NASA Johnson Space Center Oral History Project
Edited Oral History Transcript

Timothy R. North
Interviewed by Jennifer Ross-Nazzal
Houston, Texas – June 30, 2021

ROSS-NAZZAL: Today is June 30th, 2021. This interview with Tim North is being conducted in Houston, Texas, for the JSC Oral History Project. The interviewer is Jennifer Ross-Nazzal, assisted by Sandra Johnson. Thanks again for taking some time to come visit with us this morning. We certainly appreciate it.

NORTH: Glad to be here, thanks for asking me to come.

ROSS-NAZZAL: I thought we'd start off this morning by asking you to give a brief overview of your career at JSC.

NORTH: Okay. I came here in January of '89 right after we returned to flight following the *Challenger* [STS-51L] accident. I had just finished my bachelor's degree at the University of Colorado. I went part-time at night, while working as an electronics technician under contract to the National Oceanic and Atmospheric Administration and prior to that I was in the Air Force. That was my background before coming here. Over my eight and a half years in the Air Force, I worked on B-52s [Stratofortress] avionics and taught electronics for the Air Force. At JSC, I was originally hired in to be a technical instructor in the Shuttle Mission Simulators, training astronauts and flight controllers there and in the Single System Trainers.

I did that for about two years and then transferred to being a Space Shuttle flight controller. In Building 4, the astronauts were on the third floor, the training people were on the second floor, and the flight controllers were downstairs. I just basically moved offices one floor down and became a flight controller.

I worked in mission control as an EGIL [Electrical Generation and Illumination Engineer], electrical systems operator. We covered all the electrical systems, the fuel cells, and the cryogenic reactants for those. I did that until roughly 2000, so I was there for a good 8 or 10 years. By the end of my time working in mission control I ended up working 60 Shuttle flights.

After being a flight controller, I transferred into the MER [Mission Evaluation Room], doing engineering support, and design work. During that time, I was the technical lead for the Station-to-Shuttle Power Transfer System [SSPTS], which was really kind of cool. After the *Columbia* [STS-107] accident, which I was part of the investigation team for, we had lost our extended duration orbiter [EDO] capability, and we couldn't stay on orbit as long with the Shuttle. That EDO capability gave us about two weeks on orbit, and with the loss of that cryogenic pallet with the *Columbia* flight, we could only stay for about nine days total on orbit. This left you about four or five dock days.

It became really obvious that we didn't have enough time to build [the International] Space Station [ISS] in the amount of Shuttle flights that were left, so we designed a system where once we got the solar arrays on Space Station, we could power the Space Shuttle and use less of its Oxygen and Hydrogen reactants. We basically doubled the time on orbit. That enabled us to be able to complete the Space Station in the allotted number of missions.

All through that time the fuel cells were my primary responsibility.

ROSS-NAZZAL: Fuel cells for Station or for the Shuttle?

NORTH: They were on the Space Shuttle. They were machines that would take hydrogen and oxygen, and they would make all the electricity for the Space Shuttle when it was on orbit, for the entire time. The oxygen was also used for the breathing air for the crew. Then when you combined the oxygen and hydrogen to make electricity, one of the by-products was water, so that became the drinking water for the crew, so it was a really cool system on board the Shuttle that way.

It turned out that the chemistry involved, and the reactions involved in the fuel cell are very similar to the original nickel-hydrogen batteries that were on Space Station. You could say the Space Station batteries were half of a fuel cell so to speak. They had the same electrolytes and the same type of components inside the cells.

As we progressed on into the Space Station life and we were looking at the end of the program, the Space Station needed somebody to do the feed and caring of their batteries. I was a natural fit; I was already working on the fuel cells, that kind of chemistry battery, and my experience with the cryogenic systems gave me the experience to work also with the batteries because the nickel-hydrogen cells were basically little pressure vessels. When you charged them, they made hydrogen gas, and then you used that hydrogen gas to make electricity for the Station. I had all that pressure vessel experience. I was like the EE [electrical engineer] but with all this other chemical kind of experience, and so that's my niche.

For the last several Shuttle flights where we finished Station, I worked Space Station and Shuttle. I went back and forth between the two and got shared between the organizations. The handshake agreement from the Boeing Shuttle management was John [P.] Mulholland at the time, and Joy Bryant on the ISS side. "We want to bring Tim over to Space Station," and John said, "Okay, as long as I can use him when the Shuttle is flying." That was the handshake deal, and that's how that started.

I officially transferred organizationally in 2008, early in the year. I was officially working for Space Station and being loaned back to Shuttle. I took over the sustaining engineering work for the batteries. At that time, I think the other person you're going to interview is Penni [J.] Dalton. She was the NASA ISS Battery subsystem manager up at [NASA] Glenn [Research Center] in Cleveland [Ohio]. I met her and started working with her at that point.

I don't know where we want to go at this point, but that's how I got into working the Space Station.

ROSS-NAZZAL: That's okay, you can keep talking, that's not a problem, I can always go back and ask some questions.

NORTH: We launched the original set of Space Station batteries on the 4A [ISS Assembly] Mission to Space Station at the end of November of 2000. By 2008 these nickel-hydrogens had been on orbit for eight years. An orbit is 90 minutes. You spend 60 minutes in sunlight and then 30 minutes in what they call eclipse, darkness, on the backside of Earth. These batteries do a full charge and discharge every 90 minutes. They had been doing that for eight years, and they were designed for six and a half. That's just the first set on what they call the [Integrated Truss Structure, ITS] P6, the first arrays that were up.

We launched the last set, the [ITS] S6 on the far starboard side of the truss, in March of 2009.

Around 2008 we had enough spare batteries to outfit the P6 channels, those two sets of batteries, one more time. They were programmed for the STS-127, ISS 2J/A flight. Then the 4B [Solar Array Wing], the other set, was planned for the STS-132, ISS ULF4 mission. But we were looking at okay, we're going to have to start replacing all these other batteries. If you're going to fly Space Station beyond about the middle of this next decade right on into the '20s, you're going to have to do something to replace these batteries.

Nickel-hydrogen technology is great. A lot of satellites are still in space flying this. We just finished our last set of replacements of nickel-hydrogen batteries on Station in 2020. The downside is they're heavy. We have newer technology, the lithium-ion batteries. All your cell phones are nice and light and small because of lithium-ion batteries. They've enabled a lot of really cool things.

We were looking at either having to extend the production line of the nickel-hydrogen batteries or decide to go to some new technology. Lithium-ion is a really great chemistry and a really cool solution, it has a lot of energy in a really small package. That's the great thing about it. It's also the really bad thing about it. Because when things go wrong, you see the fires, the incidences of laptops burning up, or hoverboards bursting into flame for kids, and all that kind of thing. It's great technology but it's not perfect, like anything, it's a trade.

Also, some of the materials we use for the nickel-hydrogen batteries were going to be discontinued for environmental concerns about the way they were produced. We had the option of being able to buy one more round of that material, do a lifetime buy of that, through the defense side of the government, and so we had a decision point. We either had to do that and buy that material before it was no longer produced, and that was going to be in the roughly 2009 timeframe, or choose to go to another chemistry.

I got asked to go look at this and see what we could do with lithium-ion, what that would look like. The way you charge lithium-ion is a little bit different than how you charge a nickel-hydrogen battery. We already had the full system with the chargers and the batteries on Space Station. Looking at that, the program shared with us that they didn't really want to build all new chargers if they didn't have to. They wanted to save that money and try to find a way to work with the existing chargers.

I came up with an idea of how to make the lithium-ion batteries, put some electronics in so that they would work with the old type of chargers, but it would make the lithium-ion batteries a little more complex. When our team looked at the packaging of this, it dawned on me that from a volume and weight size the nickel-hydrogens had two batteries in series, like a flashlight with two batteries in it, for every charger. There were 24 of these chargers, so there was 48 of these nickel-hydrogen batteries on board. It became really obvious to me that we could package enough lithium-ion cells in one of these orbital replacement unit nickel-hydrogen battery size packages to replace two nickel hydrogen batteries. But then you'd have to do something with that second battery slot because they were electrically connected.

If we built an adapter plate unit to plug into that space and cover that cold plate and finish the electrical connections, we could get by with launching just 24 batteries instead of 48. Then I came up with the idea for a data cable, so we could take the bandwidth of data that we had for two batteries and use it all for one. We'd get one new battery and have lots of data.

The beauty of it all though is any of the launch vehicles we had, either the Shuttle or the follow-on vehicles from some of our international customers, could only launch about six of these batteries at a time. To outfit Station with nickel-hydrogen was going to take us eight missions, six times eight, so 48 batteries. To do it with lithium-ion we could do it in four missions.

If you think of the prices of launches, the savings of going with lithium-ion would be well over a billion dollars. We built a presentation and brought it to Mr. [Michael T.] Suffredini, the head of the Space Station Program at the Space Station Program Control Board. We didn't have any cost data, we just said, "Hey, this is conceptually how we would build the lithium-ion, and here's what we'd have to do to make nickel-hydrogen work."

