Interview: Dr. Stanley Borowski

With Committed Funding, We Could Develop a Nuclear Thermal Rocket for The Moon, Mars, Asteroids, and Beyond

21st Century

Dr. Stanley Borowski

Dr. Stanley Borowski has been a leader in nuclear rocket research and development work at NASA for 23 years. He is currently branch chief of the Propulsion and Controls Systems Analysis group at NASA's Glenn Research Center, and leads the nuclear thermal propulsion program. Dr. Borowski and his team have designed missions using nuclear thermal propulsion for exploration missions to the Moon, Mars, near-Earth asteroids, and the outer planets. Before joining NASA, Dr. Borowski worked at the Aerojet Propulsion Research Institute and the Oak Ridge National Laboratory. He earned his Ph.D. in nuclear engineering from the University of Michigan in 1983.

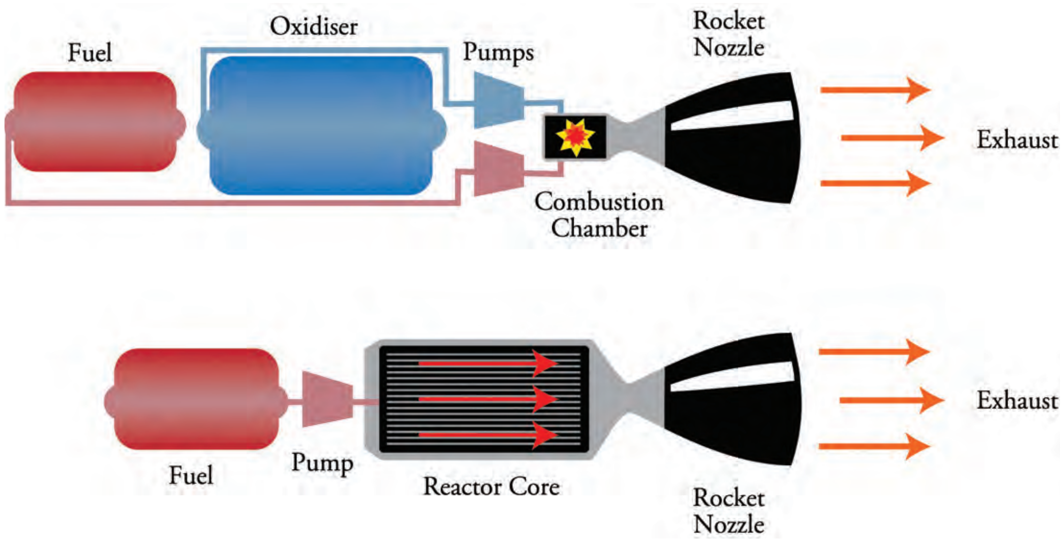
Dr. Borowski was interviewed by Peter Martinson and Marsha Freeman following his presentation at the Global Space Exploration Conference in Washington, DC, in May, 2012.

Peter Martinson: Dr. Borowski, you just gave a fantastic presentation on what's called "Nuclear Thermal Propulsion." So first, could you tell us what you do?

Borowski: Thanks, Peter. I'm the branch chief for the propulsion and control systems analysis branch at the Glenn Research Center (GRC), but I also lead the nuclear thermal rocket work that we're doing there, in support of the Nuclear Cryogenic Propulsion Stage (NCPS) project that's funded by NASA Headquarters and is being performed at three NASA centers: Marshall Space Flight center, Glenn Research Center, and Johnson Space Center.

Martinson: Could you explain what nuclear thermal propulsion (NTP) is?

Sure. A nuclear thermal rocket is a high power density, very high efficiency, high thrust propulsion system, that only requires one propellant. In contrast to chemical rockets which use liquid oxygen (LOx) and hydrogen, and use chemical combustion to generate energy, in a nuclear rocket, it's the fission of uranium-235 fuel within the reactor core which generates all the thermal power. So, what we're able to do is, in a very small, compact volume, generate a lot of power. We remove that power by using liquid hydrogen, which is flowed through the reactor core, picks up the heat, and then we expand it out a regular nozzle, like in a conventional chemical rocket, for thrust generation. The beauty of it is that, by using liquid hydrogen (LH2), the exhaust gas has a specific impulse (Isp), which can be defined as the pounds of thrust produced per pound of propellant per second flowing through the engine, in units of seconds, that is twice that of today's best chemical rocket—900 s for the NTR vs. 450 s for a LOx/LH2 chemical rocket. The other benefit of NTP is that it uses a lot of the same kinds of technologies that are used on a chemical rocket. It has pumps, nozzles, and LH2 propellant tanks. But with a NTR you get a 100% increase in Isp, compared to chemical, so as we look forward to using it in space, for exploring the Moon or going to a



Courtsey of Dr. Borowski

Comparison between chemical and nuclear thermal rocket operation. In a chemical rocket (top), the fuel is combined with an oxidizer, ignited, and the explosive reaction directed out the rocket nozzle. In a nuclear thermal rocket, liquid hydrogen is flowed through the reactor core and heated to extreme temperatures, which forces it to evaporate and expand, and it is then directed out the rocket nozzle.

near-Earth asteroid or on to Mars, the key thing is to reduce the amount of mass needed to do those missions, and with nuclear thermal rocket propulsion you can do that.

Martinson: So, you'd say that this is a much better fuel for propulsion than just regular chemical fuels for exploring the Solar System?

