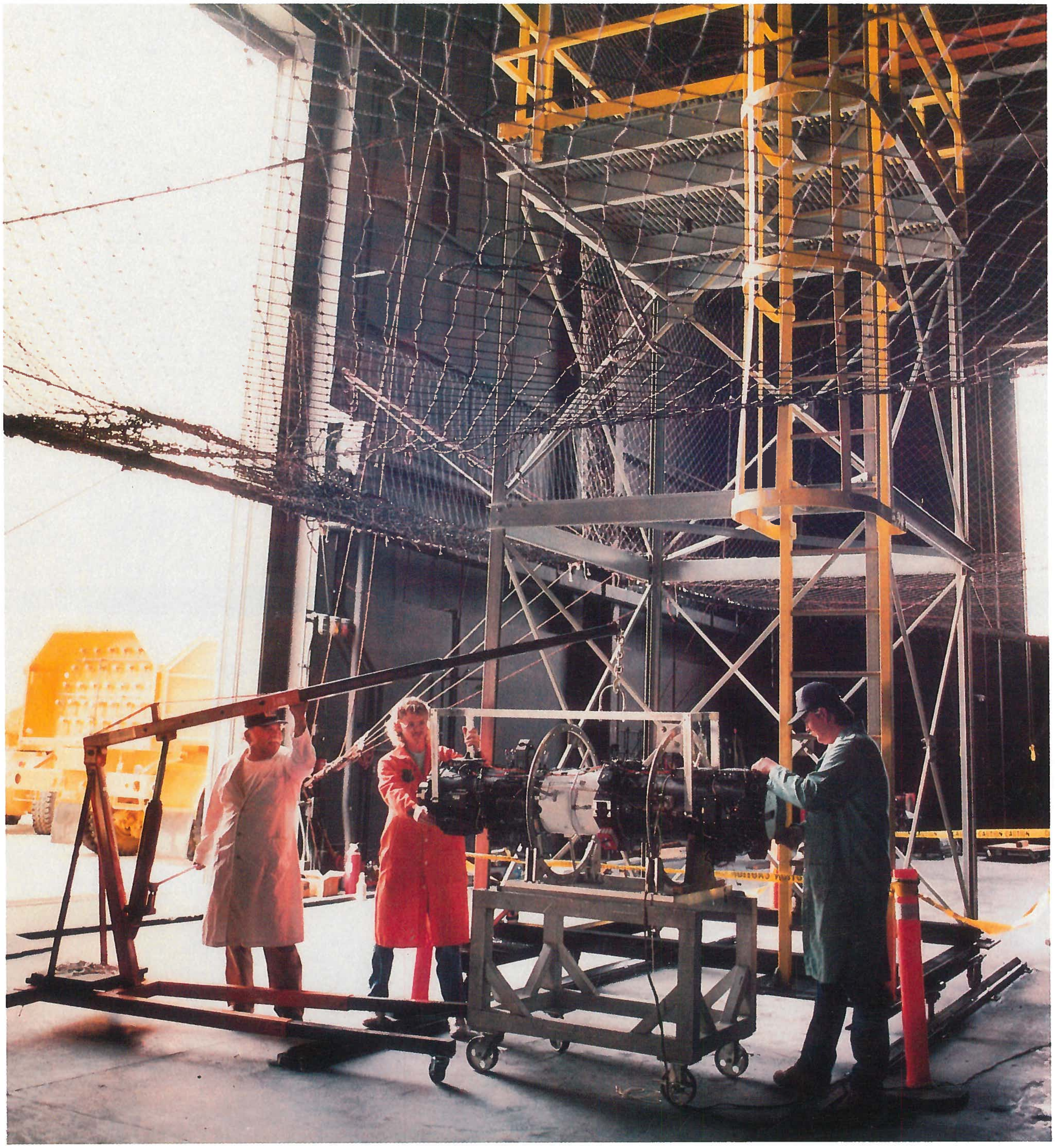
THRESHOLD

NUMBER SIX SPRING 1990



AN ENGINEERING JOURNAL OF POWER TECHNOLOGY

Rockwell International
Rocketdyne Division

COMMENTARY

COMMITMENT is one of those words that we find all too often in a casual context, with little regard for what it really entails. A prime staple of speechmaking, commitment as a way of doing business frequently lasts just beyond the applause. But commitment *to* commitment...that's something else again. Believing the method and the goal demands real stick-to-itiveness and energy.

We think you'll find the genuine article at Rocketdyne. And in Issue Six of *Threshold*, we present five variations on that theme.

First and foremost, a commitment to change, as expressed in our story on Total Quality Management. TQM, which Rocketdyne is now adopting on a division-wide scale, is very much a "revolutionary" way of doing business; one that is characterized by continuous improvement and employee empowerment in an operation where every employee is able to make a difference.

A commitment to find answers—and how the chips really fall—is the impetus involved in forensics engineering. Determining the cause—from which springs the cure—in occasional mysterious ailments in the materials we use is a key factor in quality enhancement.

A commitment to answer and resolve difficult engineering challenges—the ones "they" say simply can't be done—is the subject of our centerpiece article on the hover test program for the kinetic kill vehicle. It's a story of the willingness to commit both capital and energy to a stunning idea, which concludes with the cheers of the people who literally made it fly.

Ongoing research into the subtleties of propulsion is also dramatic evidence of commitment, as detailed in "Building a Better Blade." New investigations in exotic new materials for blade construction offer a potential for greater performance yet in a very demanding context.

And with our story on RHYFL—for Rocketdyne Hypersonic Flow Laboratory—we underscore a commitment to technical advancement that again means putting dollars on the line...which in this case will "bring" the severity of the hypersonic flight environment into the design laboratory in the service of creating the National Aero-Space Plane.

