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TOWARDS A PROCESS MODEL OF NASA'S SPACE SCIENCE INNOVATION SYSTEM

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***Abstract*—This paper proposes a descriptive epoch-shock-based conceptualization of NASA's space science innovation system. The model is based on four retrospective longitudinal studies of technology innovation at NASA, one of which is presented in detail in this paper. While the innovation process is certainly complex and circuitous, the epoch-shock conceptualization identifies common patterns across drastically different innovations. This lays the groundwork for linking the observed behaviors to the institutional routines and incentive structures that generate them. While the evidence in this paper is primarily from NASA, and specifically the space science directorate at GSFC, our observations agree with cases in other domains in most respects but the uniqueness of our context allows us to extend their theory in several interesting ways.**

I. INTRODUCTION

Continuously developing new technical capabilities and implementing them on ever more ambitious flight projects is fundamental to NASA's, and more generally space agencies', mission. Yet, to date, little work has been done to understand the processes through which innovation happens in the government space context. To the extent that these processes have been studied in government agencies it has been at the project [1-4] or force structure level [5-8], not the evolution of the constituent technologies.[1] Innovation processes have been studied in the context of corporate venturing within commercial firms [11-15], but unique characteristics of the space sector may limit the transferability of those insights. This research seeks to address that gap by building a detailed understanding of the "innovation journey" at NASA, adopting methods from the latter and contextual theory from the former. In this paper, we give an overview of the broader research project, but focus on reporting on a conceptual epoch-shock model of innovation at NASA, and potentially other technology-intensive government agencies. We briefly compare our results to the observations of the innovation journey in other contexts, as a first cut at generalization.

II. METHODS

We use a multi-case, retrospective, longitudinal process study of four *innovation pathways* as a basis for our analysis. Innovation pathways in this context are defined as the sequence of events, actions and decisions that mature a new technology from initial conception to implementation on a flight system.

A. Data

We collected two main sources of data: interviews with key participants, and documents produced during the pathway. These data were supplemented by a survey of relevant press coverage and observations made during the site visits.[16, 17]

More than 50 interviews with key participants were conducted on-site at the NASA Goddard Space Flight Center (Goddard or GSFC), and the small businesses involved with the project. The interviews were used for two purposes. First, a subset of initial interview accounts served to create a sketch of the critical events, helping to focus the document search that followed. Primary records, like contract documents were then used to validate the details of the timeline, since decade-old memories are fallible. The second round of interviews was then used to probe the motivations of the actors and understand why particular pathways were taken at different times. Interview subjects were selected initially based on introductions from Goddard's office of the chief technologist; as the research progressed, more subjects were identified who could provide complementary perspectives. This strategy of snowball introductions was pursued until all the key individuals involved in this particular innovation pathway had been interviewed. All interviews were digitally recorded using a livescribe smartpen (tm), with permission. Transcriptions were made as appropriate.[2]

Documents in the form of journal articles, contract proposals and reports, internal records, legislative actions, and

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[1] Some historical treatments do examine the details of the technical evolution, but because of their historical nature provide limited insights about the contemporary organizational context (e.g., [9] D. A. Mindell, *Digital Apollo*. Boston: MIT Press, 2008, [10] M. R. Smith, "Army Ordnance and the "American system" of Manufacturing, 1815-1861," in *Military Enterprise and Technological Change*, M. R. Smith, Ed. Boston: MIT Press, 1985, pp. 39-86.

[2] The livescribe smartpen links audio to handwritten notes made during the interviews. This proved extremely useful in going back through notes. As a result only sections used for direct quotes were deemed necessary to transcribe.

news coverage were used to validate events described by the interview subjects. One advantage of studying a bureaucratic agency is that records exist for most activities. However, given that hundreds of small R&D contracts are awarded on a yearly basis, without pointers, like names and key words from the interviews, it would be nearly impossible to construct the pathways from documents alone. Financial records were provided by some programs, but the reporting was found to be somewhat inconsistent. As a result, the uncertainty associated with particular figures is noted.

In the following discussion, statements will be cited based on the interview or document reference noted in the data tables in the appendix to maintain traceability to the sources, while preserving some level of anonymity for the interviewees.

B. Analysis Approach

The data collection described above yields an immense amount of qualitative and quantitative data. The challenge of "sensemaking" is one of how to move "*from a shapeless data spaghetti toward some kind of theoretical understanding that does not betray the richness, dynamism, and complexity of the data but that is understandable and potentially useful to others*." (p. 694) [18]. Following Langley[19] and Van de Ven[20], we conducted the analysis in multiple iterative stages. First, an analytical chronology, also known as a composite narrative, was constructed for each case was prepared and validated by key informants. The idea is to "*get on top of the data, to clarify sequences across levels of analysis, suggest causal linkages between levels, and establish early analytical themes*" (p.280)[18]. Those initial themes were then coded, and abstracted, more systematically using what Langley calls visual mapping. This strategy of graphical representations allowed a large number of dimensions to be represented simultaneously and concisely; it also allowed us to compare themes systematically across the various cases. Finally, the cases were cross-compared and a common process model articulated.

C. Case Selection

Clearly, the choice of which cases to study can have an important impact on the resultant insights. The cases for this study were selected from the population of new technologies enabling NASA science missions (with a strong Goddard component[3]) with some part of their development occurring during the decade of the 2000s. The population frame of enabling innovations was elicited from NASA experts involved in the development of these missions. Specifically, the Goddard chief technologist, project managers, and theme technologists and funding managers were polled. They were asked to suggest potential cases of <u>new</u> technologies that had been (or were being) <u>infused</u> into a flight project that had at minimum passed "Milestone A.[4]" We continued asking for potential cases until saturation was achieved (i.e., no new innovations were being suggested). We captured a brief oral history for each as a basis for down selection.

From that list of approximately 25 potential cases, a total of four cases were selected based on the following rationale. We began by eliminating technologies being developed for directed future studies and technology demonstrator missions (because demonstration is not really a comparable mission opportunity from an innovation system point of view). Next we eliminated the Mars Science Laboratory innovations for several reasons (for Mars missions, there are a whole set of dedicated funding mechanisms separate from the "normal" innovation ecosystem, a context that merits its own separate study; also, the types of measurement that are of interest on a planet's surface are hard to compare directly to the other theme lines). This left 12 potential innovations (in Earth Science and Astrophysics) all of which had really interesting stories, matured through the "same" organizational system. To narrow down this list to the target of four, we looked for comparable pairs of mission contexts and classes of innovations.

