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NUCLEAR REGULATORY COMMISSION

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33RD REGULATORY INFORMATION CONFERENCE (RIC)

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TECHNICAL SESSION - W19

SPACE NUCLEAR POWER SYSTEMS - TO CISLUNAR AND BEYOND!

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WEDNESDAY,

MARCH 10, 2021

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The RIC session convened via Video Teleconference, at 1:30 p.m. EST, Raymond Furstenau, Director, Office of Nuclear Regulatory Research, presiding.

PRESENT:

RAYMOND FURSTENAU, Office Director, RES/NRC

TRACEY BISHOP, Deputy Assistant Secretary for Nuclear Infrastructure Programs, U.S. Department of Energy

NATHAN GREINER, Program Manager, Tactical Technology Office, Defense Advanced Research Projects Agency

ANTHONY CALOMINO, NASA STMD Nuclear Technologies Portfolio Manager, National Aeronautics and Space

Administration

TINA GHOSH, Senior Reactor Systems Engineer, Accident Analysis Branch, Division Systems Analysis, RES/NRC

P R O C E E D I N G S

(1:20 p.m.)

MR. FURSTENAU: Good afternoon, everybody, and welcome back to the RIC. This session is on Space Nuclear Power Systems: To Cislunar and Beyond! And I know I've been really looking forward to hearing this session. It's going to be a lot of fun.

When we first started looking at space systems, I know when I came to the NRC in 2018, Mars 2020 was coming into being and I know that we were developing, starting to develop National Security Presidential Memorandum 20.

And we were going to have a session in the last RIC that really kind of focused on the regulatory aspects and the policy aspects of space nuclear power systems, both commercial and government flights.

But since we're a little farther along than that and we've had a successful Mars 2020 and if you look close on Perseverance, you can see the RTG that's on Perseverance when they show photos.

And I know DARPA is doing some really cool stuff. And we've got Nathan Greiner who's going to be able to talk about that. And NASA's got some cool missions going as well.

So I thought this year since things are farther along, we'd talk more about the missions and how nuclear safety plays into the missions.

You think, well, what does that have to do with NRC missions or oversight? Well, the NRC does belong to the Interagency Nuclear Safety Review Board that does do reviews for nuclear space systems and I'm a member of that board and Tina Ghosh is an alternate.

We've had people work on safety reviews of space missions in the past. But what's particularly interesting, I think, that's going on now with new space missions and propulsion systems, and I know everyone's going to talk about that on the panel, that some of these technologies I think will get directly related back to what may turn into commercial applications and licensing of activities and facilities that the NRC does have regulatory authority over.

So with that, this is going to be a fun session and I'm going to introduce our panelists before we get started.

The first panelist is Tracey Bishop. She's the Deputy Assistant Secretary for Nuclear Infrastructure Programs at the Department of Energy's

Office of Nuclear Energy.

And I've known Tracey for, I've lost count of the number of years, Tracey, but it's been a long, long time, and it's really great working, it was really great working with you when I was in DOE and I'm glad you agreed to participate in this.

And Tracey's responsible for the management of the Office of Nuclear Energy's infrastructure programs at the Idaho National Lab and the NE Field Operations at the Oak Ridge office.

And that supports the lease administration of the uranium enrichment capabilities at Portsmouth Gaseous Diffusion Plant.

She's Nuclear Energy's primary interface with NASA to develop and deploy nuclear power systems to support space exploration goals. And that's what you'll hear from her today.

She holds a bachelor's degree in nuclear engineering from Georgia Tech and an MBA from the University of Maryland.

She's a certified project management professional. And she received a presidential rank award in 2015 for her accomplishments in the area of nuclear infrastructure management.

After Tracey, the next speaker is Major Nathan Greiner. And he's a program manager for the Technical Technology Office with the Defense Advanced Reactor Projects Agency.

And we won't be able to have Nathan on video, but we'll show his picture and his slides. And he's there by voice. So, Nathan's with us.

Major Greiner joined DARPA in 2018 as a program manager in the Technical Technology Office. His interests include advanced power and propulsion technologies for land, sea, air, and space applications.

And before joining DARPA, Major Greiner completed a one-year fellowship at the Oak Ridge National Lab in Oak Ridge, Tennessee, where he focused on material research.

And he's had a whole bunch of Air Force assignments over his career as well, which I won't go over many of them.

Nathan, I don't know how you've done all of this stuff in your career. It's quite amazing. But Major Greiner, he holds a Ph.D. in aeronautical engineering from the Air Force Institute of Technology, a masters in science in mechanical engineering from the University of Utah, and a bachelor of science in mechanical engineering from the University of Saint Thomas in Saint Paul, Minnesota.

He currently manages the Glide Breaker Hypersonic Defense Demonstration Rocket for Agile Cislunar Operations, better known as DRACO to us, nuclear thermal propulsion, and advanced full range engine programs at DARPA. So thank you for joining us, Nathan.

And our other panelist is Dr. Anthony Calomino. He is the Space Technology Mission Director Portfolio Manager at NASA.

And he manages the space nuclear and power propulsion technologies under that NASA directorate, and he has engineering degrees in structural analysis, engineering mechanics, and material science.

Dr. Calomino's expertise is in durability analysis, the damage modeling of high temperature materials and composites extending from metallic super alloys to ceramic matrix metallics, or composites, I'm sorry, epilators and refractory soft goods.

He has worked in nuclear fission technology development for NASA since 2016.

So with those introductions, I'll turn it over to you, Tracey, for your presentation. And if we could have Tracey come on the screen along with her slides, that'd be great. Tracey?

MS. BISHOP: Thank you, Ray. Thank you for the introduction. It's great to be here today to talk about what the Department of Energy is doing for the space effort in totality. Next slide, please.