Good reading!

W F Ezell

W. F. Ezell

TQM
Total Quality
Management

THRESHOLD

AN ENGINEERING JOURNAL OF POWER TECHNOLOGY

NUMBER SIX
SPRING 1990

CONTENTS

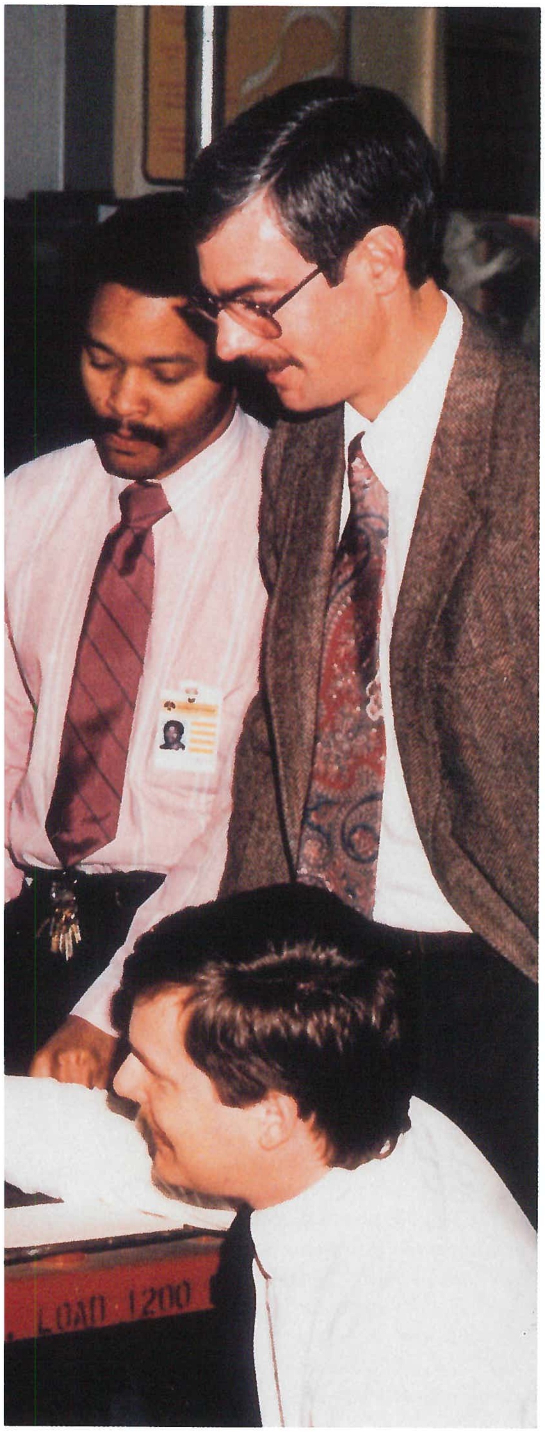
PUBLISHER: W. F. EZELL
EDITOR: J. K. MITCHELL
DESIGN CONCEPT: R. L. HARGRAVE
GRAPHIC ARTIST: M. L. COHEN
DESIGN ASSISTANCE: J. L. ALLSTOTT
AIRBRUSH ARTIST: L. N. ERICKSON
COMPUTER GRAPHICS: J. R. WILL

On the cover:
The kinetic kill test vehicle is readied for flight at Edwards AFB. See story on page 20.

Photography provided by the Rocketdyne photographers R. Felix, W. J. Kavanaugh, D. F. Phelps, Jr., A. R. Thorgusen, E. W. Silverman and S. F. Synoski except as noted.
Technical editing provided by N. S. Derr.
Printed by Rockwell International Corp., Los Angeles Basin Data Services Center.

THRESHOLD is published by Rockwell International Corp., Rocketdyne Division, Canoga Park, California. Opinions expressed are those of the authors and do not necessarily reflect those of Rockwell International. This publication is intended for information only. Its contents neither replace nor revise any material in official manuals or publications. Correspondence may be addressed to: THRESHOLD, Rockwell International, Rocketdyne Division, 6633 Canoga Ave., Canoga Park, CA 91303, Mail Stop AB57.

Members of one of Rocketdyne's original TQM groups, the CPI—continuous process improvement—team for SSME main combustion chamber plating, examine their work.



THE INDUSTRIAL REVOLUTION, PART II

by P. R. Elder

Leading corporations throughout the world are beginning to take a hard look at what it really takes to flourish in an increasingly competitive marketplace. Total Quality Management mandates fundamental changes in design and manufacturing processes and priorities. In a compilation of several "live" discussions, the author details the imperative for American aerospace companies to apply TQM principles.

THE WORD "REVOLUTION" has never rested comfortably with American industry. "Evolution" is the preferred expression, with its implications of easy and logical change in a recognizable and manageable scope. But a revolution is what's brewing in the world marketplace and its name is Total Quality Management. And as most revolutions go, we will either become a part of it or be swept beneath the tide; it's that important, and it will be that pervasive.

TQM is a reexamination of what it takes to sustain a manufacturing business in today's world market where history seems to be stuck in fast forward. It brings with it a realization that some of our most fundamental assumptions about the way we manage may be preventing us from keeping up with the pace of change around us, while at the same time, offering us a viable opportunity for dynamic improvement. Putting its genius to work in the aerospace industry, and in particular, at Rocketdyne, recently has become an urgent part of the work and challenge of the 1990s. And there is much that needs to be done.