The final selection included the following technologies:

- **Continuous Adiabatic Demagnetization Refrigerator (CADR):** ADRs have been used to maintain instruments at their required mili-Kelvin temperatures for several decades. A key limitation of the incumbent design is that they are inherently single shot (instruments can be kept cold for some fixed "hold time" before the system needs to be recycled) and prohibitively large magnets are required if long hold times at high cooling powers are required. The innovative Continuous ADR concept overcomes these limitations by creating a temperature cascade of multiple smaller ADR stages. Achieving this principle in practice has taken more than a decade of development.
- **Cadmium Zinc Telluride (CZT)** is a novel, room temperature, direct semiconductor compound with high Z and a wide bandgap. Invented in the 1970s (outside of Goddard), production was severely limited by materials growing challenges until the 1990s. The Goddard innovation involved turning a new material into a useful detector array capable of imaging in a previously unobservable energy band through more than a decade of development.
- **Microcalorimeters** measure the energy (i.e., enable spectroscopy) of single, highly energetic photons. Unlike previous approaches which measured the charge created by the incident photons in semiconductor materials, microcalorimeters measure the temperature increase of the absorbed photon. This novel approach was conceived of at Goddard in the early 1980s. While its promise was demonstrated quite quickly, bringing the idea to implementation has taken multiple decades of concerted effort.

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[3] Goddard was chosen as the research setting because of 1) geographical proximity to MIT (making frequent visits feasible) and 2) compared to other NASA centers, Goddard places a high value on innovation activities making it a fertile place to study the process.

[4] Milestone A is when projects are formally approved. Although it often takes an additional several years before an approved project reaches its operational phase, the technology baseline is frozen barring unforeseen circumstances. The main reason for choosing a relatively early milestone was to mitigate the impact of informant memory (and institutional bookkeeping) – the farther you look back, the worse the records.

- **X-ray Polarimeters** leverage the photoelectric effect to measure the polarization of super energetic X-ray sources, with two orders of magnitude better sensitivity than had previously been obtained. Although the approach was initially demonstrated in Europe, Goddard technologists have invested more than a decade turning a demonstrated principle into a practical instrument, re-inventing the concept several times along the journey.

III. INNOVATION PATHWAYS

What do innovation pathways look like? To give a sense of the phenomenon we are trying to understand it is useful to present one illustrative innovation pathway in a fair amount of detail. Equivalent composite narratives (stories that integrate multiple perspectives to create an overall picture) were developed for each case, and formed the basis for all subsequent analysis. In describing this pathway we will also introduce the specifics of the organization that served as our research setting. In the next section, we will abstract the NASA specifics in describing a more general conceptualization of what we observed.

CADR: A game-changing, cross-cutting, nearly-proven concept, with no immediate risk-justifying need.

This case describes the development of a Continuous Adiabatic Demagnetization Refrigerator (CADR) within NASA's Goddard Space Flight Center's (GSFC, or Goddard) cryogenics and fluids branch. After more than a decade of concerted development efforts, the team is still awaiting a mission opportunity on which to fly the full system. Like the traditional ADR, the CADR will maintain spacecraft instruments at the required mili-Kelvin operating temperatures. Unlike the incumbent, the CADR operates continuously (eliminating the need to pause observation time while the cooling system recycles) and provides significant mass reductions for a fixed cooling power requirement. These advantages will become increasingly important as future X-ray, IR and submilimeter observatories incorporate larger and more advanced detector arrays.

A. Gestation period

Although explicit CADR development didn't begin until 1998, relevant groundwork was laid much earlier. The magnetocaloric effect, upon which the technology is based, was first observed in 1880, and applied to develop the first magnetic refrigerator in 1933. Goddard first became interested in cryogenics in the late 70s when it became clear that future missions (including IR, X-ray and submilimeter) would require detectors to be cooled below 1K. At the time, in a seminal position paper, Dr. Stephen Castles, the head of the then newly created Cryogenics branch, argued that ADRs were the most appropriate approach to cryogenic cooling for space applications and that Goddard should develop them as an in-house core competency.[D19] Through the 1980s, the branch let a sequence of SBIR[5] contracts to develop the requisite extremely powerful magnets, and received on the order of \$8M per year from "code-R" (the historical NASA technology directorate) to develop salt pills and, to a lesser extent, heat switches – the other critical components.[6] [I24]

The first flight ADR was developed in support of the Chandra X-ray observatory; specifically to cool the XRS instrument. [I8, 24] However after nearly \$3M of further development funding, [I24] the XRS instrument was demanifested from Chandra and reincarnated as the Goddard-furnished XRS instrument on the ill-fated Japanese X-ray observatory Astro E (which was subsequently lost due to a launch failure).[7] [D20] Nonetheless, by 1996, when CSE#1, a low temperature physicist PhD by training, joined Goddard, ADRs had become the industry standard, being developed for multiple smaller missions, one of which he was working on when the idea struck.

In spring 1998, with the next generation of X-ray observatory prominently on the horizon, the cryo branch was faced with the realization that the standard approach to ADR development was unsustainable – based on trends in mission hold time and duty cycle requirements, ADRs would soon be prohibitively massive for space applications – CSE#1 and his office mate CSE#2, another low temperature physicist, began brainstorming alternative approaches. [I8, 48] As recalls CSE#1 "*one day the idea just came to me:*" [I23] The idea was an architectural innovation in nature – it could be achieved with the same components already being employed on the Adiabatic Demagnetization Refrigerator (ADR) he was working on at the time. It was elegant in its simplicity; rather than operating a single stage ADR over its full range and then waiting to recycle it (i.e., remagnetize and demagnetize), in principle, with enough cascading temperature stages, the coldest stage could be kept continuously cold.

B. Architectural exploration

The advantages of continuity were clear – up to 25% more observation time on any given mission. [I23, I35] So after running the idea by his office mate without surfacing any show-stoppers, the two began exploring the idea in more depth. After a summer of "*playing with*" simulations and "*messing around*" a little in the lab in their spare time[8] the two were sufficiently convinced of the promise and feasibility of the idea to seek out formal development funding. [I8] In fall of 1998, they initially applied for internal R&D funding in the form of DDF (Directors Discretionary Funding). [I8, D1] The proposal was accepted. [I23] Although modest, this \$65K for the first year was sufficient to begin exploring the critical element of the concept: Heat transfer between the two coldest stages of the cascade. [I23, D2]

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[5] (a congressionally mandated innovation funding mechanisms)

[6] Different book keeping standards at the time make good records of expenditures not available.

[7] The follow-on Astro EII vented its stored cryogens shortly after launch, so we don't know if everything worked on that one either.