So as you may or may not know, the Department of Energy has spent over the last 60 years being a key part of space nuclear power propulsion for the U.S. government, going back to the beginning of the space race in the late 1950s where it first started developing radioisotope power systems, particularly radioisotope and electric generators under the Atomic Energy Commission, and moving onto bigger and better efforts, including supporting weather satellites, the Apollo missions to support its aeronautical activities, also designing and deploying a reactor in the mid-'60s to test the capability in space.

And then moving on into the '70s and '80s to more deep space missions empowering probes, including some big ones like Pioneer, Voyager, New Horizons, Ulysses, and as Ray mentioned, moving into rover capabilities, including the Mars Science Laboratory and the latest Mars 2020 Perseverance rover where you can see the MRTG very clearly on the top of the rover which is powering not only the rover but the helicopter as well. That's part of the whole experiment package. Next slide, please.

So the Department of Energy is probably not thought of as having a role in nuclear space power, but we do serve as a technical design facility for space nuclear power propulsion systems that have been designed for our agency and its predecessors.

And those two areas are focused on radioisotope power systems and nuclear fission power systems as well.

How do we do this? We enable the work for our National Laboratory Complex research and development areas in a wide range of technical capabilities to advance these technologies, which you can see it's DOE in partnership with the National Nuclear Security Administration.

We have a number of national laboratories. The few I have highlighted here are key laboratories that are involved in space activities.

They are part of a consortium led by Idaho

National Laboratory, Los Alamos National Laboratory, Oak Ridge, and Sandia National Laboratories.

The other thing that the department has in our a unique role with authorities through the Atomic Energy Act is we can extend nuclear safety and business frameworks to other federal agencies in order to provide a basis to be able to execute nuclear missions and also provide the safety, oversight, and analysis work. Next slide, please.

So briefly, what is our two main technology areas? The first one is radioisotope power systems. Those systems enable advanced missions by providing nuclear power to explore environments where solar power and other chemical batteries is not feasible.

And that's for spacecraft operation and things like its instrumentation. Basically, it converts heat from radioisotope into electricity for the use of thermal couples.

The heat is a product of natural isotope decay and we utilize plutonium 238 in this energy matrix. It's the isotope of choice because of its long half-life and its high energy alpha particle.

I have diagrams and pictures here on the slide. And in the far bottom right is a picture of a Pu-238 Fuel Pellet, which is unclad, and yes, that is the actual color. It does glow very hot from that decay product.

And then we also have some specs here. There is a radioisotope heater unit, which is a very small design, which is a very small tube ram pellet that can be put in the instrumentation to keep them warm.

And then we utilize the fuel clads and put them into general purpose heat sources, and that's the battery that powers our radio isotope power systems. Next slide, please.

As I mentioned before, we have a number of power systems that have evolved over the decades. Some I've highlighted here, just a few of the major ones.

First one was SNAP 27, which was approximately 70 watts electric. That was primarily utilized for the Apollo missions.

We had astronauts actually carrying these, put them in place to be able to perform some of the first series of experiments for NASA. We were able to gain additional information to do that.

As we moved on and started employing the deep space probes, we moved them to SNAP 18 designs which are about 40 to 45 watts electric, that were utilized for the Viking and Pioneer missions, and then moving into the 100, multi-hundred-watt systems, into the late '70s with the Voyager Model Two, and then eventually into the general purpose heat source RTG, which is approximately 300 watts electric that was utilized in the '80s and '90s.

And that was through the 2000s with some of the big missions with Galileo and New Horizons. Next slide, please.

So currently, we have three systems that are flight certified. The first one is the multi-mission radioisotope thermoelectric enerator, which is pictured at the top right of the screen.

That is a system that was utilized for both the Mars Science Laboratory as well as the Mars 2020 Rovers. It produces roughly 110 watts electric each.

The next system we have is still flight certified, although last time we used it was New Horizons. It's the GPHS-RTG.

The final system we have is the

radioisotope heater units. And those are the small pellets to keep the instrumentation warm.

But we're continuing to work and move forward with NASA, looking to the future as far as what is their next step in the next evolution of technology.

So right now, we're currently working on two technology development areas. The first one is the Next Generation Radioisotope Thermoelectric Generator, which is focused on essentially being the next modification to the GPHS unit.

NASA's identified a need to have larger power systems, so we're in the process now of working with them and industry to look at those designs and look at options to be able to revamp that technology going forward.

And the second area is a Dynamic Radio Isotope Power System. And that's utilizing either a different power conversion system.

But that's not passive, it's thermal couples. And it would be utilizing either Sterling or Brayton cycle to be able to prove the efficiency of the RTS units. Next slide, please.

So how does the department execute on the radio isotope power system production? Well, it's a multi-laboratory effort that takes a few years to go through the entire process, which starts at the very beginning, which is plutonium isotope production.

Since 2015, we've reestablished the capability to produce domestic isotope activities, and that starts with Oak Ridge National Laboratory where they fabricate the neptunium-237 targets for radiation.

Those targets are then radiated and put into either the High Flux Isotope Reactor in Oak Ridge or the Advanced Test Reactor at Idaho National Laboratory, where they go in for irradiation cycles.

Once the targets are irradiated, they go back to Oak Ridge National Laboratory where the 238 is separated and put into an oxide form and then shipped to Los Alamos National Laboratory, where at Los Alamos National Laboratory, the heat source oxide is pressed and put into pellets and encapsulated, utilizing some of the fuel that's present at the lab and also utilizing cladding that was produced at Oak Ridge National Laboratory.

Once the pellets are assembled and encapsulated, the heat source assembly process then moves to Idaho National Laboratory, where -- INL, to make the encapsulated fuel clads.

They put them into a general purpose heat source. They then build and assemble that heat source into the generator, test it, verify it for flight consistent with NASA requirements, and then provide support to ship the system off to Kennedy Space Center where they work with the mission partners in order to integrate the power system with the scientific equipment and then support any launch activities, including nuclear safety support and radiological contingency planning. Next slide, please.

So in order to -- one of the improvements we've done over the last few years is we've shifted our partnership with NASA to focus on having a constant rate production approach to supplying plutonium-238 isotopes and heat sources to support NASA's missions.