***Bob Elder,** Rocketdyne's Director of Total Quality Management, has championed the cause of TQM in the aerospace industry with great distinction. A career Navy man before moving into the private sector, Mr. Elder holds a degree in Engineering from the U.S. Naval Academy and a Masters Aeronautical degree from the Naval Postgraduate School in Monterey, California.*

Most of us are a little uneasy with our understanding of TQM and what it means to us individually and collectively. It is only slightly comforting to know that there is a very checkered experience base on the subject in the United States today. Regrettably, although some industries such as the automobile industry have been struggling with the issue since the 1970s, the aerospace industry has only been alerted in the last two or three years. With some exceptions, it has taken the customer, in this case the Department of Defense (DoD), to drag the industry to the edge of the lake and to force it ankle deep into the water. The DoD has done so because it recognizes the matter as a national issue, one that has national security implications.

Leading Japanese companies that already have an advanced maturity in these techniques, have been developing and refining their philosophy, methods and tools for over 40 years. Ford Motor Company has been hurrying to catch up for most of the decade of the 1980s, but by its own admission they have much further to go. Clearly, there is a long lead time necessary before bottom-line payoff will become apparent. Other industry experience suggests that three to five years are necessary to get started.

For the moment—and this discussion—we will confine ourselves to industry examples that are not our lines of aerospace business, simply because there are not yet good examples available from our sector known to us. But these examples have direct analogies to our business. Indeed, the manufacturing technologies of the automobile business that will be referred to are not that far removed from the ones we use. Furthermore, while there are significant applications of TQM to manufacturing, it turns out that the greatest benefits to be derived come from application in non-manufacturing and manufacturing support functions. This knowledge is applicable universally. But there is no magic. The tools have been around for years. What is different is the context of why—and how—we apply the tools and the emphasis we place on using the tools.

Let's start with a customer and a product you already fully understand: You, and the car you drive.

You are personally involved in the car. You have a feeling about that car that derives from the satisfaction that you spent your money well, and that your needs to get to and from one location to another in a safe and reliable way are being met. That is your base need. Beyond that, the car must satisfy your other expectations, including self-image. However, your feeling for the car and whether you buy another one or not is also part of the total package, along with the service you get from the dealer, should you need it. If any part of the car fails to satisfy your expectations—even if the rest of the car functions well—then your perception of the car as a whole is affected.

When you return to the marketplace to purchase the next car, your choice will depend a great deal on your experience with your current car, your perceived understanding of your friends' experiences with their cars, and the cost of choices you must make. The businessperson who would like to sell you your next car must be very attentive to your wants and needs, not just at the instant of shopping and sale, but for the long haul. You'll be looking for value, based far more on your experience than the promises of the glossy sales brochures.

For his part, the businessperson must be able to provide the product that you need at a price that you can afford and are willing to pay for the perceived value. That price and value must be better than other choices available to you. And that product must be provided on a schedule which will satisfy you.

Compare two scenes that existed in certain automobile factories in the 1970s when many U.S. customers were beginning to vote for the foreign competition in lieu of our domestic automobile sources. Consider an automobile chassis coming down an assembly line:

In a U.S. factory, when the time comes to install the doors, operators place each door on hinges, check for fit, then use shims, rubber mallets and two-by-fours to bend and adjust the door to fit the frame. When done to the satisfaction of the operators (a fairly quick process on a moving assembly line), the vehicle proceeds down the assembly line and at some point through a rain simulation test chamber where water-leak checks are made. Inspectors confirm good or bad. Leaky cars are routed to a rework area where more shimming, rubber mallets, and two-by-fours are applied until there is a satisfactory fit.

Meanwhile, in a foreign auto plant, at the comparable operation of door fit, an operator picks up a door, inserts it on the hinges, closes the door and the vehicle continues down the line, with no bending or fitting required, no rain test chamber, no inspector, no rework line, and the car is ultimately delivered "as is" to a customer in the U.S. The customer of this line has received a product that functions better, is more pleasing to the eye and has a lower cost of manufacture.

TQM principles have even been instituted by Japanese car manufacturers in their American-based facilities, like this Mazda plant in Flat Rock, Michigan. Mazda officials at Flat Rock state that quality here actually surpasses that of their factories in Japan.

Rocketdyne managers at TQM "Boot Camp" undergoing intensive hands-on training in TQM methodology.

Unfortunately, the American factory managers, engineers and manufacturing people have made the assumption that fabricating and assembling doors the way they have been for many years was just the way it had to be done. Everyone knew that the many parts received from various vendors, which were welded and bolted into a door, were built with engineering tolerances and resulted in some tolerance buildup. Hence, the variation in the final product was expected and was accommodated through a trim-shim-bend-to-fit operation. An inspection process was placed to ensure that the trim-shim-bend-to-fit operation was working well. Plus, a rework line was added to ensure that the customer got what he wanted. It was also realized there would be an occasional escape of a defective fit. But a network of dealerships was in place, along with a warranty to take care of these problems. And all of that was accepted.

Until, that is, the foreign competitor came in with the door that always fit, that never needed warranty service, and that was provided at a competitive price because no expense was necessary to support the trim-shim-bend-to-fit operation. No rain test chamber. No inspection operation. No warranty costs. And no fancy marketing to convince the buyer that just because he happened to get a bad door last time, it surely wouldn't happen again.

So what was the difference between the two scenarios? The *consistency* and *uniformity* of the parts being used on the Japanese assembly line. Each part was very, very nearly the same as the one in front of it and the one behind it. Because of this lack of variation, each door looked and performed the same. And since their performance was correct, no inspection or test was required.

In a similar example—but one in which precision machining was used—a U.S. automobile manufacturer was building a car that used a transmission produced by two separate vendors. One vendor was foreign and one domestic. In this case, the engineering drawings used by both competitors were identical. In actual use a specific portion of cars was generating complaints and warranty expense. The complaints, as it turns out, were correlated to some of the cars with transmissions produced by the domestic vendor. The manufacturer was alerted, and to his credit, undertook an analysis of the problem.