Yes, that's right. Chemical propulsion has limitations, but we will always need it, because chemical rockets have a much higher engine thrust-to-weight ratio. Although they have twice the specific impulse, nuclear engines are heavier. So, from that standpoint, they're really positioned to be propulsion systems to take us from point A to point B in space, whereas a chemical rocket is what we're going to use to lift off from the deep gravity well of Earth and deliver all of our spacecraft components to low Earth orbit for assembly. So no matter what kind of spacecraft we develop, we'll need chemical rockets to get us into orbit. Then, we'll be using chemical rockets, in all likelihood, to land on the surfaces of those planetary destinations, whether it be the Moon or Mars. The nuclear engines are primarily the propulsion systems for point-to-point transfer through space, and not for launching off the ground, or for landing on a planetary body.

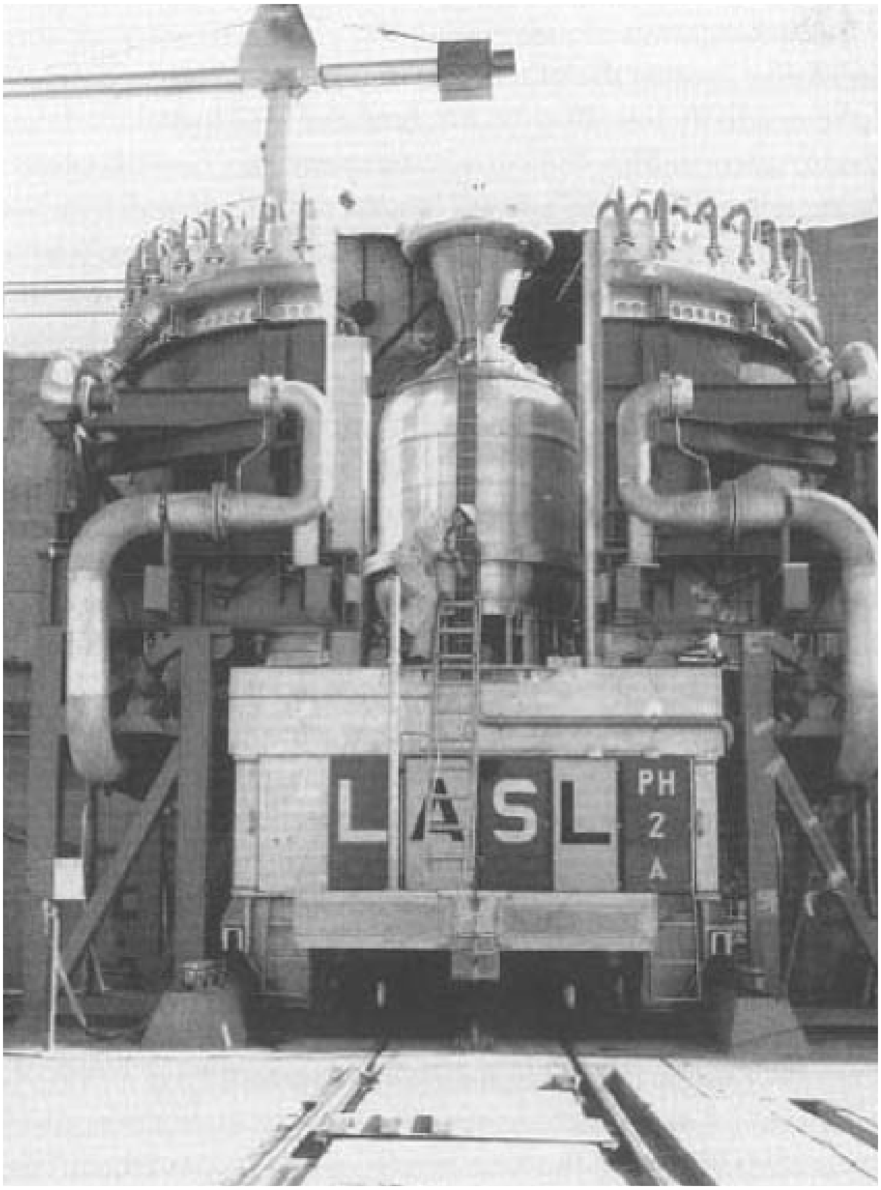
Martinson: Now the United States has some history in working on and developing this kind of a rocket. Could you review some of that?

Sure. Nuclear rocket development efforts started in the late 1950s, and during the 1960s, NASA and the then-Atomic Energy Commission (AEC) conducted what was called the ROVER and the NERVA nuclear rocket programs. NERVA stood for "Nuclear Engine for Rocket Vehicle Application." During that period, NASA and the AEC designed, built, and tested 20 nuclear rocket reactors, out at the Nevada Test Site, in sizes that ranged from 25,000 lbf[1] to 50,000 lbf, then 75,000 lbf, all the way up to a 250,000 lbf engine, which produced 5,000 MW of power when it was producing thrust. So, that was the biggest reactor that's ever been tested on the ground.

Martinson: Can you compare that to a conventional power reactor?

