Nuclear propulsion and power for space

There are three different categories of nuclear technology for space power and propulsion: nuclear radioisotope systems for generating electricity, in use today on the Cassini mission to Saturn and in regular use since the Apollo era; closed-cycle nuclear reactors to generate electricity; and open-cycle nuclear thermal reactors, which heat a propellant directly to produce rocket thrust.

Nuclear technology is now being considered for two types of missions: far-planet robotic exploration (nuclear electric power, or NEP) and human missions to Mars (nuclear thermal rockets, or NTR). NASA's primary efforts in this area are Project Prometheus, which is aimed at developing an NEP powerplant for the Jupiter Icy Moons Orbiter (JIMO), and developing advanced-technology nuclear radioisotope power systems. Limited studies on NTR, which have promise for reducing flight durations in future human missions to Mars, are being conducted at several NASA centers.

On August 10, 2004, Aerospace America *invited a distinguished panel of experts to discuss the issues involved in space nuclear power and propulsion. To view the discussion on line, go to http://boss.streamos.com/real/federal/aiaa/aiaa081004.smi [for RealPlayer] or http://boss.streamos.com/wmedia/federal/aiaa/aiaa081004.wvx [for Windows Media]*

JERRY GREY In any discussion of work in space one subject predominates—the budget. How will we pay for the development and, ultimately, the operation of these systems?

Al, since you're responsible for Project Prometheus, can you tell us what sort of prospects you see for budget development and, ultimately, budget growth in this field?

AL NEWHOUSE There are three parts to the program: a radioisotopes program, nuclear fission reactors, and nuclear thermal rockets. When we started at NASA with the new nuclear systems initiative, we really only had the first two. The idea was to begin the technology development and look at the heritage, some of which is gone. The rocket program really stopped in 1973; the reactor program SP-100 stopped in 1993. Work was being done at the DOE at a low level.

Congress gave us some money to start the JIMO mission and provided what NASA requested in the way of an overall budget. We had a mission plan, which was sort of unpriced in the sense that we don't know what it will cost because we don't know what a reactor or the spacecraft will cost. We've been working for the last two years to come up with a cost estimate we can give Congress.

It's difficult because there are many choices. Until you actually get to the point where you have a concept that you know will work, it's sort of like buying a car. If you don't know what sort of engine you want, you don't know whether you want an SUV or a truck or a sports car, it's very difficult to price it out. So all kinds of numbers are given out.

We've laid out a program that we think will result in a mission that will fly in 2015. Not all of the amount that we think we will need has been asked for. That will come when we have a better handle on the exact numbers. But, it's not going to be cheap. Nuclear technologies cannot be done on the cheap. You have to do it right; if you do it wrong, you'll leave a heritage that will not recover.

GREY What sort of administration support do you have for this activity, both in the White House and in NASA and the DOE?

NEWHOUSE I certainly can't speak for the White House, but within NASA we have one of the strongest supporters we've ever had for nuclear technologies. Administrator [Sean] O'Keefe is a very strong supporter of Project Prometheus, which is both the radioisotope program and the fission program. And the fission program may actually expand into a nuclear thermal program, depending on what requirements people in the vision and the Exploration Mission Directorate come up with.

I say expanded because our original effort was to provide power at the destination in the case of a planetary science mission. With the advent of the vision to go to Mars and beyond, the emergence of the possibility of using nuclear thermal rockets has re-emerged. We have no budget for that at the moment, but it's our plan to ask for it and work towards it.

But I think we have very strong support in the administration. At least the vision recognizes the need for nuclear power in terms of identifying a nuclear demonstration within the next decade.

GREY The president proposes, Congress disposes. Dick, what do you think the congressional reaction from the space and aeronautics subcommittee is, budget-wise and support-wise?

DICK OBERMANN At this point, I don't see any consensus in Congress on the priority to be given to space nuclear systems. Having said that, I think there is general acceptance of the funding line for the radioisotope thermoelectric generators (RTGs) used for the robotic missions; there hasn't been any real controversy over that for a number of years. Also, Congress funded Project Prometheus last year and the House funded it this year, but with some significant cuts. The Senate has not weighed in yet.

There are several reasons for the lack of consensus. One is that there is no consensus in Congress on the overall priority to give to the president's Space Exploration Initiative, of which this is a subset. The issues are both the priority it should be given within the overall NASA program and the priority relative to other national needs. That debate hasn't run its course at this point; in fact, I'm not sure it's really gotten that far yet.

Second, within the exploration program, one of the things we are waiting for is a clarification as to what is the priority to be given to nuclear systems within the overall exploration initiative. In other words, where does nuclear R&D rank relative to exploration vehicle funding, to robotic Mars exploration, to Mars sample return, and to human or robotic lunar exploration. The proposal is to do all of this on a constrained budget and, given that the costs of each of these subelements are still somewhat unknowable, we need to understand what needs to be done, what's on the critical path.

GREY Speaking of budget and administrative questions, how does Los Alamos, which will probably be responsible for developing the nuclear elements of these systems, view the budget prospects, and where do you see the issues arising in that regard?

STEVE HOWE Our primary focus is on two different regimes in the technical risk area: fuel development and testing. One of the key issues in today's environment is whether we can test systems. And perhaps most important, do we have to test them for the full operational lifetime of the mission?

These questions dictate how much budget is needed. For example, if you have to test a full NEP system, you might test the propulsion subsystem separate from the nuclear subsystem. If you have to test both components for the full mission duration, it's a terribly expensive operation. So one of the things we are looking at is how to accelerate live testing. Hence, the budget issues are somewhat dependent upon what testing we determine will be needed. That issue is still open, especially the relative emphasis on NEP vs. NTR development.

With the NTR, we have a very good base for the fuels development program. We know we had a fuel that worked, and we think we see a path for an advanced fuel in the future. In NEP there's also a well-established program to identify what the fuel form is. But we have to do that up front, and it's hard to tie down a budget without having a well-defined technological path.

GREY That leads us into the next topic: the design and development, and particularly the risk involved, in these systems. Harry, you have a great deal of background in this field. How much of what we'll do will come from heritage understanding, the kind of thing that Steve mentioned, and how much will have to be newly developed?

HARRY FINGER There's no question that a great deal of work has been done on the NTR—a nuclear fission reactor used to heat a propellant and create a rocket. We have great experience in that. Indeed, it is the only space nuclear reactor system on which we have any significant experience, most notably the proof testing that has been accomplished for the kind of operating time that would be required to accomplish some of the projected missions, whether they be to Mars or Jupiter or even more distant destinations. The fuel material, as Steve mentioned, is well developed, and significant improvements can be anticipated. Moreover, testing facilities were available, and they can be improved to provide assurance of no effluent emissions.

With regard to radioisotopes, we have used them extensively over the years and we know how to develop them. We have had very good, safe experience with them, most recently on the Galileo and Cassini missions, which have produced outstanding results.

