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Behind the icon: NASA's Mercury capsules as artefact, process and practice

During a fellowship year at the National Air and Space Museum (2003–04), I frequently spent time examining one of the central icons of America's space programme – John Glenn's Friendship 7 Project Mercury capsule, mounted on a platform in the first floor's main hall. Dwarfed by rockets to one side and planes to the other and above, it seems almost a meagre device in comparison even with the nearby Gemini and Apollo spacecraft; several of them easily could be fitted into the cargo bay of the massive Shuttle displayed at NASM's Udvar-Hazy Center near Dulles Airport. Yet the artefact that carried John Glenn as the first American into an Earth orbit remains a magnet for visitors. As I was researching the Mercury capsule's design and fabrication, it was a guilty pleasure to watch families and clusters of teens or young adults hover around it. Built by the McDonnell Aircraft Corporation (MAC), the spacecraft stands just under 12 feet (3.7 m) tall and about 6½ feet (2 m) across at its widest, and looks like an inverted cone with a plug in the top. At launch, with its escape tower and retrorockets attached, it weighed a bit more than 2 (US) tons, then dropped more than 40 per cent of that poundage before splashing down after a flight (Colour plate 5).[1]

Resisting the temptation to offer uninvited commentaries, usually I just listened. Two simple themes struck me, among many in the conversations. Male teens and adults at times peered through the astronaut's window and observed: 'Wow, there's hardly any room in there at all' (or something similar). The technologically savvy, a smaller cohort, talked about the capsule interior's crowded, even 'primitive', arrays of dials, switches and levers, appreciating its historical location and observing that we've moved a long way from such 1960s-era apparatus.[2] For me, the 'Wow' response signalled a visitor's encounter with an icon – no questions, no requests for information or context, no interaction. By contrast, those marking the capsule as technologically primitive were, in a rough-handed way, thinking about history and progress, reflecting on then and now, taking the first step to moving behind the icon.

Yet without extensive collateral information, without an enriched *context*, the capsule artefact cloaks its origins in a time of cultural fright and political anxiety, in an era of urgent NASA designing, engineering, testing, redesign and fabrication, in a world of nuclear stalemate, mutually-assured destruction, and technological rivalry. This spacecraft surely is 'frozen history', a notion David Noble evoked and Martin Collins has emphasised in this volume's introduction. Yet what does the capsule as artefact freeze and exclude? One absence is the *process* through which its creation was accomplished and, by extension, the people who activated that process.

The Mercury effort involved an expensive and erratic learning curve concerning space technologies and their associated sciences, from metal-bending to metallurgy and from soldering communications connectors to electronic theory. Consistently, the line of development ran from technological imagination through engineering design and artefact fabrication, with an occasional sidestep to commission targeted scientific research. The Mercury capsules were not a consequence of scientific findings, but rather, inverting the usual frame, provoked a broad set of questions for scientific investigation while struggling with empirical challenges that science could little clarify, *c.* 1958–63.

Evoking these macro-level dynamics and challenges can contextualise the artefact, but we also should consider how the artefact, and in Martin Collins's words, 'the details of [its] creation and use', can 'illuminate' the surrounding culture. Thinking specifically of space history and its apparatus, he has bracketed a series of themes that I will reframe as questions to which the remainder of this discussion will attempt tentative responses.

1. If science and technology have come to be regarded as 'the pre-eminent means for understanding and controlling nature', how do space artefacts confirm or challenge that pre-eminence and that goal?
2. How can a space artefact serve as a 'nexus through which one could comprehend both technical and cultural change'? In what sense does the artefact 'in and of itself offer the opportunity for insights into technical or social change'?
3. If project-management cultures are a key part 'of the structure of big technology projects', how do space artefacts embody that culture and structure?
4. How can a space artefact communicate the notion that Cold War projects 'alter[ed] social boundaries and tend[ed] to de-centre the work and contributions of individual teams or research sites'?
5. How can these technologies, and the details of their creation and use, help us recognise that 'space artefacts [rarely] were fully settled entities in a design or material sense'?

Now, rather than working mechanically through these issues, I will shift into storytelling mode, offering a group of 'Mercury tales' and images that resonate with an effort to get behind the icon, to locate the people and the process, the politics and the engineering, and to grapple with the 'stuff' that worked, the 'stuff' that did not and the unknown/unknowable bits that jumped up to bite holes in budgets, schedules and artefacts.

From the end, back to early days

At the October 1963 Project Mercury Summary Conference, principals from NASA and McDonnell Aircraft described to reporters the process and the experiences central to fabricating America's first piloted space capsules. Newspaper and magazine writers had recently stressed a report of 700 'system or component discrepancies' in the MA-9 flight capsule (Gordon Cooper for 22 orbits), three-quarters of which were 'attributed to faulty workmanship',[3] but much of interest to historians and curators of technology was also offered that morning.

NASA Deputy Administrator Hugh Dryden delivered these opening comments: 'We learn how to build things to last longer by *trying to build them, by operating them in space, finding out what goes wrong, correcting [and] learning more* about the environment [...] we learn by going into space and working there; not from some theory in the laboratory.' The ghost of Thomas Edison surely beamed at Dryden here, for this was innovation in true, empirical, Edisonian fashion, referencing what engineers have long termed 'cut and try' methods. The NASA manager continued:

> We have learned that the requirements for things to work in space are very much more rigid than those that work on automobiles or even on airplanes [...]. In the space program, for the first time we have opened up to the American public the full gold fish bowl, how a complicated research and development project proceeds in a frontier area of technology [...]. Those of us who have been engaged in such projects for many, many years, particularly in the military projects, are very familiar with all these things, but the public has not been familiar because they have not been exposed to the detail of progress of these complex developments.[4]

Yet NASA Deputy Director (and longtime Space Task Group member) Walter Williams complicated this portrayal of learning-intensive transparency, indicating that while perhaps there *was* learning, there was no learning curve:

> You might expect with time that there [would] be a learning curve, but I think *what offsets this* is, one: a mission [becomes] more complicated as we have moved on, which set the standards higher; two, I think we did decrease the mesh of the screen [through] which we were filtering these problems so that we are constantly finding better ways to look deeper, look further.[5]

Spacecraft development was not just shooting at a moving target; the entire project was constantly in motion, platforms and targets alike, facing a demand curve that escalated unevenly. Just because your team knew how to accomplish a task today didn't mean that the task had stabilised. Tomorrow or next month, it could morph unrecognisably, demanding fresh approaches, tighter tolerances, higher performance – devaluing received knowledge and shoving aside any notion of incremental learning and artefact stabilisation. In his paper for the closing conference, Williams observed, in something like a runaway sentence:

> We knew [...] that to do this program at any reasonable length of time, wherever possible, existing technology and off-the-shelf equipment would have to be used, wherever practical, and [...] although it was expected to find much equipment on the shelf, I think many of our problems were really finding which shelf this equipment was on, because, in almost every area, because of the design constraints, some new development had to be undertaken to meet the new requirements.[6]

McDonnell's Walter Burke reinforced Williams's point:

> In this particular venture, we were going into a method or mode of operation that had never been attempted before. There are no pieces on Project Mercury that are off the shelf from any other program that has ever existed. [My own sense is that this claim was too sweeping, but were it qualified a bit, the point could stand.] The problem of designing and making work this complex group of systems is one which will require and did get a degree of attention to detail far surpassing [any] that has ever been evident in any industrial effort up to date.[7]

A newsman sagely suggested that Admiral Rickover might challenge this assertion, as building nuclear submarines was arguably fully as complex and risk-intensive as fabricating spacecraft,[8] but Burke continued in his heroic mode.