Ten transmissions from the foreign vendor were purchased, tested, torn down, and measured in every critical dimension. Of particular interest was the valve body where machining tolerances are very tight and where valve operation is critical to the performance of the transmission.

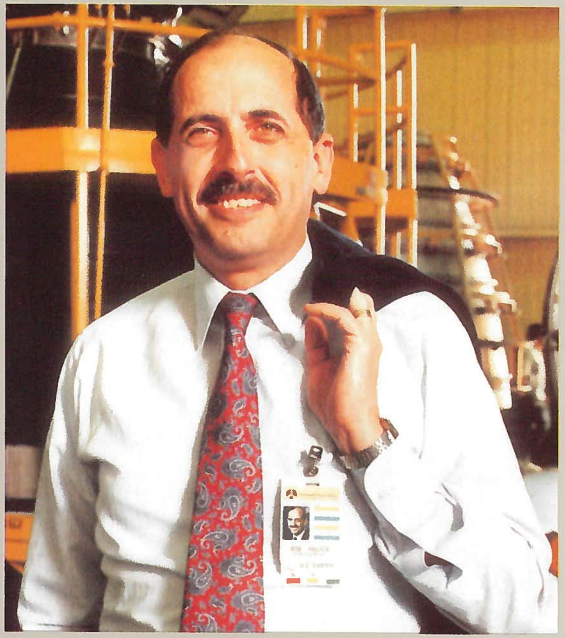
When comparisons were made, some surprising things were discovered. First, the foreign transmissions performed consistently well. Second, an analysis of the conformance of the foreign source dimension control to engineering drawings was extremely precise. Not only were dimensions within engineering drawing tolerances, but the like part-to-part dimensions among the transmissions were tightly grouped. The U.S. vendor's own data indicated that they too were well within engineering tolerances, but the dispersion of part-to-part dimensions was greater. According to the data, the U.S. source was using about 70% of the acceptable tolerances, while the foreign competitor was using only 25% of the acceptable tolerance bands. The result was much better part-to-part consistency, which resulted in more consistent performance in the customer's hands. It should be added that a machine shop that uses only 70% of acceptable engineering tolerances has generally been viewed as a very good machine shop in this country.

Why was there such a disparity? This is not a simple question. It will not be answered in its entirety here, but we must begin to answer and to understand.

First, a key definition: the word *process*. A process is defined as a series of steps or activities that if performed will have a predictable result. Common usage has referred to such manufacturing operations as cleaning or plating. However, the term can and must be greatly expanded to include virtually all work that is done. At Rocketdyne, manufacturing has a host of processes: hole drilling, grinding, milling, turning, deburring, plating, slotting, welding, and many more. Inspection has a number of processes. Away from the factory floor one finds many more: timecards, procurement, dock-to-stock, transportation, design, bid and proposal, even process development.

Now if a process is *in control*, it will produce a *predictable* result. If it is not in control, one is not certain what the result will be. A process may produce defects. A process that is *in control* produces a *predictable* number of defects. A process that is not in control will produce an unpredictable number of defects. A *capable* process is one that is in control and produces essentially no defects. So finally, *if a process exists, it can be measured. If it can be measured, it can be improved.*

In the example of the automobile transmissions, if you consider that the U.S. factory was typically using 70% of the acceptable tolerances, this is considered a capable process with very few defects in terms of deviation from specifications. The defect rate for such a process can be determined to be less than 60 parts out of every million produced. Such a result would normally have been an absolute delight to the factory manager. Yet the foreign competition, using only 27% of the acceptable tolerance band, is approaching a defect rate of a few parts in a *billion*.



ROCKETDYNE is committed to Total Quality Management. As accomplished as the division has become over the years, we're convinced that simply leaning on our technological reputation would be insufficient in an increasingly competitive marketplace. The focus, rather, must be on complete customer satisfaction, which incorporates competitive cost, technological excellence and a trouble-free product delivered on time.

It's a continuing challenge, and one that we must address, because there simply is no viable alternative. Major American companies that continue to get their share of the shrinking pie—and continue to occupy leading roles in world industry—have already embraced the TQM philosophy and methodology, with results that speak eloquently for themselves.

Rocketdyne intends to make a formidable impact on the marketplace in the coming years with an unsurpassed dedication to total customer satisfaction, and we're putting Total Quality Management to work to make sure that it happens.

R D Paster

R. D. Paster
President

Given such a process, how long would your beard be if you were an inspector waiting to detect the defect that might occur somewhere in the next billion parts? More importantly, consider again the resulting uniformity of part-to-part dimensions and the potential of an assembly line that enjoyed racks and bins of such parts. Parts would tend to assemble and perform one like the other. Defects resulting from tolerance buildup would be significantly reduced; probably eliminated. And it follows that the assembly line would very likely be unencumbered by the delays or costs associated with *defect management* such as unnecessary inspection, test, deviations, waivers, or corrective action boards. Finally, the resulting product should be far more likely to be consistent in performance in the customer's hands.

But this is just the beginning. The objective of world class competition is for even tighter control. In this country, Globe Metallurgy, the 1988 winner of the Malcolm Baldridge Award, recently was measured by its customer to be using less than 10% of acceptable specified tolerances. Globe's customer is very comfortable in its expectation of virtually no part-to-part variation, and would be wasting money with source or receipt inspection. Of particular interest is the fact that a very few years ago, Globe was using more than 150% of tolerances and was doing very poorly against its competition. The improvement is attributed to a concerted effort by the company to survive. Today, that customer would make a special effort to protect such a valuable resource.