In NEP, on the other hand, we're starting from scratch. We have no experience to speak of in fuel-related technology or in proof-testing of any concepts or systems. Indeed, there is as yet no NEP reactor concept defined, although extensive work has been done on the electric thruster portion of the system. And the question Steve Howe raised still remains: how do you prove operability reliability of the system for many years?

GREY Just to clarify what you've stated, we do have extensive experience in the electric propulsion part of the NEP system, but not in the nuclear reactor portion. Al, would you like to comment on that?

NEWHOUSE We are partnering with the naval reactor branch of the DOE to develop the reactor for NEP. They are probably the premier organization in the world for developing reactor systems, fuels, and power conversion systems. But they're just getting started on applying all this capability to space nuclear reactors. So we don't have a concept yet; they're not ready to give us one. However, we expect them to come up with a reactor that will do the job as soon as we can define what the job is. We're not quite as far behind as Harry implied.

FINGER Note, though, that there are major differences between a submarine reactor and a space system; most notably the weight limitation, the heat rejection system, and the nonavailability of maintenance or repair capability for the required multiyear operating lifetime.

GREY Gary, you have extensive experience in the development and testing of nuclear radioisotope systems. How much of that type of experience, and especially testing and facilities, can be metamorphosed into the reactor development program that will have to be undertaken for the JIMO mission?

GARY BENNETT The kind of testing we did on the RTGs was easier in some respects than what we'll have to do with either NEP or NTR. RTGs could be tested in properly constructed buildings at the DOE national labs without encountering some of the issues that we would have to deal with in testing a 2- or 3-MW thermal reactor for an NEP system that might have to be tested in a contained environment, or perhaps a much larger reactor for an NTR system where the effluent will have to be cleaned and scrubbed before releasing it.

However, there are some lessons that can be learned from our RTG experience. For example, we learned early on that you cannot do accelerated testing with RTGs. We tried to determine the lifetime of the silicon-germanium thermal electric elements, which are now in use in Cassini, and were first used on two Air Force communications satellites. Every time we tried to do the classic Arrhenius-type accelerated testing, in which the temperature is raised to simulate the effects of longer term operation, we created chemical and metallurgical phenomena that would not occur in normal operation. So we were basically restricted to testing our samples at the temperatures they would operate at in space and just letting them run.

One approach might be what is often done with turbine-engine conversion system testing in the commercial sector—putting several systems on test simultaneously and pulling them off at different times to see if there is any degradation.

The NTR has an advantage in the sense that it only has to run for perhaps an hour or two over the life of the mission. But for an NEP mission that may run for a decade or more, we will probably have to launch with limited data, perhaps a year or two, and extrapolate any degradation that occurs during that limited testing. On the plus side, we do already have considerable long-term test data on the electric propulsion subsystem. But we really need to conduct extensive analysis on how to test a long-lifetime system when it is not possible to accelerate the testing.

GREY I'd like to ask the industry people who are developing the power conversion systems, the nonnuclear elements, for their comments on systems engineering, testing, facilities, and the lifetime testing that will have to be done.

GROVER HALL We've used RTGs for many spacecraft, so we have a lot of experience with them. The real issue is how scalable that experience would be to high-wattage systems, especially for electric propulsion. Today, our facilities are really not set up. They will depend on what sort of environmental constraints we are likely to face in testing. We'll have to find some way of combining nuclear facilities with those of the aerospace industry, because they are not similar and may not be compatible. Our facilities are set up for space, not for nuclear testing.

Also, we like to "test like you fly," which may not work for nuclear subsystems. We will have to struggle with this issue and decide what additions to our facilities will be needed. This will require coordination with the designers of the nuclear systems to ensure a safe testing facility.

BOB ANDERSON At Boeing we've done a lot of development on power conversion systems. Some work was even done with Brayton-cycle power for the space station before the decision was made to use photovoltaics. We have other work going on now on dynamic power conversion systems. The power conversion method to be used for the JIMO mission hasn't yet been decided. It could go either way: passive thermoelectric or dynamic.

There are ways to test the power conversion systems without the nuclear power source being present. We're very experienced at that; Rocketdyne's space power lab was used extensively to check out the space station power systems before they were launched. We also have the ability to build various power conversion fluid loops to test Stirling, Brayton, or other cycles.

But at some point you do want to do an overall systems test with the nuclear core. That would have to be done at some DOE facility. So Al Newhouse and the people he works with must develop a test facility plan for combined testing of the nuclear and nonnuclear subsystems. We in the industry can do extensive power conversion subsystem testing, but not with the nuclear core.

STEVE HARRISON I agree; the aerospace corporations have the ability to do simulations, at operational temperatures and power levels, in our big environmental test chambers. We can test everything up to the interface with the nuclear reactor subsystem. But the power conversion system will have to be integrated with the nuclear power source at some time, to give any sort of assurance to the president so he or she can make a decision on whether or not to launch. The test facility to do that will have to be a U.S. government facility, and it will have to be incredibly secure because it will use highly enriched uranium, which is a prime target in these perilous times.

GREY Aerojet had extensive experience during the NERVA [Nuclear Engine for Rocket Vehicle Applications] program in the '50s and '60s. You worked with the Atomic Energy Commission [now the DOE] on test facilities involving nuclear reactors. Bill, could you comment on that?

BILL SMITH NERVA did test the range of thrust levels that are quite relevant for today, 10,000 lb up to 250,000 lb, on 20-some tests. There was extensive development of those facilities, and a clear capability to test nuclear rockets. So we're confident it can be done. The problem is that much of that is on the shelf, though there's a lot of documentation NASA is trying to mine right now.

GREY There is another area of possible serious concern—people. How many young, bright people are moving into this field to carry out the science, design, development, and testing that needs to be done?

CAROL BERRIGAN A 2001 study by the nuclear industry found that there would be a deficiency of the number of nuclear engineers and health physicists available to meet the demand, not just in the commercial power sector, but also in the DOE labs and other government sectors.

Since then there has been a concerted effort in industry, government, and academia to encourage enrollment in nuclear engineering or health physics. The result has been a dramatic increase in the number of students studying for nuclear engineering degrees, especially at the undergraduate level. Enrollment went from about 500 several years ago to over 1,300 today. This is very encouraging.

These students see a nuclear renaissance. They see the advent of possible new nuclear power plants. They see what NASA is doing in space propulsion. And I think they're very excited. They ask about new plants; they ask about space propulsion. These are very hot topics. As long as government and industry continue to communicate with students and encourage them, we will see students stepping up to the challenge.

ANDERSON One interesting thing we've seen that goes beyond the young engineers is that people want to be a part of something exciting and challenging. When NASA announced Project Prometheus and JIMO, young engineers coming for interviews were asking about these programs. Young engineers who were already employed were asking, "How do I get on this program? I want to work on it." Older employees too, and even retirees, were knocking on the door. This was an exciting new challenge. They could see something really meaningful coming out of it.

GREY I'd like to raise the overall question of materials. And first on the list are nuclear radioisotopes.

