Idiot-Proofing the Air Force

Human Factors Engineering and the Crisis of Systems Maintenance

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Abstract

This paper explores the research and engineering of "human factors" in the maintenance of complex aerospace systems, which intended to identify, taxonomize, and mitigate the physical and cognitive limits of the idealized maintenance worker. Predominantly, these initiatives sought to anticipate sources of error and impose "maintainability" through design elements such as color-coding, standardized connectors and fasteners, and sealed, replaceable components. Though simple and even traditional in principle, space-age human factors engineering distinguished itself with a relentless devotion to *system*, which, in this context, meant designing up-front and managing top-down. Nevertheless, some researchers eventually began to acknowledge that this "objective" approach, which reduced the human body to an engineering constraint, could anticipate only the simplest problems. In many cases, they noted, the maintainers actually had to work around the errors of the engineers.

Bombers B-52 is a terrible movie, but it is still the best film ever made about a grumpy, middle-aged Air Force mechanic with an antipathy for a hotshot pilot and foppish officer-playboy who, coincidentally, happens to be chasing his daughter. Originally titled *Flight Line*, Warner Brothers developed the 1957 picture in direct collaboration with the Strategic Air Command.[1] Unusual among similar propagandist productions of the time, *Bombers B-52* glamorized a blue-collar enlisted man in the otherwise unglamorous role of a veteran "crew chief": the leader of an aircraft's maintenance team. Such personnel had become highly prized on SAC airbases during the 1950s, but also increasingly scarce. "Although SAC is an elite command," *Fortune* wrote in 1954, "its most critical management problem is its low re-enlistment rate. The present annual turnover is 20 per cent."[2] The nature of the Air Force itself exacerbated the problem. "SAC

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[1] Steve Call, *Selling Air Power: Military Aviation and American Popular Culture After World War II* (College Station: Texas A&M University Press, 2009), 119–122.

[2] John McDonald, "General LeMay's Management Problem," *Fortune*, May 1954, 104. Cf. William S. Borgiasz, *The Strategic Air Command: Evolution and Consolidation of Nuclear Forces* (Westport, CT: Praegar, 1996); Philip S. Meilinger, *Bomber: The Formation and Early Years of the Strategic Air Command* (Maxwell AFB: Air University Press, 2012).

trains airmen to technical proficiency in radio, radar, air-traffic control, photography, motor mechanics, communications, and the like, only to find private industry bidding more for their services in money and living conditions than SAC offers. SAC is, in effect, running a technical training college for the benefit of U.S. industry." In *Bombers B-52*, the dramatic tension—such as it is—concerns a veteran maintainer deciding whether to retire from the Air Force in order to take up a lucrative job in the roaring aerospace industry. This being a quasi-official propaganda piece, our shirt-sleeve hero valiantly chooses country over commerce—or maybe just to keep playing with the biggest toys (it is really not very clear).

1 The maintainability crisis in aerospace systems

The Air Force faced a clear dilemma during the mid-to-late 1950s. On the one hand, it had very nearly realized the fantastical future presented in *Toward New Horizons*, also called the "Von Kármán report": the thirteen-volume study that had guided USAF research and development policy since 1945.[3] The years between 1955 and 1960 witnessed the introduction of virtually every advancement in aerospace technology foreseeable at the end of World War II—supersonic aircraft, automatic fire-control systems, guided and ballistic missiles, artificial satellites, thermonuclear warheads, over-the-horizon radar, and digital electronic computers—not merely in tests and prototypes, but as operationally deployed equipment. At the same time, however, the workforce needed to maintain these new and complicated systems dwindled both in quantity and experience. Despite serious efforts to retain them, the fraction of enlistees leaving the service at their first opportunity jumped from 54% to 76% between 1959 and 1961, when the Air Force shed more than 18,000 personnel in maintenance specialties it classified as "highly technical."[4] Meanwhile, the ratio of maintenance-to-flying hours for a heavy bomber had multiplied by a factor of *six* since the end of the war.

In 1961, a study commissioned by the Air Force's Behavioral Sciences Laboratory reported that over a five-to-ten-year period, a system cost 10 to 100 *times* in maintenance as it had to procure in the first place.[5] Maintenance consumed a third of the Air Force's operating costs and occupied an equal proportion of its

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[3] Michael H. Gorn, ed., *Prophecy Fulfilled: "Toward New Horizons" and Its Legacy* (Washington: Air Force History and Museums Program, 1994) reprints the executive summary along with an historical introduction. See also Michael H. Gorn, *Harnessing the Genie: Science and Technology Forecasting for the Air Force, 1944–1986* (Washington: Office of Air Force History, 1988). The entire study is available online from Government Attic: http://www.governmentattic.org/TwardNewHorizons.html.

[4] George F. Lemmer, *USAF Manpower Trends, 1960–1963* (Washington: USAF Historical Division Liaison Office, March 1965), Air Force Historical Support Office, https://media.defense.gov/2011/Mar/21/2001330246/-1/-1/0/AFD-110321-038.pdf, 36–41. Manpower figures derived from tables in *United States Air Force Statistical Digest, Fiscal Year 1958* (Washington: Directorate of Statistical Services, Headquarters, USAF, n.d. [1958?]), Air Force Historical Studies Office, https://media.defense.gov/2011/Apr/11/2001330055/-1/-1/0/AFD-110411-023.pdf, 287 and *United States Air Force Statistical Digest, Fiscal Year 1961* (Washington: Directorate of Data Systems and Statistics, Headquarters, USAF, n.d. [1961?]), Air Force Historical Studies Office, https://media.defense.gov/2011/Apr/12/2001330047/-1/-1/0/AFD-110412-016.pdf, 253.