American industry has traditionally assumed quality could be achieved if we could just build parts to print. This is commonly the objective of so called "Zero Defects" programs. We generally have never even bothered to measure the dimensions inside the tolerance. We have tended to only keep data on defects—those results outside the tolerance. We have very little idea what the distribution of our process results look like. On the other hand, world class competition starts with the parts to print and continues to improve from there.

The results of such strategies are clearly seen in the dramatic shift in the automobile industry and a host of other industries like motorcycles, machine tools, electronics and so many others. The customer votes ultimately, and the customer votes for consistent, superior performance at reasonable price. So it is no longer good enough just to satisfy a customer. A satisfied customer will walk if for no other reason than to try something new. If we wish to be in the game with such competitors, our products and service must delight the customer to such an extent that he or she will demand our product or service over every other competitor.

There are a number of definitions of Total Quality Management available, all of which attempt to get at the subject, but none of which are singularly satisfactory. One of the reasons for this is that people tend to give a definition that is unique to themselves. This is exacerbated by the fact that the term is applied liberally to practically every concept and buzz word used for "new" things in factories today. So rather than a definition, herewith is a list of characteristics which one would expect to see in a world class competitor today, whether he professes to be using Total Quality Management or some other similar approach.

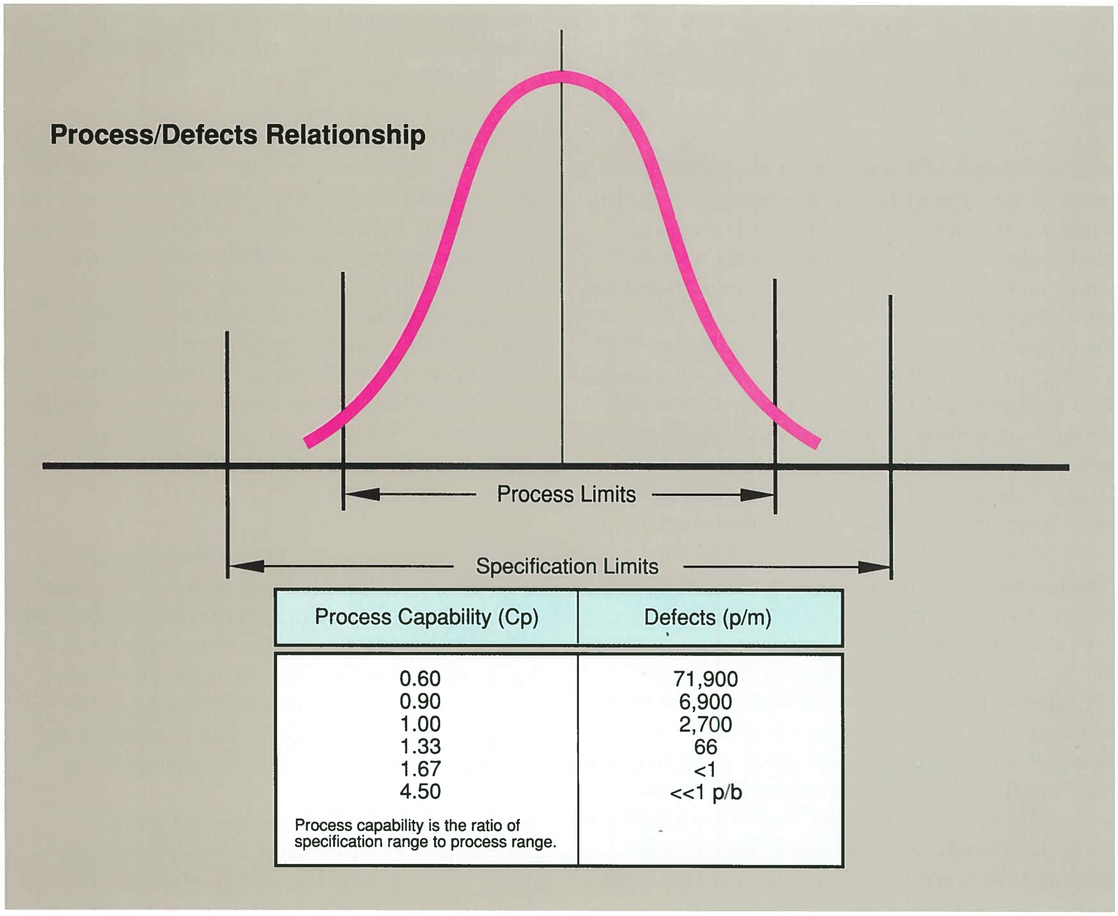
- Quality First (Constancy of Purpose)
- Customer-Oriented (Internal/External)
- Continuous Process Improvement
- Data-Oriented
- Robust, Producible Designs
- Employee Involvement
- Supplier Involvement
- Teamwork Emphasis
- Climate of Mutual Trust and Respect

Each is an indispensable component in the TQM approach. That is, the absence of any one component will significantly reduce or even destroy the effectiveness of the others.

Quality First (Constancy of Purpose). This is based on the well-known first objective dictated by W. Edwards Deming. He states simply that we must recognize that we are in a new economic environment. We must begin a top-down, pervasive strategy which focuses every resource in the enterprise to the plan of producing goods and services for the betterment of the customer and thereby establish our right to remain in business for the long haul. Here the word Quality does not simply refer to defect-free products. It refers with a capital "Q" to an enterprise that provides superior value. It reflects the enterprise that is prepared to make the long-term commitment to its people, its organizations and its capital—perhaps even at the expense of short-term gain—to achieve that end.