Previously, this work had all been done in campaign mode, where a mission would come in, we would retrain people, bring the equipment back up to operational status, manufacture the fuel, and then put everything back in cold standby.

Well, that's a very expensive and time

consuming process in order to operate in the facilities in that manner, and it also put a lot of risk onto the missions. So a few years ago, we shifted to having a stable production rate that was based on NASA mission requirements with the goal of producing one and a half kilograms per year of heat source plutonium oxide by the mid-2020s, as well as being able to produce and manufacture 10 to 15 fuel clads per year.

This was felt to be a good fix that would continue to exercise the equipment, make sure that we had a continuous production rate going forward with material, and actually have material on the shelf to support future missions.

And that really was a very effective and cost-savings measure, and we're projecting that the actual cost to the missions would be reduced by roughly 25 percent and also take about two years of scheduled risk off of a future RTS mission.

So it's just something that we're trying to work on to ensure that we've got this viable capability going forward and we can meet growing mission demands. Next slide, please.

So the second technology we focus on are nuclear fission power systems. And these are systems that utilize fission reactions to generate power for space applications.

This is an area where we've had lots of starts and stops over the decades. As I mentioned earlier, we successfully launched the SNAP 10A back in the 1960s, which is a U.S. space reactor.

Now we also had nuclear propulsion research and demonstration programs that were established in the 1960s, NERVA and the KIWI activities were some of the examples of those.

And since those major programs terminated in the early '70s, there's been modest efforts since then to, particularly to evaluate and move designs forward.

The SP-100, that's an example I have down there, but there's been others throughout the efforts. You'll hear some more about those from the other panel members here in a little bit.

One of the benefits that we're seeing now, and there's been such a growth in this area, is there's a lot of natural synergy with the DOE missions that support the commercial nuclear power industry, especially with the new microreactors and small molecular reactor efforts, areas such as fuel qualification and development, design and demonstration of these small reactors, and then also modeling the simulation capabilities.

So this is just such a -- such a great time right now where we've had a lot of different entities who are interested in the same things being able to partner together and continue to move the technology forward. Next slide, please.

And just, I don't want to elaborate on this too much, but currently we're supporting fission surface power demonstration activities to look at more sustainable power source for demonstration by 2028 in the 10 to 40 kilowatt electric range.

We're also working on nuclear thermal propulsion, where we're looking at establishing technical foundations and also supporting experimental programs, particularly at the TREAT reactor where we do a lot of fuel testing and development.

Other things we're working on, too, is there's a common fuel development program for both terrestrial and space use.

We're going to look at particle fuel, for example, to see where we can glean synergies and then also be able to leverage common platforms, common manufacturing applications. Next slide.

So what does DOE bring to the table here? Well DOE, and through our national labs, just has extensive capabilities for fuels and materials research development, qualification for technologies, and being able to demonstrate performance and safety of systems.

Over the last decade or so, DOE has really stepped up and invested heavily in capabilities to support the nuclear commercial industry from a radiation, custom radiation examination, looking at different fuels, modeling simulations, and moving into demonstrations.

And we continue to look for opportunities to leverage these existing facilities and capabilities and technical collaborations between agencies, industry, and universities to work and provide the technology to the next levels.

And the pictures here on the slide are just pictures of those, our three reactors. We've got the Advanced Test Reactor, the High Flux Isotope Reactor, and then the TREAT reactor. All three of those serve just key roles in all of these areas.

Next slide.

Nuclear Safety Framework. This is something Ray just mentioned. So we also, one of the benefits the department has is we leverage our nuclear safety framework to support all of the space nuclear power propulsion technology activities.

The new space policy, such as the National Security Presidential Memorandum 20, really aligns to the DOE nuclear safety model and provides transparency for safety reviews.

This was such a key game changer. It established risk-informed approval levels for nuclear launches. Prior to that, all nuclear launches, regardless of how much material was on there, all went up to the presidential level for approval. So this really aligned and put the risk commensurate and the approvals commensurate with the risk threshold levels.

It also established very clear nuclear safety guidelines for government launches. And it also reduced the regulatory burden and supports future commercialization goals by setting expectations that are already rooted in our existing U.S. commercial nuclear industry policies and regulations.

So it focuses on looking at risk in terms of maximum exposed individual and it sets thresholds that are consistent with both the DOE and the NRC regulatory framework.

So it provides a lot of expectation setting up front. And I think that's one of the things that when they looked at the prior process, there's a lot of questions because it was a very long process. Took about seven years to get through that.

And it was identified as one of the high-risk issues they're trying to get to launch approval at the end state.

And as you can see, here are the pictures of the Mars launch back in July. Next slide, please.

I also want to mention, too, the DOE/NASA Partnership Model. Over the last few years, we've really strengthened our partnership with NASA.

We put this structured framework in place to leverage DOE's self-regulation authority and indemnification capabilities, along with our contractual business process.

And the way we do that is we have an Interagency Memorandum of Understanding with NASA that was signed in October of 2016, and that sets the high-level agency roles and responsibilities.

It also provides indemnification protection for NASA and its contractors. And that is the governing document, and from that document, we develop interagency agreements.

And here you'll see two. One is focused on the Radioisotope Power Systems and the second one is focused on nuclear fission programs.

From there, we set -- those are five-year agreements that set very broad funding authorities as well as its goals for each of the agencies. From there, we establish one-year project plans and that goes to the next tier down.

And you can see for the Radioisotope Power System, we have constant rate production activities. We also have new technology. And then we'll also have individual missions that are shown here like the Dragonfly mission.

For the fission, we have both nuclear thermal propulsion and we have surface fission power as well.

And strategic, from there we develop detailed strategic partnership plans. Those are really our contractual agreements with our national laboratories so that NASA can utilize our national laboratory expertise and be able to assign work authorities to them to accomplish the work.