Yes, I can. A conventional, large commercial power reactor typically produces approximately 1,100 MW of electrical power at about 33% efficiency, so you're talking about 3,300 MW of thermal power being produced in a large terrestrial power reactor, versus 5,000 MW generated in the 250,000 lbf Phoebus-2A nuclear rocket tested in the ROVER program. Now, there is a difference in these systems. Nuclear engines have a lot of enriched uranium in them, because their focus is to generate a lot of power in a short period of time, to generate high thrust. The temperatures that these fuels operate at are a lot higher than that in terrestrial reactors. So, there is the potential, as we develop this technology and move forward, that higher temperature fuels for terrestrial gas-cooled reactors could become possible. In fact, gas-cooled reactor technology that uses small particles of fuel with multiple

1. Lbf means "pounds-force," as opposed to lbm, which is "pounds-mass."



NASA

The Phoebus-2A, one of twenty nuclear thermal rockets tested under the ROVER and NERVA programs.

coatings on them—called "biso" and "triso" pellets – could benefit in the future from using higher temperature coatings that are being investigated for use in NTR engines.

Martinson: You mean the pebble bed reactors?

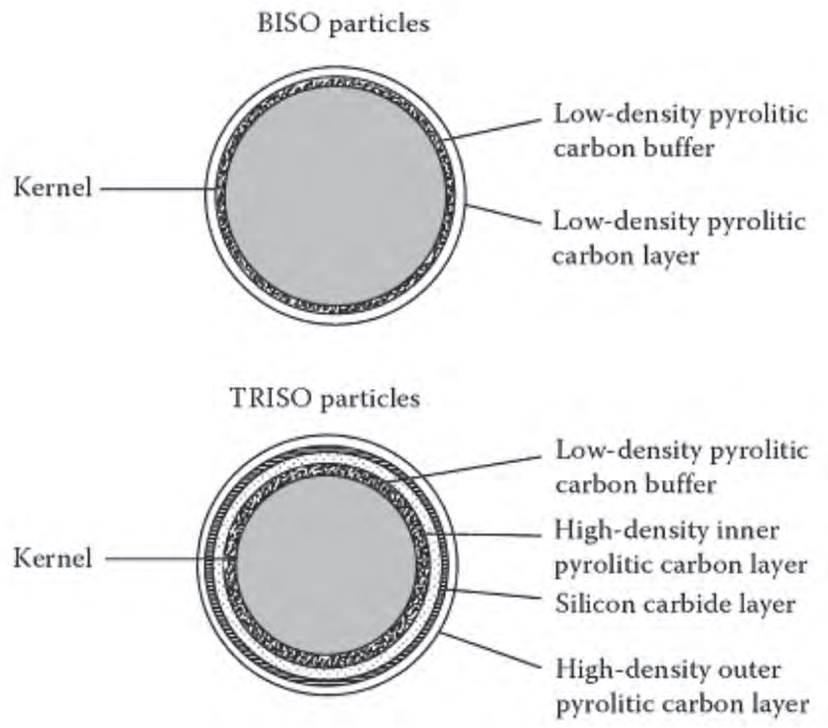
Yes, pebble bed-type reactors that contain the nuclear fuel in graphite blocks. So, with this kind of technology, we could potentially go to higher temperature coatings, that have zirconium carbide on them rather than silicon carbide. In the future, once we've revalidated our technology, if it looks applicable, it could find ways into the terrestrial gas-cooled reactor area, and allow higher temperature, higher efficiency reactors, that are based on gas-core type systems, not the pressurized water reactors.

Martinson: Now we don't have a nuclear rocket yet. Could you say how this program ended?

Great question. During the '60s, we had the Apollo program. We were going to land a man on the Moon and return him safely to Earth before the decade was out. After that we had plans to build a base on the Moon, and then to go on to Mars. In fact, Wernher von Braun, who at that time was developing the Saturn V rocket, and was also the director of the Marshall Space Flight Center, had a three decade long vision called the "Integrated Space Plan (1970-1990)," which called for building a shuttle, having an orbital space station, then after our initial landing missions, building a base on the Moon, and then going on to landing humans on Mars in the early 1980s. Central to developing a lunar base and transporting cargo from Earth to the base, then going on to Mars, was an advanced propulsion system, and what von Braun was talking about was the NERVA nuclear rocket. So, back then, we were thinking a lot about NTR technology.

But, in the end, both the Apollo program and the ROVER/NERVA NTR programs were canceled due to a combination of political issues. The use of large systems that were costly and were being thrown away, like the Saturn V, and not being reused probably came into play, or maybe it was the fact that the United States had won the race to land humans on the Moon. Maybe we were victims of our own success, because, after a while, the public got bored seeing astronauts walking on the Moon. There were actually reports of people calling up the local networks and saying, "What are you doing? 'I Love Lucy' is on right now, and you're showing some astronaut jumping around like a bunny on the Moon." So, it was a combination of things.

So they canceled Apollo missions 18, 19, and 20. The Saturn V's for those missions are on display at the Kennedy Space Center, the Marshall Space Flight Center, and the Johnson Space Center. With the conclusion of the Apollo 17 mission in December 1972, the Apollo program came to an end. The United States decided it wasn't going to go on to Mars, and the nuclear rocket, which was primarily being developed to send humans to Mars, was terminated shortly thereafter. In January 1973, a month after the final Apollo 17 mission, they canceled the ROVER/NERVA program.



IAEA

Bi-isotropic ("biso") and tri-isotropic ("triso") nuclear fuel pellets. Both pellets contain a kernel of uranium fuel, coated by several layers of material.