[8] ADR development is a time intensive process replete with "down time." Peter's branch head was happy from him to use this spare time to explore what she agreed was a promising new idea.

C. Technology exploration: Solving an identified problem

It became quickly apparent that several major component level technical hurdles would need to be overcome in order to realize the design concept. As stated in a 1999 grant proposal:

> *Success basically hinges on developing heat switches that can conduct heat very well in the on state at low temperature, yet provide good isolation in the off state. Several switches are needed to span the temperature range from 20-30 mK up to 10 K.* [D2]

Even as the original DDF was underway, CSE#1 and 2 sought out the more substantial technology development funding they would need to mature the capability to a point where it could be picked up by flight missions. The next logical step was to apply for "level 2" funding administered by HQ (called NRA – NASA Research Announcement); an application was submitted and subsequently rejected. [I8, D5]

The rejection was not a surprise to CSE#1:

> *Our feeling at the time, was that the way these technology calls got structured, HQ knew of technologies that were up and running, ready to be funded, and they kind of craft the NRAs around those, so in the NRA might solicit cooling technologies with capabilities that they've heard through the grape vine might be proposed to this NRA. We didn't fit into that description, so it wasn't surprising that we weren't chosen.* [I8]

In order to continue the development effort, CSE#1, 2 and two other staff from the cryogenics branch applied for several funding paths simultaneously. [D2, 3] In 2000, they received 2 year long DDFs and pitched another level 2 grant. One of the DDFs was dedicated to heat switch development, pursuing multiple approaches to achieve the required performance. [I23] In fact three summer students were each given a different strategy to explore. One of these paths was successful – a gas-gap heat switch – for which a patent was eventually issued in 2005. [I8, D16]

D. Returning to the architectural level

With the second DDF, they set out to prove-out the ability to make the next temperature transition up, while preparing for the next NRA opportunity. The next NRA solicitation was released under the newly created CETDP (cross enterprise technology development program), which was a much better fit for the CADR development, "*lo and behold, the technology descriptions included "continuous" refrigeration systems for 50 mK and below (an exact fit).*" [I8] The CETDP grant was awarded – 3 years totaling \$1.9M (including civil servant labor). [D6] According to CSE#1, no active efforts were made to encourage HQ to release a solicitation targeted at their ongoing work; he believes that the previous year's failed bid may have communicated the promising technology and need for it. [I8, 23]

During those three years of CETDP funding, substantial progress was made along an increasingly clearer development trajectory. They progressed from a 2-stage prototype, to a 4-stage system operating continuously at 50 mK that could dump heat to a 4K He bath (parameters suitable for flight missions then in the concept stage). [I8, 23, D12, 17, 18] In addition to the technology-centric advances, the stability and flexibility of the CETDP funding enabled the group to develop important tacit competencies. CSE#1 hired and trained several students, whose assistance contributed significantly to the development. [I23] Further, he used part of the funding (as well as some "cobbled together" resources) to purchase an electric discharge machine (EDM). CSE#1 believes that the EDM, and the technician who became an expert in its use, may be the single greatest explanation for their current status as the world leaders in ADR technologies.

During the same period, the team also received small amounts of Commercial Technology Development (CTD) funding - \$25K in each of 2001 and 2002 [D21] – to "*augment*" their other work and explore small CADR systems for lab applications. [I23]

E. Exploitation

At the end of the 3-year CETDP there were only two, albeit resource intensive, technical issues remaining before the CADR system could be considered "TRL 6" (i.e., ready for flight project-specific development). No structural analysis, or vibration testing, had been undertaken and thermal stability needed improvement.[9] Now in 2003, the team was confident that these remaining challenges could be overcome under an additional 3-year CETDP which seemed imminent. [I8, 23, 48] At his end of year project review, CSE#1 had connected with the gentleman managing the CETDPs (who happened to be a fellow UIUC alum) and been given the impression that he was in a good position to receive a follow-on grant as soon as the FY2004 program funding was approved. [I23]

F. Treading Water and Branching Out

However the funding was never approved. In fact, 75% of NASA's technology development funding was cancelled that year and reallocated to support the Constellation program. This left the team with a capability that was too mature to be suitable for the early-stage seed-funding that was still available, yet not mature enough to be taken-up by a flight project. The four years that followed are sardonically referred to by the group as the "*dark ages*." [I23, 24]

The funding drought was not confined to the CADR development (and its place in the valley of death); R&D funding was tight across the board. [I24] The cuts to intramural R&D funding coincided with the roll-out of full cost accounting. Where civil servant labor was previously paid out of generic overhead monies, under full cost accounting, time worked must be book-kept in relation to specific projects. This relatively minor administrative change had important implications for how the branch could operate. Where the branch had previously reserved 1 FTE for interesting, but not-yet-fundable concept exploration, this was no longer feasible when FTEs became "*real money*." Similarly, the early stage

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[9] ADRs are normally stable while cold because nothing is changing. However, in a CADR, the temperature cycling creates fluctuations that needed to be actively controlled; a capability that needed to be developed from scratch.

DDF of $75K went much farther, when it came with effectively unlimited[10] labor. [I24, 52]

During this period, the CADR push stayed alive (despite suggestions that it be temporarily put on hold) due to fund-finding ingenuity, and a little begging, on the part of CSE#1. [I23, 24] The meaning of "stayed alive" merits some clarification in this context. They – neither the branch head nor the champion CSE#1 – were ever concerned that the technical capability would become obsolete. [I23, 24] All of the developments thus far were also relevant to the traditional ADR design; and had distinguished the group as world leaders in the area[11] through their application, in stages, to every next flight project. Nor did they ever question whether an operational system could be developed once R&D funding was restored. [I23, 24] According to the branch head, her suggestion that the project be temporarily *mothballed* was for purely financial reasons; her job was to keep her staff funded, and money was extremely tight. [I23] She assigned all her senior staff to write proposals and find ways to insert their expertise into the few flight projects that had money (mainly JWST, the decade's flagship IR telescope). However, she recognized that every hour worked on JWST was a threat to the ADR competency; unlike the technology, which would *keep* for several years, the tacit knowledge stored in the people who worked on it wouldn't. [I23] And, once an individual has transitioned to a new project, especially an important flight project, it was nearly impossible to staff them back to R&D.

However, while the branch head saw this as a necessary evil (from her staffing responsibility perspective), [I23] CSE#1 saw this as a potential show-stopper to be actively combated (from his championing perspective). In particular, he was worried about losing one key technician – the expert in electric discharge machining – who was "*the kind of guy who would rather retire and work on his motorcycle*" [I8] than transition to another project while waiting for CADR funding to be restored. And rebuilding that kind of expertise would have taken a very long time. So, the CSE#1 found just enough funding to keep the project *alive*.

