DISCOVERY 30TH ANNIVERSARY ORAL HISTORY PROJECT
EDITED ORAL HISTORY TRANSCRIPT

ARLIN BARTELS
INTERVIEWED BY SANDRA JOHNSON
GREENBELT, MARYLAND – SEPTEMBER 15, 2023

JOHNSON: Today is September 15th, 2023. This interview with Arlin Bartels is being conducted for the Discovery 30th Anniversary Oral History Project. The interviewer is Sandra Johnson, and Mr. Bartels is at Goddard Space Flight Center in [Greenbelt] Maryland and talking to me again today over Microsoft Teams. We're going to actually talk about a New Frontiers mission that started out I think as a proposal for a Discovery mission back in 2006. Let's talk about that, those early days, and when you became involved with this mission.

BARTELS: Yes. It's a really interesting point you bring up. Of course as we're talking today, we're on Friday September 15th, we're 10 days just in advance of the sample return canister being returned home. I'm sure we'll get to those preps too and we'll talk about that status.

But in terms of the history, it also shows here how the Discovery and New Frontiers Programs, how well they tie together. Because sometimes missions don't necessarily fit neatly just into one category or the other. Sometimes they even move back and forth, like you mentioned, although OSIRIS-REx [Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer] was selected as a New Frontiers mission, it was actually originally developed as a Discovery proposal, which wasn't selected. That's probably a good place to start here, because one of the things that might be of interest to your folks is that these missions that we do for deep space rarely just come up with an idea quickly, get selected, and move into implementation. Some of these ideas take many many years. LRO [Lunar Reconnaissance Orbiter] was definitely an outlier.[1]

When we talk about DAVINCI [Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging] later, we were working on those concepts for over 20 years prior to selection.[2] The origins of OSIRIS-REx go back 30 years, honestly, and again originally conceived as a Discovery mission. But when they were not selected in that first proposal round, they recast themselves just a little bit, with a little bit of instrumentation changes and up as a New Frontiers and were selected as New Frontiers.

But the genesis of the OSIRIS-REx mission, like many of them, goes back to an idea that a science team member has or something that takes years to germinate before it blows up even into a full-blown proposal. Usually it takes a couple of cycles for a proposal to get selected. Part of the nature of Discovery and New Frontiers that maybe I should have highlighted more earlier was that these are all competitively selected missions, where each team competes against other NASA-led teams that want to go to other destinations in the solar system with different science. Part of the beauty of the Discovery Project and why they've had such a good track record of programmatic success is that it's almost like each proposal phase you get a better product. You get a better mission design because you get feedback that you incorporate. If you're not selected it's heartbreaking at the start because we work so hard on these proposals. But then we take the feedback that we get from folks, and if [NASA] Headquarters encourages us to apply again in a subsequent round, then we do that and sometimes missions propose multiple times.

[1] LRO was the first U.S. mission to the Moon in over 10 years. LRO created a 3D map of the Moon, as part of a program to identify future landing sites and resources – including deposits of water ice shadowed in polar craters. LRO continues to orbit the Moon.

[2] The DAVINCI mission will study the origin, evolution, and present state of Venus in unprecedented detail from near the top of the clouds to the planet's surface.

OSIRIS-REx only had to propose twice, once as Discovery, and then it was selected as New Frontiers. But the genesis goes like I say all the way back to the '90s and a man at Lockheed Martin named Dr. Ben Clark. He had a really interesting idea. One of the things that really surprises people when they first see OSIRIS-REx is the method by which we collect, because when people in their mind think about going to an object in the solar system and grabbing a sample and coming back, usually they think about like a claw or a scoop or a grabber or something like that. That's a very different design that Dr. Clark and others came up with early on that said, "Well, we can actually try something different."

The problem with any of those things that I just described is they have to have moving parts, moving mechanism parts, to work. Those are all things that could fail, especially if you're coming in contact with another body. A better way would be a way that had no moving parts that could completely work just on basically contact and hydraulics if you will.

The way OSIRIS-REx works is almost like a reverse vacuum cleaner in a way. The way we set it up is the main sample head, which folks will see a lot in the news over the next 10 days, is basically the size of an old-school vinyl record or maybe like an air filter in the car. It's plumbed with a gas bottle of gaseous nitrogen; they actually had two backups from a primary.

The way it works, I should have brought a prop with me. I guess I'll just use a pen as a prop. When the spacecraft with the arm on it that we call our Touch and Go Sample [Acquisition Mechanism], TAGSAM arm touches the surface, as soon as it touches the surface, sensors detect that it had touched the surface, and it sprays a high-pressure concentrated flow of gaseous nitrogen directed in a very specific way to stir up the surface, what's called regolith, and then ingest it and entrain it into this item that like I say kind of looks like a car's air filter. That was a really intriguing concept because nobody had really thought of it that way before. They'd always thought about scoops and claws and grabbers. This idea really intrigued folks.

A lot of work went into maturing that concept to show that it would actually work on the ground. In a 1 g Earth gravity environment it's hard to sometimes prove how it would work like it would work in space. Early on they did some developmental testing in NASA's what they call the Vomit Comet, the [KC-135] plane actually based out of Johnson [Space Center, Houston Texas] that flies these very specific hyperbolic loops that allow you to have 20, 30 seconds of simulated weightlessness, microgravity. There were a lot of tests that Lockheed Martin did early on to demonstrate that concept would work.