And this has worked very well. It also gives a lot of transparency and it allows NASA and other agencies to be able to leverage DOE and its contractors to be able to go out and partner with industry, universities and other entities to be able to further the mission goals. Next slide.

And in summary, I hope as a takeaway today you recognize that DOE is really a key partner, that we work to help enable our mission launching agencies.

And we really work hard to improve and continue to strengthen this interagency and industry collaborations and be able to provide a forum to help progress the development of this technology to support the overall U.S. space goals.

And with that, I am done with my presentation. Thank you, Ray.

MR. FURSTENAU: All right. Thank you very much, Tracey. And I appreciate the little history lesson and also what's been going on recently in the Department of Energy as well.

And we do have several questions coming in but we're going to save them until after all the speakers have had a -- had a chance to discuss their -- discuss their programs, since some of the questions may get answered in those other presentations.

So with that, I'd like to bring in Major Nathan Greiner from DARPA. And he's going to talk about, which is a really cool project called DRACO, and he's going to explain what DARPA's doing in that area of space nuclear propulsion. So, Nathan.

MR. GREINER: Thanks, Ray, and thanks for the introduction. This is a really exciting opportunity for us to share about a very exciting project that we're taking on here at DARPA.

And as Ray introduced, we call this project the Demonstration Rocket for Agile Cislunar Operation.

I've been gifted to be the program manager for this project that we've kind of been working to get underway for about the last two years here at DARPA. Go ahead to the next slide.

So a little bit of an overview of what it is that we're trying to do with DRACO, right. So with DRACO, we're really trying to develop leap ahead propulsion technology for space applications, right?

And really, when you look at this square in the bottom left there, we really have two kinds of propulsion on orbit right now.

We have electric propulsion, which has very high efficiency, very high specific impulse, but very low thrust, right?

But then you have another, which is chemical, which is in the bottom right of that -- of that part, which has very high thrust to weight, but has relatively low efficiency, relatively low specific impulse.

And so what we're trying to do with this project is to develop nuclear thermal propulsion. And for those not as familiar, right, so the slide on the, the square in the bottom right there, with nuclear thermal propulsion, what we do is we take the lowest molecular weight propellant that we can find, right, which is -- which is hydrogen.

We bring in liquid hydrogen into our propulsion system as depicted on the -- on the left side of that graphic.

It goes through a turbo pump in order to actually raise the pressure of that -- of that propellant, and then we flow that propellant through a reactor, split atoms, big atoms into small atoms to release heat, deposit that heat into the propellant, and heat that propellant from, you know, cryogenic temperatures on the order of about 20 Kelvin, up to extreme hot temperatures, up to 3,000 Kelvin, and then push that now extremely hot gas through a nozzle and expand it in order to actually be able to produce thrust.

And what that does, it allows us to produce a propulsion system that has thrust to weights that are very similar to chemical propulsion systems but has much higher, in efficiencies, right?

Much higher specific impulse, up to about two to five times higher. And that really allows us to do some new missions on orbit in order to get this kind of leap ahead propulsion.

So specifically on DRACO, we are interested in actually developing a high assay low enriched uranium nuclear thermal propulsion system and then launching it to above GEO, putting it on orbit above GEO, and demonstrating that system in about the 2025 timeframe.

And one of the reasons that we're looking to actually demonstrate this on orbit is because we really don't have the facilities on the ground in our

-- in our modern era to be able to actually demonstrate the system at full power on the ground, right?

So what that leads us to is that if we want to get a first demonstration complete without building new facilities here on the ground, then we're really forced to go up and do an on-orbit demonstration.

That really is the overall objective of the DRACO program. Go ahead to the next slide.

So Tracey talked about this a little bit already, but we've been launching radioisotope thermal electric generators for decades. Almost six decades, we've been launching these systems.

And so that, so launching of RTGs has become somewhat of a commonplace among missions that are -- that are going to Mars and beyond, but reactors, launching a reactor into space, has an entirely different safety profile compared to radioisotope thermal electric generators, RTG.

So one of the first RTGs that we -- that we had launched was the SNAP-3B RTG back in 1961. And as Tracey had said, these systems used plutonium-238, which decays with, you know, a half-life of 87.7

years.

And so at the time you launch these systems, they are, quote, on, right? They are producing heat, they are actively decaying as radioisotopes.

And modern multi-mission RTGs typically launch with around 60,000 curies of radioactivity at launch. And so that's not an insignificant quantity.

And obviously, we've found ways to work with it and a lot of the safety measure that we go, that we apply to RTGs, as Tracey mentioned, are really about containing the system, right?

It's about encapsulating the system so that if there is an accident on a launch, that we're able to contain the radioisotopes, that we don't disperse radioisotopes to places that we don't want them, right? So they really focused on kind of containing that radioisotope.

Now with DRACO, this will actually be the first launch, the first launch by the United States, I should say, of a nuclear reactor since the SNAP-10A reactor was launched in 1965.

And again, we're doing that because we don't have suitable ground facilities for demonstrating the system on the ground.

Now in comparison to an RTG, a reactor at launch only has about two to three curies of radioactivity from some of the radioisotopes, isotopes of uranium that are in the reactor.

So we really have a very low level of radioactivity in the reactor actually at launch, especially compared to RTGs.

But again, there's just an entirely different safety profile around reactors because with the reactor, when we launch it, the reactor has at that point never been operated at full power.

And so it's never been allowed to actually produce or to accumulate an appreciable quantity or inventory of fission productions.

And so when we launch them, when we launch a nuclear reactor, our focus from a safety perspective is really around, how do we prevent inadvertent criticality on the system.

So if the reactor, if the system were to be launched and something were to happen on launch and the -- and the system were to land in the ocean or in wet sand, how do we handle those kind of scenarios so that regardless of what happens to the reactor in an accident scenario, whether it lands in water or in sand or anywhere else, that we don't actually get an inadvertent criticality event.

