did not recommend any particular pathway, but did assess three notional pathways against these attributes, and against the technology and human physiology constraints that apply. The NRC Committee noted that the notional pathway that is closest to

NASA's current plans, has serious deficiencies with regard to the significance of intermediate destinations, logical feed-forward, dead-end systems, and exceedingly high development risk. The NRC Committee also noted that two alternative pathways that did not have these deficiencies failed against the affordability and operational tempo attributes at current expenditure levels. To quote the Technical Panel's final briefing to the entire NRC Committee in 2013, "In the current fiscal environment, there are no good pathways to Mars."

I would like to conclude with some of my own views. I understand that there is bipartisan support for a "go as we pay," approach to human spaceflight. But, just as it is not feasible to take a cross-country trip on a child's allowance, because of threshold costs, we may well never be able to get to Mars at current expenditure levels. It might be better to stop talking about Mars if there is no appetite in Congress and the Administration for higher human spaceflight budgets, and more disciplined execution by NASA. (And further relative reductions of NASA's science budgets are neither a plausible answer, nor responsible, given the fact that the findings from the Earth Science, Planetary Science, and Heliophysics programs offer far more practical benefit to humanity than does a program of human exploration, especially one that does not show significant progress relative to what we have seen before). At a minimum, we should agree on a pathway that is satisfying to the public, even if it does not lead to Mars in the foreseeable future. A pathway that includes the surface of the Moon is one obvious possibility.

Thank you for your attention, and I would be happy to answer any questions.