When there was enough thought that this really will work, then Lockheed Martin approached the University of Arizona and Dr. Michael [J.] Drake, who they'd worked with in the past, and he was excited about the idea as well. They went off and developed some of the early designs, concepts.

Actually NASA Goddard came to the table fairly late when Lockheed and Dr. Drake approached Goddard to partner with them. This is another interesting thing that shows how Discovery and New Frontiers missions work. Grassroots is the wrong term, but the mission designs and concepts typically start, not from a top-down hierarchical view from NASA, but they start from potential principal investigators [PIs] and science teams that have ideas.

NASA guides this by the [National Research Council] Decadal Survey where NASA lays out, with a full industry complement, the goals for a decade at a time of what planetary science goals are unmet and should be focused on. Smart teams that want to win align their mission concepts with what's in the Decadal Survey. But then like I say NASA doesn't just direct missions and pick PIs. It's much more grassroots, brought up from the community.

That's what makes it interesting. In a case like this again it was Lockheed Martin's first idea, then brought in University of Arizona, and Arizona brought in Goddard for this partnership, and then together that team put together a proposal called OSIRIS. It didn't have the REx at the end. That was the Discovery proposal that was not selected. But based on the feedback that they had, one of which was you're kind of pushing the budget cap for a Discovery but you would be perfectly suited for New Frontiers if you just go back and recast this a little bit and do some more work.

At the time the first proposal, they said, "What you're actually trying to do at an asteroid is an audacious thing to do. No one's ever done that before. You really need to make sure you spend some time really thinking through the whole point from the time of how you get to a small asteroid, how you navigate around it because the surface gravity of an asteroid as small as Bennu is almost nonexistent. You're almost just flying loops around a point in space more than being held by gravity. You need to make sure you've shown how to do that. That actual collection and sampling and how you'll choose the site where you'll actually select the sample from." Which is a whole story. We could easily take an hour just talking about that process. Then actually performing that safely, grabbing the material, stowing it, and then getting it back to Earth for the Earth entry when you're back to just the sample return capsule [SRC] is the only part that comes back to Earth, and the spacecraft diverts away.

There's so much that's involved to make all of that successful. In an early proposal phase you haven't had time maybe to think through all of those details. But you need to show that you've really thought through those details. By the time they got to the OSIRIS-REx proposal for New Frontiers, that second round of proposal work, the hardware was pretty well defined at that point, the mission design was pretty well defined. It was really about fleshing in those details of the whole operation sequence from basically in flight to Bennu the asteroid, and then back to Earth return.

It's a good example for anyone who's trying to propose to Discovery or New Frontiers that if you're not accepted the first time, that's actually typical, but learn from it, make your proposal better, and then on a subsequent round, especially if your mission is in alignment with the Decadal Survey, then you may well get selected. That process happened. O-REx [OSIRIS-REx], they were talking about it here on Center before I was involved, and even in the 2005, '06 timeframe. I think that first OSIRIS proposal was around 2008. For OSIRIS-REx I first became involved with just as a reviewer of the proposal as it was going in. It was selected on, I remember this, May 24th, 2011. That's the day I officially joined.

I joined as the spacecraft manager. They called it flight system manager, but basically the whole flight segment. I was the government lead for that through launch. Then at launch I took over as the deputy project manager for OSIRIS-REx for the first three years of operations. I left that to come back into the development side onto the Lucy mission, about 10 months before we actually touched the asteroid surface.[3] I was there for eight years and saw a lot of development across that time for sure. But are there any particular areas you wanted to start with on OSIRIS-REx? Any focus areas?

JOHNSON: Yes. You mentioned the way it was built and those first ideas. I know that Lockheed Martin, some of the structure and the subsystems, you can trace them back to many other flights. We talked about that some. That's one of the things that makes these missions a little more

[3] Lucy is the first space mission to explore a diverse population of small bodies known as the Jupiter Trojan asteroids. These remnants of our early solar system are trapped on stable orbits associated with – but not close to – the giant planet Jupiter.

affordable. You're not starting from scratch. You're basing them on other things. I think this was based on MAVEN [Mars Atmosphere and Volatile Evolution], Juno, the Mars Reconnaissance Orbiter.[4] [5] [6] Also the sample return is similar to what's been done before. Talk about some of that development, since you were there earlier on, and how those decisions were made, and some about the teams too that came together to make this happen.

BARTELS: Happy to do that. One of the important things about deep space missions and planetary missions that maybe the public doesn't necessarily appreciate is that because what we're doing is always exploratory or is expected to, we're going places where we've sometimes never even seen them up close. OSIRIS-REx is a great example. We only had very low-fidelity radar images of Bennu at the time.

Because the nature of the mission is so much about exploration, people often assume that the technology is at the most cutting edge as well. It might surprise folks to know that sometimes that's actually not the case. One of the most important things for these space missions is to put your risk in the areas where you cannot retire it because you're going to an unknown destination or areas that you're learning about still. The term is called heritage a lot in the space industry. If you developed something before that works, we tend to use it in as close to the form that's already been demonstrated to be successful as we can. It's our way of reducing

---

[4] The MAVEN mission will determine how much of the Martian atmosphere has been lost over time by measuring the current rate of escape to space and gathering enough information about the relevant processes to allow extrapolation backward in time.

[5] Since it arrived at Jupiter in 2016, the Juno spacecraft has been probing beneath the dense, forbidding clouds encircling the giant planet – the first orbiter to peer so closely. It seeks answers to questions about the origin and evolution of Jupiter, our solar system, and giant planets across the cosmos.