Between 2004 and 2009, the funding came in the form of two IRADs (Internal Research and Development – the later incarnation of DDF) of $135K and $100K in each of 2005 and 2006, [I8, D7, 8] yearly project support from Con-X (the next big X-ray observatory) development funds of about $25-100K per year [I8, 35], the equivalent of about $175K (+ matched funding of $275K) from an IPP seed fund partnership [D10], and on the order of $50K for the development of a 3-stage continuous ADR for an IR balloon instrument called PAPA and later PIPER [I57]. Of the four funding types during this era, the use of the IPP seed fund was the clearest. It enabled collaboration between the Goddard team and sections of the relevant industry. Of the ~$450K, $150K was contributed as matched funding by a firm specializing in low temperature read-out electronics. Together they investigated control circuits for the low temperature stability issue discussed above. Another $50K came from one of the key industrial manufacturers of space qualified cryo-coolers. This allowed the team to explore the interface with the type of mechanical refrigerator that would be used in future missions. [I23]

The $50K from the balloon program, though a monetary token, was critical from the point of view of keeping the manufacturing team working. [I54] Towards the end of 2003, CSA#7, an IR Astronomer who had previous experience working closely with the cryogenics branch, approached CSE#1 to build a CADR for his balloon experiment. [I57] CSE#1 was of course more than happy to do so. Although PAPA was never completed in the three years allocated, it was later transitioned to PIPER, a follow-on five year balloon instrument program. PIPER will fly in 2012 with a 3-stage CADR cooling its detectors. [I54] To date, the engineering model has been used extensively to test PIPER's optical system. While the development of a CADR for a balloon flight does not directly contribute to the flight maturity goal (due to stark differences in environment conditions), in addition to maintaining expertise within the group, it gave further credibility to the operational concept. [I54]

At $25-100K per year, the Con-X funding was more a way of sanctifying a relationship with a project, and augmenting other resources, rather than an avenue to further the technology development efforts. [I23, 53] To understand the project's perspective on the relationship requires some brief background about Con-X (now reincarnated as the International X-ray Observatory IXO). The Con-X program first received technology development funding in 1998 leading up to their 2000 decadal survey bid. [I53, D22] They let an NRA that year, soliciting proposals primarily in the mirror and calorimeter area (the Cryogenics branch was part of Goddard's bid for the calorimeter instrument). The Con-X mission ranked second (to JWST) in the Astrophysics Decadal Survey for 2000. As a result, while the mission did not receive approval, a mission study was directed to Goddard which included an average of $6-10M a year in technology development funding over the last decade. [I35] That money, while subject to significant variance related to budget uncertainty in the JWST program, has allowed them to make significant progress in both detector and mirror technologies that will enable this extremely ambitious undertaking, should it rank first in the 2010 decadal survey. While continuous cooling to cryogenic temperatures is not a critical mission enabler, the advantages in terms of potential science return are compelling (as an extremely positive bonus). [I35, I46]

Thus, from the Con-X project's point of view, maintaining a relationship with CSE#1 over the years has been well worth the non-competed trickle of matching discretionary funds they have provided.[I35] Further, in return for the funding, CSE#1 has supported the project on multiple occasions by preparing progress updates (for the numerous reviews that a directed study program is subjected to) and sitting on expert review boards.

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[10] Many of the scientists and technologists worked "night and day" (in their free time) on the pet projects that inspired them.

[11] Their ADR design is several times smaller, more efficient, less massive and power intensive, and even costs less to manufacture than the competition.

G. Changing Context

Also during the “dark ages” an unfortunate set of events in JAXA’s ASTRO program created an opportunity to demonstrate the CADR component capabilities already developed. Recall from above, that the first ASTRO spacecraft, designated “E” was destroyed due to a launch failure in 2000. The second ASTRO spacecraft, a direct copy designated “EII” was launched successfully in 2005, but due to an overlooked design problem, the stored cryogens were vented from the Dewar shortly after launch, resulting in a loss of cooling capability (rendering the cryogenic instruments useless). [D20] With the next generation ASTRO H already in the conceptual design phase, system redundancy became an important selling point [I56, I8] – the Japanese government would not tolerate another embarrassment. To achieve redundancy in the cooling subsystem, a 2-stage ADR design was baselined in the initial proposal (2008) that could be mated to both a 1.3K liquid He Dewar and a 1.7K JT cooler (in case the He bath failed again). [D23, I23, 56] The two stage design was approved (despite being unproven technology) since even at 1.7K, the magnet that would be required for a single stage ADR was prohibitively large.

The 2-stage became a 3-stage ADR, capable of operating at 5K, a year later when, following i) challenges space qualifying the then baselined state-of-the-art 1.7K mechanical cryo-cooler and ii) successes with mating the multi-stage ADR system to a warmer cooler (as demonstrated through the IPP seed funding). Multiple technical solutions were considered for filling the 1.7 – 5K cooling gap; however, the 3-stage ADR system prevailed as the lowest cost and risk solution. [I56] The additional qualification and production only cost the program an extra $750K. [I56] From the perspective of the project, this solution served to accomplishing the desired redundancy; from the perspective of CADR development, it provided an opportunity to flight qualify many of the components that the ADR team had developed to support a continuous (multi-stage) ADR. Although the ASTRO H team was reticent at first, to accept the risk associated with flying an unproven technology, necessity prevailed [I8, I56]; besides “*CSE#1 is very persuasive.*” [I24]

H. Flight oriented development: exploitation

More than just creating a flight opportunity for some critical pieces of the new CADR technology, developing the 3-stage ADR for ASTRO H gave CSE#1 and his colleagues a relevant “day job” again. [I8] Now, a significant amount of the time he wants to be spending on furthering the CADR can be justified as relevant to a chargeable project. Further, having several important pieces fly on ASTRO H, gives credibility in terms of risk reduction, and continues the path of the CADR towards the goal of TRL 6. [I23, 57] In fact, as the ramp-up towards near-term project relevance increases, CSE#1 has received an additional IRAD to investigate the remaining low temperature stability concerns [D9]; and once achieved, that, plus the vibration testing that will come through the ASTRO H program will yield an effective TRL 6. [I8]

The importance of TRL 6 is that it allows non-flagship missions (i.e., other than IXO) to consider CADRs in their baseline. This is relevant because where IXO can do without the continuous capability [I46, 53], for ASP (a MidEX, Absolute Spectrum Polarimeter) for example, which is a scanning mission, the continuity is critical. [I8, 57] Yet, as a mid level Explorer, ASP can’t baseline risky supporting technologies. There is a race therefore, to get the CADR to TRL 6, in time for ASP to happily bring it the rest of the way. Incidentally, the project scientist for ASP is CSA#7 (from PAPA and PIPER); he is confident in the technology and the team. [I57] As of writing (early 2010) the CADR is baselined in the study-phase and all the components and control schemes that will be needed for the 5-stage ASP CADR are being demonstrated under a current IRAD. The TRL 6 goal is looking obtainable. And, if IXO is ranked first in the 2010s decadal survey, there will be another flight opportunity there as well.