Turning to production, Burke asserted that building the Mercury capsules succeeded 'only because we were able to objectively view, openly criticize our own work and take the necessary steps boldly and with courage', claiming that there was 'never any evidence of any deliberate or sloppy workmanship'.[9] Burke was reacting to the reports of deviations from design and the widely-known delays in completing and qualifying capsules. For his part, Dryden dodged a question about whether he was 'satisfied with the level of quality controls' during fabrication. He acknowledged only that the 22-month delay 'between the planned orbital flight and the actual one' was 'the result of new information arising in the development tests'.[10]

Over and again, components when tested did not work or did not work as expected, systems once assembled from components failed to operate, and sets of systems installed in 'finished' capsules interfered with one another. All this demanded reworking, redesigning and retesting. McDonnell's Burke explained that discrepancies between blueprints and actual fabrication were inevitable:

> In doing re-work of any configuration, there are many times, when you are right on the job, you can see a different way of doing it than would have been apparent were you back at a drafting board with nothing but blue prints to look at. The requirements to go ahead and [get it done] would be the cause of the issuance of drawing deviations.
>
> Indeed, if you examine the individual pieces that go into a spacecraft and examine the limited number of such pieces that are ever built, then go back and recognize the problem of developing the tooling itself to produce these parts and the learning on the part of the employees [...], you will find that almost no pieces in Project Mercury had more than a couple hundred, at the outside, duplicates made. Now [...] in an airplane factory, it requires anywhere from sixty to a hundred or more airplanes to go down through the line before you will have coordinated the tools from one area to another.[11]

Nothing like that number of iterations was available in fabricating spacecraft.

In closing though, NASA's Williams stuck to his point about the insufficiency of 'learning' as a concept to describe the pathways through uncertainty and the unknown that aerospace development entailed. When Warren Burkett asked whether what was learned in the Mercury project 'gives you confidence that you can reduce the amount of check-out time on this first Gemini', Williams replied, 'By spreading the knowledge [from Mercury] we will not have the same problems in Gemini or Apollo. [... Yet] there [...] *we will have some problems that we have not been smart enough to anticipate or ask questions about.* The complexity is greater in these missions.'[12]

So what was going on here? Though press coverage missed the larger point, both NASA and McDonnell leaders were talking discreetly about how dreadfully difficult and demanding fabricating a spacecraft proved to be and how thoroughly their initial expectations and principles were undermined by experience. The top spokesmen for each organisation strove to underscore how much had been learned from Mercury by their organisations, their workers and staff. Critically, however, Williams in part demurred – any claims about learning curves, he argued, were more than offset by the rising engineering and performance challenges within Mercury and beyond, by the constant redesigns and frequent reshaping of production practices, and by the recognition that questions beyond the scope of existing knowledge would surely surface during Gemini and Apollo.

Yet this 1963 Project Mercury conference does provide a basis for recognising key interpretative issues that are built into the space capsules as a set of manufactured artefacts:

- The cultural and political demands of a difficult partnership between corporate and government organisations
- The challenges of dealing with recurrent error and failure
- The overriding importance of practical engineering (rather than theory)
- The tangled and bumpy path from design to usable artefact in an environment of uncertainty that features both too much information and too little knowledge
- The multilateral tensions and conflicts (between NASA, McDonnell, the Army, the Air Force and the astronauts, at a minimum[13]) emergent around shifting requirements, contract revisions and engineering changes.

To grapple with these issues and highlight others, we will cycle back to the Mercury project's beginning and make a selective tour of the spacecraft's developmental trajectory.[14] That arc led to the end-of-project conference just reviewed and laid the basis for continued experimentation in the Gemini and Apollo programmes. We may start with an overview of the six elements I regard as central to the spacecraft development and fabrication effort, before examining each in a bit more depth: programme, place, process, problems, responses and results.[15] Programme refers to Mercury's objectives and principles, whereas place indicates the spaces of design, fabrication and testing – the St Louis plant of McDonnell, the prime contractor, subcontracting firms' many, scattered facilities, and NASA's administrative, laboratory, test and launch sites. Process and problems reference the contested dynamics of artefact creation, the arrays of design changes and questions of control, quality, reliability and schedule. Responses include efforts to rethink managerial and project practices, to systematise available knowledge and generate new information, and to build effective institutions and networks for information and negotiation among the parties. Results surfaced at the 1963 closing conference – in sum, building Mercury proved to be a lumpy but successful programme, accomplishing much problem-solving but providing limited legacies for the more complex and ambitious Gemini and Apollo initiatives.

Programme

I begin with the original September 1958 statements concerning the capsule's objectives and principles. Key design propositions, for which the legendary Max Faget was centrally responsible, included the expectation that 'the vehicle' would be ballistic with 'high aerodynamic drag', that it would be 'statically stable over the mach number range', and that it would 'withstand any combination of

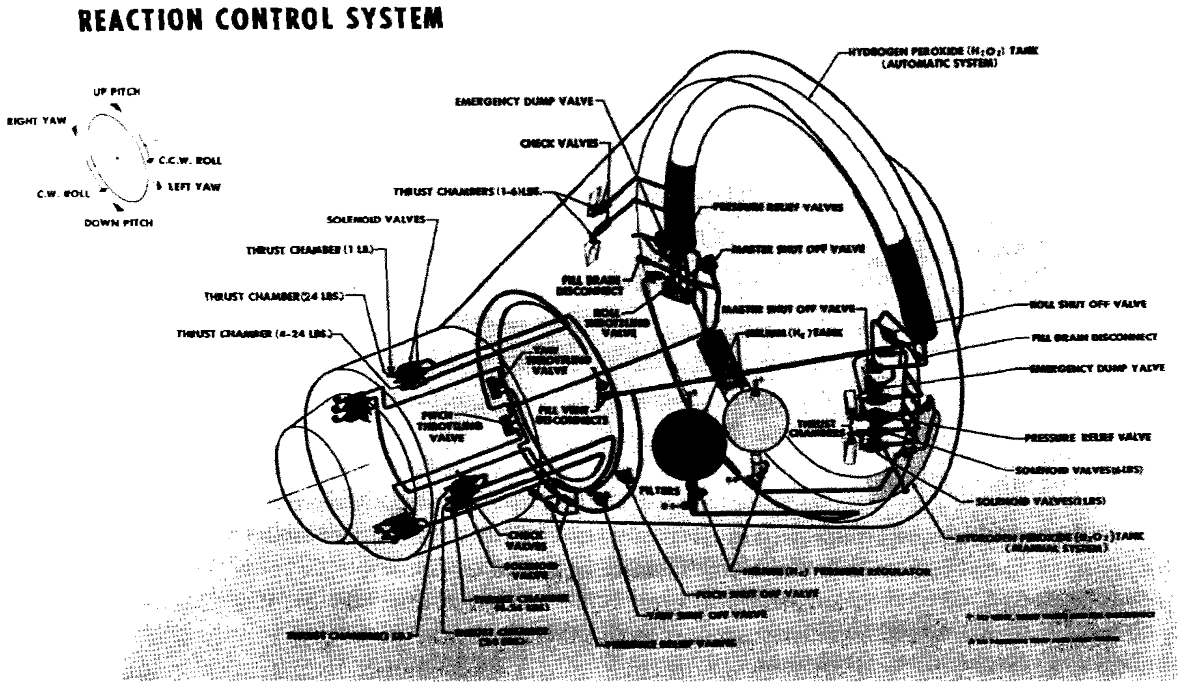

Figure 1 Diagram of the Mercury capsule's Reaction Control System. Source: Box 74, Project Mercury Photographs, Entry No. 70, History Office Source Files, LBJ Space Center, NASA Records RG 255, NARA-Southwest Region (Fort Worth). (NASA)

acceleration, heat loads, and aerodynamic forces that might occur during boost and reentry'.[16] The first item entailed the capsule's stubby cone form, broad at the base and slender towards the top, rather than the sleek needle-nosed aircraft and rocket styling that so enchants museum visitors. (After all, the thing is *ugly* and scarred by re-entry – a culturally-inflected judgment that provides an opportunity for interpretation.) It needed to be stable at all speeds, so that it would not spin, wobble or tumble, putting, for example, the narrow end forward on re-entry, which would guarantee disaster. Both structural shapes and weight-balancing aimed at this concern, with a range of attitude-control devices added to correct deviations from the norm. These were combined into the 'Reaction Control System' and managed yaw, pitch and roll – three dimensions of trouble aloft (Figure 1). The third criterion dealt with the structural challenges that stresses, vibration and heat posed. The dish-shaped heat shield underneath the capsule was the most visible evidence of design elements addressing these problems, but virtually every system, structural and operational, had to engage them, as, for example, vibration could break some of the capsule's thousands of electrical connections or dislocate instruments' calibrations. Three simple, necessary principles – a cascade of implications.

NASA supplemented these basics early in 1959, defining the project's objectives as to achieve orbital flights and recovery and to test man's capabilities in a space environment. Three additional principles appeared: that the project should take the simplest and most reliable approach, involve a minimum of new developments and operate through a progressive build-up of tests, first components, then devices, then systems of devices, then integrated systems.[17] NASA managers regularly referenced this set of principles (using a briefing slide that presented them) for the next four years; indeed, in the closing press conference speakers discussed that slide. Yet though the two objectives were achieved, none of the three principles rested unscarred by the capsule-fabrication experience.