NEWHOUSE The most important one is plutonium-238, the nonfissionable isotope used to generate the power for the radioisotope power supplies we've been using. We buy it from Russia in 5-kg lots, at a rate of about 5 kg a year. Right now, we have enough for any conceivable NASA mission. However, if we expand our vision into more missions, we will need more. The Russian plutonium can be used only for civilian purposes, but the DOE has other customers besides NASA. The DOE is working to establish a capability to make plutonium-238 for these other customers. It's in their budget planning. It hasn't happened yet because it hasn't been funded, but they have asked for funding, and the plutonium should be available if we need it.

Another approach is to generate more power with the plutonium that is available. Our current RTGs are only about 5% efficient. We're developing new power conversion devices, notably Stirling-cycle generators and others down the road that are on the order of 25% and even 35% efficient. The same amount of plutonium that generates 100 W with 5% efficient thermoelectric conversion can generate 500 W with a 25% efficient generator, or else we can produce the same 100 W with one-fifth as much plutonium. So we can extend our plutonium-238 supply by applying these new technologies.

GREY It isn't just the plutonium-238 that you have to consider; it has to be packaged into a safe power pack. Steve, where does the DOE stand on this?

HOWE The packaging is very important. It's a very precise, meticulous process. A great deal of time and effort has gone into packaging the plutonium. We put it through a lot of rigorous tests, including fire, impact, and accidents in every kind of scenario.

The lab is serious about meeting its responsibilities to supply the plutonium pellets, but that process has now been interrupted with the current shutdown. I think that will impact the Pluto mission and possibly others in the future. We will try to make up time, but these are very stringent processes that you often can't speed up, so will likely be an impact.

JIM POWELL The plutonium-238 has been made by reprocessing Navy reactor fuel. And as far as I know, they're not doing that anymore.

NEWHOUSE That's true; the decision was made to stop processing plutonium-238 during the Carter administration. But in fact, at the time there was more neptunium [an intermediate product of the process, from which the plutonium is made] than we could ever use. And if we ever want to make more plutonium domestically, we can.

GREY Gary, you did most of the testing on the plutonium-238 pellets. Do you have any comments?

BENNETT I agree with Steve Howe: There is rigorous testing, and all the fabrication, assembly, and testing processes are done to detailed standards. The fuel has to be pressed and sintered in a certain way; it has to have a certain grain structure, a certain density. The iridium which encapsulates the fuel pellet has to be manufactured in a certain way.

Early in these production campaigns we often had rejection rates of 50% or more. Whenever you start up a highly controlled fabrication process, even with experienced people, there will be high rejection rates initially as people relearn the necessary skills. We need to recognize that we will have a lot of difficulties getting everything to work just right, getting the equipment in place, and so forth. As Steve said, it is a detailed, step-by-step process to manufacture these plutonium-based heat sources, and it really can't be accelerated.

GREY Harry had mentioned that a lot of the materials work done for the NTP program was available, and the materials had been very well developed at that time.

Steve, aside from the plutonium question, are there any material issues that you see coming up in terms of the development of a new generation of reactors?

HOWE One of the key issues here is that we didn't have very good computers back in the NERVA days. The world of material science has changed dramatically, both physically and computationally. But we had gained a great deal of knowledge in all materials aspects—structural, moderators, and the core itself. We've given our materials science division at the lab a clean blackboard. For example, on the NTR we asked, "Can you make a fuel that has a certain physical geometry, but won't leak fission products? Use any technique you want to; use all your skills and whatever coating technologies you want." So the materials arena is wide open, and I think we'll see a tremendous advance in both NTR and NEP materials technology.

GREY Jim, you've dealt with high-temperature systems. Do you have any comments, just on the materials question?

POWELL We were developing a very small NTR as part of the Strategic Defense Initiative [SDI] program. We designed and developed fuel particles which operated and maintained their integrity at 3,000 K in hydrogen for several hours, without emitting any fission products.

So as Steve said, there is considerable room for hope in these kinds of materials. Also, the cermet, tungsten, and uranium oxide fuels that were developed in the '60s were in a sense very similar to the kind of fuel that's used in defense reactors that operate around the world. These fuels are excellent in terms of their fission-product retention. They still need to be demonstrated at higher temperatures and for longer operating lifetimes, but I don't think that will be a serious issue for either NTR or NEP reactors.

BENNETT The NERVA program had one of the most extensive materials testing programs I've ever seen. A very elaborate materials database was developed, and that information was fed into computer codes—we did have computers then!—that did a kind of stress-strength overlap analysis to come up with reliability numbers for the various components in the overall system.

FINGER In NERVA we explored both tungsten- and graphite-based fuels. Graphite was known to be corrosion-prone in hydrogen, so much good work was done in successfully protecting it with various coatings over the full range of power levels required. There's no question that we can now move far more favorably in that area. I have no doubt that we can develop fuel materials for efficient NTRs.

HOWE But we are still faced with the issue of how to do full length-of-mission duration testing on core materials, especially for NEP. We have no facilities to do accelerated testing, although we have proposed one at Los Alamos which will use an accelerator-driven neutron source that can give us the fluxes needed to do total fluence measurements on materials.

Nevertheless, we still need to establish policies on how to do accelerated life testing on materials components. If you don't test the full mission duration, you have to decide on the test criteria you will need for mission assurance.

NEWHOUSE The whole question of materials is tied up with what NASA calls technical risk management. If you pick a material, what is the risk of its lasting the required mission duration?

The science of materials is the key. We had an alloy that had been used successfully in the 1960s. When we tried to use it on the SP-100 project in 1990, we found it wasn't what we thought it was because the metallurgy had changed—the techniques for making it, the ability to analyze it, and so forth. We had to spend money in 1990 to recreate what was apparently beautiful in the 1960s.

We're faced with that in a sense today. Some of the materials that were proven in the past haven't been made in 20 or 30 years. We're not sure we can make them the same way today. So, do we have to run our materials for 10 years? How do I know its yield strength will stay what we expect it to be for 10 years without running it for 10 years? You can't just run it for a shorter time at higher temperatures, so-called Arrhenius testing, because it may not run at that temperature, or there may be a phase change or a break point in the material.

So the real challenge I face in Prometheus is in identifying the risk involved in using the various materials. For example, we don't have 10 years of 0-*g* operation with xenon turbines. Do you test one for 10 years, see if it lasts, and then decide to use it? Obviously not. So we have to take some risk. The question is, to what degree is that risk sensible or foolish? That's the issue we have to resolve.

GREY Another testing issue that strongly impacts budgets and development schedules is what facilities we have available for doing this type of testing, whether it be accelerated life testing, long-term testing, materials testing, and so on. We had some good facilities back in the '50s and '60s. But are they still good? Do we have to build new test facilities? Do we have to worry about new regulations on testing? For example, we no longer can run tests that might emit fission products into the atmosphere as we used to do. What impact will this issue have on overall budgeting, project schedules, safety, applications in different areas, and so on?