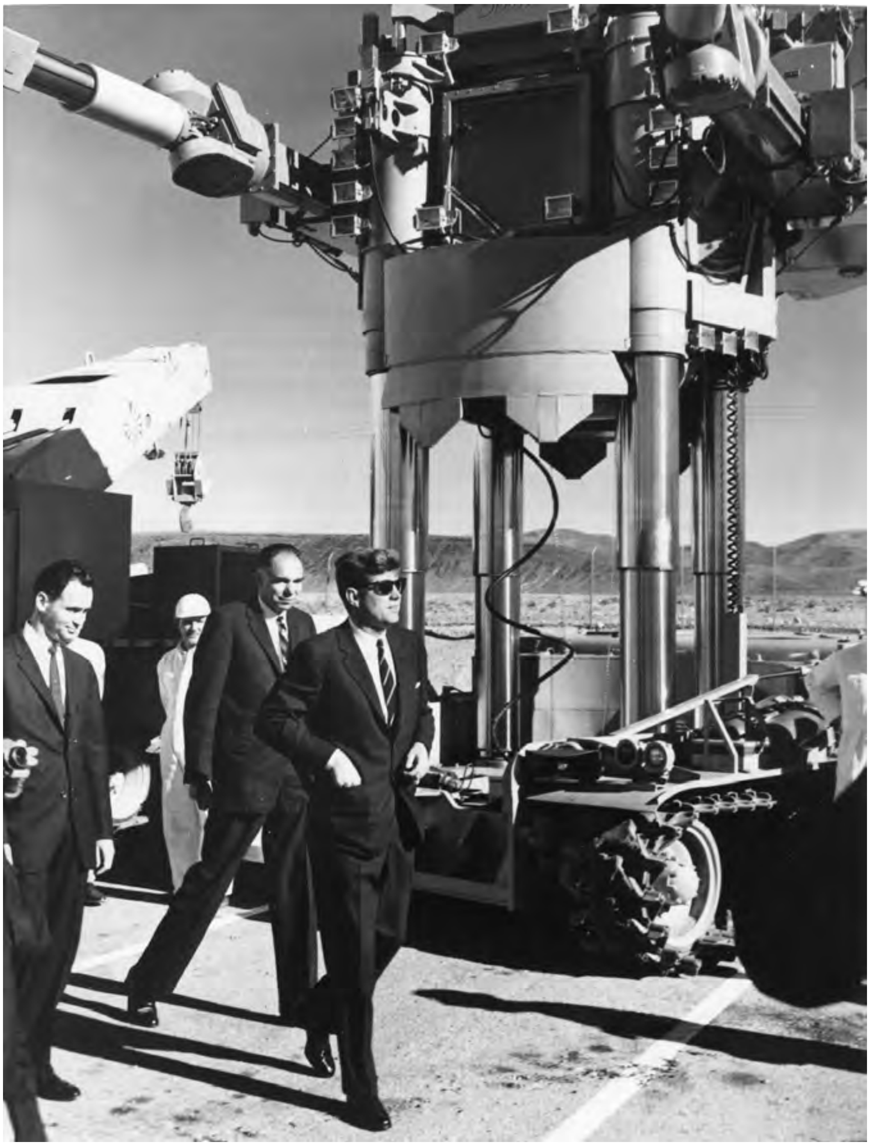
Martinson: Even though the NERVA program was at a very high level of completion?

It was at a very high level. NASA has readiness levels, and NERVA was at the 5 and 6 level, and it's at that point that you're going to a flight engine. So, it came very close, but if you weren't going to go back to the Moon, and weren't going on to Mars, then why do you need it? So, NASA decided to use its resources to build a space shuttle, a reusable space truck, that could continue to get humans into orbit, so at least we had a way to continue to send people up and down, potentially deploy and retrieve satellites, and from there the logic sequence was, once you have a space truck going back and forth to low Earth orbit, eventually that space truck would have to go somewhere. So you'd have to go on to build a space station, which we ultimately did do, and we did use the shuttle and its cargo bay as the primary vehicle for delivering up the components. But, because you were limiting all the components of the space station to smaller 20 ton increments that could fit in the shuttle cargo bay, it took a lot longer to build it, and to get it deployed. If you had a Saturn V, you could have had a couple of the Skylabs launched in relatively short order, say within a few missions, and had a giant space complex operating in Low-Earth Orbit (LEO).

Martinson: Now, part of the context of your talk is that, now, 35-40 years later, there's renewed interest in the rocket.

That's exactly right. NASA conducted its Design Reference Architecture (DRA) 5.0 study in 2007 and 2008, and the report, NASA-SP-2009-566, came out in July, 2009. This effort was followed by the Augustine panel which went back and reviewed NASA's proposed exploration plans, and then provided their recommendations about whether they thought NASA was on the right track. Under the Constellation program, NASA had plans to build a heavy lift launch vehicle, the Ares V, the crewed Orion capsule and the service module, a large lunar lander, called Altair, and we were going to return humans to the Moon. But, I think, with the change in administration, there were a number of people who were asking, "is this the right step? Are we doing the right thing?" So, the Obama Administration commisioned the Augustine report to evaluate various plans and options.

I think it was the consensus that, while we certainly needed a heavy lift launch vehicle to move forward, in times of a limited budget, it might be more advantageous to focus on one of the pieces of the transportation puzzle, namely, the in-space transportation system, as an initial starting point. By developing the technology for that piece first you can then go to multiple destinations within the Solar System, whether it be lunar orbit, or a near Earth asteroid, or to orbit Mars and its Moons. NASA's current space policy that was issued in June 2010 under the Obama administration calls for NASA, as its primary fo-



NASA

President John F. Kennedy, visiting the Nuclear Rocket Development Station at Jackass Flats, Nevada, in December 1962. Behind him is the "Beetle," a self-propelled robotic manipulating machine. At the extreme left is Dr. Harold Finger, head of the nuclear rocket program.

cus, to develop the capabilities that can allow humans to visit a near Earth asteroid (NEA) after 2025 and the current date that we're talking about for such a mission is probably around 2028, followed by an orbital mission of Mars before 2035.