He could see the monetary value of having four launches instead of eight right away, and that even with the whole project development cost, they'd save a huge amount of money. He did one of those, typical Mike Suffredini things, very forcefully saying something to the effect of, "I want everybody to have no fuzz on this, if we're going to build any new batteries for Space Station, they will be lithium-ion and not nickel-hydrogen. I want you to close down the nickel hydrogen production line and go tell us what it's going to take to build lithium-ions and write that change request and go do that."

I remember walking out of the briefing at the SSPCB [Space Station Program Control Board]. It was up here on the fifth floor of JSC Building 1. I was told, "Man, he gave you a shellacking." I said, "No, he gave me clear direction."

ROSS-NAZZAL: He gave you a mandate.

NORTH: Because there had been a lot of debate whether you should build more nickel-hydrogen or lithium-ion. That's how we got started on the project.

ROSS-NAZZAL: Can I go back and ask you a couple of questions there?

NORTH: Absolutely.

ROSS-NAZZAL: Can you talk about why you could launch six nickel-hydrogen, but it would only take four for the lithium-ion? Is it because of the size? Or is it because of the materials?

NORTH: Nickel-hydrogens, we needed a total complement of 48 batteries to outfit all the Space Station. There are eight power channels, and each power channel had six of those. You'd need 8 launches since you could only launch about six of these size batteries at a time. The replacement batteries had to fit in the same exact footprint as the original nickel-hydrogens. You had to mount it there on Space Station, so you were constrained by the size of these ORUs [Orbital Replacement Units]. If we used lithium-ion, we could outfit all Space Station with 24 batteries. You could have one lithium-ion, replace two nickel-hydrogens. Then you could have 24 of those. You could do it in four launches if you launched six at a time.

ROSS-NAZZAL: I guess maybe I didn't state that properly. I'm just curious. Were there space limitations on the Space Shuttle or the HTV H-II Transfer Vehicle]? Or were there limitations in terms of the materials, meaning you couldn't load enough?

NORTH: It was a combination of volume and mass. One of these batteries is about 39 inches by 39 inches and 18 inches tall. It's not like your cell phone battery. One of the cells in our new lithium-ion, if you had it in your cell phone, you'd probably only need to charge your cell phone about once every two months. These new lithium-ion batteries have 30 of these cells in each one. Times 24. These are not your typical cell phone or car batteries; these are massive batteries.

Probably the biggest aircraft or spacecraft lithium-ion batteries that we've built to date. I think there's some terrestrial batteries that are bigger. But in terms of a battery that's flown and certified for regular aircraft power systems or space like this is, this was the biggest.

ROSS-NAZZAL: You mentioned that there was a lot of debate over whether or not to use the nickel-hydrogen batteries versus the lithium-ion. Can you talk about those two sides and what the pros and cons were from those folks?

NORTH: The nickel-hydrogens were really super reliable batteries that had great operational experience. We had a production line open. There was very little production risk to that. The materials were the big thing, they would have to procure some raw materials. The lithium-ion though, like we talked before, can be really volatile, and everything has to be right, there has to be a lot of safety controls. Just a new technology development. There was some software we had to write with it and some other electronics and packages we had to design and build in the battery. It was just a matter of whether you want to spend the chunk of money and take the technical risk of doing a new development project. That's out there, there are always unknowns, and you learn as you go. So the questions was, do you want to go the proven technology route and launch 48 batteries, or do you want to go with new development and launch only 24?

I think probably in the end it was really attractive monetarily to save that number of launches, but it was also probably a good thing technologically, because NASA is about advancing technology and learning new things. A lot of what we learned here, are lessons learned we apply to other programs.

Now the Orion spacecraft is going to have lithium-ion batteries and also the CST-100 [Boeing Crew Space Transportation Starliner] that we're getting ready to launch in July, I helped with their battery systems and they're using a lithium-ion technology. A lot of the stuff they're going to do on the lunar surface and other vehicles will utilize lithium-ion. That's the technology that's coming. This was a really good pathway to development and furthering the Agency's use and understanding of lithium-ion. So, for a lot of reasons probably that was the right thing for NASA to do.

ROSS-NAZZAL: Talk about coming up with this concept. You said that you really came up with the idea. Were you looking at hardware, or were you primarily just pen and paper, or did you have a piece of hardware that you could look at in terms of the fuel?

NORTH: I was already the sustaining engineer for the nickel-hydrogen battery. Part of that work, for us, my company was being the original designer of those systems. With the previous ISS nickel hydrogen battery focal, Fred Cohen, as a mentor, I took on the responsibility for all the sustaining engineering activities and gained an understanding how the system worked. But our team also supports real-time mission operations in the MER [Mission Evaluation Room]. Not only did we know what the designs were, we knew how they were operated.

In the Space Station Program, the MER is used a little bit differently than it was on the Space Shuttle. A lot of times they're almost like an extension of the mission control team as opposed to just engineering support. We do that too. But they do a little bit more in terms of supporting the real-time mission ops [operations] in general. Not there 24-7, but they're present pretty much every day during the week for the flight control teams as a resource. Whenever you're doing things besides just going round and round doing science, dockings and undockings and EVAs [extravehicular activities], they'll have us there present for that too.

From looking at what was out there when we started in 2009. NASA came up with this task called the safety/risk mitigation task, understanding lithium-ion was a more volatile chemistry. It was headed up by a fellow named Eric [C.] Darcy from NASA. Penni Dalton from NASA Glenn was invited to participate. I was the Boeing person that was asked to participate. We did a survey of all the different types of lithium-ion cells that were out there and looked at what their capabilities were. We ended up with a total of seven types of cells that we actually bought. We did testing on these and we visited the cell suppliers and looked at the way they produced them.

One of the issues that you might have with lithium-ion is if the production process isn't really clean and they get some impurities in the cells. That could lead to internal short circuits in the cell. The way you produce and put these cells together is a big part of making them reliable and making them safe. We looked at that.

We narrowed it down at the end of that year to four candidate cells. So, around the end of 2009 we had a good idea of where we would start with this. In 2010 it was about time to get going in earnest on the lithium-ion development for Space Station. As so often happens, we're the technical experts, so our NASA counterparts in the program office say, "Can you help us with this change request, with the wording and what this might look like, so that we have a skeleton to start the change request process, so that we, NASA, can run this through our review and approval process and then give this to you to go do the proposal?"

I had come up with this concept of how to do it. I was already the battery guy for Space Station, so I was the natural to start that. NASA liked the concept and went through their processes.

They added the things they needed in this project and the things that were important to them contractually and requirements-wise were in this CR [change request] document. Then that officially went up through the NASA boards and was given to us, and we started the RFI/RFP [request for information/request for proposal] business side of working the change for them.

It was the spring of 2010 when that document, that change request, came to us. A couple things became really obvious to me right away. There were some things I just didn't know about how we would do this. I had ideas, but it was a lot like you said, just a pencil and paper and sketches and here's how we do this. I knew how we would plug it in, but exactly what the piece parts would look like and how we would package it and what the reliability would be, how many of these batteries would we have to build for spares, and things like that, and then how exactly we would build the software to charge and discharge this guy, and all the electronics and test equipment, how that would work.

We embarked in spring of 2010 on a series of internal trade studies to help inform us how to respond to that. NASA was gracious enough to basically say, "Okay, we'll give you an extension on the proposal since you're doing these studies on your own time to get the requirements right for us."

We did those studies along with a safety study, and then we came up with a proposal and we got what they call a UCA [Undefinitized Contract Action]. This allowed us to start development before they finalized the contract. In roughly the Novemberish kind of timeframe in 2010 we got full turn-on to go design and build the lithium–ion batteries.

There were other things I didn't know, after we did all these trade studies. I'm pretty good technically and I understand all the technical stuff, but I'm not a business guy. I've done several development projects as the technical lead but in terms of how contracts work and money over years and how you let contracts to subcontractors and all the reporting on the dollars and the cents and how that plays out over years, I would have been buried. I knew that right away. This was going to be a big multiyear development project and I'm not a business guy, and I wouldn't have any fun doing that either.

ROSS-NAZZAL: Not being an engineer.

NORTH: So I gave that some thought. It just so happened that we were finishing up the production we talked about on the nickel-hydrogen batteries, and the fellow that was running what we called the 40-battery contract to build the last set of 40 Nickel Hydrogen batteries we built for Space Station was a guy named Tom [Thomas H.] Franssen. I had met him years ago. He helped do some of our verification work for the Station-to-Shuttle Power Transfer System. When I came to work for Space Station, he was working the 40-battery contract, so we had already had a relationship.