[5] Lynn V. Rigby and Joel I. Cooper, "Problems and Procedures in Maintainability," ASD Technical Note 61-126 (Wright-Patterson AFB: Behavioral Sciences Laboratory, Aeronautical Systems Division, Air Force Systems Command, October 1961), HathiTrust Digital Library, https://hdl.handle.net/2027/mdp.39015082477111.

personnel. At any one time, about three-fourths of its equipment required some kind of repair, and 13% had broken down entirely. Only office administration consumed more collective man-(and woman-)hours, and a significant fraction of that related to maintenance activities as well. With costs and complexity rising, and the labor and talent pools shrinking, it is no accident that military officials and professional technology managers suddenly began talking about a "maintainability" crisis in aerospace systems.[6]

To the practicing maintenance engineer, *maintainability*, or the ease and efficiency of maintenance, is a multifaceted problem. It weighs such considerations as diagnostics, reliability, componentization, and quality control. Here, we focus on one broad, interdisciplinary aspect known as "human-factors engineering," or HFE. Within aerospace engineering, HFE includes considerations such as the number of instruments a human pilot can monitor simultaneously, the distance an arm can reach while subjected to various G-forces, or the amount of time a pair of astronauts can spend confined to a claustrophobic, sense-depriving space capsule before one of them blows the other one out the airlock.[7] In the context of maintenance specifically, HFE asks questions like: How far can the average man reach above his head and still turn a screwdriver? If it could cause a short, shouldn't this plug fit its connector in only one way? And what part of "DO NOT STEP" did you not understand? This may sound trite, but human factors in maintenance engineering concern elements of physiology, cognitive and social psychology, and operations research, and as such, they speak to the way scientists, engineers, and managers viewed the human laborer as a subject of study and control.[8] The Air Force's maintainability crisis reflected, in part, a condescending worry that the dullest tools and dimmest bulbs in the shop would be the maintenance workers themselves.

2 Personnel management: The original "human factor"

HFE in aerospace maintenance combined one of the Air Force's newest problems—managing technology as integrated "systems"—with one of its oldest: personnel classification and job selection.[9] "There is probably

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[6] While focused on electronics, Edward Jones-Imhotep, "Maintaining Humans," in *Cold War Social Science*, edited by Mark Solovey and Hamilton Cravens (New York: Palgrave Macmillan, 2012), 175–196 is the only secondary source we know to have fully appreciated this phenomenon. For the moment, retrospective accounts are mostly limited to participant memoirs, such as L. Parker Temple, *Implosion: Lessons from National Security, High Reliability Spacecraft, Electronics, and the Forces Which Changed Them* (Piscataway, NJ: Wiley–IEEE Press, 2013).

[7] A classic trope from such popular accountings as Tom Wolfe, *The Right Stuff* (New York: Farrar, Straus, and Giroux, 1979), some recent historical work touching on these themes include David A. Mindell, *Digital Apollo: Human and Machine in Spaceflight* (Cambridge: MIT Press, 2008); Slava Gerovitch, "Human-Machine Issues in the Soviet Space Program," in *Critical Issues in the History of Spaceflight*, edited by Steven J. Dick and Roger D. Launius (Washington: National Aeronautics and Space Administration, 2006), 107–140; Matthew H. Hersch, *Inventing the American Astronaut* (New York: Palgrave Macmillan, 2012); and Marcia E. Holmes, "Performing Proficiency: Applied Experimental Psychology and the Human Engineering of Air Defense, 1940–1965" (PhD diss., University of Chicago, 2014). Eduardo Salas and Dan Maurino, eds. *Human Factors in Aviation*, 2nd ed. (New York: Elsevier, 2010) is a contemporary practitioner perspective, while Donald A. Norman, *The Design of Everyday Things*, repr. (New York: Basic Books, 2002 [1988]) reflects on human design principles in general.

[8] See Jones-Imhotep, "Maintaining Humans" for further elaboration on this point.

[9] On the enlisted career, see Mark R. Grandstaff, *Foundation of the Force: Air Force Enlisted Personnel Policy, 1907–1956* (Washington: Air Force History and Museums Program, 1997); compare with Vance O. Mitchell, *Air Force Officers: Personnel*

no human-factors area that has received as much attention by the armed forces and is the subject of so much competent research as the assessing and cataloging of skills, capabilities, and backgrounds of personnel in their employ," observed two engineers working for an Air Force contractor in 1961.[10] Since the rise of industrial warfare, military organizations have had to rely on enlisted personnel to perform increasingly skilled tasks, such as maintaining aircraft and electronics, which require correspondingly more training and experience. Nevertheless, even a federal agency with demands as technical as the United States Air Force must still respect the general framework for personnel policy established by Congress and cannot "hire" and "fire" according to their immediate needs, which may not align with political expedience.[11] Related to this point is the fact that the military needs workers for jobs that do not exist in private enterprise. A temp agency cannot help you find a qualified nuclear-weapons mechanic—or at least, one hopes not.