Simplicity went out of the window first, as the paramount requirement for astronaut safety mandated creating redundant systems and backup components within the fixed shell. This generated considerable complexity, with the result that operational capsules were stuffed with technology, scattered about their tiny innards, as the schematic for the Reaction Control System confirms. Moreover, escalation of programme expectations added equipment and weight to each capsule and increased the complexity of, for example, the internal wiring arrangements and the interconnectivity of systems. As Charles Perrow so forcefully reminded us in *Normal Accidents*, increasing complexity generates enhanced capabilities and multiplies opportunities for failure. For example, no single individual can 'know' the entire structure, much less track its permutations, even as the likelihood of component breakdowns compounding to system failures also rises. Expert systems are created to contain the universe of information, to be sure, but they serve as a reference base, not a body of organised knowledge.[18]

As McDonnell's Burke later affirmed, hardly anything that went into the capsules, down to bolts and screws, was standard or stock. Indeed, the second 1959 principle was actually inverted, for Project Mercury provoked not a minimum, but a 'maximum' of new developments. Testing was of course exhaustive, bordering on obsessive. NASA's William Bland and Lewis Fisher noted in August 1963 that 'We have been accused, in the Mercury Program, of testing equipment to death. This may be true to a large degree.'[19] Despite this attention to detail, the 'progressive build-up' proved to be far more uneven and erratic than was hoped. The original plan to build and test components, amass these into each of 14 systems which would be tested independently, then assemble them into an entire capsule that would be tested as a unit, broke down persistently. Some components were just balky or unreliable and a constant frustration (e.g. batteries), whereas some worked fine in stand-alone tests, then failed when slotted into systems (valves were renowned for this). Some systems generated a durably-low confidence level (famously, reaction control and its small thrusters), whereas others failed almost randomly (electronics and instrumentation). The whole-capsule tests, somewhat akin to the 50-hour and 150-hour qualification tests long necessary for new military jet engines, at times turned into horrible experiences, yielding unexpected and inexplicable breakdowns. Thus, although the programme's objectives and the first set of capsule-design principles remained solid and sound, the second cluster of principles, oriented to managing the project's course, repeatedly hit snares set by complexity, production deficiencies and insufficiencies in technical experience and scientific understanding.

Place

Our next step is to visit the spaces where engineers, managers and skilled workers undertook the design and fabrication of capsules and thereby established and tested the internal and external linkages necessary for creation of complicated artefacts. Internal linkages are direct – the material connections and functional relations of a capsule's elements and systems. External relations are, to use Anthony Giddens's term, 'distanciated', that is, stretched across time and space, and here across multiple enterprises and institutions.[20] Components came from scores, eventually hundreds, of subcontractors across America,[21] and when they were deficient, long-distance raving filled the phone and telex wires.[22] Supervision and technical advice came through NASA, not just from Washington and Langley, but from its labs around the nation, from consultants and from independent testing and research institutions (some universities and separate enterprises such as Battelle or Mellon). Thus, fabrication was both centred at St Louis and decentred, in the dual senses that multiple, spatially-scattered agents were essential to building capsules and that elaborate interactions among primes, subcontractors, NASA and external organisations and specialists proved necessary to problem-solving.

Now we'll enter the McDonnell plant, midway through building the capsule series. Here it first is critical to recognise that a major phase in aerospace innovation history began in a workshop occupying a tiny proportion of McDonnell Aircraft Corporation's sprawling facilities alongside the St Louis Airport. Second, both major and minor elements of the capsule went out to subcontractors, which were both major and minor firms. For example, Minneapolis-Honeywell agreed to create the Automatic Stabilization and Control System (ASCS) on a 'very tight schedule', which necessitated a 'high order of liaison [...] through a St. Louis engineering representative [...] through periodic week-long contacts by other M-H system engineering personnel and by periodic visits of appropriate persons.'[23] AiResearch created the environmental control system, Collins Radio the telecommunications, whereas the flashing recovery light, illuminated on splashdown, went to relative newcomer ACR Electronics, and Kollsman, a precision instrument company founded in 1928, snared the altimeter and the cabin pressure indicator contract.

Figure 2 McDonnell's main work area for fabrication of the major components of the Mercury capsules. Source: Box 75, Project Mercury Photographs, Entry No. 70, History Office Source Files, RG 255, NARA-Southwest. (NASA)

Figure 2, one among a set of pictures taken on 14 April 1960, shows McDonnell's main work area for major Mercury components fabrication. At the upper left, behind the curtain wall, we can barely see the fuselages of several jet aircraft, being constructed 'next door' to the capsule workspace. In the spacecraft section, at the right we find three circular bottom plates or pressure bulkheads, with a fourth behind them, lying flat, before insertion in the empty circular work-frame. At the far right are welding machines for the main cone, whereas at the far left a partially-finished cone has had its cylindrical top attached. Very little machinery occupies this space; rather it is organised around desks and worktables, with cabinets for drawings, manuals and small parts running along the vertical centre line. The shop manager's office was at the left, outside this view, with desks for engineers and technicians in the open area nearby. Very much like Kelly Johnson's Skunk Works, Lockheed's famed centre for aircraft design creativity,[24] here the engineers work right down on the shop floor, so that regular interactions between them and the skilled workers were facilitated. What we have here, then, is a traditional metalworking job-shop layout, but notably all but a few of the workers at this moment are consulting files, checking drawings, and the like – not fabricating. That day, the photographer took three views of this shop, in which 24 men appeared, just eight of whom were at work on the artefacts. This place, then, offers a window into early spaceware production as design and paperwork intensive, as connected deeply to the culture and practice of aeronautics manufacturing, and, in this era, as a boundary zone where white- and blue-collar workers intersected and interacted in urgent but frustrating efforts.

Process

Moving away from the assembly floor for a moment allows us to view and consider the overall process of capsule fabrication. The initial plan provided for 12 identical spacecraft, following the simplicity principle. The NASA contract with McDonnell was soon modified to authorise 20 individually-designed capsules in five groups – uninstrumented boilerplates (dummies), instrumented boilerplates, animal-carrying and piloted, first for ballistic then for orbital flights. These differed in detail because some flights needed to be automated (boilerplates and animal, 24 of these in total) whereas the six manned flights needed a wholly different set of controls, redundancies, supply systems, etc. Moreover, engineers and space scientists soon recognised that there were distinctive design challenges for ballistic flights and for orbital ones. These considerations fed back into the fabrication setups, of course. Here, plainly, the Mercury capsule was an unstable artefact in that much the same exterior configuration was employed toward multiple uses.

Though McDonnell was the official fabricator, NASA was ever-present at the St Louis plant; literally through Wilbur Gray, the Agency's resident field representative,[25] occasionally through visiting panels of NASA principals, and through a constant flow of telexes and phone calls. Relations with subcontractors turned critically on quality control, scheduling and documentation, this last being a standard misery. At one point a firm which had completed a $50,000 subcontract calculated the man-hours necessary to generate all the documentation MAC and NASA wanted, and estimated it would cost $114,000 more. At times it took more effort and time to create manuals of practice for devices than just to build and test them.[26]

In terms of the paperwork flow, the lifeblood of Mercury's engineering dynamic was production of Specification Control Drawings (SCDs) for components and systems. These detailed design portraits were supposed to be 'frozen' so that procurement could proceed reliably. But the feedback from testing wrecked this linearity and stability. Failures entailed fixes; fixes had to be configured into the SCDs. Changes ranging from the moving of wires to the substitution of materials all had to be documented, but as remarks at the 1963 conference indicated, reporting and entering shop-floor alterations

Figure 3 Electrical motherboard for wiring assembly. Source: Box 75, Project Mercury Photographs, Entry No. 70, History Office Source Files, RG 255, NARA-Southwest. (NASA)

was not reliably carried out. Moreover, this flux interacted with the individualised capsules in a centrifugal fashion, as both the numbers of drawings and the volume of changes to drawings escalated, with the changes being relevant to one, some or all spacecraft, whether planned, in progress or finished.