[6] Launched in 2005, Mars Reconnaissance Orbiter searches for evidence that water persisted on the surface of Mars for a long period of time.

risk. Because we know if we've done it that way successfully in the past, we have to make sure that it's still the right design and application for the environments that we're going to see.

But one of the best ways to reduce risk is to employ tried and proven technologies. One thing that you'll end up finding with the planetary missions for like Discovery and New Frontiers is sometimes the instrument packages themselves are fairly standard and fairly low-risk. You typically only have a couple of aspects of a mission that are brand-new.

For instance for OSIRIS-REx one of the important things—and I'll go back to this—this little model here is a model of the actual sample return capsule. If you were to see it right next to one from the Stardust and Genesis missions, you would see it looked almost exactly the same. It was one of our precepts here of going into OSIRIS-REx that for the actual part that comes back to Earth, the outer shell, its size, its shape, its profile, and its dimensions, mass would be identical to Stardust and Genesis.[7] [8] Matter of fact, it was actually build-to-print from Stardust. They actually took out old drawings, converted them into modern CAD [computer-aided design], because those were '90s drawings. We converted them into what was the 2010 through '16 era type CAD modeling programs. But really designed both the sample return capsule and the mechanism which deploys it, which separates it from the spacecraft and spins it up so that it can be aerostable for capture, it's basically identical.

Now of course you might say identical, well, one of those missions had a problem when it came back, and that problem was known very very well by the same Lockheed team, and was certainly corrected immediately, the switch position which led to the Genesis issue. But even

---

[7] NASA's Stardust was the first spacecraft to bring samples from a comet to Earth. Its primary goal was to fly by the Comet Wild 2, collect samples of dust from the coma of the comet as well as additional interstellar particles, and then bring the samples to Earth.

[8] The Genesis spacecraft spent more than two years collecting samples of the solar wind. The spacecraft then brought the sample canister back to Earth where it parachuted to the ground. Despite a hard landing in the Utah desert, the Genesis samples were recovered.

down to things like on the back side where the parachute comes out that failed to deploy on Genesis, everything about it was the same.

Like I say, we try to reduce the risk in those areas, because by keeping the design identical to Stardust and Genesis from the shape, size, and profile, then that means that all of the analyses that went into the heat shield design made out of a material called PICA, and the backshell material, and the shape of its profile as it flies in, all of that had already been demonstrated and proven and validated. We could say, "Good, this is the part we know we've got." We put that on the shelf.

The part that they spent the most effort on, and I apologize for not bringing the model to show, was the actual sampling arm. There were only two aspects of the hardware design that were brand new. One was the lidar [light detection and ranging], our light-detecting radar that we use, oversimplifies it, but the lidar and the sampling arm were novel. Those were things developed uniquely just for this mission.

That's where we spent a lot of the development effort, was on those two new areas, because we had to take it from that idea that Lockheed had had, but actually mature it into a design with exhaustive testing to make sure that we had a design strong enough so that it would survive contact with the surface and that all of the gas bottles—which each time we did a contact we could exhaust one of those gas bottles—that it was designed with the plumbing shaped exactly right to create the little turbulent flow that we wanted to get to stir up the regolith in the chamber. On these sorts of missions we were using camera sets that—although the cameras from the University of Arizona were a unique design, they still had leverage from previous University of Arizona developments. They have a very strong background in optical cameras.

The cameras that they'd built had heritage at least. The cameras that we flew from the Malin Space Science Systems at San Diego again, that's a very interesting company that's built so many spaceflight deep space cameras for planetary missions. Those, not quite a catalog item, but they were close to being a catalog item.

The Goddard infrared spectrometer had a lot of leverage from New Frontiers type work. As did the same follow-up they did for Lucy. The thermal emission spectrometer from Arizona State was also very closely designed to the one that they had flown on previous Mars missions.

We tend to not have huge complex instruments like maybe Earth-observing missions can have, weather satellites, almost every instrument on a weather satellite is as complex as the entire spacecraft for OSIRIS-REx. In that development program they're focusing on those two areas. We can certainly talk them separately because they were very different developments. The one that's of most interest to folks is the sampling arm.

That idea went through several mock-ups and engineering model type designs. The science team spent a tremendous amount of time saying, "If we're going to test it and we're going to test it to pick up particles to show that it works, how best on the ground would we simulate what we think the Bennu asteroid composition would be?" They had many different approaches till they narrowed down the best mimic of what we expected Bennu regolith to be, which is a material that comes from an area called Tagish Lake. It turns out that the material there was felt to be very basaltic and similar to what we expected the asteroid to be. But they also, for different applications, would test things almost like vermiculite. You know what that is if you're a gardener. Things that would mimic what almost a weightless sample would be like.

We did extensive testing of that just over and over with different gas bottle pressures, different shapes. There was a lot of analysis using what's called computational fluid dynamics, CFD, to make sure that we were designing the best optimal system we can to pick up the most mass that we could.

Once that design was proven then as an engineering model, they moved into flight. An aspect that we had to pay attention to more so than any mission I'd been on previously was the whole nature of the OSIRIS-REx mission beyond the technology of course is the science that comes from it. Of course the O in OSIRIS-REx for Origins comes from the fact that we were looking for the earliest samples that we could get. Just like the Lucy mission is looking for primordial samples. The same is true for OSIRIS-REx. In particular they wanted to know about organic compounds that might be present in the asteroids that might talk to how organic compounds might have first made it to Earth.