This being the case, the stakes are high when selecting recruits for training in highly technical subjects. During and after World War II, the armed forces became the primary sponsors of measurements for "intelligence" and "aptitude" for the purpose of predicting future performance. According to one survey paper, the "basic reason for using tests to select men for training lies in the fact that it costs less to test a man than it does to attempt to train him and discover that he is untrainable."[12] In the military, the costs were not only monetary, but temporal, since an enlisted man typically became eligible for reserve status after four years of active duty. While contemporary critiques of standardized testing certainly apply here, at the time, Air Force personnel researchers were more interested in the problem of *sorting* than screening *per se*.[13] "Prior to 1947, assignment of enlisted personnel in the services was based almost solely upon the single score achieved from the Army General Classification Test (AGCT)," the survey continued. The state-of-art lay in the development of so-called "battery" tests, which would conceivably surpass general measures of "intelligence" and "ability" by discerning specific aptitudes within the test population:

> Classification based on a single general score such as AGCT is as wasteful as the use of a general purpose fertilizer on all types of soil without regard for an analysis of the nutritional elements available in each type. For any given soil type, many of the minerals in the fertilizer are wasted because they may already be available in sufficient quantity. Similarly, when personnel are selected for a specific training course because of high AGCT score (high average score on several different abilities), their high abilities on factors not particularly relevant to that course are wasted.[14]

Policy Development, 1944–1974 (Washington: Air Force History and Museums Program, 1997). Janet R. Bednarek, *The Enlisted Experience: A Conversation with the Chief Master Sergeants of the Air Force* (Washington: Air Force History and Museums Program, 1995) is an oral-historical reflection on enlisted life, most during the early-to-mid Cold War.

[10] B. H. Manheimer and J. R. Kelley, "An Overview of Human Factors in Electronic Maintenance," *IRE Transactions on Human Factors in Electronics* 2, no. 2 (September 1961), doi:10.1109/THFE2.1961.4503309, 75.

[11] Cf. James Q. Wilson, *Bureaucracy: What Government Agencies Do and Why They Do It* (New York: Basic Books, 1989).

[12] William B. Lecznar, "Survey of Tests Used in Airman Classification," Technical Documentary Report PRL-TDR-63-5 (Lackland AFB: Personnel Research Laboratory, Air Force Systems Command, February 1963), Defense Technical Information Center (AD0403831), http://www.dtic.mil/docs/citations/AD0403831, 17.

[13] The scholarship here is robust, but the obligatory reference is Stephen Jay Gould, *The Mismeasure of Man*, 2nd ed. (New York: W. W. Norton, 1996).

[14] Lecznar, "Survey of Tests Used in Airman Classification," 16.

In other words, Air Force recruiters already knew how to eliminate "unsuitable" candidates fairly well, and they also realized that the highest aggregate scores suggested likely success in any vocation. What they wanted was to distinguish a future vehicle mechanic from an electronics technician, or a metalworker from a wiring inspector. The Air Force had places for workers of widely varying degrees of skill and competence, and in addition to optimally filling these positions, it was thought that good career matches would help improve reenlistment rates.

Complementary to the problem of sorting candidates into favorable career fields was the trouble with defining the fields themselves. The 1956 edition of the *Airman Classification Manual* listed 43 careers for enlisted men, each with several tracks divided further into hundreds of individual Air Force Specialty Codes, or AFSCs.[15] At a high level, manipulating enlisted career-tracks—for example, by offering opportunities for quick promotion and advanced training—was an important part of the incentive structure for attracting and retaining skilled personnel according to anticipated needs. Descriptions and requirements fluctuated wildly, however, particularly in AFSCs related to maintaining aircraft, missiles, and electronics. While the Air Force tracked and approved AFSCs at headquarters, personnel officers in the field conducted most "occupational analysis": observing and classifying what people actually did on the job.[16] Thus specialty codes tended to emerge from work in specific places under local conditions, and despite systematic efforts to generalize, they were difficult to apply throughout the organization. In 1954, researchers reported seeing B-29 mechanics with the same AFSC performing different functions depending on where they worked or who their supervisors were. Any one mechanic gernally performed only a subset of the tasks in which he was formally trained while performing many other tasks in which he was not.[17] At the same time, they also determined that electronics technicians could not easily transfer their proficiency with one piece of radar-bombing and navigation equipment to a functionally similar item, even though the distribution of required skills and abilities were more or less identical.[18]

The Air Force's recruitment, training, and career practices resembled a sort of social engineering at the level of the entire organization. It imagined a human machine, with each part geared to fit the overarching bureaucratic order.[19] This was only an ideal, of course, reality being a continuous flux of recalcitrant self-agents who, despite virtually surrendering their personal autonomy as a condition of military service, often did not behave as their supervisors desired or expected. While efforts to machine the organization did not

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[15] *Warrant Officer and Airman Classification Manual*, AFM 35-1, vol. 1 (Washington: Department of the Air Force, March 1, 1956), HathiTrust Digital Library, https://hdl.handle.net/2027/uiug.30112107822378.

[16] *Occupational Analysis*, AFM 35-2 (Washington: Department of the Air Force, August 1, 1954), HathiTrust Digital Library, https://hdl.handle.net/2027/uiug.30112104237984.