So that really is our focus with regard to launch safety activity. Now, once the system actually gets above LEO on orbit after launch and it's safely locked onto orbit, we're very careful to make sure that the system actually gets launched in place into what we call a nuclear safety orbit, a nuclear safe orbit.

Such that if this reactor were to reenter after orbital decay, that the system would have been on orbit long enough, for hundreds of years, such that any fission products that accumulate after operation of the reactor are allowed sufficient time to actually decay such that if the system were to reenter, that it would be at about the same level as when it actually launched, at about that same two to three, single-digit curies kind of level.

So really, ultimately what this does is it prevents even the possibility of having the reactor reenter, what we call a hot reentry, with being able to reenter with appreciable fission products.

And ultimately, this approach meets the

guidance that's laid out in the Space Policy Directive 6, which was published on the 16th of December last year. Go ahead, next slide.

Okay, so I wanted to talk in a little bit more detail about NSPM-20. Since we're focused very specifically on this -- on this one mission, I did want to talk about NSPM-20 and how DRACO relates to NSPM-20.

And I really liked what Tracey said earlier about NSPM-20 really being a game changer, because it really is in that it has set an objective regulatory framework and it kind of has set out this three-tier system for how we classify launches that allows us to really tailor how we're going about and approaching our launch approval process, in order to help us to be able to move fast, get something done, and all the while, still be able to objectively maintain the safety of the public.

So with NSPM-20, this three-tiered system, conventional radioisotopes can fall anywhere in this three-tiered system, really pending what the quantity of the radioisotope is in the RTG and what the overall risk to the public is.

Now with reactors, they, per NSPM-20 fall within two tiers, the tier two and the tier three, each depending on their risk to the public.

And what's great about NSPM-20, NSPM-20 charges us, the sponsoring agency, which in this case, of course, is DoD, with the actual production of a safety analysis report, right, so this allows us to view the objective criteria that are -- that are -- for the risk of the public that are laid out in NSPM-20 to design our reactor and design our spacecraft around meeting those objectives and being able to produce a safety analysis report that shows that we do, in fact, unequivocally meet those objective safety criteria.

And then what it does is we then are able to work directly with the folks in the Interagency Nuclear Safety Review Board, the INSRB, to actually have that board review our Safety Analysis Report, our SAR, and actually document their findings in a Safety Evaluation Report, that provides a recommendation on launch safety to the approval authority.

And so with DRACO, we're 100 percent absolutely committed to meeting or exceeding the objective safety requirements in NSPM-20.

We have been actively engaged with the --

with the INSRB folks from the very instantiation of NSPM-20, and we've been working very close, right, because as Tracey mentioned as well, the former process to be able to go through the safety approval process was a multi-year, high single digits, and I think Tracey said seven years in one example to go through this launch approval process.

And obviously, for DRACO, we're the -- we're the first reactor -- we're the first reactor that's going to be going through this new approval process that was laid out in NSPM-20.

So we're really treading new ground here, which is both exciting and it's also somewhat nerve wracking, right, in that we want to get from A to B.

We want to draw a straight line, but there's always new things that you learn as you go through a new process.

So we're working with the INSRB early and often to make sure that we're on the same page with our path to go forward and meet the guidelines within NSPM-20.

We're also working very closely with DOE and DOE labs, specifically with the Los Alamos National Lab and Sandia to work on our design criteria and our analysis approach to actually meet the NSPM-20.

It's fantastic to be able to work with the DOE folks. They have such a wealth of knowledge working with reactors in the past.

And they really have the expertise that we have been certainly relying on and will continue to rely upon for DRACO going forward. But it's been great to learn from them.

And finally, so we're, within this three-tier system, for the DRACO program, we're seeking to launch under a tier two authorization, specifically because, and that's one of the reasons that we drove towards using high assay, low enriched uranium, is to stay within that tier two, to stay within tier two, but also to make sure that we ensure the probability of our reactor causing an accident stays well below the objective criteria of one in a million as outlined in NSPM-20.

And in conclusion, I really wanted a foot stomp, right? I mean, for DRACO, we absolutely are dedicated to producing revolutionary capabilities for the United States, but at the same time, it's absolutely our top priority to maintain the safety for the public while we launch this system and to -- and to meet or exceed the guidelines that are laid out in the -- in the NSPM-20.

If you go forward one more, I'll just show you a cool picture that you've already seen, and Ray, I'll pass it back to you.

MR. FURSTENAU: Right. Yeah. Thanks so much, Nate. This is really cool stuff that you're doing with the DRACO program.

I'm kind of envious in a way. And I know a lot of questions are coming in and we'll get to those a little bit later.

But next we want to go to Dr. Anthony Calomino. He's going to talk about the programs going on at NASA in the future.

And I don't know, Nate, they kind of match with DRACO. I don't know which one's cooler yet, the ones that NASA are doing or DRACO, but everyone can judge for themselves. So Anthony, you want to take it from here?

MR. CALOMINO: Sure. So I just, I'm going to talk a little bit more about mission sets. Then I am going to talk about some of the regulatory concerns. I think Nate and Tracey have covered that pretty well for us. So if we could move to slide two.

And basically, the Space Nuclear Technology Portfolio is relatively new to NASA. I mean, we've looked at fission technologies for quite a few decades. The SNAP-10A is an example of some of the technologies that we've looked at to generate power.

More recently, we've been focused on both our lunar mission and our Mars mission and we're looking at power requirements in those two areas.

And advancing some of the fission system technologies and system capabilities actually fit a nice need for NASA's mission.

Within my area for the fission technology development, we are looking at designing, building, and demonstrating a space-ready fission power system.

It's one of the first capabilities that we want to have, primarily because it will support our lunar mission and a sustained human presence on the moon.

And so it also gives us the ability to operate in craters, permanently shadowed craters, as well as a little bit more autonomy or independence from some of the long lunar nights.

The other activity which is quite closely aligned with Nate's and DRACO is the advanced deep space nuclear propulsion systems.

These are the architectures or transportation methods that we would be using to conduct the human exploration mission of Mars.