I. Continued branching out

These flight opportunities are not yet guaranteed. Thus, in recent years, as another way to buy-down future flight risk, and increase the potential for flight opportunities, the cryogenics branch has continued to pursue a number of ongoing R&D efforts which build on, and feedback into, the continuous/multi-stage ADR paradigm. Specifically, ADR stages capable of working up to 30K have been under development for some time [D24]; this represents the less efficient region of mechanical cryo-cooler operation. However, if ADRs are to become feasible in this region, major innovations in the area of superconducting magnets will be required. [I54] To this end, the group has supervised a series of SBIR contracts with two small businesses. It turns out that the same techniques driving improvements in high temperature magnets, can be used to improve the low-current leads bringing power to the ADR magnet; this technology will be employed on Astro H. The process continues.

IV. MAKING SENSE OF THE PROCESS

At first pass, the pathway described above seems highly idiosyncratic; governed by chance encounters and the persistence of key individuals. However, when compared to other pathways, there are common patterns among the types of behaviors that were observed. Rather than trying to define a *typical* sequence of events, in making sense of the process we focus on identifying characteristic epochs and the shocks that initiate transitions from one to another. The idea is that while the sequence of epochs varies from one project to another, the dynamics they embody (and corresponding management levers) are surprisingly consistent across the cases. The usefulness of this approach lies thus in leveraging those identified levers. It must be emphasized that this is not a revised stage gate model (e.g., [21]), where epochs replace stages, regulated by shocks instead of gates. Where a stage-gate conceptualization seeks to regulate the flow of increasingly mature capabilities through a sequence of imposed development stages, the proposed epoch-shock conceptualization seeks to identify management levers in an inherently random pre-development discovery processes.

A. *Characteristic Epochs*

In reviewing the longitudinal case histories of the development of these innovations we inductively identified four characteristic epochs and two result states; namely, Technology Exploration, Architectural Exploration, Treading Water and Branching Out, Exploitation. We call the pre-pathway period gestation, and identify two types of pathway terminations: the Technology Graveyard or a first Flight. These epochs are framed in the combined language of so called exploration/exploitation (c.f., [22, 23]) and component/architectural[14] innovation. An overview of these epochs and the relationships among them are presented in Figure 1. The below text describes the way these epochs can be identified and the behavior they entail. It was observed that the behaviors governing each epoch tended to persist unless a shock of some sort forced a transition, noted as arrow labels in the figure. The types of transitions are introduced in context in this section and elaborated upon in the next.

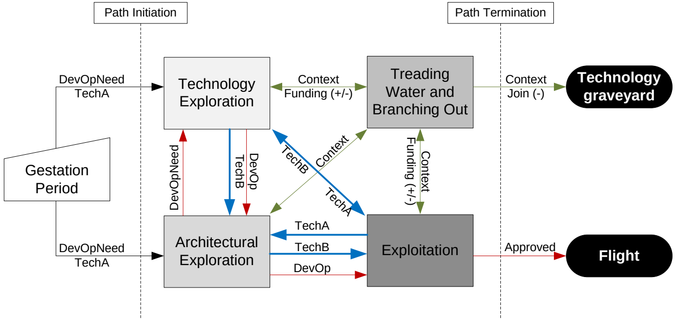

Figure 1 – Overview of the Epoch-Shock Conceptualization

The *Gestation Period* describes the time leading up to the formal initiation of the innovation pathway. Consistent with the observations of Van de Ven et al. [12], there was typically an extended period in which people (who would become key participants) engaged in a variety of activities that set the stage for the eventual development. They were typically engaged in other, often tangentially related projects at the time. Although not technically part of the pathway, it is important to consider this pre-pathway period because it sets the initial conditions which can have a strong influence on the path that follows. In this context, relevant initial conditions include the existence of relationships among future team members, experience with the relevant constituent technologies, familiarity with potential applications and access to resources. As Kingdon[24] argues, it is often possible to trace the origins of a particular technology (or in his case policy) back in time nearly indefinitely. For consistency, we chose to fix the end of the gestation period as the first time the particular new capability is explicitly pursued by name within the innovating organization, in our case NASA. We examined the gestation period at the level of detail, and as far back as was necessary, to understand the initial conditions described above.

Shocks: In the cases we studied, innovation pathways were initiated in one of two ways. Either a compelling new technical approach was proposed, or the need for a specific limiting technology was articulated. Whether these shocks precipitated a *technology or architectural exploration* depended on the level of the insight/need. For example, in the CADR case, the technologists' insight was at the architectural level; he didn't identify the key technical constraint until after engaging in architectural exploration.

Technology Exploration describes a pattern of behavior characterized by the simultaneous pursuit of multiple new technological approaches. In this epoch, there is typically a small core team of experts (be they scientists or technologists) internal to the organization, augmented by multiple *ad hoc* collaborations with external counterparts. These external relationships can be quite short lived – they're often initiated through in-person encounters at technical meetings, or by introductions from colleagues and last as long the technical interests of both parties overlap. It is not uncommon for the core team to nurture multiple of these collaborations simultaneously, limited by the resources available to them and the number of component level innovations being pursued. Resources in this epoch are obtained through some combination of R&D grants from multiple institutional levels (e.g., DDF and CETDP), supplemented by slack resources at the branch-level (e.g., if a technologist is working full-time on a flight project, any down-time and unofficial overtime can be spent on the innovation effort). Funding from different sources is applied for indiscriminately, without differentiating among target maturity levels. During this epoch the overriding goal is to fund the effort for long enough to find some strategy that works and proves the concept in a laboratory environment.

Shocks: Transitions from an epoch of technology exploration occurred for one of two reasons. Either a breakthrough was achieved (i.e., a practical solution was found) leading to continued exploration at the architectural level; or a project opportunity prompted a direct transition to an epoch of *exploitation*. In the latter case, some level of success must have already been achieved for the opportunity to be relevant. Although it wasn't observed in the cases we studied, a change in context could conceivably threaten the persistence of the project (i.e., forcing a transition to the treading water epoch).