Once the cones were welded and their structures completed, workers levered them onto wheeled carts and rolled them to one of a series of 'clean rooms' built inside the St Louis aircraft plant. With fluorescent overhead panels, flat-surfaced partitions, no windows and workers in white jumpsuits and hats rather than street clothes, the clean room was a place substantially different from the open shop, a place for more delicate and intricate processes. There, technicians completed electrical wiring work at a number of stations, with components then installed in the capsule frames and bottom panels before the latter were linked to pressure bulkheads and the all-important heat-shield dish. At the electrical stations, mock-ups replicated the elaborate spaghetti system of capsule wiring flattened onto a panel (Figure 3). Hold this image in your mind, then consider what troubles would be caused by implementing scores of electrical design and component changes.

Other photos from 14 April show the insertion of electrical, communications, environmental and instrumentation apparatus into partially-assembled capsules. Many of the outside plates had been installed, but most had not. Thinking about this for a moment suggests how staggeringly complex the fabrication process was, for each external plate could only be bolted on when everything underneath its particular space had been installed. When design or parts changes occurred, gaining access to concealed components was miserably time-consuming, for elements of the 14 systems were distributed throughout the capsule and multiple outside plates had to be removed in order that replacement parts could be substituted.[27] Clearly, in constructing one of the space age's iconic, hi-tech-for-its-time artefacts, McDonnell employed urgent and problematic system design and relatively low-tech, job-shop fabrication practices, to which it appended an early version of a clean room.

Problems

As noted earlier, material deficiencies caused persistent problems in building Mercury capsules; these aggravated organisational inadequacies traceable to the project's complexity and the interacting firms' and agencies' differently-framed competencies and interests. One index of material problems with capsule fabrication is the flow of requests for rework by subcontractors, another is the flood of Engineering Change Requests for individual parts substitution or redesign (which reached into the thousands by 1962). A third is the accumulation of the more substantial Contract Change Proposals (CCPs), the mechanism through which project costs rose from an initial $15 million to roughly ten times that sum over five years. By January 1960, after just 13 months of effort, either McDonnell or NASA had filed 125 CCPs; in November 1961, at the close of Mercury's third year, that total reached 360.[28] In consequence, Mercury's draftsmen worked overtime creating, checking, releasing, revising and re-releasing thousands of engineering drawings (Figure 4). This chart, issued in late March 1960, shows the dramatic effect that engineering changes had on design drawings. Six months into the project, planners had expected that about 500 drawings would be needed to detail the Basic Capsule Configuration (Point A). Actually, 700 drawings had been needed, but with changes included, the Basic Configuration demanded 1600 drawings (the September 1959 point on Line D, labelled 'Total Releases including Changes'). By March 1960, the base drawings for the 20 capsules in their varied configurations reached 1100, but engineering changes swelled the total drawings released to 5000.[29] Little wonder that McDonnell reported that it often ran its Mercury facilities on three shifts, 24 hours a day.

Testing, of course, was a key initiator of artefact instability; it operated in four domains: components, systems, development and whole-capsule operations. Testing to failure presumed to establish the life expectancy of components, but as so many of these had been

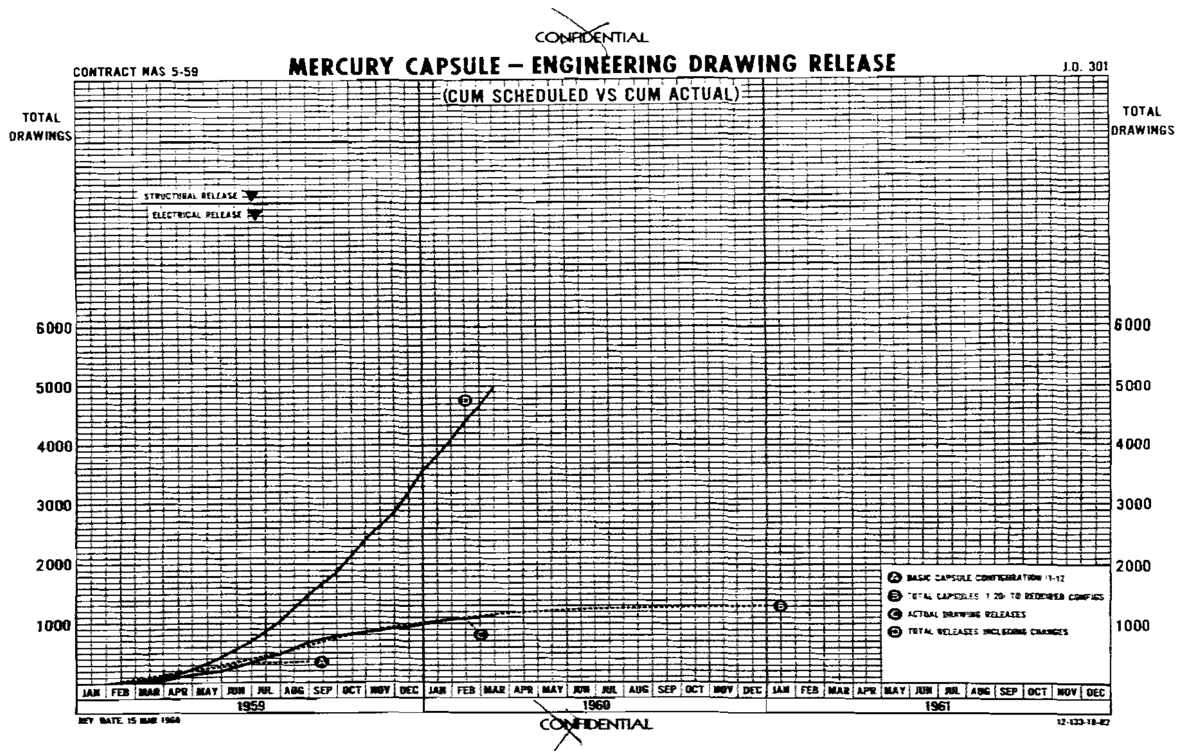

Figure 4 Engineering drawing release for the Mercury capsule, March 1960. Source: Box 22, Entry 100; Contract Administration Files: Procurement Division, RG 255, NARA-Southwest. (NASA)

ordered and produced in batches and often redesigned, the small-numbers problem made it statistically unreal to expect such testing could assure reliability. Component acceptance tests aimed to certify that items provided by subcontractors worked as planned, but often they did not. Systems tests were more aggravating, as at times the causes of deficiencies proved elusive and alternative hypotheses difficult to test in mock-up systems or impossible to trace in failed, installed systems. As testing gurus Bland and Fisher explained, producers could trigger surprise problems either when skimping or when improving:

> We have seen occasions where components, after having been completely qualified through the rigorous Mercury-qualification program, would exhibit a history of failures. These failures would occur when production units were subjected to acceptance tests or other routine testing. The subsequent investigation revealed that the vendor had hand-built the prototype units [used for qualification] to the highest standards of quality control. When production began, however, the units were made by different people, by different methods, and to relaxed quality control standards. Sometimes parts were rearranged as an expedient in production to cut costs.
>
> A second aspect of this problem is when the vendor decides to make small 'product improvement' design changes. No matter how seemingly innocuous and straight-forward, small changes [...] can completely

> invalidate the qualification of the unit. The side-effects of such changes – that is, the[ir] effects [...] on the operations of the system as a whole – cannot always be anticipated [...]. Such things have led us to a philosophy which says, in effect, that where components and systems are operating satisfactorily, leave them alone and don't try to improve them. Don't change things just for improvement's sake.[30]

Operating away from the assembly shops, development testing had a distinctive role: it was the foundation for 'engineering studies', research designed to increase MAC/NASA's knowledge base regarding new materials and techniques put forward for possible use in capsules and their fabrication. Examples from 1959 concerned exploring beryllium's properties at elevated temperatures; it was being considered for the heat shield, but was dumped in favour of an ablation technology. Ablation here refers to the shield's capacity to shed tiny fragments of burnt heat-absorbing material on re-entry without cracking or losing overall integrity. Materials such as graphite, PTFE and some ceramics could have this property, but they, and ablation more generally, were poorly understood scientifically, so testing of the heavy (600 lb, 270 kg) metallic shield went forward in parallel with attempts to fashion a lighter, fibreglass-based alternative shield.[31] Here, problem-solving looked more like R&D laboratory work, unlike the majority of component and system fixes undertaken.