These systems are high-risk technologies right now. We're looking at both the nuclear thermal propulsion system that Nate talked to in detail, but we're also looking at the nuclear electric propulsion.

We're using electric propulsion devices and using the nuclear reactor developed electricity to power those. Currently, actually, that NEP system is the baseline system that NASA is looking at for its Mars architecture.

So we're doing trades on both. I'll talk a little bit more about them and some of the investments there.

And then, obviously, looking to collaborate and develop working relationships with other government agencies, such as Nate's and Tracey's, looking for synergistic technologies related to materials, fuels, and development and fabrication efforts.

And as always, NASA wants to look to get industry engaged as well as academic interests. And we'll try to align as we can with some of their approaches and solutions. Next slide.

So just a couple of things. The fission surface power, I talked a little bit about this. It does give us that solar independence, that continuous power production.

And I'll talk a little bit about what our threshold power requirements are. They're very similar for the moon and for Mars.

They are required to have a sustained presence for the long-duration lunar operations. And we're looking at the -- at the moon as sort of giving us that foundational system to demonstrate that power capability and then work out some of the design modifications or some of the other extensibility options that we would have to move that capability to Mars.

On the nuclear propulsion side, the big challenge for NASA right now is looking at these opposition class missions.

Read opposition class missions as sort of coming in early during the synodic period with Mars, which is around two years and having a short duration, fast transit out to Mars, stay for a short period of time on the surface of Mars, 30 to 40 days, and then leave and still have an opportunity to return to Earth, which typically would be about 750, 700 kinds of day missions. That would reduce the amount of radiation exposure to the astronauts. That's the big advantage for us there.

It's going to require extending some of the performance requirements for the NTP system. It also puts some challenging burdens on the NEP system.

And, of course, for both, we're looking at critical craft load management technologies for the propellants and some of those other systems.

So a lot of these areas that we're investing in in these technologies have direct synergy with DARPA, and we're working with Nate and his group to collaborate where it makes sense.

Right now, the agency has prioritized the lunar surface power as the investment area and continues to support the propulsion capabilities as well. Next slide.

So looking a little bit more in detail as far as what we're doing with the propulsion and power areas, talk a little bit about the numbers.

The fission surface power system is actually managed out of NASA Glenn in Cleveland, Ohio. The propulsion activity and investments are managed out of NASA Marshall, which is in Alabama, Huntsville, Alabama.

The fission power system, we're looking at lightweight 10-kilowatt dynamic power conversion technology or system on this one.

We are interested primarily in HALEU solutions although we're open to do comparisons and trades on HEU still, but HALEU has a lot of advantages to us.

And we are engaging or actively looking to engage design and trade space studies with industry on that power system.

On the space nuclear propulsion, the reactor on that one is much larger. We're looking at about, for NTP, we're looking at a 500-megawatt thermal reactor to drive high ISP engine.

These engines are going to be 900 second ISP, but I think for folks that work reactors and some of the materials technologies, what that really translates into is temperature for the reactor -- for the propulsion component.

And in this case, we're looking at a reactor that would be operating at about 2,900 degrees Kelvin to produce a hydrogen propellant that would be at about 2,700 to give us that ISP that we need.

We are also working with NASA and DOE and DoD to establish a fuel production capability. This is a coated particle fuel production capability.

And it has interest for DoD's PALLEY (phonetic) program. Obviously, the TRISO particle has had quite a bit of development and interest out of DOE over the -- over the recent decades.

And NASA's looking at that as a fuel form that we can use, we believe, for a lot of the different applications.

So there are studies that show that we can use it for those surface power systems, for the -- for the lunar mission, for NTP. As a matter of fact, that's our primary fuel approach for NTP as well as applications for NEP.

And we currently are engaged in an industry solicitation. It's on the street. We close those out at the end of March. This will be a design effort, and I'll (audio interference) more about that.

Next slide.

So just a little bit about the fission surface power. Details there. Integrated story. We are working closely with DOE on this, looking at DOE's subject matter expertise, looking at DOE also to help with their authorities on nuclear regulation and their ability to elicit and get some of the procurements and contract efforts with reactor development companies in industry.

We are currently looking at a sort of two-phase approach, one first being in design, second lead up to a build and demonstrate.

We'll do a lot of development on the ground. And that will be an activity that hopefully will lead us into a flight qualified system for power for the moon that we can launch in the late '27, perhaps (audio interference) activities that we've brought in that may push into 2028.

And then we would demonstrate that capability on the surface of the moon for about a year and make sure that we understand the system, run it through its paces, and then look at what other modifications or changes we might need to do to make that same performance capability work on the surface of Mars.

As I said, we're looking at HALEU solutions that enables us to engage a broader sector of industry as well as allows us to reach out and talk with some of the industry and academic interests to bring them in and help with some of the fuel development and moderate material development efforts. Next slide.

Go through it quickly. We're looking for a 10-year lifetime. We want modularity. In other words, we do expect the power to grow, 10 kilowatts is getting in -- sort of threshold power requirement that we have.

We do see institute ISRU that we would need to do. We also need to look at other sustained robotic missions that would be on Mars.

So right now, the thought is we'd be at 40 to 50, perhaps even 100-kilowatt power requirements on the surface of the moon that we would demonstrate.

We do have a government reference design, which is a segmented moderated HALEU system. We use that system to inform our investments, on NASA's side, and to invest in areas where we think we can get some early work done and reduce the technology development risks to industry.

And that segmented reactor is (audio interference) moderated reactor using HALEU fuel. And the request for information was sent out in February (audio interference) and with the change in administration (audio interference) been a little bit of a delay in that, but we would like to get that (audio interference) right now.

A little bit different from what NASA's doing, because we are stepping in this area, is really leaning on the experience at DOE as well as some of the experience out in industry to define what does it mean to design a safe fission reactor?

All that would be tested and verified for space application (audio interference) we were going to work together on that by using some of industry's design knowledge and design tools and bringing those into the activity that we're using to get that capability out there.