Architectural Exploration describes a focused form of exploration that can serve different purposes at different times in an innovation pathway, be it fleshing out a system concept or searching for a new way to reconfigure existing components to solve a new problem. It is marked by the presence of an articulated performance-oriented objective, and a focus on reconfiguration of existing system modules rather than the development of new ones per se. Scientist (users), and the corresponding project hierarchy that involving users entails, play a bigger role in this epoch than other types of exploration, but the same dynamic of multiple *ad hoc* collaborations with external experts persists. Technically, the emphasis is on demonstrating feasibility of the mission concept, which may involve breadboarding major subsystems or constructing detailed simulations to explore architectural alternatives. If this exercise unearths technology-level show-stoppers a *Technology Exploration* epoch may be initiated. Activities during this epoch are funded in much the same way as during technology exploration – primarily via more substantial directorate-level R&D grants, supplemented by any other resources that can be obtained.

> Shocks: Transitions from an epoch of architectural exploration occurred in three main ways. Either a technology-level need was identified (dropping the level of exploration to the relevant component), or the team ran out of funding, or a flight opportunity was secured. Interestingly, successful demonstration of the practical feasibility during this epoch did not precipitate any transitions; what seemed to matter was the timing of the next mission opportunity after the breakthrough. If it followed closely, there was a transition to *exploitation*; if it didn't an epoch of *treading water* ensued.

The *Treading Water* epoch shares many surface indicators with the *Technology Exploration* epoch, but serves an entirely different purpose. As in the *Technology Exploration* epoch, funding is being applied for at multiple institutional levels, and parallel technologies are being pursued simultaneously. However the strategy motivating these pursuits is fundamentally different. This is a survival mode. The parallel technology paths leverage the same core innovation and apply them to different, but related, contexts. The goal is to increase the likelihood of finding a flight opportunity, or at least further development funding, by branching out to as many application areas as possible. To the extent that new relationships are formed, their purpose is to facilitate this branching out process (i.e., bring onboard potential customers, rather than researchers with complementary technologies). Mostly though, the core team is preoccupied with keeping key team members funded, so they won't be permanently reassigned to other unrelated projects leading to path termination in the technology graveyard.

> Shocks: During the *treading water* epoch, finding a way out is of primary concern. The way out transition typically corresponds to a change in context; a new flight project may identify a relevant technical need, or a change in administration may initiate a new technology program. If a transition out of the *treading water* epoch doesn't arise soon enough, key team members will be forced to transfer to paying projects, leading to a terminal transition to the *technology graveyard*.

Exploitation describes a set of structured actions to mature the components of a particular systems architecture towards flight readiness. These actions are governed by formal institutional regulations regarding e.g., the types of testing that must be performed. While problems identified during this epoch can certainly lead to novel technical solutions, the search process is much more focused than in either of the exploration epochs. Where exploration is looking for an approach that will work, exploitation is looking to ensure that the selected approach works efficiently and reliably. The cost of activities in this epoch is proportionally much higher than corresponding laboratory demonstrations; as a result it is often, but not always, conducted as part of a flight project. Further, this epoch tends to entail a major expansion in the size of the innovation team; an increase by a factor of 10 is not uncommon. Within NASA, exploitation is the domain of engineers and project managers, and most of the new additions will be of this cadre.

> Shocks: The *exploitation* epoch typically ends with a transition to the implementation phase of a flight project by means of the formal approval process. However, depending on whether the innovation is being matured in the context of a flight project or independently, changes in context or resource draughts can force transitions to an epoch of *treading water*; and the identification of a major technology problem, or a new technical insight can induce transitions back to exploration epochs.

In defining these epochs, care was taken to minimize the association of particular dynamics to project phases. This is because all the above described behaviors can exist, both inside and outside approved projects; they are fundamental to the innovation pathway, not the imposed institutional structure, as will be seen through the case illustrations presented later in this paper.

B. *Transition Inducing Shocks*

Having introduced the types of shocks that were observed to induce transitions from a particular epoch to another, this section elaborates upon and categorizes the above described set in terms of technical breakthroughs, development opportunities, changes in context and critical collaborations.

Technical Breakthroughs (Tech)

Several different types of technical breakthroughs can occur both inside and outside of the core development team and at the component and architectural level. The two main types of breakthroughs that occur are proofs of theoretical feasibility "*TechA*" and practical demonstrations "*TechB*".

1. TechA (i.e., the first laboratory demonstration that a new technological approach can yield the desired effect) can provide a sufficient shock to open up a whole new search space. Depending on the timing, this can initiate a new innovation pathway or cause a major shift in development direction. Whether this type of breakthrough occurs inside or outside the team makes limited difference, as long as the relevant community is small enough.

2. TechBs are marked by the first time that the space mission utility of the new capability is demonstrated. Where *proofs of theoretical feasibility* often exhibit poorer performance than incumbent technologies, *practical demonstrations* overcome important hurdles (be it demonstrating that the device can be sufficiently broadband, or attaching microstructures to a new semiconductor compound). From a utility perspective TechBs are critical, but their role as shocks is weaker than TechAs. This is because they serve to legitimize the current path rather than initiate

a new one. TechBs need to occur inside the team to be relevant.

Both proofs of theoretical feasibility and practical demonstrations can occur at either the component or architectural levels. While the impact of a component vs. architectural, TechA or TechB, are similar, the transition they initiate tends to occur in the direction of the breakthrough. For example, a TechA mediates between component and architectural exploration, while a TechB mediates between exploration and exploitation.

Development Opportunities (DevOp)

Development opportunities are idiosyncratic to the particular organizational context under study. Nonetheless describing the patterns of those present at NASA will shed light about the types of shocks that are possible. DevOp shocks can take the form of identified technical needs or funding opportunities. Ideally, funding opportunities correspond directly with identified needs, but this is not always the case. The key conceptual difference between the two types of opportunities is that where technical needs are typically identified while trying to implement a predefined concept, a funding opportunity provides the means through which to define said concept. Both the identification of a technical need and the prospect of a funding opportunity serve to the focus efforts of technologists and scientists; however their presence in different mission contexts (i.e., Flagship vs. Explorer) create different types of shocks.

3. DevOpFlag: The science objectives for *Flagship* class missions are developed by a consensus process within the science community, coordinated by the NRC Decadal Surveys and implemented by NASA. One implication of this extended process is that the corresponding instrument community is given approximately two years advanced warning about what will be requested next. Given the revolutionary aspirations of Flagship class missions, this type of DevOp typically prompts a search for a radically new approach in particular technology areas, funded by several additional years of dedicated technology development prior to a formal instrument selection. Thus, the prospect of a Flagship class call can pull significant advancements in fairly specific areas. The announcement of the next Flagship mission happens fairly predictably in the year following a Decadal Survey.