The summit of factory testing was the Capsule System Test (CST), which evaluated the integration and proper functioning of all 14 spacecraft systems. For the first two capsules, these efforts demanded two months' work apiece, with many fixes triggering delays in mating capsules with boosters and in organising launches and recovery teams. Once boilerplate capsules had been sent aloft (the final test before launching primates and people), NASA and McDonnell engineers discovered that, despite all efforts at careful assembly and cleaning, a variety of 'space junk' emerged from crannies in the artefact under zero gravity, floated about for a while, then deposited itself all round the capsule interior. Consisting chiefly of metal and plastic shavings and tiny parts, this was very dangerous material, for it could potentially interfere with electrical links, slip into places to jam levers, or, as did happen, clog a fan inlet, producing a failure. Thus the Project devised an additional testing procedure, capsule tumbling, in which a 'finished' spacecraft was bolted into a frame, then spun and rolled so as to loosen this detritus. The yield from tumbling Capsule No. 13 in December 1961 appears in Figure 5, and includes washers, nuts, wire, plastic sheaths, insulation and, at the centre, what seems to be about a ¾-inch hex-head bolt.[32] So many things could go wrong, and some unknown number of them, like the floating space junk, could be discovered, as Dryden explained at the end-of-project conference, only by going into space.

Figure 5 Yield of loose materials from tumbling Capsule No. 13 in December 1961. Source: Box 76, MSC Capsule No. 13 Photos, Entry No. 70, History Office Source Files, Folder 1, RG 255, NARA-Southwest. (NASA)

A briefing chart created in March 1960 attempted to anatomise the flood of engineering changes, the information flows and paperwork which threatened to derange project personnel, if not derail the project as a whole. Only 20 per cent derived from 'improvements and requirements changes' – for example, upgrading valves and the Reaction Control System and installing the astronauts' window. The remaining 80 per cent of the capsule redesigns came from development work – testing, manufacturing and special engineering studies. Because of 'concurrency', simultaneity in design, fabrication, testing, research, *et al.*, most of the project was in a development phase at all times. Both the chimpanzee and human flights, after all, were tests. In the manufacturing bloc (25 per cent of all changes) necessary rework could be traced to vendors not meeting specifications, to shortages in materials (forcing substitutions), to production and tooling problems (some parts could not be made as planned and had to be rethought) and to physical interferences among components once assembled.

Engineering research (10 per cent) generated redesigns chiefly in structures, instrumentation, materials and electronics. However, testing forced nearly half of all changes (45 per cent), a tribute to the rigour of Bland and Fisher's colleagues and source of many conflicts with MAC management, engineering and subcontractors.[33] Not

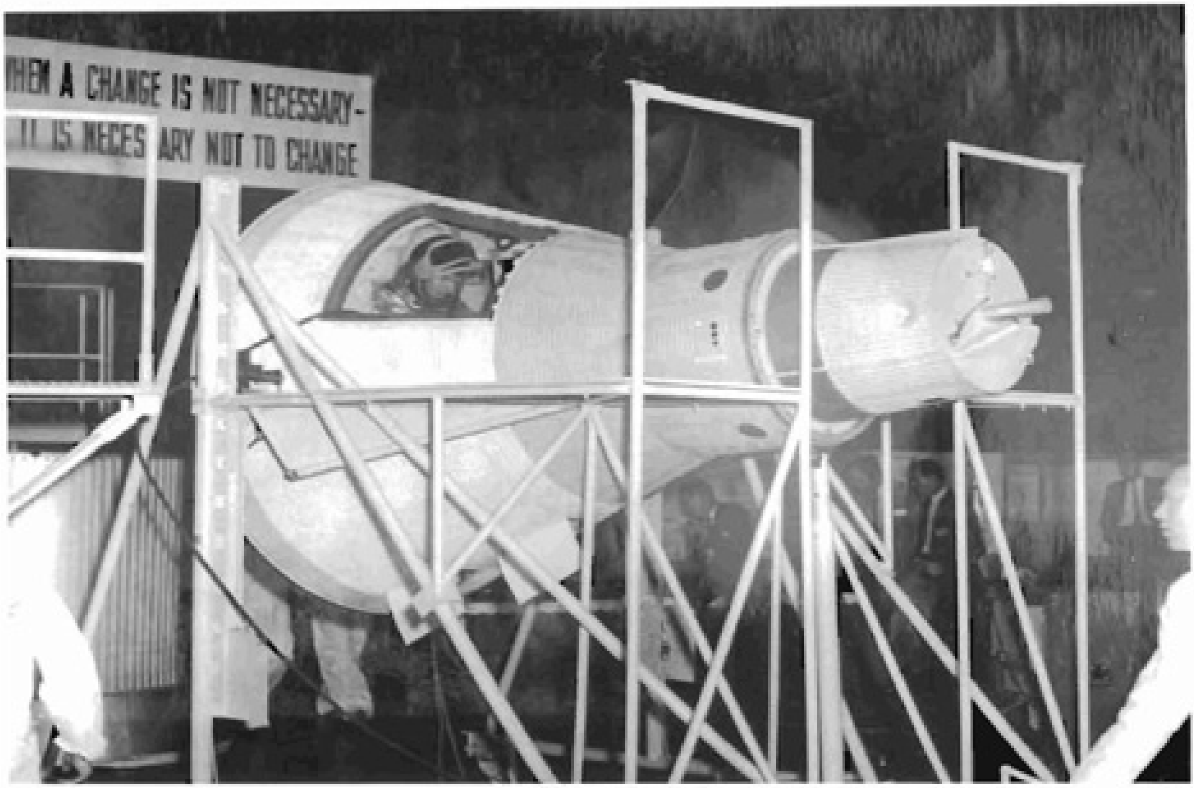

Figure 6 Mock-up Mercury capsule with sign. Source: Box 74, Project Mercury Photographs, Entry No. 70, History Office Source Files, RG 255, NARA-Southwest. (NASA)

surprisingly, placards appeared in the McDonnell plant urging that changes be kept to a minimum, undertaken only when 'necessary', as Figure 6 indicates. Yet the definition of what was necessary was hardly obvious, often contested and rarely settled among the contending partners struggling to fabricate a spacecraft that was workable, safe and reliable.

Two major testing failures indicated how fragile the capsule as artefact actually was. On 29 July 1960, test flight MA-1 boosted Mercury Capsule No. 4 toward an instrumentation run, the first occasion on which a spacecraft was mated with an Atlas rocket. Testing and rework had consumed over two months following the capsule's delivery to Cape Canaveral in late May. Bad weather caused a series of holds on launch day, but a little after 09.00 the Atlas blasted off into the heavy cloud cover. A minute later all contact with the rocket's instrumentation was lost; the missile 'either exploded or suffered a catastrophic structural failure' about 6 miles above the Earth. Ironically, the capsule's telemetry continued to broadcast until the whole apparatus slammed into the Atlantic, 7 miles offshore. As the water there was but 40 feet deep, recovery efforts gathered many portions of the shattered capsule, which were 'painstakingly reassembled' for an engineering analysis, a process that stalled the programme for six months (Figures 7 and 8). In a double irony,

Figure 7 Capsule No. 4 wreckage on the floor. Source: Box 72, Project Mercury Photographs, Entry No. 70, History Office Source Files, RG 255, NARA-Southwest. (NASA)

this comprehensive failure occurred on the very day that NASA announced its plans to follow Mercury with a more ambitious programme called Apollo.