[17] Guy G. Besnard, "Shred-Outs of Tasks Performed by Senior B-29 Mechanics (AFSC 43151-B)," AFPTRC-TR-54-4 (Lackland AFB: Air Force Personnel and Training Research Center, April 1954), HathiTrust Digital Library, https://hdl.handle.net/2027/mdp.39015081946058?urlappend=%3Bseq=37.

[18] Robert B. Miller, John D. Folley, Jr., and Philip R. Smith, "A Comparison of Job Requirements for Line Maintenance of Two Sets of Electronics Equipment," AFPTRC-TR-54-83 (Lackland AFB: Air Force Personnel and Training Research Center, December 1954), HathiTrust Digital Library, https://hdl.handle.net/2027/mdp.39015081945951?urlappend=%3Bseq=65.

[19] Cf. Gareth Morgan, *Images of Organization* (London: SAGE Publications, 1986).

abate, mounting costs and safety issues, combined with external disruptions to its personnel policy, inspired the Air Force to find a new way to discipline the minds and bodies of maintenance workers: deliberately re-engineering the tools, equipment, and physical environment with which they worked.

3 Human factors: Engineering systems for maintainability

Postwar "mission-critical" systems (namely, any involving nuclear warfare) catalyzed the Air Force's interest in and adoption of HFE techniques in maintenance. Air Force laboratories conducted numerous studies and contributed disproportionately to the rise of the field in theory as well as practice, offering such ready material as the *Guide to Design of Electronic Equipment for Maintainability*, first issued in 1956. "This guide was written to provide principles to be applied during electronic equipment development for 'building in' provisions for more effective maintenance," according to the authors. "The basic premise of the guide is that relatively small expenditures of time and money for maintainability will produce much larger savings in maintenance costs."[20] The first section presented a set of management techniques for engineers to account for human factors at the design stage, encouraging them to plan for necessities ranging from installation and supply provisions to documentation and test equipment. The remainder of the 150-page guide presented a heavily illustrated collection of "dos" and "don'ts" for designers to guard against such common faults as bent pins, stripped screws, mismatched connectors, and pinched cables, as well as advice for moving, opening, inspecting, adjusting, and replacing parts. It recommended placement positions for handholds, test points, hinges, component slots, and access hatches, while also providing biometric data on the dimensions, reach, lifting capacity, sight, and dexterity of the "average" maintenance worker in various postures. "Many of the recommendations in this guide are 'rules of thumb,' " the authors acknowledged. "Some are not yet supported by adequate research data because human research data for maintenance is new and relatively undeveloped."[21] As the field advanced, the Air Force's human-engineering laboratory published other widely used handbooks such as the *Guide to Design of Mechanical Equipment for Maintainability* and the *Guide to Integrated System Design for Maintainability*.[22] While compliance was at first voluntary, the Air Force eventually began to impose maintainability guidelines on contractors through the systems-management

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[20] J. D. Folley and J. W. Altman, *Guide to Design of Electronic Equipment for Maintainability*, WADC Technical Report 56-218 (Wright-Patterson AFB: Aero Medical Laboratory, Wright Air Development Center, April 1956), Defense Technical Information Center (AD0101729), http://www.dtic.mil/docs/citations/AD0101729, 2.

[21] Folley and Altman, *Guide to the Design of Electronic Equipment for Maintainability*, 3.

[22] James W. Altman, Angeline C. Marchese, and Barbara W. Marchiando, *Guide to Design of Mechanical Equipment for Maintainability*, ASD Technical Report 61-381 (Wright-Patterson AFB: Behavioral Sciences Laboratory, Aeronautical Systems Division, August 1961), HathiTrust Digital Library, https://hdl.handle.net/2027/mdp.39015082477749; Lynn V. Rigby, Joel I. Cooper, and William A. Spickard, *Guide to Integrated System Design for Maintainability*, ASD Technical Report 61-424 (Wright-Patterson AFB: Behavioral Sciences Laboratory, Aeronautical Systems Division, October 1961), Defense Technical Information Center (AD0271477), http://www.dtic.mil/docs/citations/AD0271477. See also Rebecca J. Green, Herschel C. Self, and Tanya S. Ellifritt, *50 Years of Human Engineering: History and Cumulative Bibliography of the Fitts Human Engineering Division* (Wright-Patterson AFB: Air Force Materiel Command, 1995), HathiTrust Digital Library, https://hdl.handle.net/2027/mdp.39015034905318.

process. Once NASA adopted a nearly identical policy, both the Army and the Navy had to adapt to the changing industry as well.[23]

The government's promotion of HFE considerations in maintenance further precipitated studies in industry and academia, which fed back into the Air Force's own design and research programs. By 1960, Electronic Industries Association had held three annual conferences on the Maintainability of Electronic Equipment, resulting in the edited collection, *Electronic Maintainability*, a portion of which directly addressed maintenance issues within the armed forces.[24] In 1961, the *IRE Transactions on Human Factors in Electronics* (predecessor of the *IEEE Transactions on Human-Machine Systems*) devoted its second issue to designing for maintenance. While none of the articles specifically addressed aerospace maintenance, almost all of them shared research applicable to the needs of the Air Force. For example, one author cited the reduction of downtime—that is, a period during which equipment is inoperable—measured against design costs as a primary reason to design for maintainability upfront, considering not only tools and manuals, but maintenance technicians with "various levels of competence as assured by their selection and training." The "over-all return on a small engineering investment can thus be enormous" after accounting for the cost of maintaining the device or system throughout its entire operational lifetime.[25] For the Air Force, the potential to reduce long-term personnel requirements was just as attractive as the possible financial relief.