Tom is a great project manager, he's really good with numbers and budgets, he understands what boards you'll have to go to for this, and how all this works. I knew he was finishing up this other contract. It was right about the time when Space Shuttle was getting ready to be put to bed. The manning was going down on the contractor side of the house. I went and visited Tom and said, "Hey, Tom, you want to be the project manager for lithium-ion?"

He said, "Well, how would we do that? Is there a req or something?"

I said, "No, I've got to fill out the manning charts. I'm just going to put your name on here."

He said, "You can do that?"

I said, "Yes."

He said, "How's that going to work?"

I said, "I don't know, we'll see." I just put his name on there, and everybody had already associated Tom with batteries, so all of a sudden, he was the de facto project manager. It was really cool, I got to hire my own project manager, and nobody ever asked who assigned him, they just assumed that somebody did. We had a great relationship. Tom really looked out for the business side, and I took care of the technical. The way it formed up over the several years, Tom was the business side, I was technical, so my counterpart was Penni Dalton at NASA Glenn, and Tom's counterpart was the NASA project manager. Eugene [R.] Schwanbeck was the NASA project manager through most of this, but early there was a couple different people at NASA until that all sorted out. But eventually as we got through this it wound up being Eugene was Tom's counterpart and Penni was mine. It worked out really good.

Penni and I could focus on all the technical aspects; they took care of the business. There were a lot of other people too; it wasn't just us. But we were the two main technical leads, and they were the NASA and Boeing project leads. It all worked out really well. Those were the two unknowns, the money and technical. We put all that together, and by the end of the year we were on contract to go build this thing.

ROSS-NAZZAL: Would you talk about that movement into building a prototype and those challenges?

NORTH: Sure. We hit the ground running. We did a couple really interesting things. A normal design project starts with a system requirements review, and that's where you write down all the requirements. Remind me to come back to systems requirements review. Then the next is normally the preliminary design review [PDR]. There supposedly about 10 percent of your drawings are done, and you know what the basic design is. Then next is the critical design review [CDR] where about 90 percent of your drawings are done. Those are the main stages. Then in there you'll build engineering prototypes and breadboard units and all that kind of stuff. Then usually within the next several months after a CDR you build your qualification units, which are essentially flight units but they're just used for testing, so you beat the snot out of them to prove that they're going to work in the way they ought to.

Tom and I went back and forth about this, but we did a couple things that are maybe a little different than your normal process. We added an extra design review we called the system design review after the system requirements review but before the preliminary design review. That was at my insistence. Because what I see with a lot of these projects is you get to the system requirements review and they have requirements there, but you end up with RIDs, review items for disposition. You spend several months trying to sort through that. If in parallel with that you're doing all this preliminary design review and drawings, you don't really have a firm set of requirements. You don't know exactly what you have to meet and you're trying to do design work.

About three and a half months after the system requirements review, we had a system design review. In my mind that was to set all the main pieces we're going to have in this system and how they interrelate to each other. You have the concept of ops at that point settled down. We had finished up all those RIDs for the requirements. We had a firm set of requirements and it was time to get back with our NASA customer and say, "Hey, this is no kidding the set of requirements we're going to design to, and this is what we're going to build to, and this is what we obligate ourselves to design and build to from performance and reliability and everything else this box will do, how it launches, what are the environments that it has to survive, all that kind of thing, and then here's the main components of it."

It was a good time to get back together and make sure everybody was on the same page. Why I think that was valuable to us. I see a lot of projects will have this system requirements review, and they end up arguing—I hate to say arguing—it's more rehashing requirements and reviewing requirements. I've seen projects at the critical design review when you're supposed to be 90 percent of design done still haggling over what the requirements are. When you write requirements this is what you have to build, this is what it has to do, and part of that is also this is how you verify that it's going to do that, this is how you test it or how you do analysis for it or a combination thereof. Without having that firmly set, it puts you on a path for just not doing well and overrunning. We purposely set that up, and it ended up being really good.

Coming out of that system design review we had firm requirements. We knew how we were going to test everything. We knew what the project looked like. By that time we had a really good timeline. We had our subcontractors, the suppliers for cells and piece parts, and the main supplier that was going to actually do some of the internal design of the batteries and the build of the batteries. All in contract and settled. From that system design review in early 2011 we were set. All we had to do was perform now. There were things that changed, and we learned things over time, but that's how we started off.

From there instead of just building, the first thing we wanted to do was make sure we could work with the charging unit that was already on ISS, what's called the BCDU, the battery charge-discharge unit. The subcontractor who did some of the design of the electronics and the internals of the battery was Aerojet Rocketdyne out in Canoga Park, and they did a lot of the original design work on what's called the IEA, the integrated electronics assemblies, the big truss assemblies that have the solar arrays. They did a lot of the electronics design for that early on. They already had the background on how the thermal system worked, how the charge and discharge unit worked, because they were part and parcel to that, and how the batteries worked. They came in with the best proposal. It was really good. We had a contractor who was experienced and could work with us. That's what we did.

Their original box was just an electronics box that we could actually talk to, and on the back of that we connected a battery simulator and worked out all the communications protocols between the batteries and the charge units. We were going to take data from two different batteries, and the two data lines from two different batteries were going to hook to this one battery, so we had to get all that timing and synchronization of signals working for that. We got all that handshaking stuff done first.

Then, rather than build a bunch of breadboard units for the battery, we chose to build what we called EM units, engineering models that were really lifelike. They had the full finned cold plates on the bottom, the enclosure, and if you were to walk up from the outside and look at them, they would look like a flight unit. We decided to build really high fidelity. It took a little bit longer, but since we had all the communications and the electrical interface stuff already solidified with that first test, that's how we chose to do it. You didn't have a whole lot of just little benchtop piece parts here. We already knew what the outside had to look like, and the interfaces looked like, so we just went to that.

That helped us along. We were able to take those engineering models and run them through full qualification tests and all that through the 2012 and '13 timeframe. That put us really ahead of the game.

ROSS-NAZZAL: Can you talk about those qualification tests? What did you do with that testing? What's testing like for these types of units?

NORTH: The qualification testing has all the launch vibration and shock. You had to do thermal vacuum testing, where you take it down the vacuum and show that it can charge, discharge over a range of temperatures. A lot of performance charge and discharge tests. Impedance checks, EMI [Electromagnetic Interference] tests, everything. We had fit checks with the EVA people that all the piece parts could fit and the connectors the way they want. Mechanical and structural tests on it.

ROSS-NAZZAL: Was that all done here at JSC or up at Glenn?

NORTH: On the batteries themselves most of that was done out in California at Aerojet Rocketdyne. For the battery units themselves. Then we brought a qualification unit over to the IPL [ISS Power Lab] that's out at Sonny Carter [Training] Facility. We have a full-up electrical power system lab. We ran it with flight software, made sure that it ran, we could talk to it, you could get telemetry out of the box, and you could command it and do everything you needed to do with it there from the systems level. We did the battery unit there and the systems level there.

We had also what we call an adapter plate unit, because when you put a battery in one IEA slot you still have another open slot there. This guy covered that open slot and then it had the cable hooked over to the new battery to get the data there and some heater power. The testing of a lot of that, we contracted the actual mechanical build of the Adapter Plates to a place called Atec [Inc.] over in Stafford, Texas, so not far from here. Smaller company. They did a fantastic job for us building these guys. Then we supplied to them the heater plate assembly to bolt on. The beauty of—well, anyway, we'll talk about qual [qualification] test.

The qual test for the Adapter Plates, some of it was done out there at Atec, some of it was done in the IPL lab, the integrated stuff, and then all the shock and the vibe and the thermal vacuum test and all that was done here at JSC facilities. We had a mix, some of the stuff was here, some was at the IPL, and then some was out in California at the supplier.

ROSS-NAZZAL: Any surprises that came up, anything that had to be changed as a result of these tests?

NORTH: Yes. But our biggest change came a little bit before we actually had to go into qual. Something just occurred to me, can I do an aside?

ROSS-NAZZAL: That's the way oral history is.

NORTH: I told you before we only had six positions on a carrier to launch batteries. But we wanted to launch six batteries and six adapter plates. We built the adapter plates with some mounting hardware on the top and heater plate on the top of them, and so on the launch vehicle you'd mount this adapter plate and then bolt the battery on top of it, so you could launch six that way in one launch. You could still do everything in six positions. That was part of the whole thing that made this work, the ability to launch in the four flights and save all that money and time.

The big thing that happened in change for us was we were just going along great guns, building the EM units, looking at their test data, finishing up all the design work we had open on that, and heading toward our CDR and building the flight units, getting ready for flight. Then, in early 2013, the new 787 aircraft had two separate instances of lithium-ion battery fires. One while on the ground at Boston's Logan Airport and another on a flight over in Japan. The FAA [Federal Aviation Administration] grounded the 787 fleet, which is a Boeing Company product. The cells they used for those batteries were from the same manufacturer that we used for Space Station. Boeing knew that I had been to the supplier multiple times and had a relationship with the cell suppliers, and that I was working on building lithium-ion batteries for the space Station. I got a call in the middle of January of 2013. It was like, "Hey, Tim, I know it's Friday afternoon, but can you stick around? The 787 guys are in a pinch with their batteries, and they have some questions they want to ask you about lithium-ion cells." I said, "Okay." It was about three o'clock for me and they wanted to meet at three o'clock west coast time, so, I stuck around for a couple hours to be on the phone.