Customer-Oriented (Internal and External). Such an enterprise recognizes the priority of the customer. In a macro sense, the external customer establishes the marketplace and makes the choices among products and suppliers. To properly serve this customer, especially on the field of competition, the prudent businessperson must know the customer and the customer's needs intimately. Gaining knowledge about the customer may require a great

Process/Defects Relationship



Process Capability (Cp)	Defects (p/m)
0.60	71,900
0.90	6,900
1.00	2,700
1.33	66
1.67	<1
4.50	<<1 p/b

Process capability is the ratio of specification range to process range.

Quality has traditionally assumed "building to print," as suggested by the Specification Limits on the graph. However, shrinking those tolerances still further to within the Process Limits on the curve results in greater part-to-part uniformity, enhanced defect avoidance, and ultimately, reduced cost.

deal of effort. And once the knowledge is gained, a similar amount of effort may be required to ensure that the knowledge is in the hands of all those people in the enterprise who may need it to guide their day-to-day decision making.

As a subset of the attention to the external customer, focus on the internal customer is a natural extension. We find that each of us in the enterprise is at once a supplier and a customer. Each of us has a customer or customers inside the organization to whom we supply products, services or information. It is these relationships, rather than merely a dogmatic allegiance to a vertical organization, that becomes more important if we are to ultimately satisfy our external customer in the most effective way. For example, product design engineering activities have historically been heavily focused on the external customer requirements; yet the enterprise and the customer are best served if the internal customer—manufacturing—is given nearly equal emphasis. Similarly, engineering is a customer of both manufacturing and quality for process capability data. In the world class organization, these functions serve each other in concert at the individual process level, with a common eye on the customer's ultimate needs.

Continuous Process Improvement. World class companies relentlessly pursue continuous improvement of their enterprise processes. This is at once a philosophy and a structured method to examine each process against its performance in the eyes of the internal or external customer. This philosophy is the basis for all other methods and techniques that are spoken of under the umbrella of Total Quality Management.

The continuous process improvement (CPI) model is normally carried out by a process team that is made up of key members of the process itself, is more or less permanent, and will invest time each day in process improvement. The team begins with a thorough analysis of the process customer's needs, followed by a detailed process examination and documentation. Then follows process data collection, analysis, trouble cause identification and improvement development. Finally, the results are tested against the customer's needs and the cycle repeated on a continuous basis. The objectives of the model are typically defect reduction, variation reduction, and process cycle-time reduction.

Data-Oriented. To permit unimpassioned, objective decision-making in an enterprise, we find world-class companies to be stridently oriented toward the use of data. If a process cannot be measured, then it is little understood. If it is not understood, it certainly cannot be controlled in a predictable way. But if it can be measured, then it can be improved.

Robust, Producible Designs. The single most important phase in the product life-cycle is product development which spans the customer needs determination, and the translation of those needs ultimately into a product design that can be manufactured and delivered to the customer. It is in this critical phase that the ultimate performance and reliability of the product in the hands of the customer is determined. It is at this time that the cost of manufacture and service is determined. The product development process, then, is without doubt the point which requires the greatest focus: the point where the most leverage can be gained from improvement.

The natural evolution of the product development process has led to what has become known as concurrent engineering. Concurrent engineering is the nearly parallel development of the product definition and associated manufacturing processes, with intent to provide the customer a product that will perform consistently even when subjected to the limits of the customer environment. A means to this end is to develop product system engineering to meet those needs and at the same time plan the manufacturing processes that will yield consistent results supporting the intent of the systems engineering even at the limits of the manufacturing environment. Hence we say we are striving for designs that are robust in the customer's environment. This forces us to ensure that we are also yielding a design that is robust in the manufacturing environment. The parallel development leads to mutual optimization of both product and process designs.

Robustness, in this context, means hearty, tough or insensitive. In the customer's perspective, it refers to the ability of the product to perform well repeatedly within a wide range of environments. For example, the electronic pager built by Motorola today is touted to have a mean time between failures approaching 150 years. While you and I will not live that long, such robustness should assure us that it will perform for us reliably throughout our expected use and probably even under adverse conditions like rough handling or variation of operating temperatures.

To manufacturing, a robust process design is one which will yield a consistent product even with normal variation in operator ability, or machine performance, or shop temperature or contamination conditions. It should be understood, as well, that no decision is made to use more expensive manufacturing processes unless it can be shown that the more expensive process is necessary to minimize the overall product cost.

Obviously, creating a robust design places a significant burden on the engineering community. Quality function deployment (QFD) is a planning tool that has been developed to help sort the numerous requirements and place them into a context which better enables the engineer to consider all factors. It starts with an extensive analysis of the customer needs, permits the engineer to compare these with the technology and resources available to the company, and forms a matrix of information on which the engineer can base decisions for further technology or process development.

We find that concurrent engineering is just as applicable to a single product as it is to multiple products. Logically, when all of one's resources are to be spent in the production of a single product, one would like to be certain that the planning is carefully done. As a matter of fact, a Japanese company first used the QFD planning process in a shipyard where the product was a single ship.

Achieving a successful concurrent engineering process has significant implications for up-front effort. As a gauge of the changes that are necessary, the Japanese automobile industry spends 40% of its engineering budget in the joint optimization of product and process designs—in comparison with a historical 2% of budget expended in the United States. However, return on investment can be substantial. Evidence is clear that if properly done, significantly improved product development and production start-up cycle times are achievable, engineering changes that are indicative of start-up problems can be significantly reduced, and all the benefits of improved capability of processes can be realized throughout the production and service cycles of the product.