NEWHOUSE I run a risk because of my DOE heritage and I don't want to say anything that may not be absolutely correct today for DOE. But the test reactor system in the U.S. is basically down to one reactor. We don't have any fast reactors anymore to provide the test environment that we might be likely to use in space.

Testing fuel is a laborious process. You start out with little pieces and then big pieces, and you keep going to the point where you get a fuel element. That's true whether it's a thermal rocket reactor or a power reactor for space.

The ATR is a good but limited test facility, used principally for naval applications. Anybody else who wants to run a nuclear reactor in this country has to test there; you can't export nuclear fuel to test elsewhere. But the number of people running it, the number of people available, the technicians who slice the material to look at it under radiographs and hot cells, is very limited. We need to expand that.

Once you get the fuel tested, the spacecraft part of our mission probably can be tested in existing industrial facilities. But what we can't test is the integrated system. We may have to figure out a way to test the reactor on a spacecraft mockup and pray somehow that when we put it all together it will work. That's not a good way to do business. So we may end up with a situation where we combine the power conversion system and the reactor and test those together, and then worry about the electrical interface later.

We have the Plum Brook facility, which has a great thermal capability. It can handle a power reactor. It certainly can't handle a thermal nuclear rocket. It can't employ nuclear material. So we're going to have to develop what we call an electrical surrogate or electrical replica. The people at NASA are doing a lot of work in developing electrical test capability with shape heaters, to give us the capability to simulate a reactor up to a certain size. Once you get past that size, though, that isn't going to work.

As far as the thermal rocket testing is concerned, you are right. We cannot test in the atmosphere. We cannot risk having fission products released into the atmosphere. The Environmental Protection Act doesn't allow that. But to human-rate an NTR that might be used to carry crews to Mars, we have to test to failure. We have to know how far it can go before it fails. That means we have to expect failure, which means we have to expect fission products. Therefore, we will have to contain the exhaust.

We looked at this in the '90s. A facility-concept was developed—expensive, but it could be done. It was a big chemical engineering job, but we knew how to do it. There are other ways it might be done. Steve Howe has suggested some ideas using the weapons testing facilities in Nevada, underground or in tunnels. We don't know yet whether those can be used—whether or not there may be environmental concerns. We'll have to look at that.

So, we have some ideas about testing NTRs. We have ideas about how to test the fission hardware. We're okay on the testing of radioisotopes until we begin doing new things. For example, we tested the RTGs for reentry situations, but not necessarily launch situations. We need to do some additional testing in that area.

POWELL Testing NTRs has one advantage over testing NEP systems because they operate for short times, so they don't have high burnups and therefore don't have high fluences.

NEWHOUSE But with an NTR it's not just that first burn to get away from Earth. We will have to restart the engine after months in space, perhaps three or four times. And quite frankly, I don't know how to test for that. You can't run an NTR in a vacuum chamber.

FINGER Major restarts have been done. In one series of tests the NTR experimental system ran for about three hours with over 20 restarts.

I do want to add one point, because there's been some allusion to the possibility of doing some of these flights without significant testing. There is a very substantial safety requirement on nuclear systems, especially in the early flights of any new system. Before undertaking a flight it has to be proven unequivocally that the system can operate satisfactorily for a significant time, to demonstrate that there is no hazard to humans, to the atmosphere, or even to the solar system. So testing becomes a very significant consideration.

HOWE We have a large accelerator at Los Alamos. It's a milliampere beam at 800 MeV. And when you hit tungsten with it,

it makes a lot of neutrons—fluxes in the 10^{15} range. It's not a critical assembly, but the neutron spectrum is pretty much like that of a fast reactor. This is a machine you can turn on and off. Because it's not critical, it avoids all the problems of a critical assembly. Also, we can actually build in the ability to temperature-test fuel—all year long if you're willing to pay the electricity cost.

GREY There are other associated risks involved in the development and use of nuclear propulsion systems and, in fact, in any other systems which are involved in the JIMO mission. When we move into the operational phase, there's the question of ground transportation; integration with the launch vehicle; the launch itself; operations when we get to orbit; for example, will we need to do any orbital assembly? Can the system operate for the necessary total mission time, something like 10 years? These are issues that need to be dealt with. Some are not quite nuclear issues, but they're related. Has industry looked at them?

HARRISON I was the coordinator for the Interagency Nuclear Safety Review Panel [INSRP]. Every time we launched a nuclear payload the safety review analysis started from zero. When the Apollo program launched RTGs with every mission, that analysis became pretty much of a rubber stamp, because we launched the very same nuclear payload each time on the very same launch vehicle.

The original JIMO concept would have used one launch to orbit, but that would have required us to develop a brand new class of heavy-lift booster. I suggest that the safety review could be done more routinely by orbiting the reactor on an existing launcher and then assembling the spacecraft on orbit. Although that might be more expensive from a launch operations standpoint, it would avoid developing a new launch vehicle and allow you to tailor what you put on each mission.

BOB PARK Any ground transportation of the nuclear part of the system would be handled by DOE. The concept would probably be that the reactor would be assembled with the rest of the spacecraft and launch vehicle at the Cape prior to launch.

With regard to single launch vs. on-orbit assembly, NASA's doing a lot of trade studies for the new exploration initiative. To achieve their exploration goals, they'll definitely need heavier launch vehicles than the Delta IV and Atlas V vehicles we have now. Ongoing trade studies are looking at heavier new or shuttle-derived launchers, heavy versions of Delta and Atlas, and how much should be put on one launch vehicle vs. how much on-orbit assembly should be done.

GREY With on-orbit assembly we will need some kind of a process for on-orbit test and validation. Grover, has Lockheed Martin looked at this at all?

HALL Yes, but it all goes back to the need for scalability. If you really want to make a power supply scalable and usable, you need a whole different concept that integrates it with the system and is scaled to the system, because it can dominate the mass of the payload. So the real struggle is going to be to keep the power supply and the payload separate and really make the system a high-integrity one. We got a lot of experience in doing this on the space station, where we took the solar array up in pieces and installed them on orbit.

NEWHOUSE If we are truly interested in going to space in a real way and doing big things like going to the Moon and Mars, we'll never have a big enough launch vehicle because we'll always have something bigger that we want to launch. So we need to learn how to put things together somewhere in space.

Doing it at the space station was one idea, although it's probably in the wrong place for many of the things we want to do. There's talk about using the Lagrange libration points, or locations in low Earth orbit or middle orbits. Since we're going to be constrained by not ever being able to build a big enough launch vehicle, we might as well start considering in-space assembly at some point. The big questions, as usual, are who pays the bill and how do we pay it?

Clearly, automatic rendezvous and docking can be done. The Russians have done it for years and it's still used by their Progress space station resupply craft. I understand there will be some demonstrations next year. It's very critical that we understand not only how to do it, but how you make sure everything's going to work when it gets put together. You don't want to put them together and have them go fizzle. Testing and validation, especially without having to have astronauts there, will always limit the process.

GREY We've discussed a number of the technical issues involved at great length. We also have to explore advanced concepts. Where will Project Prometheus and JIMO lead us, not so much in this decade or the next decade, but in the next century? How will we go from JIMO into really advanced space programs?