Throughout 1960, a series of panels attempted to establish the reasons behind the crash, but as these remained obscure, efforts soon focused on improving the interface between the spacecraft and the booster. Then in September another Atlas on a non-Mercury mission 'failed severely. This forced a wholesale review of the Atlas as a launch vehicle. Everybody responsible for MA-1 was trying to determine the cause of that failure, but each only discovered that there were too many other bodies, both organic and organizational, partly responsible.' Questioned about this indeterminacy at a late-October press conference, NASA administrator Robert Gilruth responded: 'We have answered all the questions we have asked ourselves – but have we asked the right questions? We can't be sure.'[34] As before, though engineering and science were crucial to the project, insufficiencies in reliable knowledge and a surplus of uncertainties meant that just knowing you were asking the right questions presented huge challenges. A month later, a Mercury–Redstone flight package took the legendary 'four-inch flight', when the rocket engine shut down just after liftoff at the Cape. The booster–spacecraft combo settled back onto the launch pad, and though it neither fell over nor

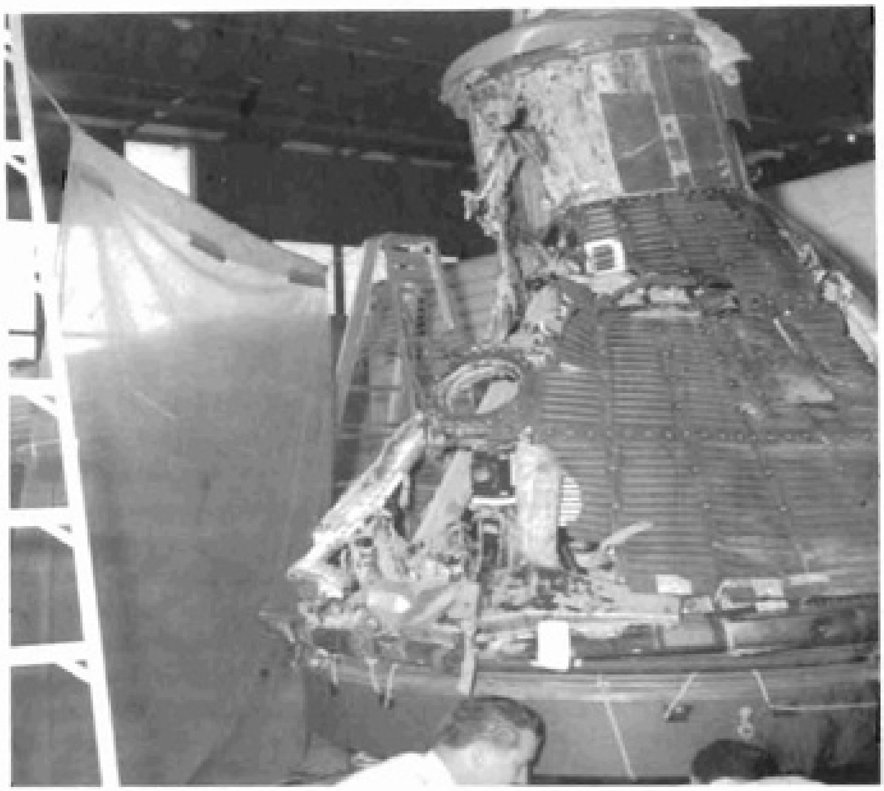

Figure 8 Reassembled Capsule No. 4 wreckage. Source: Box 72, Project Mercury Photographs, Entry No. 70, History Office Source Files, RG 255, NARA-Southwest. (NASA)

exploded, 'November 21, 1960 marked the absolute nadir of morale among all the men at work on Project Mercury.'[35]

Still, not six months later, Alan Shepard rode Freedom 7 (on a Redstone) skyward, marking the US's first piloted space flight. Another ten flights in 1961 were wholly or largely successful, including the second human-carrying launch, with Gus Grissom. Yet just as John Glenn was finishing training for the first orbital flight (February 1962), on 9 January Capsule No. 2 burst into flames during a McDonnell test procedure. This capsule had flown on an unmanned Redstone mission, was recovered at sea and returned to St Louis, where after cleaning and equipment updating it became 'a Reaction Control System [RCS] Development Test Bed'. It had been subjected to a 12-hour orbital test simulation on 6 January, during which the RCS's 'one pound roll clockwise assembly failed to fire after 8 hours and 52 minutes'. That device was replaced, but three days later the same assembly caught fire after a 13½-hour test sequence, due to a 'small propellant leak'. Technicians extinguished the fire within a few minutes, but damage to the capsule's underside bulkhead was considerable; in space such a fire, fuelled by the hydrogen-peroxide propellant, could have been disastrous.[36]

If you look back to the schematic of the Reaction Control System (Figure 1), you will notice the two curved, sausage-like elements at

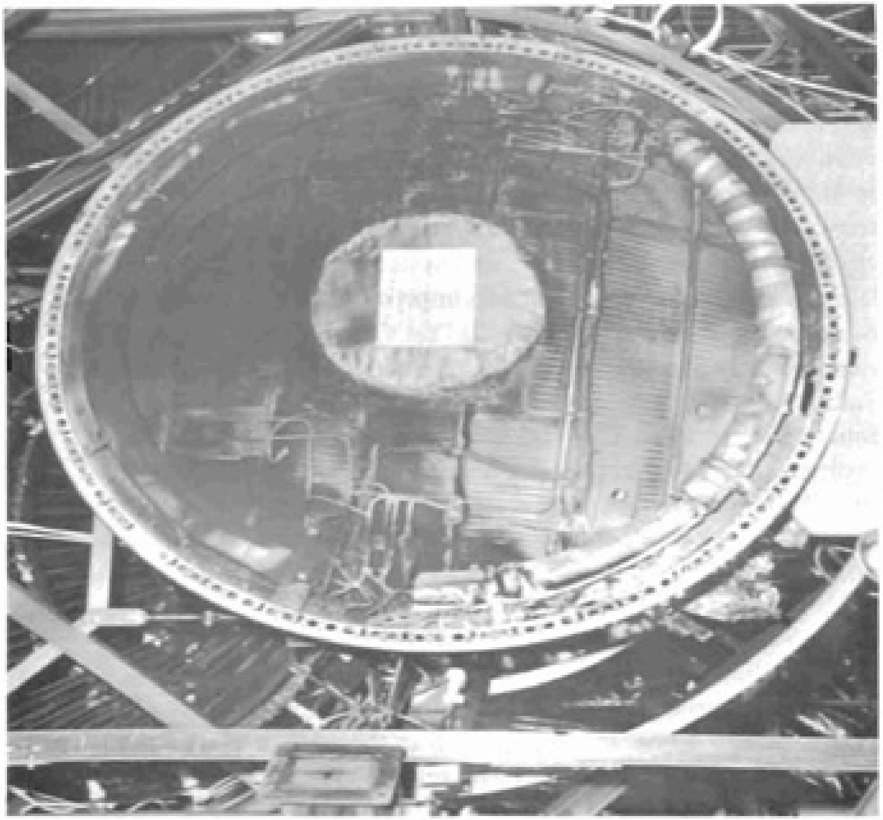

Figure 9 Fire-damaged large pressure bulkhead, January 1962. Source: Box 27, McDonnell Technical Documents (Mercury Project Office), Entry No. 198C, McDonnell Technical Reports, Report No. 8626, 'Investigation of the Capsule No. 2 incident'. (NASA)

the right, forming a circle along the capsule bottom. In Figure 9 one of these has almost disappeared, flattened by fuel loss and blackened by the fire. Ever thorough, McDonnell included scores of diagnostic photographs in its 89-page report on the 'incident', issued on 16 January. But two broad messages were implicit: replacing components could involve errors that could generate component failures and accidents, and, in spacecraft, fires could destroy missions and mission personnel. A few weeks later, John Glenn reported RCS failures during his orbital mission in Friendship 7, the capsule that sits so serenely on the NASM's ground floor. This forced him to take manual charge of attitude control (an RCS right-yaw thruster didn't work), using other system elements to dampen cycling oscillation. Those efforts completely depleted the spacecraft's RCS fuels, but there was no fire, just a good deal of stress.[37] In Mercury, as everything was an experiment, testing and redesign carried no performance guarantees.

Responses

Given the variety of problems that capsule construction spawned, responses at NASA and McDonnell were diverse as well. Yet managerial or engineering attempts to respond rationally to a non-rational environment (persistent uncertainties, repeated deficiencies and failures, insufficiencies of reliable knowledge, along with political pressure for performance/success) can border on the comic. On the engineering side, we must take seriously the tension between Bland and Fisher's leave-well-enough-alone 'philosophy' and Wilbur Gray's relentless pursuit of the perfect testing procedure, a tension internal to NASA, but evident throughout the programme. Remember, the test-it-to-death pair eventually reached a 'philosophy which says, in effect, that where components and systems are operating satisfactorily, leave them alone and don't try to improve them. Don't change things just for improvement's sake.' Yet Gray resolutely and a bit remorselessly oversaw and chronicled every conceivable discrepancy and malfunction, as if intensified fixes would yield a stabilised, well-functioning artefact. This did not happen. Instead, on one hand, project conflicts continued – a May 1960 report carefully noted that 'NASA–MAC relations were strained in many instances while attempting to resolve differences of opinion as well as technical differences'.[38] On the other hand, having no time for perfection, NASA moved on to building Gemini and Apollo capsules, working on the two concurrently, and, in a sense, hoped for the best.