You may have heard at the conference about 2033 as the Mars mission date because for short orbital stay missions, there's significant variation in the energy requirements to get from the Earth to Mars and back again. The orbital mechanics of Earth and Mars go through a minimum, and then a maximum and this "min-max cycle" occurs every fifteen years. It just so happens that 2033 is one of those minimums. So, if you want to do a short round-trip orbital mission to just demonstrate that you can get people to Mars and bring them back healthy and sound, 2033 would be an opportune time to do that.

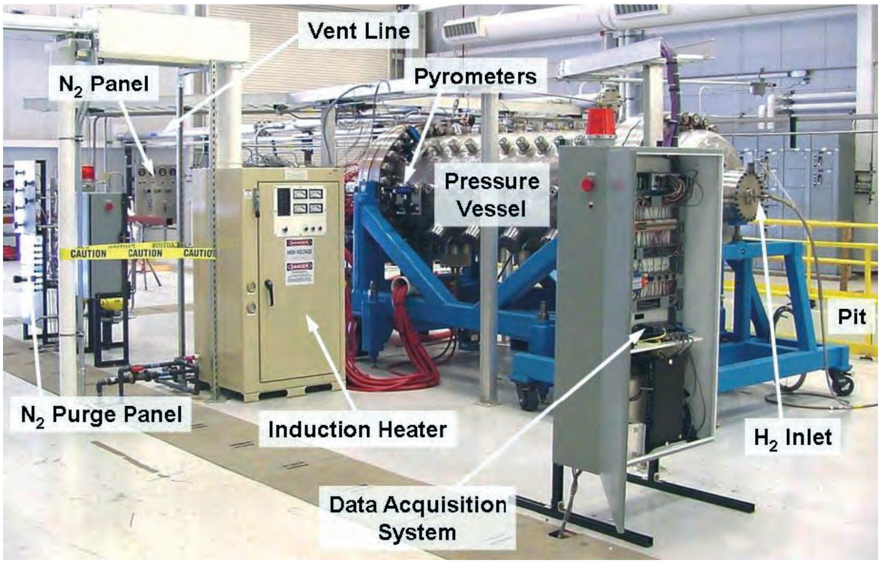
Afterwards, you can transition to a landing mission, which would give you more time to develop a Mars lander and other key surface systems.

Focusing on transportation initially is probably a good idea because it is one of the critical pieces you need no matter where you're going. Whether it's to the Moon, Mars or its moons, or to an asteroid, in-space transportation is one of the key things, and how efficiently and affordably it gets you there is one of the key questions.

Martinson: Could you describe the current roadmap for the development of the Nuclear Thermal Rocket?

I'd be glad to. NASA is currently evaluating different concepts and approaches to help it lay out its plans for what's required to get humans out of low Earth orbit and that could involve returning humans to the Moon or sending them to a NEA before embarking on a human mission to Mars. In 2010, NASA began putting together plans for how it would conduct an affordable nuclear thermal rocket program. We initiated this program in fiscal year 2011 under AISP—the Advanced In-Space Propulsion program—which was a part of ETDD the Exploration Technology Development and Demonstration program. Under the nuclear thermal rocket component of AISP we identified five key elements. Fuel recapture, revalidation and development is one of these key elements.

We identified two candidate fuels. The first fuel option is NERVA "composite" fuel, consisting of a graphite matrix material fuel element containing uranium-zirconium carbide fuel. The second fuel option was the backup to the ROVER/NERVA carbide-based fuel and is a ceramic metal fuel referred to as "CERMET." In NASA's current NTP technology development effort, we're pursuing both options. Working with the Department of Energy,



NASA

The Nuclear Thermal Rocket Element Environmental Simulator (NTREES), at NASA's Marshall Space Flight Center, is designed to closely approximate the conditions within a nuclear reactor, in order to test fuel element design for the NTR.

we want to fabricate both fuel types, and then do non-nuclear testing of them in the test facility at the Marshall Space Flight Center called NTREES, which stands for Nuclear Thermal Rocket Element Environmental Simulator. In this test chamber we'll be able to subject the fuel element to the kind of pressure and hot hydrogen environment it would see in an operating engine, but we will use high-power radiofrequency or RF power as the substitute for nuclear power generation to heat and simulate the actual temperature profile along the length of an element.

Martinson: So it's not actually a nuclear reactor?