The most important thing about a sample return mission is to make sure that anything you find when you come back isn't something that you actually took with you from Earth all the way out and back. Just like with Mars Sample Return now, there's a tremendous effort to make sure that everything is not only just as clean as it can be—a lot of missions worry about cleanliness—but here we had to make sure there were no traces of any organic compounds whatsoever. That meant we had to change a lot of the materials. Both the materials that are used in the fabrication of the hardware. We had to be very careful of solvents and lubricants and things like that to make sure that we weren't accidentally contaminating anything with that, with something that might pollute our sample.

We use the term pristine sample a lot to talk about making sure that none of the materials that we use would contaminate that beautiful, prized sample that we're getting back. But that also meant our technicians had to learn a lot of things, to do things they normally wouldn't either in terms of just tools and how we manipulate things. We couldn't use zip ties, couldn't use cable ties, anything with nylon on it. Couldn't use nylon gloves. Many of the things that people were used to, we couldn't afford to use here because we had to make absolutely sure that nothing that we did during the buildup of this hardware would result in a false positive of finding an organic when there was no organic at Bennu, it was just cross contamination that we had introduced during the build.

The interesting thing that was sort of a bit of a milestone in the development here is that arm, because our whole method of contacting the surface—I'm sure other folks have already told you. We called it touch-and-go sampling, TAGSAM [Touch and Go Sample Acquisition Mechanism]. We always talk about how we just sort of kiss the asteroid quickly and then get the sample and pull away. But we already had a designed-to-print container to put it in later that opens up at the line where the white and the orange meet. It opens up there, and we insert the head and close it back. Now that was pretty much build-to-print, except for the little head itself. But the arm was brand-new. So how do we make these two things go together? Because they had to line up very precisely.

Another thing that we try to do with these planetary missions is make them absolutely as simple as possible. We don't want anything that we had to steer and try to get the head in. The head that was at the end of that arm was done without any ability to move it to the—think of it this way—left and right. It could only come in and insert in directly. That was to make sure we didn't have a mechanism that gets stuck or something or get it in a position that wouldn't allow it to seat. We had to make sure that the arm didn't get bent when it touched the surface, because everything had to line up exactly straight.

One of the brilliant ideas that an integration and test engineer had one afternoon there was to instead of designing these things separately and hoping they line up, let's just make these part of a separate assembly. But make it all just one combined assembly that came together. Then they could develop the spacecraft over by itself doing one thing while this entire assembly was developed as a system. Then this whole system could just get mounted on top of the spacecraft later. That was a real epiphany that team had that showed how this technology all came together. Leveraging a very heritage piece and a very novel piece in a modular way so that we could mount it then on the spacecraft.

From that point on the Lockheed team split into two different groups, one that was focused on the sampling system, which we called the SARA, Sampling and Acquisition Assembly, and the spacecraft. There were two parallel teams side by side working at Lockheed, while all of the instruments were still being developed at their other locations and being brought in as well. That was one of the main technology developments. The other one is the lidar. The interesting thing with lidar is it's becoming more common for us to use lidars for docking at the [International] Space Station, and many of the projects that are looking to go back to the Moon involve some sort of lidar.

What was interesting was that the technology change that occurred there was missions had typically used radars for landing, or close approach, or what's called proximity operations going back to the '70s at least, or probably dates maybe probably even farther. But those take a lot of power. They're big. There was always a desire to find a way to get smaller packaging.

When in the early '90s people started making compact lidars like the ones we talked about for MESSENGER [Mercury Surface, Space Environment, Geochemistry and Ranging] and for LRO, that spurred even with the industry to make even smaller and more capable ones.[9] For

[9] The MESSENGER spacecraft orbited Mercury for more than four years, and the mission determined Mercury's surface composition, revealed its geological history, discovered details about its internal magnetic field, and verified its polar deposits are dominantly water-ice.

our mission, we thought that a lidar would be able to help us get just what we needed to get to steer into our patch of Bennu because we thought there would be large expanses of area on this asteroid that would have material that would actually be sampleable we call it, that we could stir up and then entrain in our head.

The thought was as long as we had a patch of ground large enough that we could land anywhere within, the technology of the lidar that really only tells you distance would be just fine. The original design, and actually the one we carried all the way to Bennu, we ended up not using it because Bennu chose not to cooperate and didn't give us the size of patch of ground that we were expecting. We had to find a different technology, which we'll talk about too, that was able to get down to a size of like a parking space from something that was like 25 meters. But the sort of lidars that could do that sort of work were still in their infancy in the 2011 time period, so we chose a company called ASC [Advanced Scientific Concepts] out of San Diego to build our lidar for us. It was their first time building hardware for deep space. They were actually designing terrestrial applications for lidar that they were looking at for things like collision avoidance for cars and things like that.

But they had a very intriguing technology and they had done some early development work with SpaceX and they'd had some NASA seed funding. But they'd never actually built a unit to fly in space. We spent a lot of work with that team working side by side with them to help make sure they understood what you have to do differently to build a scientific instrument of that complexity for a space environment.

For OSIRIS-REx those were really the only two real technology stretches that we did for the mission were the sampling arm and that lidar. Of course we had to use the sampling arm and it worked perfectly. Worked just as designed. The lidar did too. Like I say just that the asteroid made it so that a lidar of almost any type would not actually help us there. That's when as a backup plan, going back even into the mission critical design review phase, we wanted to have a backup method. Because you always want to have a backup method of doing anything. We already had the idea of steering down to a location based on basically rendering maps on the fly and steering from them.