4. DevOpEx: Explorer class mission announcements, on the other hand, are explicitly non-specific (in terms of target science), come with little advanced warning and expect a high level of technology maturity in the proposed baseline. Where Flagship missions incorporate multiple advanced instruments, explorers are typically organized around one or few targeted measurements. As a result, they provide great opportunities for first flights of new technology; however, that technology must have been previously developed outside of the mission context for it to be selected. Thus the timing with respect to other types of shocks (particularly breakthroughs) modifies the impact of DevOpExs significantly. The spacing of Explorer-calls is somewhat unpredictable, and depends on budgetary constraints from other program elements (e.g., if a Flagship is delayed or overrun, the next explorer call will be delayed too).

5. DevOpNeed: Mission or subsystem concepts sometimes evolve outside the context of any particular Flagship or Explorer opportunity. As the details are worked out, technical roadblocks are sometimes identified. Similar to TechA described above, a DevOpNeed can initiate a new innovation pathway or significantly change an existing trajectory. The key conceptual difference here is the direction of the impetus, which often relates to the background of the initiator (e.g., a scientist is more likely to start from a system concept, identifying required technology improvements as the concept is fleshed out, whereas a technologist may identify opportunities from improvement in the context of the technology s/he is working on).

Changes in Context (Context)

Innovations pathways don't proceed in a political vacuum. The prioritization of particular science questions (e.g., when Flagship class missions are ranked) alters the chances of success for some developing technologies and limits the prospect for others. Similarly international collaborations force compromises with respect to who develops what – while agency competencies are certainly taken into account, sometimes the desire for friendly relationships can shelve a decade's worth of development. This category of shock is idiosyncratic and highly unpredictable (from the perspective of the innovation pathway) but can have a substantial impact on it. For the most part, changes in context correspond directly to one of the previously described shocks (e.g., DevOpFlag); however one type of context merits its own category: draught.

6. Draught: Non-project technology development funding opportunities arise on a yearly basis at both the center- and directorate-level targeted at new concepts of various levels of maturity. Technologists rely heavily on these grants to sustain their research; however as shocks, the availability of such grants only act negatively on the technology trajectory. Namely, receiving funding has a neutral affect on the shape of the trajectory, but not securing funding leads to an epoch of treading water (whatever the current epoch). It's worth clarifying that draught in this context refers to an unexpected loss of funding. For example, in the CADR case, the technology was progressing well and would likely have received continued funding except that a top-level policy change eliminated all potential funding sources simultaneously.

7. Context: This tag will be used for context changes that aren't captured by another label.

Critical Collaborations

The addition or departure of key team members can have a major impact on the evolution of the innovation pathway.

8. Join: In the context of the relatively small core teams, each member (particularly when outside researchers are recruited) tends to bring a particular capability; be it expertise in a component of the innovation, or access to a critical facility. In the pathways studies, additions had much more impact than departures (as most departures not caused by funding draughts coincided with a loss of interest by one or both parties). New collaborations were most commonly initiated following the annual or bi-annual technical conference (of the relevant domain), but some meetings happened off cycle as well.

C. *Example Epoch-Shock Sequence: CADR*

In order to concretize the above descriptions of epochs and shocks, let's consider the CADR case in these terms. Figure 2 illustrates the path taken by the CADR innovation.

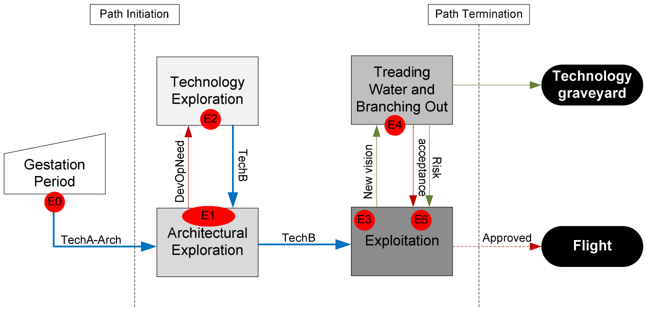

Figure 2 – Illustration of CADR innovation pathway

Table 1 provides a description of each of the epochs and shocks enumerated in Figure 2. Specifically, E0 in Figure 2 corresponds directly to E0 in Table 1. The arrows are not numbered but the labels are matched. Note that the descriptions are in terms of the people involved, characteristics of the technology change, sources of funding, and development context. These distinctions will become important in the discussion of future work below.

Table 1 – Description of Epochs and Shocks along CADR pathway

E0 - Gestation Period (~20 yrs since "ADR for NASA") People: team already formed as "cryogenics branch" Technology: ADR standard for sub kelvin cooling Funding: working on flight ADR project, brainstorm improvements during "down time" Context: trend of dramatic increase in cooling requirements
S0 - TechA: NASA technologist struck by architectural insight (1998)
E1- Architectural Exploration (3yrs, 2ppl) People: no change Technology: explore concept in simulations to determine number of stages, create laboratory model Funding: Initially applied for division-level grant (rejected); received center-level R&D funding, followed by division-level grant Context: expected cooling requirements for future flagship missions becoming clearer
S1 - DevOpNeed: heat switch (component) identified as limiting factor (1999)
E2 - Technology Exploration (1yr, 5ppl) People: student researchers hired to explore multiple alternative technical approaches Technology: need for switches in new temp range and mode of operation (work at architectural level continues as well) Funding: no change Context: no change
S2 - TechB: practical gas-gap heat switch demonstrated in relevant range (2000)
Architectural Exploration continues until 2001 **E3 – Exploitation (4 yrs, <10ppl)** People: team expands slightly with addition of technicians Technology: 2-stage lab experiment matured to 4-stage operational system Funding: division-level grant, supplemented by commercialization funding for new technology Context: no change
S3 - Draught: new administration cuts 75% of all technology development funding (2004)
E4 - Treading Water (5 years, <5ppl) People: team begins to shrink as members are forced to work on "paying" projects; key members retained Technology: minimal progress made collaborating with industry 1) mating with alternative warm ends and 2) control electronics Funding: scarce; limited resources obtained from industry collaboration, involvement with balloon and future projects Context: tech funding tight across the board
S4 - Context: sequence of failures on relevant mission increases value placed on redundancy vs. risk of new technology. Decision to implement multi-stage ADR on flight (2009)
E5 - Exploitation (project) (3 yrs, <5ppl) People: no change (the members that left are stuck with responsibilities) Technology: emphasis on flight qualification of multi-stage ADR; CADR-unique stability demonstrations conducted separately Funding: Project funding, supplemented by center-level R&D for CADR-unique activities Context: increase interest in continuous operations from proposal-stage missions (ASP)
S5 - DevOpEx: ASP propose in response to 2010 Explorer AO (2010)
Astro H flight development continues. If ASP is successful, CADR will be developed for its first flight
Launch: multi-stage ADR on Astro H (2012); CADR on ASP (?) ~2014 (14/16yrs)