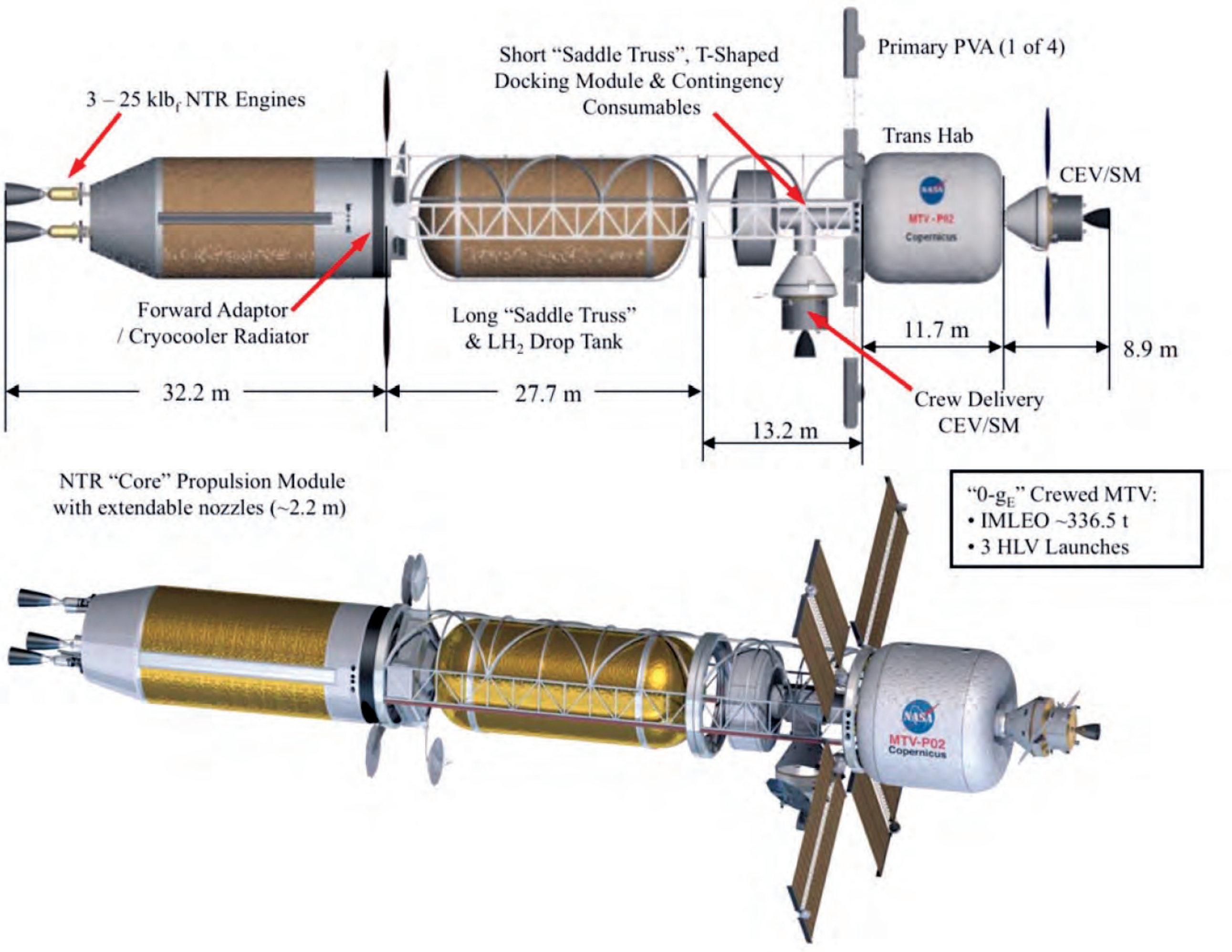
That's right, NTREES is not an actual nuclear reactor, but it simulates many of the operational conditions. It would expose the fuel, the materials, and the coatings to the kind of temperatures that a fuel would see, and hopefully, if it all hangs together successfully then it becomes a strong candidate for follow-on irradiation testing in the Advanced Test Reactor (ATR), located at the Idaho National Laboratory. So by using separate effects testing involving non-nuclear testing of full length fuel elements in NTREES, and then irradiation testing in ATR, we should be able to validate the promising fuel element designs.

A second key element of NASA's NTR effort is evaluating affordable ground testing options. We can no longer test our engine in the open air as we did in the ROVER/NERVA program. Even though these tests would potentially be conducted at the remote Nevada Test Site (NTS), we can't just let the hydrogen exhaust escape into the atmosphere. So, when we do these tests, the exhaust has to go into either a contained exhaust scrubber system, located above ground, which could be expensive, or we can exhaust into the ground out at the NTS into existing vertical shafts referred to as borehole tunnels, and use the soil as our large holdup tank and as our filter. The tunnel and adjacent soil surrounding it collects and filters the exhaust, and can hold it for a long period of time. We've already analyzed this concept which is called Subsurface Active Filtration of Exhaust or SAFE for short, and it looks to be a very effective test option, and could be very cost-effective as well.

Another key activity we're doing is detailed state-of-the-art engine modeling. As I said earlier, twenty rocket reactors were tested during the ROVER/NERVA program. On a lot of these rocket/reactor tests, they designed and manufactured one engine, then rolled it out to the test site to start conducting tests, and when those tests were done, they rolled it back to the EMAD (Engine Maintenance Assembly Disassembly) facility at the NTS to examine the fuel elements while they were rolling out another one to test. They hadn't even gotten the feedback from the previous engine to make any required changes. So in that sense, it was kind of a gold-plated program similar to what existed during the Apollo days. We had to get a lot done in a short period of time, and limitations on funding wasn't an issue then. Today we can't conduct that kind of program, so we're focusing on two fuel types and two fuel element geometries. We'd like to use a common element design for each fuel option, validate it, then do detailed engine modeling, so we know all the energy deposition in every single element throughout the reactor core. That information will help us to program the RF power that we put in when we're testing these elements in NTREES, so that they're exposed to prototypical kinds of thermal temperatures that they would see in an operating engine.