The Project Prometheus task is to develop a capability to conduct really intensive science missions with a great deal of power and with a great deal of propulsion capability so you can move around the solar system. How many more missions like that are there beyond this? Are we going to have to build new and advanced types of systems in order to do those missions?

The first question that always comes up is: How much will all this cost? Dick, has Congress thought about the support of nuclear space power and propulsion in terms of how many more times are we going to use this capability after we've spent $10 or $20 or $30 billion developing it?

OBERMANN That is one of the questions Congress has been asking, because it gets down to priorities within a constrained budget. We're talking about spending, as you say, many billions of dollars to develop this capability. The question will be, what's the opportunity cost of spending the money on this mission vs. other space science missions? And once we have this capability, how often will we be able to employ it?

Initial discussions with NASA indicated that they foresaw perhaps being able to fly a mission with these large power capabilities maybe once in a decade. That's a significant investment for perhaps limited return. There was concern in the '80s that in space science we were just flying a few flagship missions, and a lot of the other scientific endeavors were suffering. Members don't want that to happen again.

Another concern is that within a year or so of the initiation of the JIMO mission, NASA itself had slid the mission by three to four years, and had transferred money from that activity to other areas of the exploration program. So still remaining unanswered is the Congress' own question of what are priorities within the exploration program.

NEWHOUSE I'd rather not get into what the rest of NASA is thinking since I don't represent my management, per se. Clearly, as Dick points out, some of the money was transferred away and the mission was delayed. There are budget priorities. There are priorities as to what the president has defined for us in the vision of Moon, Mars, and Beyond.

We were not ready to fly on the original date that was provided. We recognized that our technology was not maturing fast enough. We did not have a reactor designer on board, so meeting a 2011 flight date was probably not realistic. We are still shooting for 2015, though the budget may not support that. But, we are going to get a good cost estimate for what JIMO will accomplish.

JIMO is not just one mission. One of the things we asked industry to look at is, what other applications of the technology and the system that we hope to design can be used. For example, we've already determined that we can probably go to Saturn and Titan with essentially the same system. So now we have the possibility of two missions with the development of the one technology. Similarly, there are other places in the solar system, such as Neptune, which are within reach of the JIMO package. There are other missions, perhaps less adventurous, for which we could use the JIMO system.

Of course, there's always the tendency to put everything on a mission that you can, what we call to "Christmas tree" it. It's hard to resist. But we don't have any money today in our budget for manned or megawatt-level systems. We're planning to see what we can come up with in the way of fuel development and system developments for those kinds of things should the requirements process in the exploration directorate determine that those technologies are appropriate.

The technologies we're developing in power conversion, reactor fuels, and other areas are all multimission, not just for JIMO. The only thing about JIMO that is probably unique is the amount of radiation hardness we will have to build into our systems, because Europa is probably the worst place in the solar system from that standpoint. But even that technology will be of use to other missions; it's not wasted just on Europa. The DOD can use it, and there are other places in the solar system that do have high radiation intensities.

So we are looking at Prometheus as an investment, and not just an investment in missions, but an investment in people and industry. If we get to build JIMO, we will energize the industry and we energize the people. We'll get people excited about doing this. More people will come to it; they'll generate new ideas, missions we hadn't even thought of, systems and concepts that we haven't begun to work on, simply because we're doing it.

GREY Among the things we're looking at, although they may be very far in the future, are some very advanced missions, advanced technologies that will enable us to go well beyond JIMO and its concept. There's an organization called the NASA Institute for Advanced Concepts, for example, which is looking at interstellar, even intergalactic, propulsion systems. We are far from realizing those, certainly. We won't see them next year or even in the next decade. But, there are some interesting concepts which may allow us to extend what we are going to learn on JIMO and other similar missions in the future, and move even further out. Jim, you've worked on some of these. What do you think?

POWELL I do have somewhat of a different philosophy on using nuclear technology for space science and exploration. Rather than Prometheus's NEP, there are a lot of advantages to going the route of a small NTR. For example, to explore Europa, an NTR could get there in two years instead of the seven or eight it takes with NEP.

NTR also allows us to land on and take off from a surface, which will be very important in exploring these bodies, and particularly exploring the subsurface ocean on Europa to see what's down there. An NTR can refuel using electrolysis of water or ice from Europa and other bodies, so it could even return samples back to Earth.

We could consider melting through the ice on Europa's surface with a very small nuclear reactor probe to explore the subsurface ocean, and return with samples back to Earth in an elapsed time of only about five years.

The same technology used for a small NTR can be applied to a nuclear ramjet. We had built and tested one successfully in the 1960s. It would allow us to fly for unlimited times and distances in the atmospheres of the gas-giant planets Jupiter and Saturn. Galileo's probe at a single location on Jupiter lasted about a half-hour. With the ability to take many thousands of data points all over the planet, we could really understand the atmosphere phenomena on the gas giants.

Further-out concepts using pellet drive, magnetic fusion reactors, laser propulsion, antimatter annihilation, and other advanced technologies could deliver very high specific impulses. It's hard to see these ideas being very useful for missions in the solar system, but perhaps they could be considered for trips to the Kuiper Belt, the heliopause, or ultimately into interstellar space.

FINGER These advanced concepts are certainly very uncertain, but it is worthwhile to spend some time examining them for a variety of reasons, including the possibility that they may lead to other steps. But it is also very important to encourage people to generate concepts of that sort, to stimulate their imaginations and their excitement while we restore the technology base that we have and encourage people to work on that as well.

GREY There's no question that the interest of young people in some of these advanced areas, such as Steve Howe's research on antimatter and Bradley Edwards' studies of the space elevator. These are concepts that will certainly not come to fruition soon. In fact, the NIAC scope of interest is anything that might come about somewhere in the 10-40-year timeframe, not next year. But this does excite young people, and properly so.

FINGER There's one concern that I need to air, although it is not specific to nuclear technology. In order to create the budget and the resources for the new space exploration "vision," we are cutting back on a number of science missions that NASA would otherwise be doing. Some have already been delayed, and some may even have been postponed too far for them ever to be done. So how do we trade off the very desirable goal of exploring Mars and the rest of the solar system against some of the science missions that would have to give way to do so?

PARK I have a little problem with some of that. Certainly, as a desirable goal, exploring Mars is way up on the list. But we're doing that right now and we're doing it very well. We've got a couple of explorers up there. They're smart guys and they never break for lunch, never complain about the cold nights, and I think we're doing exactly the right thing there now.

The public needs to be educated about that, about what it is we're really trying to do. The great quest, scientifically, is to find life to which we're not related. That's why Mars is one of the targets, and that's why the icy moons are the other big targets. People have to understand that we have never seen a life form to which we are not related. If we find one, we'll know more about ourselves and how we came to be.

These are things people are excited about, and I think we can convey that to them. But the idea of sending humans to Mars to look for life is upside down. I guarantee you, if we send humans to Mars to look for life, we'll find life that's going to look awfully familiar.