And there's been quite a bit of strong interest from industry on this area to participate. And they are actually looking for commercial products that they could use either in LEO or also for some of the commercial activities that we would envision for the surface of the moon. Next slide.

On the space nuclear propulsion side, next slide, little bit of the story there. Nuclear thermal propulsion is our primary investment right now (audio interference) where we have this significant amount of investment in this area. We've been averaging in the $30 million to $50 million a year on these investments for the propulsion side.

As I said, we really see this big challenge here as getting the reactor temperatures up (audio interference) materials, materials knowledge, our understanding of material performance in these temperatures to their limits.

So there's a lot of activity looking at how we would design those materials and how we're going to characterize those materials.

I already talked about the common use of fuel production and the collaboration with DOE, but I kind of want to expand on that collaboration with DOE here.

And I should have really talked about this more in the fission power activity as well, is that we have a blended team, and it's very much of a blended team between NASA and DOE.

As a matter of fact, for the propulsion side, we've taken in one of DOE's folks from INL and they are (audio interference) for our area in NASA, and so they basically are on full-time with one of our fuel development activities, which is really one of our key investment areas.

So it needs a lot of engagement, regular weekly meetings, a lot of across the fence kind of exchanges in terms of technology, and it's been working very well.

I've been very happy to say that these teams are productive, and everybody has a piece that they're playing in terms of advancing that capability.

The other area that we're looking in nuclear electric propulsion, we don't have a lot of investments in there. We do have some electric propulsion investments, some of the electronics investments on the PMAD (phonetic) side.

It is currently the agency's reference configuration. There's a lot of advantages of fewer launches from Earth to get the capability in space. And it also has a little bit -- it has a lower mass that we would use to leave Earth for that departure.

So there are some economic advantages to that capability. And it also has some longer-range interests for NASA for some of its deeper space missions to the outer planets beyond Mars.

Talking about the nuclear thermal propulsion on the next page, the reactor designs, we use, as I said, the high assay low enriched uranium. That's across the board for power and propulsion.

Right now, we're marching toward a subscale engine build on this, about 12,500-pound force, thrust engine.

Our idea is that (audio interference) we would deliver that engine in the late 2020s, and it is a system (audio interference). That decision hasn't been made. That will close out -- we released it on the 12th of February, we'll close out at the end of April.

This will be for phase one contracts. We're looking anywhere from two to four contracts, nominally three.

And really this is just to get an idea of the preliminary reactor design, so it's really an engineering design activity. It could configure different concepts and (audio interference) that industry would offer.

We've actually had a couple years' worth of trade studies that we've been doing with industry for (audio interference). We have a pretty good understanding of what we're going to get out of that.

As we move into the phase two contracts, we would actually start to look at building hardware, reactor hardware, and conducting some tests, proofs of concept on their design, making sure that we can get to the operating temperatures and performance conditions that we need.

Eventually, that would lead into a final contract where we would -- we would do a reactor build, and that would be the one that we would demonstrate. Next slide.

All right. So on the closeout, I think here, just a couple more slides to do. One of the other things that we have been doing in comparing NTP and NEP systems, NASA wants to make the right choice for this transportation system.

It would be a significant investment for the agency. It will be looked at as having a long-term capability that we would use for our missions. We've engaged the NASA Engineering Safety Council to look at technology maturations of the two capabilities between NEP and NTP.

And there's been a lot of commonality in all of these studies. We've had an Internal Mars Transportation Architecture Study and then a National Academy of Sciences, Engineering and Medicine study, which was just completed (audio interference). They submitted their final report about a month ago.

Most of these studies, I'm not going in through all of these bullets, but they indicate that for a late 2039 human exploration of Mars, both systems could be available with a very aggressive investment posture, a little more aggressive with NEP perhaps than NTP, but they both could be made available for that.

One of the first things that we would want to do is probably demonstrate that capability in its full system in the mid-2030s on a cargo mission before we actually use it for a human mission.

They both are interested in and would need to have CFM, cryofluid management technologies. Liquid hydrogen is a significant challenge for zero boiloff.

Obviously, we've launched a mass of that propellant into space, we want to keep it in a tank until we can use it in the engine. So we have a lot of investments that are going into zero boiloff for large hydrogen tanks in space.

And on the National Academy of Sciences studies, they kind of indicated very similar things. One of the things they did point out is that for an NEP system, we are dealing with a lower TRL base.

And we found that to be true in NESC and the Mars Transportation Study. But one of the challenges for NEP is scale up, going from some of the systems that we're used to to some of the systems we'll need.

We're talking about an 8-megawatt reactor in space, we're talking about using about 2 megawatts of electric power to run this system. These end up having large thermal radiators, significant amount of integration that would be required in space. So it's the scale up and complexity of integration that really end up being big challenges for NEP.

And my last slide, so I'll just kind of get off the stage here. Power and propulsion, they're offering us a lot of opportunities.

We do want to leverage industry design approaches for reliability and safety. We'll lean on both industry and DOE for that.

We want to make certain that we have a dominance of knowledge in the nuclear space technology capabilities. NASA is very much aligned with supporting that.

I think Nate talked to this, about ground testing approaches. Full system tests on the ground are going to be difficult for NEP. So we're looking for innovative ways to test these systems before we put them into space.

And as I said, some of the challenges we're working now are commercial alignment, basically making certain that the government is investing in the right areas for risk reduction.

Obviously, always with the government is to maintain stable funding profiles. And then one of the activities that'll continue to evolve is (audio interference).

What do we mean when we say human rating first (audio interference) system in terms of operational reliability for use either as their transportation system for Mars or as a power system for human operations on the surface of the lunar planet (phonetic). And that's the end of my talk.

MR. FURSTENAU: All right. Well, thank you, Anthony. All of you did a great job. I think there's some exciting programs going on.

I wish this session was about an hour longer because we've just got a whole bunch of great questions that come in. So I'm going to get started on those with the time we have left.