Now again, in 2023, this is not an unusual thing. The Mars missions do this. They call it terrain-relative nav [navigation]. With ours it's called natural feature tracking. But now we actually use optical imagery with enough brains on board the spacecraft to actually take imagery, compare it against a map that it had in memory, and from that then choose how to steer. Which we had to do with OSIRIS. That was an interesting case where the hardware was very standard but the software and the algorithms to actually do the steering were very different. When I said that there was only two types of technology developed, hardwarewise that's true, it was the arm and the lidar. But then using the standard optical cameras to actually steer our way safely down to the surface was certainly a brand-new technology as well. We could follow up on any of those at some later time if you wanted to.

JOHNSON: Yes, that's good, and we can stay with the samples, since that's the time we're living in right now. But one other question I want to ask is you were talking about how the sampling device had to be pristine, and I know with like the Stardust and Genesis, Johnson had a lot to do with creating those clean rooms for making sure things were put together. But this was done at Lockheed Martin. You mentioned that it was new. Was that a long development for them to handle that? Or just a little different.

BARTELS: You're right. For Stardust and Genesis all of the hardware work, and again that cleanliness, was also done at Lockheed Martin. But they weren't looking for organics so much. But now what's done at Johnson is actually the interesting part and it's where our OSIRIS-REx sample will be by Monday the 26th hopefully if all goes well in September, is in what's called the curation facility at Johnson in Building 31. We've actually toured the Stardust areas at Johnson, in particular to see their clean room.

Johnson Space Center has built a whole new clean room to current sizes and expectations just for our samples that's in the same area where the Apollo Moon rocks still are stored as well. Johnson has a fabulous curation facility approach where they're at. That also makes sure that at the last stage of the game when the samples arrive at Johnson they'll go immediately into a very pristine environment. What I was talking about was more the—I can see why it wasn't very clear. The clean room facilities in which the spacecraft is built and tested.

JOHNSON: That was at Lockheed Martin. I just want to make sure that's clear. Was that something that was new for them? Or had they built them in that kind of condition before? Because you were mentioning some of the materials that they couldn't use.

BARTELS: Right. Almost every spacecraft is built in a clean room of some kind. The cleanliness requirements are usually established by which piece on the spacecraft is most susceptible to contamination. If missions have ultraviolet [UV] instruments or X-ray instruments, you're very used to having to be very clean from materials that outgas or that have particulates in them because they can obscure the optics. Lockheed had been used to building in their clean rooms missions that even had UV aspects. The part that was new was that even just the most minute traces of organics that would become transferred from like nylons or from other sorts of materials that could be—normally we're just trying to make sure that we're not applying something that'll obscure a sensor's ability to work, and so they call that outgassing or off-gassing and for laymen the easiest way to think about it is new car smell. The things that are coming off the dash. When those things can lay a coat of film on your windshield, especially in Houston I suppose. Or if you're buying a brand-new car in Houston. You get that sort of hazy film on the inside of your window of a brand-new car. It's the same idea with other materials on spacecraft except you're depositing it on the optics of your cameras for instance and so there's a concerted effort in these clean rooms to make sure that you're not going to leave a very thin layer of contaminants or particles on the optics.

What was unique for the Lockheed folks and for some of us on the mission too was not being allowed to have any material though come in contact with the hardware that would have a possibility of an organic contaminant. One of the things that we did that was very unique in my experience at least, because I don't believe Stardust or Genesis were as worried about organics as we are, though I don't know those missions as well, is that we built—basically along with each piece of hardware that might actually ever come in contact with the sample—we actually built a little sampler coupon of that same material and we mothballed it as well. That way we have a whole inventory of little piece parts that are representative of the parts that went into the flight build.

The reason for doing that is because the scientists over the next decades who will process hopefully this material that comes back, if they see something that says, "Well, that's funny, that seems to have the same chemical signature as a known lubricant might have had, that's very unusual, we need to know. Did this come from the asteroid or was this a contaminant introduced during the fabrication?" Then they'll be able to go to those samples that we've got all stored away and test and see. Oh, we do or do not have that material present on the sample. Then we can say, "Well, shoot, we polluted the sample. That's why you see this type of polyethylene or something there. Because we actually introduced it." Or if all of our samples are devoid of that material we can say, "Look, we really do have a scientific discovery. There really is an organic of this type that we brought back."

What was new to Lockheed was the prohibition against using any materials that would have any chemical composition that might mimic the organics that the team was looking for. But the actual cleanliness standards themselves were not all that unusual. What it did do was it made it very interesting for our contamination control engineers from Johnson, from Goddard, and from Lockheed because they had an entirely new dimension that they had to be watchful for that other missions really hadn't. Because normally they just are looking for things that outgas or particulates. But here they had to be involved in the material selection from the very beginning, and the science team, the curation type science teams, had to work with our contamination control engineers to look levels deeper than they ever had had to do on other missions to ensure that only allowed materials were allowed to be used.

That was a very unique flavor to the OSIRIS-REx mission, was how those contamination control aspects of material selection filtered through every aspect of the build of the mission. That will come back to us again because it's a good lead-in for what we'll be doing here starting in 10 days. That chain of trying to protect it to keep it pristine has to be maintained now from this device that's screaming back into the Earth's atmosphere here starting at 27,000 miles an hour when it gets first released. It has to make sure that that whole process then of recovering it, hopefully intact, just as it is, and it gets helicoptered over to a clean room that's being built there at [U.S. Army] Dugway Proving Ground at the Utah Test and Training Range, there's a special stand-alone clean room that they've put in place just for this operation to bring it there to do some initial testing. That should happen on Sunday morning on September 24th and then, per the current plan, by Monday the 25th we'll already be flying that sample in a C-130J airplane directly from the Utah Test and Training Range to Ellington Field in Houston, and then from there just a short jaunt over to be where you are at Johnson.