To an extent, researchers did realize that workers could be assets to systems development, instead of just constraints to be designed around. In the same volume, contributors from the American Institute for Research—a nonprofit established in 1946 by pioneering aviation-psychologist John Flanagan—called on engineers to better respect their subjects' "expert judgment." With regard to maintainability, they argued that "the 'real' experts ... are the maintenance technicians or field engineers who actually have to maintain the equipment under field conditions"—not the designers or system managers.[26] Another author urged designers not to automate simply for the sake of automation, but to design integrated systems that "capitalize upon both the merits of automation and the capabilities of humans."[27] In 1963, a speaker at the Electronic System Division's Maintainability Conference concluded with a plea to consider design from the maintainer's perspective. "If anyone should doubt the importance of a maintainability program, he needs only to listen to the people who *use* the equipment":

> I recently conducted a study of human errors in the operation of electronic checkout equipment which took me to ten field organizations using and maintaining five completely different weapon systems.

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[23] George A. Steiner and William G. Ryan, *Industrial Project Management* (New York: Columbia University Press, 1968). See also Stephen B. Johnson, *The United States Air Force and the Culture of Innovation, 1945–1965* (Washington: Air Force History and Museums Program, 2002).

[24] F. L. Ankenbrandt, ed., *Electronic Maintainability* (Elizabeth, NJ: Engineering Publishers, 1960).

[25] Joseph G. Wohl, "Why Design For Maintainability?" *IRE Transactions on Human Factors in Electronics* 2, no. 2 (September 1961), doi:10.1109/THFE2.1961.4503312, 87, 89.

[26] M. R. Munger, M. P. Willis, and J. W. Altman, "Quantification of Expert Judgment in Maintenance Design Decisions," *IRE Transactions on Human Factors in Electronics* 2, no. 2 (September 1961), doi:10.1109/THFE2.1961.4503314, 97.

[27] Robert G. Demaree, "Designing the Human Element into Maintenance," *IRE Transactions on Human Factors in Electronics* 2, no. 2 (September 1961), doi:10.1109/THFE2.1961.4503317, 110.

> I interviewed supervisors and administered questionnaires to scores of technicians, gathering much information about errors and difficulties the technicians experienced as well as their opinions and suggestions for improvement of the maintenance system. There were many reports of parts and check points hard to reach. One technician reported that to replace a certain transformer on a Tacan [tactical air-navigation] unit, it was necessary to remove the entire front of the unit, disconnecting other wiring and parts, requiring about two hours. If the transformer had been easily accessible, ten minutes would probably have been adequate. Also removing and replacing the front panel often resulted in other malfunctions or required circuit adjustments.[28]

Furthermore, "a large percent of all technicians in this study felt that better technical data, diagrams and check lists would speed up maintenance. Much of the equipment in these systems did not have adequate handles for lifting, had inadequately marked access openings and parts locations on chassis." Efforts to improve maintainability would continue to suffer these setbacks until engineers responded more enthusiastically to feedback.

Why did designers resist? According to Alan Swain, a maintenance engineer at Sandia National Laboratory, it was not that they failed to appreciate the importance of the "human element," but rather, the way they thought about it. At a symposium in 1964, he criticized the field for its "Alice-in-Wonderland viewpoint toward human errors," which devolved into "wishful thinking": " 'If they would just train people properly…' " or "If people would do what they are supposed to do, there wouldn't be any problem." Unfortunately, "the willingness to assign blame for errors to the operator or to the production worker is characteristic of too many design engineers and managers":

> Some even talk about providing "idiot-proof" designs which make maximum use of "goon meters" for "trained apes." And Murphy's Law has received so much over-emphasis that some design engineers believe, in spite of evidence to the contrary, that *the* way to a reliable system is to eliminate man from the system…It may be easier for a designer to blame man, yet the "cause" of human error many times lies not so much in the attitude or motivation or skill of the human as the design of the controls and displays or other equipment he must read, manipulate, or deal with in some way.[29]

While certainly phrased more sympathetically, Swain's views were ultimately not so unlike those of his hypothetical rhetorical opponent, in that they both aspired to anticipate and change the worker's behavior through design. "When we think about changing people," he said, "we often are attacking symptoms rather than causes." For example, "at one military installation, maintenance technicians consistently walked on a large bomb [presumably nuclear] associated with an aircraft":

> The authorities were upset, and rightly so; thus they recommended that caution signs be printed on these bombs. The reviewing agency rejected this recommendation; this agency stated that the technicians should be indoctrinated not to walk on the bombs. A different recommendation, but the same type

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[28] Louis T. Pope, "Human Factors and Maintainability," in *Proceedings of the ESD Maintainability Conference, 12–13 March, 1963* (L. G. Hanscom Field: Electronic Systems Division, Air Force Systems Command, June 1963), Defense Technical Information Center (AD0406780), http://www.dtic.mil/docs/citations/AD0406780, IVA-5.