At five o'clock on a Friday afternoon I dialed in to this telecon. They said, "Okay, welcome, guys. Everybody on this telecon, you're our root cause and corrective action team for the 787 battery. We need you all on flights to Seattle tonight." It was like oh my. I got home at Easter. But when a company the size of Boeing has a plane that's in production that they're selling grounded, that's huge.

ROSS-NAZZAL: Yes, that's a lot of cash.

NORTH: You're burning through—I don't know the numbers—on the order of millions of dollars a day while this guy is grounded. It needed to be fixed. Got up to Seattle. I didn't end up getting there [on Saturday], because of flights and everything I couldn't get there till Sunday morning. I walked up to the building and went to the assigned conference room where everybody was, and there was a whole team of guys, and they said, "Oh, you're Tim."

I said, "Yes."

"Okay, what do you want to do?" He goes, "How about we go look at the airplane?" Right from there, I put my bags down, walked out to the airplanes, and looked around, looked at the av [avionics] bays. It was a forward and aft av bay where they lived. I knew it was an all-composite aircraft.

I asked, "So how do you do the grounding on this guy?" That was one of my first questions. You can't use structure. You got to use have one. "What's that look like?"

He goes, "I don't know but I'll get back to you."

This is like Sunday midafternoon I guess by now. Midday Monday I'm working with the team, and somebody knocks on the door. "Yes, I'm looking for Mr. North."

"Yes. Here." They had a couple of PhD guys do this white paper on the grounding system and how it was done.

ROSS-NAZZAL: Oh no. That's not a good sign.

NORTH: I'm like, "Oh my." Right then it dawned on me. It's like this is important to my company. The Boeing Company is really amazing. One of our guys on our team, Dr. Glen Brown, worked satellite batteries out in California and could speak fluent Japanese. He had actually lived in Japan for a while when he was growing up. He became our rep to go over to Japan. But what other company on Earth could you—oh, gosh, we have a problem with batteries with cells from a supplier in Japan and that happened on Japanese aircraft. There're aviation authorities from Japan and the cell supplier and the airline representatives, and we [Boeing] have a guy who's a battery expert and speaks fluent Japanese. We briefed him on how it worked over there and sent him.

Then, it was like the first Tuesday afternoon in Seattle. These two guys in suits come by. I've only been there two, three days. They walk into this conference room. There's like five or six of us that are this core team. I guess six for the root cause and corrective action. They come in and go, "Hi blah blah blah, so what do you guys think?" We started talking about it and I explained to them what we had looked at so far and what we were going to do in terms of testing and analysis to figure out what the problem was and for redesign.

I knew by the way they were dressed and everything that they were somebody important in Boeing. It turned out that it was the president for commercial airliners and the chief technical officer of Boeing. They were just like normal guys, and they just wanted to know what happened. Someone mentioned, "You just briefed them like they were regular guys". I'm like, "Yes. I didn't know who they were." These are people you see on pictures on the walls.

We spent several months figuring out what was wrong and what we needed to change about this battery to make it safe. We built an enclosure system for the batteries. Besides all the design changes we did to the cells and the batteries themselves to prevent the problem from happening again, that enclosure system enabled us to now have this problem with the 787 be more of a reliability issue, because it would be fully contained and keep the rest of the avionics and aircraft safe then, than being a safety issue.

I got to come back around Eastertime. I did get to fly home one weekend in February. It worked out great. I flew home on a Friday. My first granddaughter, Brynn, was born on Saturday afternoon. My son Ian and his wife went to the hospital Saturday morning. I got to go hold her for a couple minutes on Sunday. Then I went right back to the airport to go back to Seattle.

ROSS-NAZZAL: Good timing.

NORTH: My granddaughter has perfect timing! I didn't come home for that; it was just for a visit home.

ROSS-NAZZAL: She knew.

NORTH: She's all right. She had good timing. When I got back around Eastertime, I got a call from our chief engineer in Boeing and he goes, "Mr. Suffredini would like to see you in his conference room."

I said, "Okay, so what's the board and what charts do I need?"

"No, it's just me and you, Friday afternoon at two o'clock, he wants to see." Everything's Friday afternoon. I think that's when everybody has time on their schedule.

I walked in. It was in that big fancy conference room where they do the SSPCB. There was him and his chief engineer and I think the assistant program manager, and then there was my chief engineer. He said, "So how'd it go up there?"

"Okay, I think we're good, FAA gave us approval, we're going to fly again, and life is good."

He said, "So what I need to know from you is what are you going to do about our Space Station batteries so that that will not happen to Space Station and our crew."

I said, "Well, here's what we already did—" Because of all the safety stuff we had done and the studies we did in 2009 it had dawned on me that the way we were approaching our safety for the lithium-ion batteries up until that point in the NASA programs was that's a really unlikely scenario for a battery to go bad, to have what they call a thermal runaway event. Big exothermal self-destruction I guess would be the engineering way to say it. Or catastrophic exothermal event.

But first thing we did when we were building requirements, part of that whole churn time to get the requirements right was we assumed that it could happen instead of that it's remote possibility and probably will never happen. From day one we were designing our batteries with the intent of having to be able to manage this, contain this kind of failure, and keep that from endangering the rest of Space Station. We had already been on that path.

"Well, Mr. Suffredini, we had this paradigm shift before we started building." I gave him the "That's why you hired Boeing, right?" kind of thing. Since we had already done that. I said, "But, there are some things that we were able to bring from what we did here to help the 787 batteries be better. By all the testing and analysis we did there and the design changes, there's some things we're going to bring back to here."

From that we changed the way we were doing the venting system for our batteries. Then we added what we call thermal radiant barriers between the cells. These cells when they go into thermal runaway produce a lot of heat. The big danger is that this one cell that goes bad is going to heat up its neighboring cell, and its neighboring cell and neighboring cell and you have this reaction, this propagation is the term that everybody uses for this event.

These thermal radiant barriers, we had built them into the 787 battery. We got that concept from there. We used different materials there because the economics of those aircraft batteries, you're producing hundreds and hundreds if not thousands of these batteries, is a little different than what we did. But we engaged one of the thermal engineers that I had met through 787 out in El Segundo, a guy named Bruce Drolen, brilliant thermal engineer. We engaged him and his team and we were able to use some of the radiant barrier technology they had developed for our satellites in Boeing and use it here.

They ended up looking almost like big overgrown index cards. Our cells are about 10 inches tall by about 5 inches wide, and these radiant barriers that are stacked up materials, kind of more proprietary, we won't talk about that part, but you stick them down between the cells and then it limits heat transfer, so you don't propagate to the next. Our thermal team led by Matthew Jurick along with Bruce Drolen's team did a lot of analysis to prove that. We got data from cell suppliers of how much energy would be released and what all the chemical compositions of the cell electrodes were. We calculated how much energy that would be.

By all our numbers within limits of how far you charge the batteries—when you charge you have a certain amount of stored energy, so when you have a thermal runaway it's a function of how much stored energy you release, the electrical energy. That's the big, huge flaming spike you see. Then there's this long smoldering while you burn up all the reactants and the rest of the electrolyte decomposes. The profile of one of these things looks like a big energy spike, like megajoules of energy. Then you get this smoldering. When we factored all that into there, these radiant barriers, our data said that it wouldn't propagate.

Also, after that Mr. Suffredini said, "Well, that's nice you're going to do all this stuff for us and not burn our batteries up." But they had the NASA Engineering Safety Council, the NESC formed a team, and they came, did an internal review of us in that spring/summer of 2013. Then they hired Aerospace Corporation who sent a team of their experts to come do a review. We, Boeing, also stood up our own internal review team of battery experts around Boeing. Some were 787, that work, and some other experts around the company. We brought them in. Over the next few months, we had three independent review teams go look at our design and the safety of our design.

I was hugely busy through the whole rest of 2013, because every one of them had a laundry list of oh, go do this analysis, go check this out, maybe you ought to go think about this, what are you doing about this. All those kinds of what-ifs, as you can imagine that a review team is going to give to you.

Other than the radiant barriers and some tweaks to the way we were doing venting it turned out we got a pretty clean slate. But there was still this lingering question from NASA. You didn't actually go blow up a battery, burn up a battery, and prove that it didn't propagate. You did all this by analysis. We had a lot of engineering data. We did a lot of testing for 787. But that lingered as a concern for them.