The team has spent the majority of the last three months—if you don't mind me making a big changeup, because this is an interesting time. As we talk to this, 10 days before reentry, at this stage we've practiced every aspect that we can think of for the recovery operation, starting from the time where USSPACECOM [U.S. Space Command] first sees this projectile, this hot projectile coming in, and where it was likely to land at the Utah Test and Training Range, we've deployed recovery teams multiple times now to drive out and drive down. We've played Easter egg hunts, put it in places where the team had to go find it, where they didn't know where it was, and they had to figure it out. They've dry-run that process all the way through the flying to Houston, landing at the airport, the roads they'll take to get to Johnson, how long it takes to get into the clean room when they get to the clean room, what tools do they need to take to remove the sample and hand it over. The reason I mention that, the contamination control aspect now tying all the way back to the very beginning really matters here at the end because for a sample return mission, again, we have to ensure that in these very last steps to get from Earth return all the way to the Johnson clean room, we can't do anything to pollute the sample then either. Or else it lessens its scientific value.

That same thinking about contamination control and the sort of materials that can be used matter all the way here to the very end. I was thinking about that in terms of materials because the same sort of contamination control engineers and curation folks who specify the materials that could go into the construction of the hardware have also been informing us the materials that can be used for the recovery. As we start to take it apart what bagging can be used? What purge lines cleanliness needs to be used and things like that. That level of preservation to keep these material samples pristine started with some of these curation folks and contamination control folks all the way back in the proposal phase in the 2009, 2010 timeframe. All the way up through seeing it through to that very bit at the end, which should be September 26th of 2023 in Houston.

JOHNSON: Yes, that's a long arc to keep everything as pristine as possible. I did read an article that they've been practicing doing it, but also once it lands, it's on the ground, and taking samples of everything around it on the ground. Just to make sure in case something happens, they can separate it out too.

BARTELS: That's exactly right.

JOHNSON: This is coming in by parachute and landing. It's not being hooked by a helicopter like the Genesis, right? Or as Genesis was planned.

BARTELS: Correct. Right. When you see the helicopters in the training videos and things, that's still because there's a helicopter aspect not trying to catch it on the way down and grab it out of the sky, but it'll first deploy a small parachute called a drogue parachute at supersonic speeds. Then it's only in the last I think 50,000 feet or so that the main parachute deploys because you have to have enough atmosphere for the parachute to really do much good. It'll come down and hit the ground at about 11 or 12 miles an hour and should be nice and intact.

Then at that point there's a big sling and lift that the technicians and recovery team will put around it and that sling will then be hoisted by helicopter and the helicopter will still bring it back to that portable clean room there at the Utah Test and Training Range. There actually are I believe four helicopters involved in that in terms of people doing reconnaissance and then flying in the actual recovery and curation team members who will do just like you said. First make sure everything's safe. They have to make sure there's no unexploded ordnance in the SRC, which is used to deploy the parachute to make sure it's safe to approach, or that the battery hasn't caught on fire at impact and all those sort of things.

Once we know it's safe for people, then the next step is the curation team like you say does a big thorough mapping and sampling of the environment immediately around the SRC because there is a vent. You have to find a way to get that vacuum of space back in so it's safe. There's a vent material that will allow some atmosphere to be introduced back in. They just need to make sure that that filter is designed to make sure that nothing contaminates the sample. But just like you said, in case when we see the sample, we see something that looks suspiciously like the material in Utah, we need to make sure that we've done the samples around it, to make sure that what was ingested in back through the filter hasn't contaminated the sample.

The curation folks, the same people we talked about, they're involved all the way into being the people who go right up to the unit and are part of its recovery because in case we do have any sort of damage to the SRC as well, they need to be there to give advice to say how do we protect that sample material. It's actually where I'm being introduced back into the team because I left in 2019 to go work on Lucy. But the reason I'm part of the recovery team is the role that I'm doing is what's called the Interim Response Team [IRT] lead. What I do is if for some reason something goes wrong and it goes off-nominal, there's contingency, a mishap of some kind, then me and the small team that I lead actually takes over from a safety standpoint to make sure that everything is prepared for an eventual mishap board. The part where I'll be involved in this last part is a completely different role than any of the roles I had before. But because I'm familiar with the recovery operations, when I left to come on Lucy and now on DAVINCI, they asked me to come back and participate in that role.

But that same attention to maintaining—they call it the integrity of the sample—how pristine it is, is something that will go in every off-nominal condition as well. I mentioned all the training that they did. They trained everything from the decision while still in space to release the capsule as it's flying in down to the minute of every single operation that it takes. We also have run a series of off-nominal or contingency plans as well where we did tabletops to say here's a scenario, let's imagine this particular type of off-nominal or mishap type case. How will we do what? What materials and tools do we need? How will we protect the sample integrity?