[29] A. D. Swain, "Human Factors in Design of Reliable Systems," Sandia Reprint SC-R-748 (Albuquerque: Sandia Corporation, June 1964), SciTech Connect (4070176), https://www.osti.gov/scitech/biblio/4070176, 2.

> of thinking. Apparently no one thought to get beyond the symptom and look for the cause. Why did technicians walk on bombs? Did they need a workstand? Large bombs provide a reasonable and handy facsimile of a workstand to a technician trying to meet his schedule.[30]

Taken to its logical end, this approach would seem to place an enormous responsibility on the designer to act as a social psychologist, with tremendous empathy and understanding for the subject, as well as an engineer—a tremendous feat of cultural translation for anyone. "Designers have to know themselves too, to design effectively for others," Swain acknowledged while neglecting the problems inherent in his proposition:

> They must remember that they have college educations (or equivalent) and that they probably have higher than average intellectual abilities and that they are intensely motivated to make their gear work properly. The average production worker, on the other hand, is probably not college trained. He often has average or even below average intellectual ability. His primary motivation can be merely to put in his time on the job… A good designer will make it his business to find out as much as he can about the type of operator who will use his designs and the conditions under which the designs must be used. An efficient design firm will see to it that their designers get this kind of information.[31]

The argument was very nearly circular; HFE may not have regarded its goal so crudely as "idiot-proofing" sensitive equipment, but it was at least in the business of building better idiots.

This ambivalence is perhaps best illustrated by research on so-called "job-performance aids." Philco-Ford surveyed the topic for the Department of the Labor in 1967, drawing primarily on maintainability studies generated by Air Force laboratories and contractors. In the midst of the Great Society, their aspirations appeared notably benign. "Whether or not expressly stated, the assumption that underlies most of our efforts to combat poverty and unemployment is that, given a particular set of job requirements, there are only two vehicles for obtaining human work performance: selection and training."[32] Job aids offered a third possibility, which, according to the definition adopted in the report, were *not* merely tools or training materials, but mediating devices that compensated for "basic aptitude deficiencies" as identified through testing or lack of credentials. "Whether it be a checklist, a nomograph, or a computerized job information system, the main consideration is that the 'device' assist the worker by storing or other handling *information*." For example:

> The lubrication chart in the filling station, by specifying the activities to be followed and showing the locations of the parts to be lubricated for each model and year of car, is an excellent example of a job aid which substitutes for the lengthy training and experience that would otherwise be required if the mechanic had to rely exclusively upon his memory to accomplish such tasks. With only a minimum of training, any gas station attendant utilizing the job performance aid can lubricate most vehicles to the

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[30] Swain, "Human Factors in Design of Reliable Systems," 2.

[31] Swain, "Human Factors in Design of Reliable Systems," 4.

[32] Albert B. Chapulsky and Thomas J. Kopf, "Job Performance Aids and Their Impact on Manpower Utilization," WDL-TR3276 (Palo Alto: Western Development Laboratories, Philco-Ford Corporation, May 1967), Education Resources Information Center (ED015316), https://eric.ed.gov/?id=ED015316, 4.

> same level of performance, and very likely with greater reliability, than would be achieved by a skilled mechanic who had to rely entirely upon his previous training and experience.[33]

The authors ultimately hoped that methods cultivated by the military could also help equalize civil society, addressing "the employment problems of the non-white or the older worker, the handicapped, and other disadvantaged groups" as well as "the basic question of how we can improve the effectiveness and the efficiency of our methods for achieving satisfactory human performance in a work environment with a rapidly accelerating rate of change." The inconsistency in their ambition, however laudable, is not difficult to detect. After all, it was not as if Air Force officials had ever been coy about their intent to use HFE in order to *reduce* their manpower requirements.

Nowhere were they more successful than the Minuteman program. Unlike earlier intercontinental-range ballistic missiles, such as Atlas and Titan, Minuteman was the first weapons system designed to fit into its logistics and maintenance organization, and not the other way around. More than 1,000 Minutemen were on fifteen-minute alert within a decade of the program's initiation in 1958, while Atlas had been retired completely, and only 54 Titan IIs remained. The idea for the project originated within the Air Force Ballistic Missile Division in Los Angeles, where a colonel named Benjamin P. Blasingame reacted unfavorably to a request from the United States Air Forces in Europe for a solid-fueled rocket to replace the antiquated TM-61 Matador cruise missile. "I do not feel that the IRBM [intermediate-range ballistic missile] program is a good objective for the [solid] propellant program," Blasingame wrote to his superior in July 1957. "Our real need is for an adequate deterrent force; this can be guaranteed to be effective only when it is securely based on our own soil and operated by our own people."[34] General Bernard Schriever, the division commander, ultimately agreed to defer the IRBM concept to a newly formed solid-propellant "working group," which would also consider plans for a "next-generation" ICBM.[35]

Although Blasingame remained with the Titan program, his attitude guided the solid-propellant group as it evolved into a dedicated project office. After a meeting about the future project organization, Blasingame urged his colleagues to "consider the history of the Titan system":

> All of our procurement data described only the missile itself. There is not a single word in all the procurement data about the base to which this missile was to be adapted nor was there a single word about the ground support system which would go with this bird. History today shows that these elements of [ground-support equipment] and base design are the most important elements of a missile system insofar as the Air Force is concerned. They are many times as expensive as the bird itself.[36]

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[33] Chapulsky and Kopf, "Job Performance Aids," 1, 3.