In 2015 the NESC got back together and were able to find some money. The NASA Engineering Safety Council. They sponsored a test. I worked with their team, and we built up from residual parts we had left over from the high-fidelity engineering units we built and from some of the nickel-hydrogen batteries that were returned from ISS, the enclosures, and that kind of thing. We built a test unit with cells, and we took it out to White Sands [Test Facility, New Mexico]. Yes, this was really cool.

ROSS-NAZZAL: I've been out there. They were doing testing of lithium-ion batteries for computers, so we got to see some of that.

NORTH: As part of the early testing we did for our EM units we had built what they call MMOD shielding into the batteries. It's for micrometeoroid and orbital debris damage concerns. You get these particles, either space junk or meteoroids, that come and hit Space Station, you have certain requirements you have to build for. We had built a shield inside of our battery, inside the top. To prove how that worked we had done some developmental testing and we took it to the hypervelocity range. This was before the 2015 tests.

We had taken cells and packaged them the way we were going to and built this coupon of what this shield would look like in the inside of the battery. We took 10-millimeter aluminum balls and we accelerated them to 7 kilometers a second on that hypervelocity range and we shot them through this to look at the effectivity of it. We did some shots where we took the ball and put it right down the center of the cells. I should have brought a cell to show you as an example.

ROSS-NAZZAL: Oh yes. Maybe we can get a picture.

NORTH: But right down the center. This was a fully charged cell to the max you could charge it. It was spectacular. It was high-speed video, that's the best thing I can say, it was amazing. Just huge flames. It resolidified that we were on the right path to assume that this could be an ugly failure if it happened.

When the NESC wanted to go test, we said, "You know what, we know a chamber. We know folks out at White Sands, a counterpart of JSC that can do that testing." I helped the team, and we built a test unit out here at the high-energy test facility, shipped it out there, and got it all set in there. A guy named Jason [R.] Graika from here, NASA guy, was going to be the test director for them. He came up with a device where you could start the thermal runaway with a drill. You cut a little hole in the side of this test unit and the enclosure. This drill would protrude in through that hole and the drill would drill into the side of the cell and short out the cell and then the cell would go into thermal runaway.

You didn't want to do micrometeoroid, you wanted something that was more akin to an internal cell short. We did that in the ORU, it appeared to just sit there, and the pictures were really just not spectacular. The whole ORU with the enclosure just sat there. Through the vent port you just saw some billowing smoke come out. The MLI [Multilayer insulation] blanket on the outside maybe raised a little bit as it was coming out. Maybe the smoke got underneath that. Everybody was like, "Oh."

ROSS-NAZZAL: That was the feeling amongst everyone? You probably were relieved.

NORTH: I was happy. I'm really happy. But the people at White Sands that blow things up for a living and the NESC guys were like, "Oh, we spent all this time." To build one of these units took a couple months to put it all together.

ROSS-NAZZAL: They were hoping for fireworks.

NORTH: Yes, I think so after the last time we were there and we purposely forced cells to spectacularly go like that. This was all contained. This was inside the ORU unit, instead of just a single cell by itself. But it was contained, and it was nice. Then they did a couple other tests here at JSC with single cells. We took some of the enclosures from the old nickel-hydrogen batteries that had flown and come back from the P6 element and shot them off in there. Even when the whole internals of the cell came up and hit the case it just dented the side of the enclosure. But all the tests showed that we would contain it. Even if you did have a problem. Then we had so many layers of production controls and checks along our production and test. Then just from the system software and the hardware for controls everybody got comfortable that we had a good design and we were ready to go.

I think if we hadn't made that choice early in the 2010 timeframe, that thermal runaway could happen and we needed to design for it, when we got to 2013 with the 787 event, it would've been difficult. Everybody had forgot about that design choice we made. But within the lithium-ion battery community I think that was a pivotal point for anybody who designed spacecraft or aircraft for lithium-ion, because you went from assuming that this was a highly unlikely kind of thing and probably wouldn't happen. It changed our paradigm at Boeing. And I think it changed the paradigm here at JSC that this could happen, and you really need to guard for it.

If you look at haz [hazard] reports earlier in the Station Program you'll see a decided difference between the ones from there on, in designs too. I think we had made that decision to look at it that way for this Station battery since it's such a huge battery and you really got to have it, Space Station can't stay in the sky without these batteries. Then in 2013 the enhancements we made based the 787 program and what we were able to share with them was really a cool thing.

When you said lessons learned, that was probably the big inflection point lessons learned along the whole process of how you go about designing a lithium-ion battery.

ROSS-NAZZAL: That's a big one, really. I was unaware of that, which is why it's nice to do these interviews.

NORTH: That changed the whole playing field for anybody that wants to design lithium-ion batteries anywhere.

ROSS-NAZZAL: Interesting. Were you able then to get Suffredini's blessing and move forward with the manufacturing once you delivered this data?

NORTH: I think the day I met him in 2013 he's like, "Yes, okay, I believe you, but we got to check you." It reminds me. I'll tell you an old Shuttle anecdote. I used to work in the Shuttle MER in the last parts of the Shuttle Program. We had a guy named Joe [Joseph E.] Mechelay who was one of the MER managers. Joe always had this motto, "In God we trust, and all others bring data." That's always stuck with me. I think in 2013 that was a great example. Mr. Suffredini is like, "Yes, okay, I hear what you're saying, but." We as a company felt the same way. I felt that same way. I asked for the internal Boeing review team to assemble the experts. Mr. Suffredini on his side got the NESC involved. Then in addition they hired Aerospace Corporation. You got two extra looks. Because doing something bad for Space Station is not good for anybody.

I think that was a classic example of that kind of mentality that the program had built, and from the heritage programs that came before, from the Shuttle.

ROSS-NAZZAL: Did you have any fears that this might upset the plans that you had and bring about some delays in your program?

NORTH: I think we had to do the whole venting analysis on NASA's behalf. I think we had approached it the right way all along that we had to contain it. I think we learned a whole lot from the 787, and it had us sharpen our pencils and really look close. At that point it's like I really felt pretty confident about our battery but there's always that little thing in the back of your mind, what did you miss and what don't you know? I think it was really healthy for us because it made us go back and relook at our design. We did a couple of upgrades for that, the radiant barriers, the way we managed the venting, and also looked at the way we would charge it and the max amount of energy we'd want to have in the battery, those kinds of operational things we would put with it.

But I guess I was confident. Was I 100 percent, would I stake my life on it? That kind of thing. Maybe 90 some percent. There's always that what don't I know here. I think if you talk to anybody that builds spaceflight hardware, especially if it's some high-risk or new technology kind of thing, and they tell you they're absolutely 100 percent confident that nothing will go wrong, and they know everything there is to know about it, I don't trust that person. There's always unknowns with new technology and that's part of what we do at Boeing and NASA is bring new things to bear. You got to deal with the unknown. That's part of it. I think all my experience with the Shuttle Program set me up with that mentality. Everything I did, personal hobbies and the things I did in the Air Force and from Gene Kranz's approach in the Shuttle Program operations. Be prepared. At any time the worst thing can happen to you.

I don't think it was him. But somebody had said spaceflight operations is kind of like hours of tedium and boredom laced with moments of terror and panic when things don't go well. I remember when I was a young flight controller, during STS-93, Eileen [M.] Collins was the commander. We had a short circuit on the AC bus during ascent and one of the main engine controllers went offline. For me it ended up being a lot like the simulations. Oh, that's a bus short, we've got to turn off the AC bus sensors. I remember hearing from my back room, "Short," in this kind of panicky voice. But it ended up working out and being just like a sim [simulation]. In mission operations, it's business as usual until it's not. But you rely on your training and your preparation to make sure you're going to have it right.

Coming from that environment and then coming over to design gave me that perspective all along. That's I think why we did that. Assuming that failure could happen and designed for that in the batteries. You need to be prepared and it needs to be functional and people's lives matter.

ROSS-NAZZAL: Oh yes. Very much. Yes.

NORTH: Yes. I think that my background set us up on that path. Either because we were really good designers, or we had a great team of mechanical and thermal designers that helped us. Guys like Ryan [A.] Luke or Matthew [J.] Jurick. Ryan was a structural mechanical, and Luis LeBron too, and then Matt Jurick and Keyla Robles were the thermal folks. Along with Bruce Drolen from southern California we got to help us with that thermal analysis, just did a great job understanding all that and helping us through that, and helping us design for it originally, and then making sure in hindsight that we still had all the right pieces and parts. Then there were guys like Jose Gonzalez that stepped in to keep things moving while I was away working 787. It all worked out. In the end I think we had a really good design.

ROSS-NAZZAL: Then you moved on to manufacturing in 2015, 2016?