GREY You raised a very important point: What is the public's interest? They are fascinated by the Mars robots. Even Mars Pathfinder, back in the mid-1990s. NASA's Website got more Internet hits than anything else that ever had appeared on the Internet. But the public doesn't yet know about JIMO and Prometheus. How do we begin to communicate the concept that we are doing something really exciting over the next 10 or 15 years?

It's a long time for people who are going to school now to wait. They say, "I'm going to be working for an investment broker by that time. I'm not going to be interested anymore." How do we stimulate the interest of the public in these future missions? NASA tries, but I don't think they do a very good job of communicating with the public.

PARK Yeah, they have not done a good job and I don't understand quite why. There is a belief that we have to have humans along on these missions to get public interest. That's just not so. As you point out, people got terribly excited about the robotic Pathfinder mission. I spoke to a class of first and second graders, and they cried when the little Sojourner robot couldn't locate its mother.

I took my university class out to NASA Goddard when we did the flyby of Neptune. And there on that big screen, one line at a time, the image was building up, the first time any human had seen this. I looked around at my students and they were holding their breath. They were doing the same thing that I did when [Neil] Armstrong stepped off onto the Moon. And it didn't matter that it was a robot. They were seeing what human beings had never seen before. It's kind of democratic, too—we all get to go along on the mission.

ANDERSON True, the Mars robots probably broke the Guinness record for hits on the JPL Website. But let's not forget that they are probably going to die in the next few months, because the decision was made to use solar power.

We have the next opportunity, though: the first of the Prometheus new technology missions will be the Mars lander, in 2009. It will probably have one of the new isotope power sources on it, so it will be able to send back pictures and explore Mars for perhaps four or five years instead of four or five months.

POWELL My earlier comments were on the role of NTRs in space exploration, but nuclear electric power certainly has a role, especially in surface power on the Moon and Mars. The requirements for developing a nuclear electric system for surface power can be a lot simpler and easier than those for NEP in space. For example, we've looked at a small reactor based on the use of standard Navy reactor fuel. Such a reactor could generate a megawatt of power, and the fuel is already developed.

The logical way to do a Mars mission for humans is to drop a small reactor and factory unit on the north polar cap. There's water there, and the atmosphere is mainly carbon dioxide. This allows the manufacture of a whole range of supplies: hydrogen propellant, breathable air, plastics, and a whole host of materials that can be stored in melt cavities. You can make caves for future astronauts.

GREY The public does have to be involved. They got involved in the Mars robots beautifully. That was a great example. We still have to address the whole question of safety and public perception. But first, how will the administration and the Congress react to the concept of using nuclear power in space?

FINGER Going back to a comment Dick made earlier about congressional support, some members are asking, "What really are you going to do?" Because this is a very long-term kind of activity, NASA has the job of trying to lay out the specific elements of the exploration initiative and start moving on them.

GREY We still have the basic controversy over this being done with nuclear energy. "Nuclear" is a dirty word as far as the public is concerned. It doesn't matter if it's in space, on the ground, or in the oceans. They tend to overlook the naval reactor program, perhaps because they are all hidden in submarines or carriers. Yet, there are things we can do with nuclear energy that would go over well with the public. How do we resolve that?

BERRIGAN I disagree with your assumption that the public doesn't support nuclear power. The most recent surveys that our organization has done looking at support for nuclear energy for electricity production show significant public support for nuclear; 65% of the general population supports it, and 73% of college graduates. A lot of that has to do with the public's understanding the benefits of unclear for energy reliability, for a clean environment, and for energy independence.

For nuclear space propulsion, you need to express the benefits to the public. The public is intelligent. They'll look at the benefits and make up their minds. That's a challenge for NASA. But there is significant public support on the energy side.

FINGER There was extensive public-attitude research done relative to space nuclear propulsion activity. At no time did the results support in any way the assumption that there is broad public opposition to it. We've always said that we applied nuclear energy in space only when it realistically enables the missions. And that's what we're talking about here in terms of going to the far planets. We don't use nuclear power for normal orbital missions where solar energy is applicable. Of course, there will always be a segment of the public that is opposed to nuclear energy on any terms.

GREY The tough question is, how do we get that message across? I don't think that even the informed general public realizes the benefits. How do you communicate to them what they are?

OBERMANN I take a bit of exception to the contention that it's widely accepted that nuclear is fine for space applications. In the political arena the burden of proof will be on NASA to demonstrate that they in fact have clearly identified the various risk factors and have mitigated them appropriately. I don't think there's a knee-jerk rejection of nuclear space systems, but there really needs to be a transparent system to identify the risks and work through the various risk factors.

Any time there is a major accident or problem with one of our space systems or launch vehicles, people want to have confidence that the risks to those systems were accurately portrayed before the accident and that we're not underestimating them.

When the shuttle was used to launch Galileo, NASA's estimate of the shuttle risk of loss was 1 in 100,000. After Challenger, it turned out to be 1 in 78. Cassini was launched on the Titan IV. The very next Titan IV blew up. If that sequence had been reversed, whether there would have been the public acceptance of the launching of Cassini on that timetable is not at all clear to me.

GREY Gary, you've spent a good deal of your post-NASA life dealing with this public question. Would you care to comment on what you've discovered?

BENNETT One thing I've discovered is that using numbers to talk to the public doesn't cut it. I saw that happen in the terrestrial nuclear power field, where people would say the likelihood of a nuclear reactor accident is one in a million or one in a billion or whatever.

What seemed to have worked in the commercial world is that when a utility

goes out and involves the local community, they look at the site, they look at the design, they get a feeling for what's going on, and they develop an understanding of the safety systems. Something similar was done by DOE and NASA prior to the launch of Cassini. People went to Florida and talked to citizens and explained what the mission was.

I guess the analogy I have in mind is an editorial that appeared in *Science* a number of years ago on animal experiments. The animal rights community had been very effective in stopping or controlling any medical experiments with animals. A scientist wrote in and said our mistake was in letting them use pictures of an animal being experimented on, while the scientists cited numbers on illnesses we were curing. He said a better approach would have been to have shown a picture of a baby that had been cured of some disease because of experiments that had been done in a biology lab.

We need to find something like that in the nuclear arena, because people react emotionally. Also, the risk studies have shown that people will accept risk that they feel they have some control over.

I know intellectually that my flying here was safer than my drive to the airport. But I have control over my car, whereas I do not have control over the 737 that flew me here.

I agree with Carol and Harry: People are smart. If you level with them and explain the situation, what you're doing, and they understand it, I think they will go along. Of course, there are professional agitators who make a living by opposing nuclear power, or any other technology. We somehow have to deal with them as a separate issue from the broader public, who may have legitimate concerns that need to be addressed.

POWELL One of the things you can do is make it very plain that, with nuclear propulsion, the risk of astronauts going to various destinations is greatly reduced because the trip time is a lot shorter, they get a lot less radiation in space, the psychological stress is a lot less, and they can carry a lot more materials with them to use when they get there. The margin of safety is greatly enhanced. I would drum that message home to people.

