

The Continuous Adiabatic Demagnetization Refrigerator (CADR) Innovation Pathway

This pathway 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 submillimeter observatories incorporate larger and more advanced detector arrays.

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 submillimeter) 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 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.¹ [I24]

The first flight ADR was developed in support of the Chandra X-ray observatory; specifically to cool the XRS instrument [I30, 46]. However after nearly \$3M of further development funding, [I46] 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).² [D20] Nonetheless, by 1996, when CSE#2, 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#2 and his office mate CSE#5, another low temperature physicist, began brainstorming alternative approaches. [I30, 70] As

¹ The different book keeping standards at the time, limit the comparability of expenditures.

² The follow-on Astro E2 vented its stored cryogens shortly after launch, so it's impossible to confirm instrument performance.

recalls CSE#2 “one day the idea just came to me:” [I45] 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.

Architectural exploration

The advantages of continuity were clear – up to 25% more observation time on any given mission. [I45, I70] 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 time³ the two were sufficiently convinced of the promise and feasibility of the idea to seek out formal development funding. [I30] In fall of 1998, they initially applied for internal R&D funding in the form of DDF (Directors Discretionary Funding) [I30, D1]. The proposal was accepted [I45]. 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. [I45, D2]

Technology exploration: innovating to solve 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#2 and 5 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. [I30, D5]

The rejection was not a surprise to CSE#2:

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. [I30]

In order to continue the development effort, CSE#2, 5 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. [I45] In fact

³ ADR development is a time intensive process replete with “down time.” CSE#1’s branch head was happy from him to use this spare time to explore what she agreed was a promising new idea.

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. [I30, D16]

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).*” [I30] The CETDP grant was awarded – 3 years totaling \$1.9M (including civil servant labor) [D6]. According to CSE#2, 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 [I30, 45].

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). [I30, 45, 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#2 hired and trained several students, whose assistance contributed significantly to the development [I45]. Further, he used part of the funding (as well as some “cobbled together” resources) to purchase an electric discharge machine (EDM). CSE#2 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. [I45]

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.⁴ Now in 2003, the team was confident that these remaining challenges could be overcome under an additional 3-year CETDP which seemed imminent [I30, 45, 70]. At his end of year project review, CSE#2 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 [I45].

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

⁴ 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.

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*” [I45, 46].

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 DDF of \$75K went much farther, when it came with effectively unlimited⁵ labor [I46, 74].

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#2 [I45, 46]. The meaning of “stayed alive” merits some clarification in this context. They – neither the branch head (BH#1) nor the champion CSE#2 – were ever concerned that the technical capability would become obsolete [I45, 46]. All of the developments thus far were also relevant to the traditional ADR design; and had distinguished the group as world leaders in the area⁶ 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 [I45, 46]. According to the BH#1, 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 [I46]. 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 [I45]. 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), [I46] CSE#2 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*” [I30] 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#2 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, [I30, D7, 8] yearly project support from Con-X (the next big X-ray observatory) development funds of about \$25-100K per year [I30, 57], the equivalent of about \$175K (+ matched funding

⁵ Many of the scientists and technologists worked “night and day” (in their free time) on the pet projects that inspired them.

⁶ Their ADR design is several times smaller, more efficient, less massive and power intensive, and even costs less to manufacture than the competition.

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 [I79]. 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 [I45].

The \$50K from the balloon program, though a monetary token, was critical from the point of view of keeping the manufacturing team working [I76]. Towards the end of 2003, CSA#13, an IR Astronomer who had previous experience working closely with the cryogenics branch, approached CSE#2 to build a CADR for his balloon experiment [I79]. CSE#2 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 [I76]. 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 operating environments), in addition to maintaining expertise within the group, it gave further credibility to the operational concept [I76].

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 [I45, 75]. 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 [I75, 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 [I57]. 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) [I57, 68].

Thus, from the Con-X project's point of view, maintaining a relationship with CSE#2 over the years has been well worth the non-competed trickle of matching discretionary funds they have provided [I57]. Further, in return for the funding, CSE#2 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.

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 that had already been 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 “E2” was launched successfully in 2005, but due to an overlooked design problem, the stored cryogenics 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 [I30, 78] – 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, I45, 78]. 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 faced while space qualifying the then baselined state-of-the-art 1.7K mechanical cryocooler 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 [I78]. The additional qualification and production only cost the program an extra \$750K [I78]. From the perspective of the project, this solution served to accomplish 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 [I30, I78]; besides “*CSE#2 is very persuasive*” [I46].

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#2 and his colleagues a relevant “day job” again [I30]. 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 [I45, 79]. In fact, as the ramp-up towards near-term project relevance increases, CSE#2 has received an additional IRAD funding 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 [I30].

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 [I68, 75], for ASP (a MidEX, Absolute Spectrum Polarimeter) for example, which is a scanning mission, the continuity is critical [I30, 79]. 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#13 (from PAPA and PIPER); he is confident in the technology and the

team [I79]. 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.

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 [I76]. 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. And so, the process continues.