Employee Empowerment. This philosophy is universally recognized as fundamental to the success of any of these endeavors. The power of continuous process improvement is gained by providing a method in which employees are permitted to fully utilize their knowledge and experience to control and improve the processes in which they are involved. This is a stride away from the classic Taylor model used in the United States for so many years. The Taylor model based its success in U.S. industry on the ability of a few individuals to design repetitive procedures that relatively unskilled workers could do assembly-line fashion. The model made sense when workers were unskilled farmhands new to Henry Ford's factory, but it evolved into a we/they worker management environment that was commonly uncooperative. Worse, it limited an enterprise's ability to improve to the capacity of the minds of the few rather than enabling the special experience, knowledge, and imagination of the workers in the system who dealt with the problems firsthand, day-in and day-out.

In world-class companies, we find a new respect for all members of the enterprise. *Everyone* has a stake in the business and is knowledgeable about the business. Everyone has a means to contribute directly to the business through participation in the CPI or analogous method associated with his or her process. It is through the power of all these minds that the enterprise really begins to reach its potential.

Supplier Involvement. An enterprise striving to achieve high part-to-part consistency with vastly reduced variation cannot even begin without a constructive vendor relationship. Any assembly is only as good as its smallest part. Assurance of product integrity requires cooperative attention to variation control on the part of the company and its vendors. This should not include increased inspection. On a well-known Japanese automobile production line, their vendors actually drive their trucks directly alongside the assembly line and deliver their parts to the assembly line workers for immediate installation. Such a cooperative arrangement must be based on great trust and confidence in the vendor's ability to deliver highly consistent, defect-free parts.

It is also evident that key vendor involvement in the product development process is extremely important. For example, as a member of the concurrent engineering team, the vendor brings to the table special knowledge of his own manufacturing processes. Despite our best efforts, we can easily design a part to be fabricated by the vendor which does not take advantage of the vendor's real potential or which would prove more difficult, costly, or inclined toward defects. On the other hand, a vendor who is made a part of the design effort up front will make a strong team member to the benefit of both enterprises and the customer.

In this environment, one strives for a reduced number of vendors, a number as low as can be prudently tolerated. The vendors selected must be able to demonstrate both sound process control and a management approach which assures a consistent emphasis on continuous improvement.

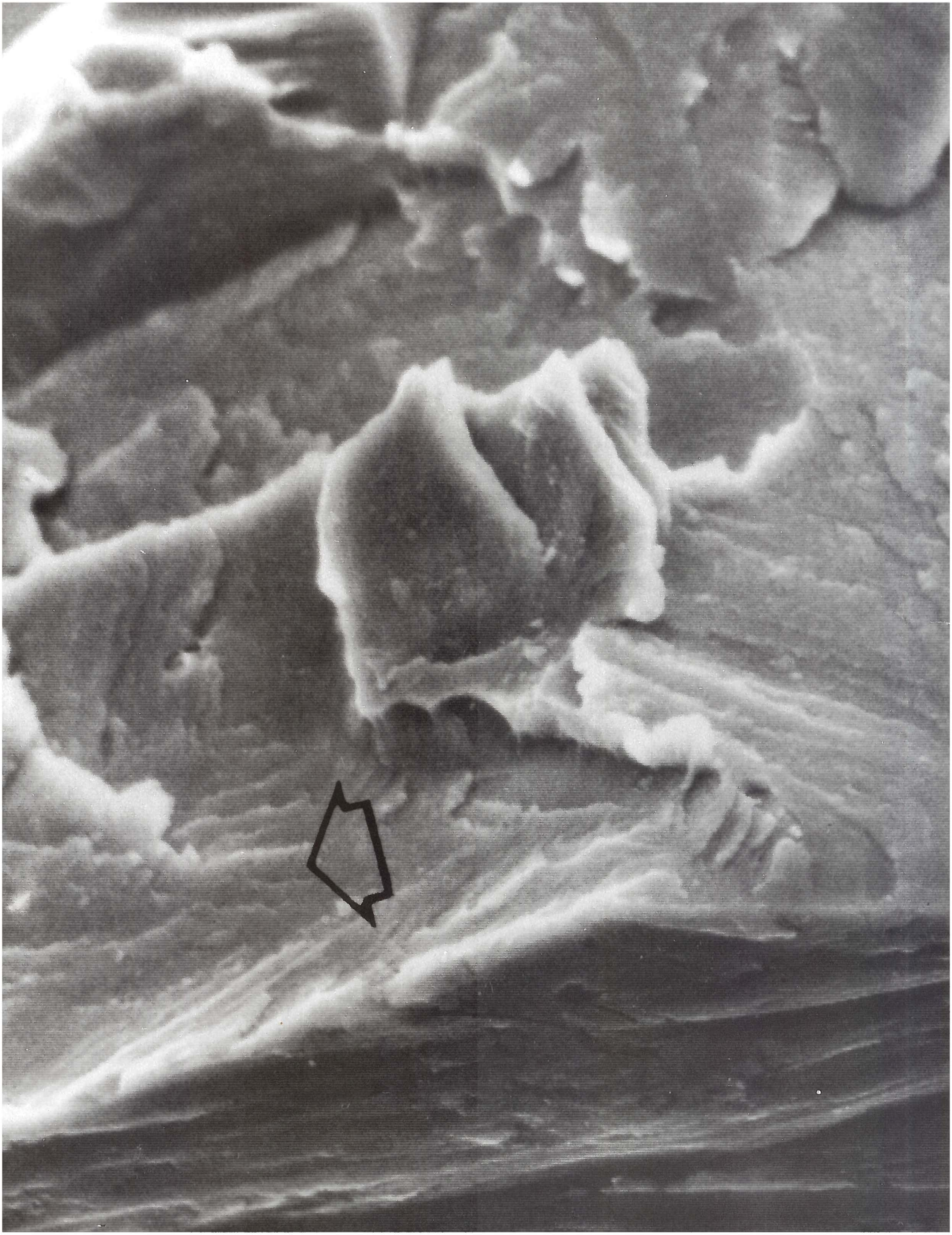
Teamwork Emphasis and Climate of Mutual Trust and Respect. Throughout this treatise, the allusion to teamwork at every level should be obvious. The CPI model is based on the concept of cross-functional team activity aligned with the process under consideration. The concurrent engineering process is dependent on good teaming arrangements, and supplier involvement is an extension of the concept. Indeed, a vital enterprise characteristic is that every member is considered a member of the team, with a stake in the business and potential for reward based on the success of the team.