[34] Col. Benjamin P. Blasingame, Director, WS-107A-2 Project Office to Col. Charles H. Terhune, Deputy Commander, Ballistic Missile Division, "ICBM Solid Propellant Program," July 17, 1957, exhibit 21 in Robert F. Piper, *The Development of the SM-80 Minuteman* (Wright-Patterson AFB: Historical Office, Deputy Commander for Aerospace Systems, Air Force Systems Command, April 1962), Digital National Security Archive (NH00024).

[35] Maj. Gen. Bernard A. Schriever, Commander, Ballistic Missile Division to Maj. Gen. J. W. Sessums, Vice Commander, Air Research and Development Command, September 20, 1957, exhibit 28 in Piper, *Development of the SM-80 Minuteman*.

[36] Col. Benjamin P. Blasingame, Director, WS-107A-2 Project Office to Col. Charles H. Terhune, Deputy Commander, Ballistic Missile Division, "New Ballistic Missile System Office," September 18, 1957, exhibit 27 in Piper, *Development of the*

He further expressed his personal frustration that "when the [Titan] contract was awarded to Martin, there was no understanding at all, either at Martin or here, of what the support equipment should include for such a missile," the result of which was "a very difficult problem of integrating the [ground-support equipment] because it was not understood from the outset what the roles and responsibilities would be of each contractor in the program." Future design studies, Blasingame insisted, should include the supporting environment as an initial parameter.

Colonel Edward N. Hall, a propulsion expert and the former director of the Thor program, agreed with Blasingame when he took charge of the management office, code-named "Q," in late September. "There is no question in my mind whatever that [ground-support equipment] and base considerations must be introduced right from the word go," he wrote in response to Blasingame, "since in the case of our new missile family…these considerations may have an important effect on the configuration of the missile itself."[37] Accordingly, Hall directed the Ramo-Wooldridge Corporation to conduct its preliminary design studies with a silo-based launch configuration in mind. The work statement for a design study contracted to Lockheed also included specific language concerning basing, maintenance, personnel, and even manuals and handbooks.[38] By the end of 1957, the Q office had decided that the new ICBM should exhibit a quality of "woodenness" to the operator. In the field, crews needed to be able to transport the missile, load and unload it from its launcher, and, of course, fire it; for all other purposes, however, its internal workings—propulsion, warhead, guidance, etc.—should remain as opaque as possible. Hall's group also offered the "missile forest" as the metaphorical extension of a "wooden" missile. With its daily operation kept simple, the Air Force could afford to maintain hundreds of solid-fueled ICBMs in unattended silos, monitored remotely and serviced by roaming maintenance crews. Today, Minuteman has almost single-handedly enabled a half-century of land-based ICBM deployment within the continental United States at a tolerable cost in both money and military personnel. Whether this represents an achievement or not is, of course, a matter of perspective.

4 A final analysis

The story of "Damascus incident," as vividly retold by Eric Schlosser, involves the kind of quintessential "human error" that HFE had promised to obviate.[39] On the night of September 18, 1980, a maintenance team checking out a low-pressure warning on a Titan II siloed near Little Rock accidentally dropped the

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SM-80 Minuteman.

[37] Col. Edward N. Hall, Director, "Q" Office, to Col. Charles H. Terhune, Deputy Commander, Ballistic Missile Division, "New Ballistic Missile System Office," October 7, 1957, exhibit 31 in Piper, *Development of the SM-80 Minuteman*.

[38] Memo, Col. Edward N. Hall, Solid Ballistic Weapons Office "Study to Be Performed by Lockheed on the Conduct of the Development and Production Program for a Weapon System to Satisfy AF GOR #161," November 8, 1957, exhibit 33 in Piper, *Development of the SM-80 Minuteman*.

[39] The following narrative unfolds gradually throughout Eric Schlosser, *Command and Control: Nuclear Weapons, the Damascus Accident, and the Illusion of Safety* (New York: Penguin, 2013).

nine-pound socket from their socket wrench, which fell seven stories before skipping off a support structure and piercing the skin of the missile. The first-stage propellant tank ruptured, and over the next eight hours, fuel vapors overwhelmed the underground facility. After the missile crew evacuated, maintenance personnel twice reentered the facility to measure the vapor concentration and, if possible, vent the propellant tank. Despite their misgivings about the conflicting and equivocal orders coming down from SAC and wing headquarters, the enlisted men did as the officers instructed. The fumes finally combusted during their second incursion, triggering an explosion that blew the 740-ton blast-door off the top of the silo and projected a 9-megaton nuclear warhead several hundred feet from the opening. It did not detonate, but the explosion killed one man and severely injured another.