One of the neat things that you'll find in these deep space missions is probably true for most NASA missions, but it's more obvious on some of the deep space missions, is that we plan for not only all of the nominal cases, but all the off-nominal cases as well. It's almost more like human spaceflight where they spend much more time worrying about the off-nominal cases than just the does it go well. Practicing the case where things go just as designed is necessary, and we do that until it becomes second nature. But then we start practicing all of the cases where something goes wrong that we hadn't anticipated. That's partly a lesson from the Genesis mishap because at the Genesis mishap they hadn't had the foresight to know to plan for all these off-nominal cases because they seemed low likelihood. But one of the first things I did in my role as the IRT chair was I talked to the person who headed the mishap investigation board for Genesis, and said, "Had there been an Interim Response Team in place, what would you have wanted them to have done for you?" That sort of informed then the approaches we've laid out of how we're going to handle any off-nominal or mishap case.

We've even gone so far as to look at the cases where not just one, where if the parachute fails and it hits a hard impact like Genesis did, but what happens if for some reason there's a slight hang-up in terms of how the SRC comes off the spacecraft, so that it doesn't land where it's supposed to. Maybe if it lands outside of that military operating area of Utah. If it lands in Farmer Brown's field next door, what do we do then? What do we do if it lands in Salt Lake? What do we do if it hits Salt Lake City? Those are extreme cases. But just what do we do if it lands where it's not supposed to be? We've actually dry-run all of those processes of how we'd coordinate with FEMA [Federal Emergency Management Agency] and local police and authorities to make sure that it's safe to—and coordinated with whoever's property it's landed on.

The amount of time we've spent on preparing for off-nominal coordination we entirely hope is wasted effort because we don't want to have any of those things happen, but it is the nature of this type of work that we prepare for every credible off-nominal scenario we can think of. That's what we've been doing a lot over the last month or so. The things that you might have seen on blogs or on NASA sites have been both just the easy part, which is preparing for a nominal capture where everything happens just like they expect it to, and then also trying some of these off-nominal cases of what happens if it lands in mud, what happens if for some reason it breaks, what happens if the parachute fails, what happens if it lands off-site. All of those what-ifs, limited only by our funding and our time to get them in, because you can't practice for everything. But hopefully when we meet again in a few weeks I'll be able to tell you that I was just an enthusiastic bystander during this whole thing.

As part of that role though I do fly with it all the way to Johnson. Goddard's role in this ends at the moment where there's sort of a ceremonial handoff in the clean room between Lockheed Martin's recovery team and Johnson's curation team accepting it with a very happy principal investigator, we hope, with us at the time. Then at that point Goddard's OSIRIS-REx role is over and Johnson's really takes off from that point. When we eject the SRC towards the Earth, if we don't divert the spacecraft, it would come right in behind the SRC. Of course we don't want that to happen. They're doing a special divert maneuver, and that's when OSIRIS-REx then goes into its extended mission called OSIRIS-APEX [Origins, Spectral Interpretation, Resource Identification and Security – Apophis Explorer]. Its new target won't be the asteroid called Bennu anymore, it'll be the asteroid called Apophis, which is the one that has the highest likelihood of a—it's a near-Earth object—of an Earth impact. So Goddard will continue to fly a spacecraft that no longer has any sampling capability. It'll still have an arm. But it no longer has a head on it to do anything. The SRC will be first in Johnson and then in the Smithsonian.

But all of the cameras that we use to scout out the asteroid to pick the TAG site, that same methodology that was used to do very detailed surveys of the surface to understand the surface composition and to find the place to grab the sample from, we'll employ that same set of instruments and techniques to look at this asteroid Apophis to learn more about it just in case future generations need to find a way to divert it. The best information known. These are very different things up close than they are from a distance.

JOHNSON: I know that that's part of it, is making sure that these near-Earth objects don't pose a threat and learn enough about them. If you want to talk about that for a minute that'd be great.

BARTELS: Because it's the single biggest surprise this mission ever encountered when as I mentioned I think from the ground we were able to get the shape of the asteroid pretty well. The science team did a pretty remarkable job of getting the shape of the asteroid right just from radar observations that were very low fidelity. But in terms of what the actual composition of the surface looked like, no one really knew what it was going to look like up close.

One of the most interesting parts of the entire mission was as Bennu became resolvable in our camera images from a single pixel and then growing by the day to one pixel to two pixels to four pixels to eight pixels to where it finally built up an image of the surface and we saw it looked nothing like what we thought it was going to look like. Based on what European's [European Space Agency] Rosetta mission had done when they'd gone to the comet called Chury [67P/Churyumov-Gerasimenko], we thought that there would be vast patches of areas that looked almost like ocean beach in a way, and that's actually what our head had been designed for. But what we found instead was that this—and this has now become common, we see this from other asteroids like the Japanese [Japan Aerospace Exploration Agency, JAXA] have traveled to for their Hayabusa missions. If you've ever seen a picture of this asteroid called Bennu that we went to, it is really what's called just a rubble pile. It's a condensed pile of just rocks. There are no sandy beaches anywhere to it. That's the realization as this became fully resolved for us here, and we saw there's no easy place to touch down and TAG and grab a sample.

That's when we had to abandon the idea of using that lidar and move over to this idea of using the optical cameras from Malin Space Sciences and then putting in the smarts to steer our way to the surface. We're really really glad that we had anticipated that we might need a backup to the lidar, because if we hadn't, we would have really been scrambling to try to devise on the fly after we'd already captured into orbit something we'd started thinking about in 2013, which was this ability to use the cameras, create extremely detailed topographic maps of the surface, load that map into the spacecraft, and then take real-time images that compare against that onboard map to tell us how to actually get down to the surface.