And this one is kind of for all of you. I think, Nate, you kind of started to get at this when you talked about launch safety and propulsion systems like DRACO. And we talk about the -- about the review panels, INSRB, and we look at launch safety.

So what do you think from a launch safety standpoint, are fission systems at the launch stage more difficult from the safety standpoint or is it maybe the radioisotope power systems with heavy loads of radioisotopes?

So I think, Nate, why don't you start since you kind of started to talk about that during your talk?

MR. GREINER: Sure. Yeah, absolutely, Ray. And to some degree, what I was trying to get at with my part of the presentation, right, was that to some degree, it's not necessarily like one is more difficult than another.

But what certainly is true, though, is we have a long history that helps us to make ourselves comfortable with launching RTGs with radioisotope power sources, right?

We have a long history with that. And we can kind of look back at previous programs and say well this is what we did then, it was safe then, we've shown and proven through the best methodology we have, right, which is experience, but then when you get into actually launching reactors, it's just -- it's very different, right?

And what we've found, even kind of within the launch community is explaining, this is a nuclear reactor, right, and then just being able to explain the difference to kind of our launch community as well, who's not necessarily made up from folks from the -- from the -- from the nuclear community, right, but marrying those two things up.

And there's a little bit of an education that needs to happen, right, on nuclear reactors and how they're different, right, and how when we launch them, they're essentially cold metal, right, with similar hazards to like a heavy metal, like a lead, versus like a radioisotope, right.

And so probably, if I had to stand up in front today and say which one's more difficult, a lot of it is, you know, the difficulty we have with reactors, a lot of it is just a different mindset that we have to get into for reactors and kind of the education process to go from kind of a radioisotope-centric mindset over to a reactor.

I think both are absolutely doable, obviously for radioisotope power sources, but for our reactor, we're absolutely, it's a doable project. But that education part is certainly a hurdle that we need to clear over the coming years.

MR. FURSTENAU: Yeah, thanks, Nate, and maybe for Anthony or Tracey, as we look at programs that are responsible for doing the safety analysis for space launches, on fission systems, how do you take into account possible reentry?

Let's say you've launched it. Maybe there is no fission product inventory to -- the reactor at launch because it hasn't operated yet, but then the thing gets into space, you operate it, and then -- and then it can possibly have fission products build up in space and then somehow there's an event that -- cause reentry.

Do you account for those types of things as you -- as you look at the hazards for these future launches?

MS. BISHOP: Hi, Ray, it's Tracey. I'll take that on. Yes, absolutely, and I think one of the great things with NSPM-20 is that it's going to allow us to really leverage, at least from the department's perspective, how we identify those hazards or potential accident scenarios up front early in the process.

One thing I failed to mention, one of the things that we're trying to be transformative with NASA is start to developing safety analyses that are based on the technology independent of the mission so that the missions walking into looking at how they go to a power, what power needs do I have, we'll have all that information up front rather than developing that information two, three, four years into their planning and design efforts.

So it's going to really kind of move that safety discussion a lot further into the process up front, very clear.

And we look at -- we have those thresholds that are identified in (audio interference). It's going to allow us to identify what are those high-risk hazards.

And in prior launches, we looked at everything from initial ground phase all the way up to complete to launch and potential reentry, so of all of that does get captured in the process.

So those are things we want to continue to work on and move forward with.

MR. FURSTENAU: Thanks, Tracey. The next question I'm going to direct to Anthony and then maybe Nate can jump in.

I mean, both of you in your -- in your discussion talked about the propulsion systems and using high assay LEU and to define it, the high assay LEU is uranium enriched to less than -- less than 20 percent.

And rather than, let's say a weapons grade, very very high proportion of U235. And you guys brought up a high assay LEU. And where are you going to get it?

And you mentioned the advantages of it. I think, Nate, you did, with regard to NSPM thresholds. And maybe you can explain what that threshold is.

But, Anthony, do you want to start with high assay LEU and why you chose that and where you're going to get it?

All right, it looks like we maybe lost Anthony. He's been having some trouble with connections here. So, Nate, that means you have to take the question on.

MR. GREINER: Sure. Well, I'll take on the question from a DARPA perspective, certainly. So that's a -- that's a really great question, right? I mean, when we look at DoD applications, right, usually performance comes first, right.

And from our perspective, when we look at -- when we looked at high assay low enriched uranium versus highly enriched uranium, it really came down to looking at NSPM-20 and this tiered system, right.

So for anyone that reads through NSPM-20, right, you see that tier two accounts for, in terms of reactors, reactors that both fall under two categories, right.

One is using low enriched uranium, and two is being able to prove that you have that one, less than one in a million chance of, I think it was a five rem dose to the public, right.

And so it was both risk-based and enrichment level based. And what that tier two allows within NSPM-20 is that the approval authority is delegated from the Presidential/Office of Science Technology and Policy level, down to the agency director, which in our case would be the Secretary of Defense.

And that's a huge change for us, especially, and an enabler. And then for tier three, right, if you want -- if you want to go to a highly enriched uranium system, that would drive you to a tier three system just automatically, regardless of the risk of dose to the public.

And so that really is what -- go ahead, Ray.

MR. FURSTENAU: Yeah, thanks, Nate. Sorry, Anthony, you didn't get a chance to answer the --

MR. CALOMINO: I've been having -- I've been having a lot of challenges with my system. Thank goodness it didn't kick me out. Hopefully I'll --

(Simultaneous speaking.)

MR. FURSTENAU: Well, I really have to apologize. We've ran out of time. The session has gone quickly, and we had a lot of great questions.

Like I said, I wish we could have stayed on another hour and had this conversation because it's really great stuff.

I just want to thank all of you on the panel. Tina, thanks for backing me up as a coordinator of this. And I really appreciate all the participants with the great questions we had come in.

So with that, thanks again. And we'll close this session. And have a great rest of your day.

(Whereupon, the above-entitled matter went off the record at 2:47 p.m.)