V. GENERAL RELEVANCE AND PATH FORWARD

Going forward, it is expected that understanding the interactions of these categories will hold the key to being able to determine where to exert management control on the process. Already, this model provides a way to make sense of an otherwise extremely messy process: The CADR innovation pathway is a story of a domain expert identifying a way to drastically improve his system; upon fleshing out the idea, he comes up against a technical hurdle, which he overcomes through an exploratory search process[25]. Armed with a working solution, he seeks to apply it; however, without an immediate risk-justifying need he needs to cross the "valley of death" on his own[26]; and he might have, if not for a political decision to eliminate technology funding. With the funding pulled out from under him, he scrounges to keep the project alive long enough for "the next" opportunity to implement his innovation. It takes five years, but the waiting is worth it; external events fundamentally change the risk reward tradeoff associated with infusing his unproven technology[1], and he is ready to take advantage of this window of opportunity[24].

Although this is a story of a highly specialized space system module, it could be one of any number of other new technologies trying to gain acceptance in other markets. The difference is that with only one potential buyer (NASA) a policy change like the new vision in 2004 can end a productive pathway, which may not be a desirable result. Studying these pathways at this level allows us to understand the implications that these macro-changes have for the micro-behaviors of individuals and the technologies they generate.

Due to space constraints, we have focused the discussion on one example innovation pathway – the continuous adiabatic demagnetization refrigerator. However, the model is based on three additional cases which differ greatly in terms of the types of people involved, nature of the technology and mission context. The model explains these other cases equally well (the CADR case was chosen for reporting purposes because it is the shortest and least circuitous, but all other narratives are available from the authors upon request). Nonetheless, these cases are all of innovations developed by NASA, at Goddard, in the space science directorate, so an important question is: Are the insights relevant in other contexts?

Short of conducting a follow-on study in another research setting, the best way to provide a first check of the generality of our insights is to compare our observations to those of other scholars studying other domains[17]. The Minnesota Innovation Research Program[27] is perfectly suited for this purpose. That study examined 14 "innovation journeys" across different organizational and technical contexts. A key output of that work was twelve propositions about the nature of the innovation journey (see p. 23 of [12]). Our observations agree with theirs in most respects but the uniqueness of our context allows us to extend their theory in several interesting ways.

Firstly, the MIRP argues that the innovation journey is a nonlinear cycle of divergent and convergent activities that may repeat over time and at different organizational levels if resources are obtained to renew the cycle. We observe a similar phenomenon but note that in addition to different organizations, the cycling happens among and across both component and architectural product levels. This is an important distinction that merits further study because while engineering project managers are well aware of the integrative complexity of the systems they manage, the tools like TRL do not account for this cycling.

Second, the MIRP identifies multiple diverse roles that management play at different times in the journey, as well as noting the fluid participation of team members. This leads to the suggestion that management in the early stages should be more hands-off and harness the chaos embodied by the fluidity of ideas and participation. In NASA, there is already very little centralized management control in the early stages of innovation and as a result, the concept of fluid participation manifests quite differently. The internal core team tends to stay with the innovation from inception to implementation, but there is significant coming and going among peripheral and external participants. This observation suggests that relaxing management control may actually solidify the core innovation team by forcing them to take ownership of their own innovation. Thus, if the goal is to harness the new ideas that come out of fluid participation, changing the management control may just shift the management problem to a different level of the organization.

Finally, the topic of where this research is going merits a few words. The above described model is only practically useful to the extent that it yields insights about how to better navigate the "innovation journey." Prescriptive insights will require an understanding of how the observed behaviors are generated, and importantly, the extent to which those behaviors can be influenced by various actors in the system. In presenting the CADR case in the framing of the model (Table 1), each epoch was described in terms of people, technology, funding and context, as a way of decomposing the top-level behaviors. The shocks also correspond roughly to these separate, albeit interrelated, tracks. We are currently in the process of unpacking the underlying processes that generate the observed behaviors in terms of routines governing the evolution of each track. For example, do the interaction of prescribed R&D funding cycles and the incentives for individuals to write grants explain the periodic shortfalls (and subsequent treading water epochs)? In addition, we are also broadening the scope of our study to test these preliminary findings in other institutional settings. Work is currently being initiated to perform a similar study in the US National Security Space context.

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APPENDIX – DESCRIPTION OF DATA

Interview#	Code	Time	Functional description
I8, I23, I54	CSE#1	3hrs	Cryogenics branch engineer
I24	N/A	1hr	Branch head
I35, I53	N/A	1hr	Flight project program manager
I46	N/A	45 mins	Project scientist (past)
I48	CSE#2	45 mins	Cryogenics branch engineer
I56	N/A	30 mins	Flight project systems engineer
I57	CS#7	30 mins	Project scientist (future)
I15, I17, I22, I42-I45, I52	N/A	3hrs	Funding programmatic perspectives

Doc#	Type	Description
D1	Grant proposal	DDF FY1999
D2	Grant proposal	DDF FY2000 – 1
D3	Grant proposal	DDF FY2000 – 2
D4	Grant proposal	DDF FY2001
D5	Grant proposal	ROSES FY1999
D6	Grant proposal	CETDP FY2000
D7	Funding records	IRAD FY2005
D8	Funding records	IRAD FY2006
D9	Funding records	IRAD FY2010
D10	Grant proposal	IPP 2006
D11	Journal Paper	Cryogenics (2001)
D12	Journal Paper	Cryogenics (2004)
D13	Journal Paper	NIM-A (2006)
D14	Journal Paper	Cryogenics (2010)
D15	Journal Paper	J. of Low Temp. Physics (2007)
D16	Patent	2005: Passive gas-gap heat switch
D17	Journal Paper	Cryocoolers 12 (2002)
D18	SPIE Proceedings	multiple papers in SPIE
D19	Report	ADR "X-Doc" (1980)
D20	Press coverage	Repository of material on Astro missions
D21	Press coverage	IPP newsletter
D22	Grant solicitation	Con-X NRA 1998
D23	Presentations	Internal presentation (2008, 2009)
D24	Grant proposal	ROSES FY2003