NEWHOUSE Gary is right. Galileo demonstrated that going out and flooding the public with information doesn't necessarily work. We're trying with Prometheus and with the nuclear initiatives to do something a little different. We have brought in risk communications experts, by hiring a company that's been very good in remediation and bringing issues together: the Keystone Center. They worked with the Army in chemical weapons disposal and were able to bring together some very hard viewpoints to reach a conclusion that apparently has worked. We've asked them to advise us.

We're looking at setting up a dialogue, where we will talk to the environmental groups, the people who are neutral—not the hardliners, but people who haven't made up their minds yet or haven't paid attention to the issue—those that don't yet know what we're doing, or at this point don't care. They have other issues that are more important to them.

We're bringing them together to find out what it is that bothers them. What is it about what we're doing that creates concern? Is it the fact Gary mentioned, that they don't control the risk? We have to look at trust, liability, and consequence. What worries them about launching a reactor into space? What worries them about launching radioisotopes in space? What worries them about transporting reactor waste from their power plant to Yucca Mountain or wherever it's going?

If we don't ask we can only presume, and we may be presuming the wrong thing. So we're trying something very new for NASA and DOE, to bring the public into the dialogue in a continuing process to make sure we are addressing and looking at those issues that really bother the public.

This may not work. It may not prevent the pickets and the "grandmothers for peace" or whatever that will be at the launch site complaining about what we are doing. But we won't find out unless we try, and that's the purpose of what we are trying to do.

ANDERSON We're looking at two different parts of public perception here. The first one is nuclear power and propulsion in space. The public is intelligent enough to realize that's the only way humanity is going to go to all of the places we want to go. A *Scientific American* article by one of the generally negative Washington foundations said they opposed nuclear power in Earth orbit, but beyond Earth orbit they said it's the only way to go. I think the public understands that.

What the public is concerned with is how it might directly impact their lives. How are we going to safely acquire these nuclear materials? How are we going to safely test them? And how are we going to safely launch them? That's where NASA has to focus its energies in getting that word out to the public as this program develops. Al Newhouse and his people have taken some very good steps by going out and trying to get a lot of people involved at the early stage.

BENNETT The American Federation of Scientists, the Union of Concerned Scientists, and the National Resources Defense Council all might have been expected to have opposed the Cassini mission but did not. They are fine as long as NASA is doing it and it's being done safely and it's going far out where there isn't much sunlight. But the moment NASA gets involved with the military, where there's any kind of military spinoff, some of these organizations may very well turn against the program. So I would leave a word of caution out there for NASA management: Keep this thing a civilian application, please.

GREY One final point I want to raise before we close out this discussion: What is the scope of international participation in activities of this type? The Europeans recently launched a major program into deep space, the Rosetta mission, powered by solar energy because they did not choose to use even radioisotopes. Now, that may be because they don't have a supply of radioisotopes. But I wonder, if we do go into missions that are deeply involved with nuclear power and propulsion systems, will we be able to do this on an international basis?

The Cassini mission is an international mission, a very good one. It uses nuclear radioisotopes, which is an accepted old-line form of nuclear power as far as space is concerned. When we begin to get into some of these newer areas, are we going to be able to involve foreign partners? I believe this is a very important consideration for space exploration.

FINGER There is no question that there has been very significant nuclear materials research and other research that's been done in Russia. There are certain benefits we can derive from some association with that work. Similarly, I think other countries can contribute significantly in those areas, and there are benefits politically, as well as in broad relationships in the world. So we should really try to encourage international participation in various ways, especially technical ways.

GREY This is an issue that is similar to the public perception issue. For example, with the new vision of space exploration, we've gotten a fairly negative response from the Europeans and the Russians. They have their programs and would like to go ahead, but they imply that they are hesitant to work with the U.S.

HOWE International cooperation in space has been sort of a mantra at NASA. But it keeps running into a much more powerful "realpolitik" that is mainly industry-based. The International Traffic in Arms Regulations [ITAR] is a subset of that. There have been missions people were planning as international efforts, when suddenly they got their legs chopped off because of internal industrial-based politics here in the U.S.

So, we offer to play and then run home with the ball.

NEWHOUSE I agree with Steve. Also, in the nuclear area there is another set of rules that makes it difficult to cooperate. The DOE has to deal with weapons proliferation and materials. There are materials in Russia that we could make use of. But trying to bring them here to test them, to validate them, is almost impossible. There are other areas of technology, though; for example, Prometheus has just bought a Russian electric thruster, which has great possibilities for use in JIMO. But we have to test it to show that it does in fact do what they say it will.

ANDERSON The Europeans have done a lot of work on electric propulsion. Some of the great theory work, and a lot of the testing, has been done there. They have facilities we might be able to use. The Russians have similar kinds of things. We ought to be able to find a way in the nonnuclear areas to do more than we're doing. But experience has been, in many cases, that the commitments are not made at the national level, they're made scientist-to-scientist or agency-to-agency, and sometimes they don't happen.

Space scientists have been burned on a number of occasions when they have planned a mission to use a particular device from another country which never got funded, and all of a sudden the mission is thrown out. The Mars Reconnaissance Orbiter is a good example. We had to substitute our own equipment for some that were planned.

So there's good and bad. As Steve says, we take the ball out, we say let's play, and then we go home with it. That's probably unavoidable in the big picture. We're running into that issue with the Space Exploration Vision right now. In July, Adm. Steidle was at Farnborough drumming up interest in the "vision," and finding that, although he likes the Joint Strike Fighter model for international cooperative projects, the Europeans don't.

Clearly, there's something to be learned there. The space station may not be a good model either. It's a difficult topic that NASA is looking at very seriously.

PARK My impression is that Congress has been very good about funding things for nationalist reasons, but that you lose that support when you go international. There is an element of national pride. Our international efforts, like ITAR and the space station, have turned out to be disasters.

GREY But there are successes, especially in science. We have had some wonderful cooperative missions. Cassini is a fine example, but there have been many others in the past. There are dozens of missions, small missions every year, that are cooperative.

And in terms of international cooperation by industry, we have any number of joint endeavors being pursued by companies from different countries. We do of course have the problem of export control, where the U.S. is kind of shooting itself in the foot. But there is a good record of successful joint international ventures. International Launch Services is a fine example; Sea Launch is another.

The pursuit of international cooperation does not necessarily have to be in opposition to nationalistic endeavors. Obviously, it is strongly affected by poli-

tics, and that's a real concern.

I'd like to now ask if anyone has any comments on anything we've talked about today. If you want to air your views on something, now's your chance.

HARRISON The trade space is humans and robotics, and that trade space is where NASA really has to make its investment. The entire aerospace industrial base depends on that. You send humans when you need to. How much nuclear power you need depends on the systems. That's where I'd urge NASA to invest its time.