NORTH: Yes. Around the time we did the testing in 2015, we were basically finishing up with the qual tests on the qualification units and getting into production. Qual tests went pretty well, no real big surprises. A couple little issues here and there. One of our mount bolts got snagged and we had to replace that in one of the tests. A little bit of learning with the thermal chambers and the vibe tables to make sure everything worked. The charge profiles, our flight software lead was Casey [J.] Adams. She's an electrical person but did all the interface with the software team. Then our test engineer Dave [David A.] Montgomery helped with a lot of the charge profiles. We knew how we were going to do it but once we got into that integrated test facility IPL, we were able to fine-tune that and Dave helped us with how we would build the charge profile to be exactly what we needed for Station. Casey did a great job getting Shawn [M.] Root and his team over in the software world building all the right interfaces so that when we plug it in, it works and Station talks to it and it does all the things. Because it really has to automatically charge and discharge, every insolation and eclipse period, for Station.

We got into production and got it all together and our first flight was in December of 2016. We were outfitting 1A and the 3A, the inboard channels. We could do all those replacements robotically, and that was one of the cool things about doing this project. I started from the idea, and since our team also does the mission operations, I got to help with all the launch integration part of this. That was something too. In 2010 when we wrote this, we knew we weren't going to have a Shuttle at our disposal. Mr. Suffredini and the ISS Program had partnered with JAXA [Japan Aerospace Exploration Agency] and so we were going to launch on the HTV launch vehicles. That meant we needed a special carrier to fit into their vehicle. So in parallel with designing the batteries I was part of the carrier design team to work with the JAXA folks on their carrier and how it would interface with our battery and what you needed for all that kind of stuff. That was a parallel thing going on in this whole timeframe.

We spent quite a bit of time over in Tsukuba [Japan] with them in addition to all the trips to Kyoto where our cell supplier was. But that was really a cool thing. We tested. When it came time to actually integrate them to the launch carrier, they sent another test engineer, Enrico [J.] Obregon and I. Rico is a great test engineer; he also designed what we call the status/charging unit to charge and discharge cells and check their health on the ground. When we had to pick somebody to go to Japan with me to go put the batteries on the carrier, I knew a lot about the batteries, and he was the charge-discharge status/charging unit guy. It was like Rico, come on, let's go to Japan.

We spent about three weeks over in Japan. You'd take a battery out of the shipping container, install it, and then charge it. Then repeat that five more times. That was the whole thing. I recall Penni Dalton and Eugene Schwanbeck being instrumental in helping us get all the regulatory permissions to be able to fly these batteries over to Japan and do all the transportation things. I had to supply a lot of technical data. They worked with the FAA and the NTSB [National Transportation Safety Board], the transportation folks, to get all the shipping permissions. There were a lot of moving parts to this whole thing.

The Tanegashima Space Center is on this little island out in the middle of the Pacific [Tanegashima, one of the Ōsumi Islands], and their operations, the way they man and operate that site, is different than what we do with KSC [NASA Kennedy Space Center]. At KSC, we've always got people there all the time. Tanegashima pretty much has a small skeleton staff for facilities and security people. Then when they have spaceflight equipment that needs to be worked on, they'll travel from either Tsukuba or one of their other contractor sites there. They'll come down to the island. You take a ferry or the little jumper plane over there from the mainland. Then they'll man up.

We met over there and pulled the battery out of the shipping container. You go bolt it on to the carrier, which is all cranes and a lot of eyes on it. The Japanese, the people working there from JAXA and MHI [Mitsubishi Heavy Industries], their equivalent of a Boeing over there, who built the pallet for JAXA, were all there. And they're just meticulous to a fault. They were really good about every little thing. It was like every little blemish and mark we had to account for on the batteries. Oh, look, this little stitching on this MLI is not perfect. Okay, here's the paper. We got that document. There's all that kind of thing that goes on. Plus the language barrier.

We get them bolted on and then the charging takes about 10 hours apiece. We were basically on a day shift kind of thing. The six batteries spread out to about two and a half weeks that we had to be in place at the space center. Really cool place, different than mainland Japan with the big cities and the mass transit. Stayed in a little ma-and-pa hotel. It was great. We walked pretty much everywhere. We all shared a rental car, went out to the space center each day. It was really a different piece of Japan and their culture. Mostly farming and fishing is the economy there, except for the space center and the whole south end of the island. The island is about 10 miles wide and 30 miles long. It's not a really big place. But really neat, cool to go. Good experience.

ROSS-NAZZAL: Did you watch the launch then from that location? Or did you come back to the States?

NORTH: No. For launch I was back here. That was another trip. I think Eugene Schwanbeck got to go for one of the launches, maybe the third launch. Because once we finished our part, then they would have to go take this whole pallet, this carrier pallet with the batteries on it, and they would put it into the HTV vehicle, and then that would have to go out to their equivalent of a VAB [Vehicle Assembly Building] and stack it on top of the H-II rocket before launch. That took another couple months before launch. There was really no technical need for me to be there for launch. I didn't get to see that.

ROSS-NAZZAL: How closely were you monitoring the launches that had your batteries on them? Were there any challenges when they were going up?

NORTH: The battery cells for these—here's the characteristic about lithium-ion cell. When you charge it, it swells a little bit. The electrode becomes a little thicker with all those ions packed in there. When you discharge it, it contracts slightly. To meet all the launch vibration and shock requirements, we had to have these batteries charged to a certain level, which meant that when we charged them almost 90 days before launch, we charged them a little higher than the minimum amount you had to have for launch. I was busy monitoring temperatures and stuff and doing all the analysis to make sure that we would have adequate charge on the cells, that they would survive the launch. That was really our part of that, to make sure that we did all that right and everything was set. Once we unplugged from those batteries and they were charged, then it was just, "Well, we'll turn them on when we get on orbit and we'll see how they did."

The first set of batteries we launched in December, we installed them in early January. The way the holidays and the way the EVA timing all worked out, they sat on the carrier for that long.

Just to see, we had a pool going in our office. The winner was going to get a Coke or something. It ended up being a little HTV patch and a little key chain thing we got at the visitor center when we were at Tanegashima. We had a pool going for everybody on our team, who's going to guess exactly what the voltages on the cells are going to be in these batteries, the average voltage for all six of these batteries, when we first turn them on. Whoever got the closest was going to get the patch and the key chain.

I purposely abstained from that because I had all the technical data on the discharge rates of the cells and all the test data and was there when we charged it and had all that, and I knew what the temperature regimes were going to be. I calculated it and just kept it to myself. One of our young engineers, Jennifer Thompson, got closest. She got the key chain when we were done. It was good. I was only two-one-hundredths of a volt off of the average. I was pretty close. The batteries did really well during ascent. We plugged them in and turned them on and everything worked great, and so they've been running since January of 2017 now, that was the first set of batteries.

Over the next couple years we launched the next sets of batteries. We launched four launches. That was HTV6. HTV7 was in September of 2018, so that was our second flight. Batteries were ready, we were just waiting on the launch vehicle availability. In that period JAXA had another high priority launch that was for their government that wasn't related to NASA. We got bumped. The HTV7 flight was bumped to 2018. Then 2019 for the HTV8. Then 2020 in May for HTV9. A little over a year ago now we got our last set of batteries there.

All that seemed to go pretty smoothly up until the spring of 2019 when we were installing the 4A batteries. We had launched them in the fall of 2018. Due to the EVA scheduling we didn't get to install them until the springtime. We turned on what we call the 4A3 battery and the heritage charging unit that was on ISS had a catastrophic short inside the converter, in what we call the fault isolator unit.

The solar arrays in that side of the system fed the short in this battery charge unit and then the battery fed it from the other direction. The fusing we have inside the battery opened up, and so the cells were perfectly healthy, but we couldn't use the battery because the circ [circuit] protection that's built inside the battery wouldn't allow us to run the battery anymore. We had to scramble around and find a way to launch a spare battery.

In the meantime, we put two of the old nickel-hydrogens back into that to work with the new 4A3 battery charge-discharge unit. We ran that channel on the two new lithium-ion batteries and the one pair of old nickel-hydrogens. Luckily, we had had the foresight to build the software so that you could run what we called a mixed channel configuration. A lot of debate whether we should have spent the money on that early in the program. But we pushed hard on NASA that if you ever got in a pinch and needed to use nickel-hydrogen somewhere along the line it would pay off. Of course it did on that day.

We were done with the HTV launches, and we only needed a single battery launch, by that time SpaceX was doing cargo missions, and we were asked to go build a cargo carrier to fly the spare lithium-ion. Ended up flying on SpaceX 19 in December of 2019. That was a really interesting project. We had a project lead named Ian Falkinham from Boeing; he does a lot of cargo integration work, and he was able to find an old what they call FRAM cargo carrier. Then our team designed an interface plate so that you could bolt our battery stuff. Out of storage we found a heater plate from a different project. So we pieced together all these, this one plate we built and machined with this heater plate and this other FRAM assembly, and we did this whole thing in about six months. Put it all together with the heater and put the battery on it and got it over to our KSC processing team. A guy named Matt [Matthew J.] Fields and his team were great. They'd done the feeding, caring of the nickel-hydrogens all these years. With the lithium-ions you have to go take them out—we freezer storage, refrigerator storage them. They're in vacuum-sealed bags that are nitrogen-backfilled to keep them pristine. About every three months he needs to take one out just to top off the charge and make sure it's okay and do a health check. Matt has done a great job over the years.