So, detailed engine modeling, fuel element fabrication and testing, and validation of the borehole for an affordable approach are three of our key elements. A fourth important element is mission analysis and vehicle conceptual design. We're looking at a lot of different types of missions. Lunar missions, precursors robotic missions, human missions to near-Earth asteroids as well as to Mars. The reason why we do this is to determine what the requirements are on the engines. How long do they have to operate, how many restarts are there, what's the maximum temperatures that these engines will see? These are important questions and impact the test program for fuel development and validation. Requirements definition is an important activity also so it's a combination of all of these task elements. The fifth and final key task element is putting everything together into an integrated plan that makes sense and is affordable.

As I mentioned previously, all of this work started under the Advanced In-Space Propulsion program in fiscal year 2011, and is now continuing under the new Advanced Exploration System (AES) Project called the NCPS, the Nuclear Cryogenic Propulsion Stage. The five tasks discussed above are also key elements of the NCPS project, and we'll be working for the next three years to fabricate elements, test them, and at the end of these three years, be able to select one as our primary fuel and element design approach. Then we hope that in the next four years, say around 2015, to get the OK to go forward with an integrated ground technology demonstration test of a small engine by 2020. Using our common fuel element, we'd fabricate and bundle together a number of these elements in a smaller, lower thrust core, build it and test it out at the NTS using the borehole approach. And then, once we've validated that it operates successfully, take that same small engine design and do a flight-technology demonstration mission. Maybe we'd fly to a near Earth asteroid as a robotic precursor. Then five years after that, we'd scale up the core to the full-size 25,000



NASA

Concept crewed spacecraft for NASA's Design Reference Architecture (DRA) 5.0, featuring the NTR for in-space propulsion between the Earth and Mars.

lbf thrust engine, put together the vehicles that you saw in my presentation, then fly to a near Earth asteroid with a crew potentially by 2028, which is when a number of candidate NEA missions are available. That will set the stage for testing everything out in a deep-space environment so we'll be ready for a Mars orbital mission in 2033 or thereabouts.

Martinson: If you had the funding profile that we had back in the late 1960s and 1970s, a miracle happened, we got full funding for the Mars program, and we needed that nuclear thermal rocket, how would that change the program?

With "Authority to Proceed" and committed funding, we certainly could develop a NTR and the spacecraft needed for the missions and dates I discussed above. Since we are focused on a given size engine—25,000 lbf—rather than a single real big engine, we'd use a three-engine cluster of 25,000 lbf engines, because it provides an engine-out capability. If you lose an engine, you still have two good engines to continue on. If you have only one big engine, and you lose that, then you're stranded and could lose the mission and the crew. So, engine-out is a good thing to have, and by being really focused, and using affordable SAFE ground testing, my belief is that we could probably develop a 25,000 lbf engine, ground test it and fly it for somewhere in the area of $3.5 billion. You also have to build the stage and overall vehicle, and put all the other hardware together. But, if the country decided to move forward, and if it were an international effort, I would think that the nuclear thermal rocket stage would be but a percentage, and not a major percentage of the total investment required. Certainly I can't see it costing as much as the SLS [the Space Launch System]. I mean, that's a big effort, over the next five years, to put together a 70 ton heavy lift launch vehicle, expandable up to hopefully 130-140 metric tons, so I think it would be in that same ballpark or possibly even less.

I certainly think that, if the country said it wanted to go ahead and do this, we could do it. I don't think the nuclear thermal rocket would be one of the key large items, because there's a lot of synergy with other technologies that would also be needed. The heavy lift launch vehicle is going to have a large liquid hydrogen tank, because the launch vehicle will use liquid oxygen and liquid hydrogen propellants. What we saw in NASA's Mars Design Reference Mission 5 study, was that the Ares V heavy lift vehicle had a large aluminum-lithium hydrogen propellant tank that was 10 meters in diameter, and 44.5 meters long. One of those tanks, cut in half, with two extra end domes, would give you the two tanks that you need for the crewed transfer vehicle to get to Mars.

A lot of the hardware that we'll be using in other transportation elements, like the heavy lift vehicle, chemical propulsion landers and ascent vehicles, are going to have pumps and nozzles as well that will also be used in the NTR. So, I think all of this parallel technology development should help to reduce the overall cost of NTR engine and vehicle devlopment.

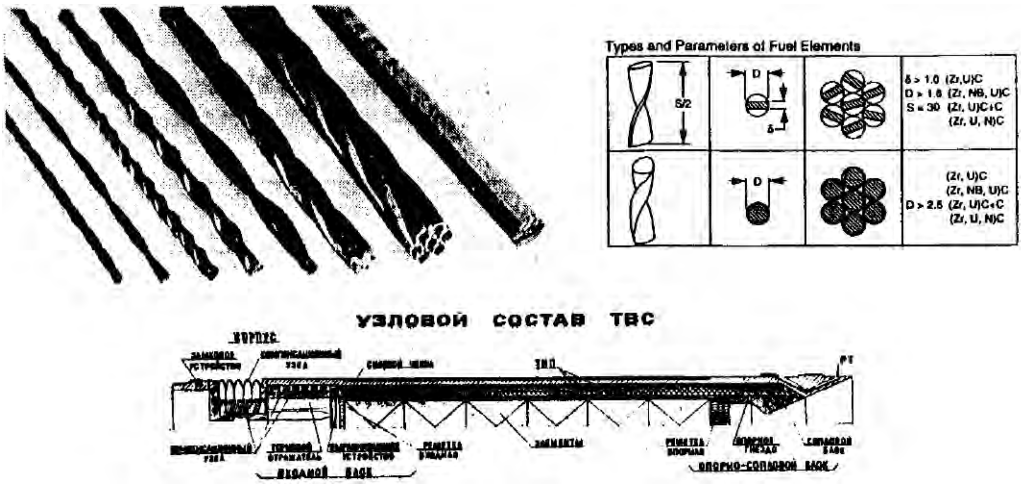
Marsha Freeman: One of the things that makes this almost an endless program, is to focus it entirely on Mars. One thing that's very interesting which you mentioned before, is that with the doubled specific impulse, you can go more quickly to Mars, and you're going to do that with people. However, the other tradeoff, is that you could use this more efficient system to deliver more cargo as well. There have been numbers of designs, Krafft Ehricke had one of them many years ago, for using a nuclear powered freighter for the Moon. What would be the applications for using NTR for the Moon?