That was certainly the biggest surprise I think on the whole mission. Although the overall shape of the asteroid was known by the science team before we got there, knowing how uncooperative this asteroid was going to be for the technology we'd sent to it to sample the material was a real surprise. There was some real head-scratching moments with the first images saying, "Well, we thought there would be these vast basically sandy beaches to grab material from. This is nothing but a boulder field. Everywhere we look. How do we do this?"

But then once we realized well, the closer you look you can see there are patches that you can avoid. Hazard avoidance became the thing at that point on. We spent a tremendous amount of time mapping out the surface which originally was thought to have been done to get the most scientifically rich sample. We were looking for the most diverse composition of materials. It was almost like a treasure map. We thought, "Where's the place that's going to have the best combination of material to ingest?" That always stayed important. But we had to have this other layer to get added almost immediately which was safety and hazard avoidance. We couldn't go somewhere where we would be hitting boulders and we couldn't actually ingest any sample, or any boulders that were so big that we might actually hit the spacecraft or hurt the spacecraft.

There was a huge effort spent by our team to really make sure they could identify first the four sites they chose as potential sites, and then as they did more image analysis overlaying this ability for hazard avoidance as well, that's when they eventually were able to get to the site called Nightingale that they chose the sample from. By creating special masks there, what they did is we didn't necessarily just steer our way all the way right down. But what we did is we pointed for a spot on the surface, and we could tell on the way—that we knew we'd be safe, parking lot size—and we knew on the way in if the imagery told us that we were not in the corridor we wanted to be in, we were going to maybe hit a rock or something, we could eject back out to a safe environment.

When we talk about natural feature tracking, that's one of the reasons we use that term rather than the way the rovers actually use imaging—the Martian rovers—use imagery to help steer around. Because what they use, they call it terrain-relative navigation where they look for objects and then figure out the way to steer through them and avoid them.

What we had to be a little simpler from a spacecraft coming down to the surface, where we knew if we were in a safe corridor, we were going to keep coming all the way down. But if for some reason we knew that we were going to be unsafe on the way down then we would just eject back out and try again. We knew that after a certain number of tries we would always be able to get there eventually. It turned out it happened on the first site because they did a nice series of practice runs, which folks can find from YouTube videos and the rest that showed the way we did rehearsals, where we would come down. We had two rehearsals and each time we came closer without touching the surface. Then on the third try we came all the way in for the actual sample site. I'm sure those videos will still exist for anyone who's trying to research this later.

JOHNSON: They ended up getting more than they planned at first and had trouble closing up because of some pieces of rock that were in there.

BARTELS: That's exactly it. Two ways. Not only was there more sample than we had anticipated, which was great by the way, because to be honest with you we designed the head to be oversize so that we could actually gather more material if it was available, so that was great. But one of the unexpected results you may have seen if you've looked is we had a limit on the size of a particle that we could actually stir up, ingest, and then we call it entraining it in the head with a Mylar flap that was supposed to close over it.

What actually happened is we were able successfully to gather in a bigger particle than we thought we would be capable of. But that particle was so big, that pebble of small rock was so big, that it actually stuck out farther than we expected. Because of that it was lifting this little Mylar flap that started to let some of the other material escape. Because that final sequence where we open the lid like a clamshell and then take the arm and insert that head in place, clamp it in, sever it, and withdraw the arm, that we were planning on being very slow and taking a couple of weeks to do it if we had to. Just because you're doing this all remotely and you want to make sure you don't do anything dumb. You had to make sure we seat the head into its capture ring correctly so that it latches into place. Then basically it's almost like cutting your arm off and leaving the hand behind as you withdraw your arm as macabre as that is. But we thought that would be something that we'd be able to do very leisurely over a period of time.

But because of what was happening there, the head inside. I'll bring visuals next time. Actually because that flap was held open by this large rock, we were actually losing some of the particles into space. Although we had way more than our mission required, every one of those our science team was saying is very precious. You can't put a dollar amount on the fact every one of these samples we lose to space is something that we should be studying on Earth.

The Lockheed Martin operations team did a tremendous job of really accelerating that process of getting the head seated inside its spot in the SRC so we could clamp it up and get out of there. They were able to accelerate that process by a factor of four I think it was.

Yes, you're right, it's a great problem to have, which is we have much more material than originally designed. Now the problem becomes how do we distribute that material, because there are people who are expecting to have samples coming back. Now we have we hope—I'll be able to tell you in two or three weeks that we have many times more than the minimum amount. There is an estimate that folks have had based on the imagery that we took of the head before we inserted it. There were folks that hoped that we have about four times the amount of material that we set out to get. If so, that's going to make a lot of scientists happy for a long time.

JOHNSON: Yes. Sounds like it. We're at our hour, so I don't want to keep you any longer today.

BARTELS: Boy, so quick.

JOHNSON: Hopefully once you get back and you have some time then we can go ahead and finish talking about OSIRIS-REx. That would be great.

BARTELS: Hopefully everything will go so smoothly that we'll be able to—I hope I don't have a very exciting tale to tell you, because if we do, that means things happened we hadn't expected to happen. Hopefully we'll be able to just talk about the fun easy parts of the mission.

JOHNSON: I appreciate you talking to me today and taking some time. I hope everything goes well.

BARTELS: Thank you, I'm sure it will, I'm sure it will.

JOHNSON: I'm hoping to watch it live.

BARTELS: Yes. Sunday morning Central time right about 10:00 a.m.

JOHNSON: Should be fun. All right. You have a good time.

BARTELS: All right, we'll talk to you in a few weeks.

JOHNSON: Take care, bye-bye.

[End of interview]