His team put together this carrier and all the piece parts that came in from everywhere and then did all that work and then actually went over across site at KSC. SpaceX is just off-site over on the Air Force side of the station over there. Matt did all the charging on the SpaceX vehicle with the battery charge unit that Rico had designed. That all went really well and really smoothly. We had to go do a lot of range safety work because we were launching this big giant lithium-ion battery and then had to work with the Air Force guys because SpaceX launches on the Air Force side of the site. Also the SpaceX engineers, to make sure that they were comfortable, and they thought it was safe to launch our battery. But we worked through all that. We had a wealth of test data to show that it was safe. And all those other launches. It all worked out really well.

Now our first lithium-ion has been running for what, it's 2021, so about four and a half years. The newest set is a little over a year now. So far so good. We're learning things as we go along. We learned a lot from that charger failure about how we activate batteries with the old chargers. These guys, the original charge-discharge units were designed in the '90s and launched in the early 2000s, so they're not new. They're like everything on Station, beyond its design life. We're going to bring that charger unit back down and repair that. We're going to do some design changes going forward to upgrade those guys. All along it's been a really cool project.

ROSS-NAZZAL: What is the lifetime on those lithium-ion batteries? How long do you expect them to last?

NORTH: The spec lifetime is 10 years. Back in 2010 when I was bringing the requirements to Mr. Suffredini knowing that the nickel-hydrogens were speced to be 6 and a half years, and we were wanting to get closer to 10 out of them, I went into the program review board, "Here's the fly sheet." We called it the fly sheet spec. "The batteries are going to last." We had 10 years on there. "Here's how much energy they had and how much they weigh."

He goes, "So when you build this 10-year battery you're going to certify it for 10 years. And it's going to last a lot longer, right?" That was the question I got in the SSPCB. I was like yes, sir. That came to play when we were doing the cell selection. Remember we did the project with NASA where we got it down to maybe four cell suppliers. Then we in Boeing did our own cell selection process. We did a whole bunch of testing on these four cells; we visited the companies. What did we do? We brought in an independent review team. Penni was part of that.

What we did with this independent review team was we provided them with all the technical data that we had assembled for this cell selection process, and the requirements for what these cells and these batteries were going to need to do for us. What we didn't share was cost data with that independent review team in Boeing. We purposely wanted it to be a technical review for our cell selection. Our intent was to just get down to one cell supplier early in the program because that would affect the way you design how the cells are held and packaged inside the ORU. It would change the way the baseplate assembly had to be designed. That's a huge engineering feat to have this solid piece of aluminum 39 inches by 39 inches and a couple inches thick and you machine it all with all the bossing mounts and all these fins that are every quarter inch all the way across the base and not have it warp and flex and do crazy things to you.

But their suggestion back to us as a project was, "We think you should take two cell designs through the cell qualification program instead of choosing today and do two parallel designs of your baseplate and the battery electronics until you finish the cell qualification." They felt that that was a risk mitigation. It's all fairly new technology and you've got to pick. If you have a cell failure and you only have one, you're in deep water when you get a year and a half, two years down the line and now you don't have a cell supplier. That's the heart of what makes your battery work. No cells in there, it's like an empty box.

We chose to do that. We had our two cell suppliers. Basically it was almost a runoff competition. On our side we were designing two parallel baseplates and electronics that would work in this box. Then we were running the cells. We did destructive testing, which our JSC counterparts did. Ron [Ronald M.] Galvez and Monique [S.] Wilburn out here at JSC, NASA opened up their test facilities and they ran the program. We did overcharge testing. What else did we do? Overdischarge testing. We did heat to vent testing and a whole bunch of other things. There was a big, long report on both of these cells.

That was the whole safety characterization part that fed our down select for cells. Then we also did a bunch of cycle testing on the cells, electrical testing. We did the performance and shock and vibe testing on both cells. We had a pretty good view. We took them through a full qualification so the cell would be qualified.

One of the cells at that point was the clear winner, head and shoulders, and that's who we went with for the cells for the lithium-ion battery. It ended up being that this company build their cells in Japan. There was a whole question of do we become an importer of cells. It turns out they have a subsidiary company in Atlanta, Georgia; it was like an arm of them. So they would import the cells, they would do an acceptance test when they got here, they would do the first wrap of

Kapton insulating on the outside of cells and prep them for delivery to us to integrate. We delivered them to California Aerojet Rocketdyne to put into the batteries.

Part of our safety plan always was out of every lot of cells that we got, we were going to take one cell and run it through 100 cycles of 100 percent depth of discharge. Way higher a depth of charge and discharge than you do for a normal flight battery. But we knew that a lot of the degradation characteristics and a lot of the things that would come up in that first 100 abuse cycles would show any defects in manufacturing. Then we took that same cell. We had picked that out at random. Each lot was 100 cells. You got three battery units out of one lot. Neither here nor there. But we would take this one cell that we cycled 100 cycles 100 percent and then we would do a DPA [Destructive Physical Analysis], we would tear it down. They built a rig where you could take the winding of the cell out of the case and you could unwind it, and we would go over it with magnifying glass and a fine-tooth comb. When there was anything in the electrolyte that just didn't look perfect.

Sometimes you get just little abnormalities in the way the cell was built, or you see imperfections or what they call halos, a little bit of a spot that changed color due to maybe heating or something during charge. We would take them and put them under a microscope and really look at them and analyze them. Not only did we have the pedigree of how every cell was built, and all the build paper at the manufacturer, and we had done production line audits to make sure cleanliness that we did throughout the program, but we also had this spot check of every lot of cells.

Every cell got individually tested completely [to ensure] that it functioned, and then for this one cell that you picked at random, you'd go deeper and tear it apart and look. That was part of the whole thing to mitigate the chance of one of these cells coming apart in flames. That ended up being pretty fruitful. Over the 1,200 or so cells we bought, we have a test history on every single cell and then all these DPAs.

ROSS-NAZZAL: That's amazing.

NORTH: Huge amount of work over a lot of years to get these guys.

ROSS-NAZZAL: When you say a lithium cell, how big are we talking? How big is that?

NORTH: Each of these cells is about 10 and a half inches tall, about 5 inches wide, and about 2 inches thick. I'll show you that in this. There's probably a picture in here of what they look like in this set of charts I gave you.

ROSS-NAZZAL: I printed it off and read it. But not being an engineer.

NORTH: I thought it had a picture of a cell.

ROSS-NAZZAL: I don't remember seeing one.

NORTH: This version doesn't. One of the earlier ones did. This is a picture of that adapter plate and the battery itself. The cells are about 10 and a half inches tall, about 5 inches wide, about 2 inches thick. They weigh close to 10 pounds, 8 or 10 pounds apiece.

ROSS-NAZZAL: They're bigger than I was thinking. When you said microscopes, I was thinking smaller.

NORTH: We would cut a piece out of the electrode assembly. When you build one of these lithium-ion cells, the negative electrode, if you can think of a roll of paper, but it's a roll of copper, and when you run it through a machine called a coating machine and you mix up this slurry of all the materials that go onto there, and it's essentially like a printing press. There's a drum and there's a spray bar and you coat this side of the copper and it goes through a drying machine and there's a whole bunch of processes that go with that. We'll just leave it at that. Then you do the same thing with the positive electrode. It's an aluminum sheet, a big, long roll of this stuff.

The separating material is a porous material but it's nonconductive and it goes between these two. You take the separator materials and the positive and negative electrode windings, and you put them on a winding machine, and you roll these up so they're separated. You end up with this big, tall cylinder-looking thing. Call it a jelly roll. Then you shape that and stick it inside of the can.

When we were doing DPAs we would put it on this machine. We basically cut open, machined open the top of the cell, and then opened it up. You do an inspection and check the electrolyte that was in there, the residual, a little bit in the bottom. Then you would unwind it and you would look. The winding is nearly 50-feet long, it's a big, long roll of this material. We don't look at the whole thing under a microscope. Not microscope but magnifying glass and bright light. Any abnormalities in these surfaces we would cut out and then look at them under a microscope. Not the whole cell itself. Just the piece parts.

That was the interesting thing. When I came up to do the 787 work, we had already built this process of how to tear apart these big cells. When I went up to Seattle [Washington], one of the things we wanted to do after we tested, down at Boeing Field in Seattle we had the high-energy test facility there, we were basically causing cells to go into thermal runaway and doing nasty things to them and learning about the battery design for 787.