The propellant team had used the wrong tool. A recent technical order had instructed maintenance personnel to only loosen the oxidizer valve with a torque wrench instead of a socket wrench. Furthermore, the men who reentered the facility had deviated from procedure while desperately trying to save the missile—at hazard mostly to themselves. The survivors' interviews with Schlosser revealed their incredulity with their orders, but like good soldiers, they obeyed them even against their better judgment. Nevertheless, the official reports and subsequent discipline foisted blame primarily on the maintenance teams, citing one man for dereliction of duty, and committing two others to a mental hospital. SAC even began dispatching officers to watch over maintainers whenever they entered a Titan facility. "The morale among the [propellant specialist] crews at Little Rock Air Force Base was terrible," according to Schlosser. "A number of [propellant] technicians refused to work on Titan II missiles, citing the danger of the job, and their security clearances were revoked. Drug and alcohol use increased." Most of the men involved in the incident were quietly drummed out of the service. Meanwhile, "no one at SAC headquarters was fired. Many of the enlisted men in the 308th [Strategic Missile Wing] thought the Air Force was scapegoating the little guys in order to hide problems with the Titan II and protect the top brass."[40] The Damascus incident was not even the most lethal mishap involving the problematic Titan II; in 1965, a civilian working in another silo near Little Rock accidentally cut a hydraulic line with an acetylene torch, starting a fire that killed 53 people. The missile's warhead, however, had been removed during the construction project.[41]

Enlisted personnel in their late teens and early twenties are too easily blamed for what should be probably understood as systemic phenomena. The engineers who revised the technical order intended to prevent maintenance crews from overstressing the pressure valve, not from mishandling the socket in a socket wrench. The crew Damascus did remember they were supposed to use a torque wrench, but since the order had recently changed, they had left it in their vehicle. Overworked and behind schedule, they elected to proceed with the tool they had used hundreds of times before rather than consume another hour performing rigorous exit and re-entry protocols in order to retrieve it. Meanwhile, headquarters, fearing that an explosion would eject the warhead from the silo, rejected their immediate suggestion to vent the fuel vapor by opening the

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[40] Schlosser, *Command and Control*, 437–438.

[41] David K. Stumpf, *Titan II: A History of a Cold War Missile Program* (Fayetteville: University of Arkansas Press, 2000), 215–251 describes five fatal accidents involving the system during its 25 years of service.

blast door (the explosion eventually blew it open anyway). Mid-ranking officers had known for years that the Titan II was expensive and troublesome to maintain, and yet whatever limited role it played in the strategic nuclear-war plan continued to override their concerns. It is the nature of managerialism, however, to seek out proximate causes and short-term remediation at the expense of fundamental reevaluation.[42]

The inevitable consequence of seeking to establish scientifically what humans *can* do is the circumscription of what they *cannot*, casting the worker as both an instrument and a liability. The "man-machine" view generally regarded the human as a constraint to be passively engineered, just like any other mechanical or electronic component, rather than as an intelligent, adaptive element capable of compensating for the mistakes and oversights of the designers themselves.[43] In the final analysis, of course, human factors engineering has succeeded in making aerospace systems vastly safer over the last half century while keeping public and consumer costs manageable amid increasing technical demands. The social benefits have been widely acknowledged, and while it is difficult to argue with the outcome, maintainers had no say in the means by which it was achieved, despite their obvious equity in the process.

This unfairness is not a purely moral point, because with little input from the maintainers themselves, there is nothing to assure us that the path taken has necessarily been the *best* one: only that it satisfies the scientists, engineers, and managers—and ultimately, the powers *they* answer to.[44] However ambivalent one may feel about America's place in the world, reducing military manpower requirements, both in terms of skills and numbers, *did* restrict an important source of social mobility.[45] Moreover, some argue that the end of conscription has enabled political leaders to wage careless or interminable conflicts overseas without risking the mass unrest that characterized the war in Vietnam.[46] And while we have concentrated here on military applications, private entities have eagerly adopted HFE in order to eliminate relatively well-paying maintenance positions as well.[47] So even though it may be difficult, it is by no means impossible to imagine a world that acknowledges human limitations while better respecting uniquely human abilities.[48] In this pivotal historical moment, we are all potential idiots in someone else's design.

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[42] This point gestures at an entire field of inquiry but Thomas Klikauer, *Managerialism: A Critique of an Ideology* (New York: Palgrave Macmillan, 2013) is a reasonable introduction.

[43] Cf. H. McIlvaine Parsons, *Man-Machine Experiments* (Baltimore: Johns Hopkins University Press, 1972).

[44] The classic work here is Loren Baritz, *The Servants of Power: A History of the Use of Social Science in American Industry* (Middletown, CT: Wesleyan University Press, 1960). Compare, however, with Edwin T. Layton, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession* (Cleveland: Press of Case Western Reserve University, 1971) or Kelly Moore, *Disrupting Science: Social Movements, American Scientists, and the Politics of the Military, 1945–1975* (Princeton: Princeton University Press, 2008).

[45] See, for instance, Glenn C. Altschuler and Stuart M. Blumin, *The GI Bill: A New Deal for Veterans* (Oxford: Oxford University Press, 2009).

[46] Most prominently by Andrew J. Bacevich, as in *Breach of Trust: How Americans Failed Their Soldiers and Their Country* (New York: Metropolitan Books, 2013).

[47] Cf. David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Knopf, 1984).

[48] This perspective recalls Lewis Mumford's intellectual trajectory, particularly as manifested in his later writings such as *The Myth of the Machine*, 2 vols. (New York: Harcourt, Brace & World, 1967, 1971). See also David A. Mindell, *Our Robots, Ourselves: Robotics and the Myths of Autonomy* (New York: Viking, 2015).