BENNETT I'd like to pass on words of wisdom from two great space nuclear philosophers, Robert W. Bussard and Harry Finger. Bussard once told me that you've got two windows of opportunity on any one of these programs. One is technical and one is political. If you make the wrong technical choice, he said, you will spend so much time fixing the technical problems that you'll miss the political window of opportunity for funding.

The other key factor, whether it's international or national, is that we need to take a look at the management model. Harry Finger set up the joint Space Nuclear Propulsion Office, back in the days of the Atomic Energy Commission [AEC] and NASA. The Air Force had a similar joint management structure with the AEC on the nuclear airplane program, and the Navy had one with the AEC in a marine reactor program.

That is the key to success: a joint office where people are physically collocated. They have badges and security clearances for both agencies. When I was at what is now NASA Glenn Research Center, we all had a red NASA badge and a green AEC badge, but we thought of ourselves as having a purple badge because we didn't represent either agency; we represented the project.

So I would urge speediness, the right technical decisions, the political aspect, and a good, integrated, strongly focused management structure.

NEWHOUSE We have to address nuclear safety. It's not surprising that we haven't mentioned it here, because we all think of it as a "given." But one of our principal things in public acceptance and in actually making this all work is to make sure that what we do is safe from a nuclear aspect. If it isn't safe, it won't fly. So we're making sure that what we're doing does not present a hazard to the public or to the Earth.

HOWE I want to summarize what I think the NTR can do. Harry mentioned the legacy we have from the testing program in the '60s. I've come to the conclusion that the NTR, or potentially a bimodal NTR that can produce both electricity and thrust, is a key technology if one is going to expand into the solar system. If we end up only doing robots, maybe we don't need it.

But my vision is that humanity will eventually expand into the solar system. The small NTR that was tested, the "peewee" system, can do lunar transport in 24 hours. So, if someone gets injured you have the accident response capability of bringing him or her back.

In a 1985 study of a 400-day round trip mission to Mars, we used a Nova launch system that allowed two months on the surface. Now we're looking at missions with a three-year stay in the radiation environment of space. The NTR offers the ability to move out into the solar system with much faster trip times, and it can evolve into higher-performance technologies. In summary, the NTR really enables us to march forward, starting with the Moon and eventually moving out into the solar system.

FINGER I want to mention the significance of the NTR for science as well as for human missions, using very small systems which would not only offer a very fast trip time but would be a lot simpler. These would also allow us to begin earlier, which would improve reliability. Also, we need to bring together the broad capabilities that are available in each of the areas and find a way of drawing them together to provide a team of capabilities under a single direction. It can't be multiple organizations, where one has to wait for the other. It has to be treated as a system right from the beginning.

PARK I'm very encouraged by everything I've heard here today. To flog my dead horse just a little more, I would point out that we measure a society's success by the extent to which tasks that are menial or dangerous are done by machines. That's how we judge a successful society, except in the space program.

HALL The general public says to go explore space, but at what price? We've learned from Columbia that the public can't accept death as a price for progress. So it's very difficult to convince the public now that we're going to handle this safely, especially if we want to scale these systems up and go to the next level. They'll say, "But you can't even bring a crew back or launch it safely. How are you going to convince us you're going to use nuclear energy safely?"

We have to come to grips with that, because although the existing launch vehicles are going through an upgrade, we can make electronics redundant but we can't avoid single-point failure possibilities on structures. And every once in a while, they will fail.

So we have to sustain our present emphasis on the crew's survivability and to work the same issue, and have the same convincing case, for the use of nuclear energy. This really means that we have to start launching multiple payloads and doing servicing missions to put them together in space.

That doesn't mean we shouldn't use the technology; we need it to get started. But we have to make a convincing case to the general public that we as a community can handle this safely.

SMITH Nuclear propulsion, whether NTR or NEP, really provides enabling capability across a continuum of missions. It's not one or the other; we need both. I would hate to see the community once again become divided between the two. We need each other, and we need each other to get this issue solved.

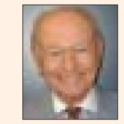
So it's extremely important that we in industry work together. In fact, industry is a force multiplier of what NASA wants to do. If we're behind it, we can help.

POWELL There is one very important aspect to this that we haven't addressed. I make three points: We know that doing this type of development occurs about once a century. We know that a house-sized rock passes between us and the Moon's orbit every month. And we know that the total number of people looking for these things is about equivalent to the staff at a McDonald's. The point: NTR really is our only option if we really want to get out there fast and intercept something. This is a major argument for why we need nuclear propulsion.

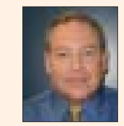
FINGER We owe a great deal to NASA for having stepped in to take another look at the use of nuclear energy broadly, to establish the direction we really want to go in the future. This is the way we should be looking at the space exploration initiative, as a vision. Nuclear energy may have a very significant role in that vision.

GREY That's a great final perspective on the topic of this panel, and a good place to end it. Thanks to all of you.

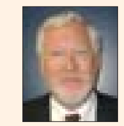
PANELISTS



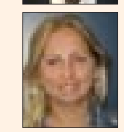
Jerry Grey, moderator, is a professor of aerospace engineering and the former director of the Nuclear Propulsion Research Lab at Princeton University. He is also the director of public policy for the AIAA.



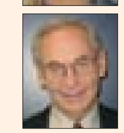
Robert Anderson is the manager of government business development for Boeing NASA Systems and Rocketdyne Propulsion and Power.



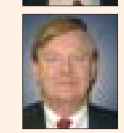
Gary Bennett, a consultant, is the former director for space nuclear power and propulsion for NASA.



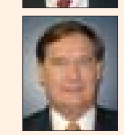
Carol Berrigan is the director of industry initiatives for the Nuclear Energy Institute.



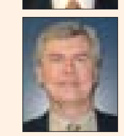
Harold Finger, a consultant, is the former director of the joint NASA/Atomic Energy Commission Space Nuclear Propulsion Office.



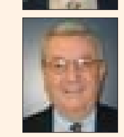
Grover Hall is the vice president of technical operations for Lockheed Martin Space Systems.



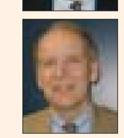
Steve Harrison is the director of Washington-area marketing, NASA programs and technology development. He previously served as SDIO program manager for the SP-100.



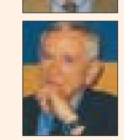
Steven Howe is the program manager of the reactivity and compression program element for the nuclear weapons program at Los Alamos National Laboratory.



Alan Newhouse is the technical advisor for NASA's Project Prometheus. Earlier, he worked for 30 years for the DOE's Naval Reactors program and worked on the SP-100.

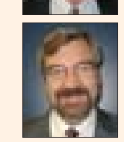


Richard Obermann serves as the Democratic professional staff member on the House Committee on Science, with primary oversight responsibility for all civil space activities and aeronautics R&D activities.



Robert Park is a professor of physics at the University of Maryland.

James Powell, head of Plus Ultra Technologies, is the former chief of nuclear propulsion at Brookhaven National Lab.



William W. Smith is the executive director of business development for Aerojet, responsible for strategic growth for the company's Space Propulsion Operations.