The first cell that we wanted to take apart, I got a call that said, "Hey, the guys need you down at Boeing Field, they want to go do a DPA, destructive physical analysis, tear down the cell." They told me the lab building to go to. I walk into this room and it looks like a pharmaceutical lab. There's all these workstations with the shelf up above them with all the chemicals. I'm like, "That's interesting." They got this cell sitting in an argon glove box. The glove box is maybe 3-feet wide and maybe 2-feet tall where you put in your hand. "Okay, so we need you to help show us how to take the cell apart."

I said, "This won't do, we need a table that's maybe about 3 and a half, 4-feet wide, and we need it to be about 35-feet long, and we need good ventilation because when you open this stuff up the electrolyte is an organic solvent." Smells like a strong chemical cleaning agent, not really alcohol, more like an ethylene type of liquid. You need a respirator when you're opening these things up.

It has to be in a high bay place. The look on this lab manager's face when I said, "No, we can't do it in there, it's not going to work, this thing is only 3-feet wide," she was horrified.

"But it's in a glove box, what if it catches on fire?"

I said, "Well, when we've done it before." Because you touch the negative positive electrode you cause an arc and there's a lot of fumes. So I said, "Normally we just reach out. We have a glove; we just come and go like this [pat it out] and it goes right out."

She was like, “Ah.” You could see the things clicking. She said, “I don’t know how OSHA [Occupational Safety and Health Administration] would ever, I don’t know where we’d get a high bay like that, I don’t know how we do this.”

I said, “I don’t know, but that’s what we’re going to have to do.” Remember I was telling you I was part of that root cause and corrective action team. When one of us guys from the core team would go out to the factory floor or to another test facility, usually a midlevel Boeing manager was down there, maybe not necessarily riding with us, but would show up and follow us along and just be keeping notes. That’s when it dawned on me really what those guys were doing. They were seeing what’s going on with this root cause team and what do they really need.

She said, “I don’t know what’s going to happen.”

This guy was just taking notes over on the side there. I got a call the next morning about 9:00 a.m., and I’m up in Everett now, which is 35 miles from downtown Seattle. They said, “Hey, the techs are getting the respirator training this morning. The high bay is all set up. They’ve got everything you need down at Boeing Field. They should be ready for you around eleven o’clock.” They went from I don’t know how we’re transporting all these cells from the high-energy facility over to the new lab, I don’t know how we’re going to set this up, how we do the ventilation, how we get everybody have that training. Overnight. That’s the kind of emphasis our Boeing Company was putting on getting those 787 batteries right. That happened like the story with the white paper. Things like that happened like 50 times that spring. I just asked. I had to be really careful what I asked for.

ROSS-NAZZAL: That’s funny. It’s like had little moles with you that whole time or something.

NORTH: Yes. I have a whole different perspective of my company and what they're capable of when they put their mind to it. They always give us this mantra, a one Boeing Company. I'm like, "Okay. We're here in Houston. We're supporting the NASA customer." But it's a worldwide company. There's a lot of capability they have. When it's important to them they can bring a lot of horsepower to bear on it. We had pretty much a standing army at our disposal to figure that out. It was really cool.

ROSS-NAZZAL: What do you think your biggest challenge was when you were working on the Space Station batteries?

NORTH: I think the whole safety thing was a challenge, and it was for me just a lot of moving parts. It wasn't just a small electrical box. It was something that touched the structural and mechanical. You had to have robotic interfaces and EVA interfaces. Besides all the flight software pieces of this. The cell selection and the cell safety part of this. You had MMOD [micrometeoroid/orbital debris] testing. It was just a lot technically to keep track of and to stay on top of and make sure this person and this design team and that design team was doing it all. Each one of the disciplines really had their own team. Then we had subcontractors doing things.

Once we had done all that up-front work and come up with a concept, and we knew that this was how we want to build it and how we integrate it to Station and how we're going to operate it, then the challenge was just how do you cram 80 hours of work in a 50-hour week every week. Didn't happen a lot that it was a 50-hour week. It was usually a lot more. I think there was just sometimes personality things you had to get over and get people working together.

Tom Franssen, I love him to death, but when I enlisted him to come be the project manager, it was his business, to make sure that we came in on time and under budget. Keeping our suppliers that way. When I came back from Seattle and said, "Hey, we want to add these radiant barriers," Tom saw money and I saw safety enhancement. There was that. But we got along really well, and we came to know each other well. I would say it was a healthy tension.

Then of course NASA had to help with that because they're on the hook to approve changes. It had to be justified from a budgetary and schedule impact, whatever that meant. We had a similar thing when we were building the power supplies. The Aerojet Rocketdyne guys wanted to use a power supply that was a commercial, it was one that they already had a design for, and they just wanted to port it in. It really didn't meet our needs for the way the batteries were being powered and controlled downstream of these charging units, and so we really needed one that was a special design that had a couple different safety interlocks and signals built into it for when the battery would activate and the electronics would come alive. That ended up being not a cheap thing to do, and it wasn't something that was originally priced.

I think that was a hard sell for me to our Boeing management, to make that happen. The supplier, who was resistant, not wanting it to happen. Our NASA customer was going to have to help pay for it. It was things like that that came up, that we had to work through. In the end I think the saving grace was everybody had the common goal to do what's right for the Station Program and build the right piece of equipment.

A lot of times I had to be the stand-up guy for what I thought was the technically correct thing. I didn't always get my way but if it was anything about reliability and safety, almost uniformly everybody got on board—it took a lot of work sometimes and a lot of convincing. It was challenging at times. But it all worked out, I think.

ROSS-NAZZAL: What do you think is your proudest accomplishment in this project?

NORTH: Just that we did it. It's been so cool to come up with hey, we have a need for something on orbit, to come up with an idea, and then to see it from nothing to taking shape on paper and being the technical lead for the design team to make it a reality. Then shift over to do launch integration and work with the international partners to put it on there. Then to be in the Mission Control Center in the MER when we were doing the EVAs and the robotic arm ops to put it in. Then to see it work. Where I'm at with my career, I'm probably not going to be around to do another 10-year development project. This started in 2009 when we were doing studies, and got turned in in 2010, and we've just finished launching it.

When I go home, I look up in the sky and see the Station, and know what, I helped build the batteries for that guy, and that's kind of cool. Just the whole idea to fruition kind of thing. Getting to see the whole span has been really cool.

ROSS-NAZZAL: Yes, that is cool. Sandra, did you have any questions?

JOHNSON: Just more a curiosity. What's the next battery? Is there anything out there or anything that people are starting to work on?

NORTH: There is. I've become an associate technical fellow for my company, so I get to look at a lot of different technologies. For the short term, for things that need to have technology that are able to support within the next year to two, three years, I think the lithium-ion batteries, that's what's out there. There are several things we're doing looking at fuel cells where there are machines that would take oxygen, hydrogen, or perhaps methane, and reform it with hydrogen and use that to make electricity. The idea is to get zero emissions. I think some of the life issues there and just some of the robustness of the technology probably still needs—although we flew fuel cells on the Shuttle for years. But it's a little different going from a specialized really expensive piece of gear to something you'd put in a car.

There's a couple other battery technologies and enhancements to lithium-ion. I think right now we're in that phase where it's a fairly mature technology but there's a lot of things you can do to refine and to optimize that. That's probably where a lot of the research work is going on on batteries right now.

I know NASA is doing a couple of research projects to look at nuclear type devices to provide power. On the backside of the Moon batteries are not going to be viable because you don't really have a way to recharge them. It works on Space Station or an orbiting satellite where you have good Sun [exposure], where you charge it in insolation and discharge it in eclipse. But for things like the backside of the Moon, or as you go further out to Mars and beyond where the solar energy is not as strong, especially in dusty environments where solar arrays would tend to get filthy, you're going to have to do something different.

I think battery technology, there's a couple different iterations of that that are still going to be with us for a long time, and new technology breakthroughs. But I think long-term for future space exploration, you're probably going to have to move more into the nuclear range. We've had some of those. On the Galileo we used what we call RTGs, radioisotope thermal generators for the deep space probes. They take heat energy produced from that reaction and then have a device to make electricity from that. Whereas a reactor would be more akin to what you see with a naval nuclear submarine or a power plant is what they're moving towards. I think that's probably what they're going to have to go to to do deep space [missions]. For real longevity. If you want it to be a long-term power supply for them.

JOHNSON: Thank you, I was just curious.

ROSS-NAZZAL: Do you think there's anything we haven't covered that you wanted to talk about? Like I said you're welcome to make additions to the transcript once you receive it.

NORTH: I don't know unless you've got more questions.

ROSS-NAZZAL: I think we covered it.

NORTH: Yes, it's been good.

ROSS-NAZZAL: Thank you so much for your time today, we really appreciate it.

NORTH: All right.

JOHNSON: Thank you.

NORTH: Okay, you're welcome.

[End of interview]