Nonetheless, the project had to be managed somehow, and this was undertaken through a host of organisational units, a series of special initiatives and a blizzard of paper, all in the service of communication and integration of NASA and McDonnell approaches. For the spacecraft, the crucial managerial unit was the Capsule Coordination Group (CCG), a joint committee through which flowed everything from Contract Change Proposals to concerns over securing licence plates for 'the trailers to be used at the various launching sites'.[39] Its members each took responsibility for oversight of one section of the capsule project – for example, structures, controls or telemetry. Four subgroups rapidly emerged and recurrent all-hands meetings at McDonnell's plant served to tackle the flow of changes and controversies. By September 1960, the CCG had morphed into the Project Control Board, with mechanical, electrical and operational subunits, attempting to limit the changes in the capsule configuration and thereby speed launch readiness.

In parallel both NASA and McDonnell produced a mass of internal publications. McDonnell began issuing 'Mercury Newsletters', and NASA circulated capsule activity reports, project status reports, CST daily outcome statements, with collaboration on Service Engineering Department Reports (SEDRs), which became the operating manuals for capsule systems. SEDRs also contained specifications and protocols, but had to be regularly revised, given the rush of changes. In managerial terms, as problems multiplied McDonnell established a 'reliability section' at St Louis, while NASA undertook to create its own quality-control procedures, borrowing practice from the Department of Defense and from the private sector. Still, troubles continued, yielding summits and emergency conferences, ventures into implementing statistical methods from operations research, and introduction of the Development Engineering Inspection. From this distance, collectively these efforts appear to have been fevered attempts to throw all available management techniques at the project, though none of them had been designed for an environment where the necessity for constant 'product' redesign defeated any attempt to prioritise efficiency, standardisation, scheduling or cost management.

Nothing worked well, or well enough, and, apparently exasperated, on 8 January 1962 NASA announced the mandatory application of PERT (Program Evaluation and Review Technique) to McDonnell's operations.[40] Designed to identify the most 'critical paths' in an ongoing project, provide those handling them with immediate resources, and calculate repeatedly each segment's position ahead of or behind schedule, PERT had originated in connection with the Polaris missile programme for Admiral Rickover's nuclear submarines, being the product of a 1956–57 collaboration between the Navy, Lockheed and consultants Booz, Allen & Hamilton. Perhaps more effective as ideology than practice, the approach spread like wildfire by the early 1960s, although there is 'considerable evidence that the method was oversold [by the military], with the aim of keeping Congressional and other critics at arms length'.[41]

In 1962, two months after NASA forced PERT on McDonnell, an industry observer announced that some 52 management techniques derived from Department of Defense attention to 'long range planning and management efficiency' now crowded the field, many of them PERT variants.[42] At NASA/McDonnell, implementation went hand in hand with adaptation, as planners began to build in schedule time for surprises – perhaps not quite what the methods' originators had envisioned. A November 1962 PERT Analysis reported that: 'The most critical path for [the] MA-9 flight [Gordon Cooper, the last Mercury launch in May 1963] is the preparation of the spacecraft.' Managers had created a testing plan 'with approximately 18 working days allowed for making changes which are not scheduled (or possibly not known) at this time'.[43] There may have been a learning curve after all in Project Mercury's responses to problems, but its trajectory involved learning to schedule time for the unknown instead of asserting management control over time and technology.

Conclusion

Having undertaken to contextualise Project Mercury's spacecraft along lines of *programme*, *place*, *process*, *problems* and *responses*, and recognising that the *result* of the joint NASA/McDonnell effort was an anxious, messy success story, we now return to the artefactual interpretation questions with which this discussion opened. How can this artefact's 'details of creation and use' speak to issues: first, in the wider American culture of the era, second, in understanding the significance of technology and science to that culture, and third, relevant to 'technical and cultural change'? On other fronts, what can the Mercury spacecraft evoke concerning big technology projects and their management, the dynamic amalgamation of individuals and teams within projects and the instability of complex technological artefacts?

Starting with American culture broadly, appreciating the capsules' fabrication resonates with the national fascination with technology, with puzzles and problem-solving, with overcoming natural obstacles in order to plant the machine in the garden, or in this case way, way above the garden. Building and using these artefacts also speaks to our national impatience – get it done, now! – a certain contradictory stubbornness, and our reliance on and discomfort with expertise. With no authority, shop workers made fixes and redesigns on the spot, repairing some problems and initiating others, while sending Wilbur Gray into paroxysms of outrage. NASA and McDonnell fought over opinions, technology and money – each certain of its own rectitude, each blaming the other for slowing down the work. The capsules must be helped to voice these interpretations, to be sure, but delving into the documents behind the icon can make this a straightforward matter.

On the significance of technology and science and on technical and cultural change, the spacecraft have much to teach museum curators and visitors. The entire project, with the capsules literally on top, was a distanciated, disaggregated, experimental engineering works, with technologies, materials, processes and designs both scattered spatially and in flux empirically, even as Capsule No. 20 was being readied for the final Mercury launch. Science did not inform Mercury's efforts in any linear application way; instead, because science was so incomplete on matters extraterrestrial (zero gravity, near-absolute-zero temperatures, for example), elaborate engineering simulations and a great deal of estimation had to suffice. Certainly, there was technical change in Mercury, even across just its five active years, but a great deal of this change fell into the 'doesn't work, try something else' Edisonian category. Putting a series of capsule interiors side by side would, at a minimum, show the technical change from the boilerplate to the animal to the piloted ballistic and piloted orbital designs.

Moreover, as Williams noted at the closing conference, in effect once a technical competence was achieved, another sort of change arrived as NASA or McDonnell raised the stakes – 'Nice work, now let's put two guys in a spacecraft; good job, let's try for the Moon.'[44] Thus, in Project Mercury, technical change was both *urgent* and *temporary*, and this process of relentlessly displacing achievements surely reinforced a cultural change in engineering that perhaps began with Second World War emergency projects: 'slow and steady loses every time to fast and intense, to upping the ante and raising the stakes'. In the first generation,[45] NASA projects, like earlier efforts to build 50,000 aircraft or struggling to master jet propulsion, were exciting, frustrating, high-pressure experiences, followed by much more routine times or by unemployment and career shifting. 'The best years of our lives' is a phrase of great meaning here, for subsequent projects could rarely match the glow from Mercury, Gemini and Apollo.

Perhaps putting the capsule builders into the same vital, anxious, even terrifying, spaces the astronauts inhabited could help integrate the artefact's interpretative messages. Even as pilots, engineers and managers projected a calm competence, a professional demeanour, one contradiction could hardly be avoided, for those inside the projects knew that terrific risks were being run in the face of a great many complexities and a host of unknowns. Likewise, the instability of the artefact itself – its endless changes, its components' irritating unreliability, its sudden fragility and vulnerability (see Figures 7–9) – also contradicts its iconic solidity on the exhibition-hall floor. These are both productive, instructive contradictions, which imaginative curators can translate for publics through research and through revoicing the icon.

Notes and references

1 http://encyclopedia.lockergnome.com/s/b/Project_Mercury, Table 1

2 Oddly enough, these reactions are mirrored in the on-line Wikipedia entry for the Mercury capsules, which opens: 'Mercury spacecraft (also called a *capsule* or *space capsule*) were very small one-man vehicles; it was said that the Mercury spacecraft were not ridden, they were worn. Only 1.7 cubic meters in volume, the Mercury capsule was barely big enough to include its pilot. Inside were 120 controls: 55 electrical switches, 30 fuses and 35 mechanical levers.' See the Wikipedia Project Mercury Webpage at http://encyclopedia.lockergnome.com/s/b/Project_Mercury.

3 Swenson, L, Grimwood, J and Alexander, C, *This New Ocean: A History of Project Mercury*, reprint edn (Washington DC: NASA History Office, 1998), p507

4 Dryden, H, transcript remarks, 'Project Mercury Summary Conference', pp1–2, RG255 NASA-JSC Records, Entry 196: Subject Files, Box 1, File: Mercury Final Conference, September–October 1963 (emphasis added)

5 Williams, W, transcript remarks, note 4, p5

6 Williams, W, 'Project review', RG 255, NASA-JSC, Entry 196, Subject Files, 'Mercury Final Conference, September–October 1963', p1

7 Burke, W, transcript remarks, note 4, p6

8 For a contemporary perspective on this issue, see Sheets, H E, 'The engineering of submarines', *Mechanical Engineering*, 84 (January 1962), pp37–42. Sheets was Chief Research and Development Engineer at Electric Boat in Groton, CT, which built a number of Rickover's nuclear submarines.