Ultimately, I think everyone would like to see humanity build a base on the Moon, and establish a permanent human presence there. Some folks want to go to the poles, because they think there's cometary ice there, but the fact of the matter is that, when you look at all of the places you want to explore on the Moon, the pole is just one of them. There's the large crater Copernicus, along with a large number of other sites.

Focusing on the poles is almost like saying that Christopher Columbus should have gone to the North or South Pole first, and then expand outward to explore the New World! Hyper-focusing on the poles also doesn't make sense to me because the Moon is covered in minerals that have significant oxygen content.

One of the things I found most impressive, and exciting, was that on the last Apollo mission, Apollo 17, Harrison "Jack" Schmitt, our geologist-astronaut, was bouncing around the Moon near Shorty Crater, and he kicked the soil, and shouted out, "Gene! Gene! Look at this! It looks like orange soil!" And Gene Cernan said, "Nah, it's all gray here on the Moon!" But, they kicked it up, and sure enough, it was orange soil. So, they scooped up this orange soil, took it back to Earth, and it turns out that this orange soil is volcanic glass, ilmenite, with a high oxygen content. So, you can take this iron-oxide rich volcanic glass, stick it in a chemical pressure cooker with hydrogen, and reduce it, and create water vapor and oxygen.

Apollo 17 was conducted in the Taurus-Littrow Valley, which is located at the southeastern edge of the Sea of Serenity. That whole gigantic area is volcanic glass, thousands of square kilometers in extent, and estimated



NASA/Borowski

Russian designs for "twisted-ribbon" fuel elements.

to be over five meters deep. There's enough oxygen, if you process the volcanic glass there, to allow you to do 24 hour commuter flights to the Moon every day for the next thousand years or more.

Nuclear power is key to processing and reducing iron oxide-rich glass to produce oxygen on the Moon. You definitely need it, because you have 14 day lunar nights and days, so you'll need plenty of power to keep the air conditioning cooling your base during high-noon on the Moon, and at night to keep everything warm. Nuclear propulsion is also key, because you also have a significant delta-V [i.e. change in velocity required] to leave Earth orbit, to capture into lunar orbit, and then to return to Earth. That's where nuclear propulsion comes in and shows its value.Again, with a propulsion stage, and maybe an extra saddle truss and a drop tank, you can carry significant payload to the Moon, you can return stuff, but primarily you'll just want to take equipment out there to build up the base infrastructure. So, I think nuclear power for both propulsion, in-situ mining, and for maintaining a base during the 14 day-long lunar days and lunar nights, it's really the key to allowing us to get to the Moon, set up a presence there, and to maintain it.

Freeman: Years ago the Russians had a very active, well-funded and well-researched nuclear space program. That fell by the wayside, especially through the horrible years of the 1990s, and what happened to their space program. Recently, they have announced that they have restarted their program. Are you familiar with what they're doing?

Well, I'm not totally familiar with what's currently in the works. You see a lot of articles that appear in the press associated with [the Russian Space Agency] Roscosmos, and various other components of the Russian space program, talking about nuclear propulsion. They say it's an essential technology for doing human Mars exploration, but it's unclear whether they're talking about nuclear electric propulsion, or nuclear thermal propulsion. Just like in the United States, there are various national laboratories which advocate certain things, and various NASA centers advocating certain things. They've got the same kind of setup in Russia.There are institutes and research centers there, all of which have experts who are trying to advocate a particular approach. The Russians definitely have in the past worked on nuclear thermal propulsion.

In fact, we're working with the composite NERVA fuel and the CERMET, but beyond those fuels are even higher temperature fuels called ternary carbides, that consist of uranium, zirconium, niobium carbide, which have even higher operating temperatures than the composite and the CERMET. So, the Russians had been focusing on these options, and developing what they called "twisted ribbon" fuel elements that are approximately 2 mm wide and about 100 mm long, that are bundled together, and then stacking one on top of another to produce an overall larger fuel element that produces the desired amount of power for its NTR engine. I'm sure that, if they go forward with a nuclear propulsion program, they'll continue to look at this fuel option, and possibly some others that they've mentioned in the past. But, I'm sure that they'll look at nuclear electric propulsion as well. So, as part of this global space exploration initiative, maybe as we go forward, we can learn more about what everybody else is doing, and decide what the best approach is, who can bring what to bear on the initiative, and we'll see how we can go forward. Hopefully, with an affordable approach, because that's going to be the key.

Martinson: I think that's probably good, and gives a good overview of what the future potentially holds for manned space flight. Thank you very much Stan.

Peter, it's been my pleasure, thank you.