9 Burke, W, transcript remarks, note 4, pp7, 8. This odd phrasing, 'deliberate or sloppy', may be a transcription error, as Burke may have said 'deliberately sloppy'.

10 Dryden, H, transcript remarks, note 4, p11

11 Burke, W, transcript remarks, note 4, p15

12 Williams, W, transcript remarks, note 4, p16

13 The Army and Air Force provided launch vehicles and communications/tracking technologies and expertise, which was not often a smooth process. The astronauts were

powerful, roving critics of capsule design, most famously in demanding a window be added. Mercury-programme documents in the National Archives also suggest that US intelligence services had some interest and involvement.

14 Other elements of the larger project impossible to review here include the rockets upon which the capsules were mounted (Redstone, Atlas), transportation/launch facilities and practices, communications and tracking stations and their technologies, capsule recovery and astronaut training.

15 Again, other elements were also critical, though perhaps not so directly related to the spacecraft as artefact, including politics, finances, contracting practices, publicity and media relations.

16 Swenson, L, Grimwood, J and Alexander, C, note 3, p111

17 Swenson, L, Grimwood, J and Alexander, C, note 3, p134

18 Perrow, C, *Normal Accidents*, rev edn (Princeton, NJ: Princeton University Press, 1999)

19 Bland, W and Fisher, L, 'Reliability through attention to detail', Lecture No. 39, Seminar on Engineering Design and Operation of Manned Spacecraft, 9 August 1963, pp9–10, RG 255, NASA-JSC, Entry 196, Box 1, 'Conferences and Symposiums (General)', 1963

20 Giddens, A, *The Consequences of Modernity* (Stanford, CA: Stanford University Press, 1991)

21 Arguably, political exchanges through Congress reinforced this spatial scattering, but researching this plausible assumption is beyond the scope of the present work.

22 Classically, subcontractors would essentially hand build prototypes to secure contract approvals, then would produce components on standard machinery to save time and money. Once delivered, these items regularly failed to meet specifications or proved disappointing in use, triggering sharp exchanges and a great deal of rework (for which NASA was reluctant to compensate McDonnell as the prime contractor responsible for managing capsule subcontracts).

23 'Engineering status report, 12 January 1959 to 1 April 1959', p11, RG255, NASA, JSC, Entry 198C, McDonnell Technical Reports, Box 6A, Engineering Status Reports

24 Rick, B R, and Janos, L, *Skunk Works* (Boston, MA: Little, Brown, 1994)

25 Most of Gray's daily reports can be found at RG255 NASA-JSC, Entry 198E, Contract Administration Files, Box 12, NASA Representative Files (organised by date, e.g. April–May 1960).

26 RG 255, History Archive – Mercury Series, Chronological Files, Box 49, File 1, Project Mercury, Space Task Group, 'Report of Capsule Coordination Committee', 1 August 1959, p5

27 One of the positive legacies of the Mercury capsules for the Gemini programme was that these systems were modularised such that removing access panels would allow technicians to work on most or all of their components in one location within the capsule. See Hacker, B and Grimwood, J, *On the Shoulders of Titans: A History of Project Gemini*, NASA Special Publication 4203 (Washington DC: NASA, 1977), pp33–4.

28 RG255, Entry 100, Contract Administration Files, Box 20, Contract Change Proposals Status Reports. Not all McDonnell CCPs were accepted at NASA headquarters, though.

29 *Ibid.*, Box 20, CCP Status Reports, 1960

30 Bland, W and Fisher, L, note 19, pp10–11

31 Empiricism and urgency, not a deepened scientific understanding, led to the selection of the ablation shield after *one* successful flight test (Big Joe, 9 September 1959), which showed two-thirds of the fibreglass shield intact after a very steep, hot re-entry. Swenson, L, Grimwood, J and Alexander, C, note 3, pp127–8, 200–7. Other development tests in the project's first full year involved testing the foamed plastic materials for the pilots' body-moulded couches and doing fabrication studies on very tough titanium sheets.

32 RG 255, Entry 70, Source Files, Box 76, MSC Capsule 13 Photos, Folder 1, 'Trash removal from Capsule 13 – 12/22/61'

33 RG255, Entry 100, Contract Administration Files, Box 20, CCP Status Reports. At one point in 1961, so many engineering changes had been processed which NASA

detailed as McDonnell's fault (and thus not fundable) that McDonnell seems to have threatened to cease work unless its bills submitted for this work were paid. This was one flashpoint in the ongoing tensions between McDonnell and NASA, with the former claiming the latter was too critical and fussy and NASA regarding McDonnell as sloppy and contractors as slipshod. (For the 1961 conflict, see RG255, Entry 100, Contract Administration Files, Box 4B, General Correspondence, SA56 Supplementary Agreements.)

34 This discussion drawn from Swenson, L, Grimwood, J and Alexander, C, note 3, pp275–9, quotes from p279.

35 Swenson, L, Grimwood, J and Alexander, C, note 3, pp293–4

36 For details see the full report, RG255, NASA-JSC, Entry 198C, MAC Technical Reports, Box 27, Lilienkamp, R H, 'Investigation of the Capsule No. 2 incident, 9 January 1962', Report No. 8626. NASA's Wilbur Gray, resident representative at the McDonnell plant was far more acid, however. His report on Capsule No. 2's 'Initial Reaction Control System Checks', held on 4 April 1960, 21 months before the fire, reads, in part, as follows: 'During this first day [...] it became apparent that: 1.1 Work was poorly organized. 1.2 No "dry run" or other preparations had been made by the [test] crew prior to receipt of the capsule [...]. 1.4 There were too many people in the capsule test area to permit compatibility with safety restrictions or systematic step-by-step procedure of the test [...]. 2.1 *Almost every joint in the system leaked*, indicating improper installation procedure. 2.2 Plumbing lines were found to be improperly installed and were re-shaped more or less on the spot, without, in our opinion, adequate inspection supervision.' Gray, W, 'Memorandum for Mr. J.A. Chamberlain', 8 April 1960, RG255, Entry 198E, Contract Administration Files, Box 12, NASA Representative, April–May 1960 (emphasis added).

37 Swenson tells this story well (Swenson, L, Grimwood, J and Alexander, C, note 3, pp428–32), but the underlying transcript of Glenn's debriefing is riveting (see RG255, Entry 198E, Contract Administration Files, Box 31, File 'MA-6 Pilot's Debriefing'). The RCS presented persistent problems; a thorough review can be found in Greil, K, 'History of the Reaction Control System', 1963, RG255, NASA-JSC, Entry 70, Source Files, Box 7, Mercury Technical History Project.

38 Bland, W and Fisher, L, note 19, p11; Kleinknecht, K S, to Gray, 5 May 1960, RG255, Entry 198E, Box 12, File 'April–May 1960' (Kleinknecht was Mercury Program Manager)

39 For the licence plates see 'Report of Capsule Coordination Group meeting', 4 August 1959, p3, RG255, Entry 70, Source Files, Boxes 49–50, Capsule Coordinating Committee Records, 19 May 1959 – 3 April 1963.

40 Purser, P, NASA, to Burke, W, McDonnell, 8 January 1962, and Burke's reply on 12 January, RG255, Entry 100, Contract Administration Files, Box 12, PERT Reports, File 'PERT'. For more on PERT, see Steiner, G and Ryan, W, *Industrial Project Management* (New York: Macmillan, 1968) and Morris, P, *The Management of Projects* (London: Thomas Telford, 1997).

41 Morris, P, note 40, pp27–31, quote from p31

42 Geddes, P, 'The year of management systems', *Aerospace Management* (March 1962), pp89–91

43 'Manned one-day mission (Mercury spacecraft)', PERT Analysis, 16 November 1962, RG 255, Entry 100, Box 12, File 'Remainder of PERT Reports'

44 As Bart Hacker describes it, Gemini started as a collusive extension of Mercury with both NASA and McDonnell personnel scheming to do bigger things before top leadership had either funding or plans. Hacker, B and Grimwood, J, note 27, Chap. 2.

45 A term used to frame the years from Mercury's beginning to Apollo's triumph, which I first encountered in Howard McCurdy's work on NASA engineering cultures.