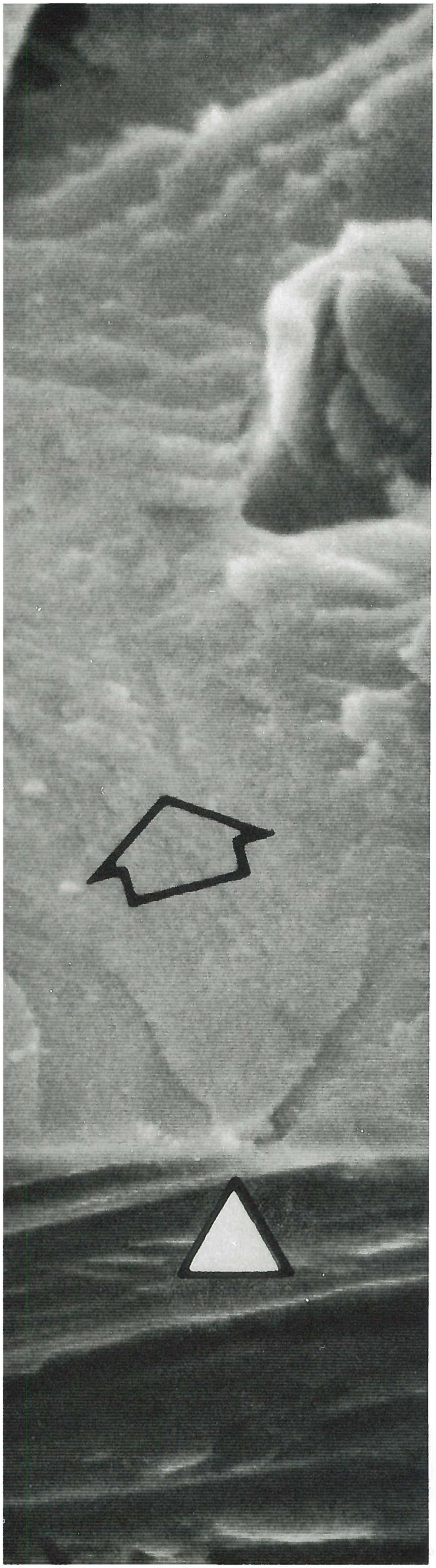
Fundamental to a productive relationship among members of any team is the need for a climate of mutual trust and respect. In the absence of this essence, one should not expect success. Such a climate should be the objective of every manager in the enterprise. But it is perhaps the most difficult to achieve. The right to expect such an environment must be earned by an enlightened management setting the example and wielding the finest touch of personal leadership.

The evolving role of effective management will focus on processes and the people in those processes. Currently, in classic industrial organizations a manager spends an exorbitant amount of time working "brush fires" that seem to spring up at the most inopportune times. Commonly, when I ask managers what portion of their eight-hour day is being spent working at their real jobs instead of peripheral (but perceived essential) activities, the answer that repeatedly comes back is less than two hours. Management's real job, then, is to work on and improve the processes, which can only be done if time is dedicated to that end. TQM, it should be understood, is in no way an abrogation of management's responsibility to manage. On the contrary, management's challenge is to learn about and continuously use these new methods to improve its own effectiveness.

TQM represents a fundamental change and must be understood as such. Our purpose is continued growth and success while providing each member honorable, rewarding employment. To do that, we must adapt our enterprise and ourselves to a rapidly changing world environment. To fail to do so will jeopardize our future. To successfully do so we must continually *earn* our right to serve our customers by providing products and services which exceed his expectations in all aspects of product performance.

If you were Rip Van Winkle, fell asleep today and awakened in five years, you should expect to see profound change reflecting a new adaptation to the world economy and markets. Beyond just keeping up, we must set standards for others to meet. Each of us is involved in this change. We must begin by learning, and we must start now. ■





High magnification (10,000X) SEM view of crack origin on a high-pressure fuel duct. The arrow overlays indicate specific areas and features of the fracture.

FORENSICS ENGINEERING

by M. A. Reid

Tracking down flaws in elaborate propulsion components is a study in discipline and strict procedures. Rocketdyne's forensics group unravels errant fabrication mysteries of daunting subtlety.

BROADLY DEFINED, *forensics* describes any endeavor that is investigative in nature, with its most widely recognized application being in the realm of criminal law, but with similar disciplines in medicine and engineering. Its role with respect to engineering is the identification of the nature and causes behind aberrant hardware, leading to a definition of specific steps to control recurrence. It is a field made necessary because of deficiencies or errors that can develop within the five basic stages of a component's evolution. Those five stages include the raw material (cast or forged), fabrication into finished hardware, storage of the finished component, assembly into final product and the actual operating environment. Considering the complexity of the hardware and the multiplicity of steps and contractors required, plus the performance demands made on materials, there exists potential for deficiencies or errors that can enter the process and compromise performance requirements. For example, the raw material could be flawed in a number of ways, including departures from specified chemistry limits, casting or forging defects. Other factors could include contamination such as inclusions, macro and microstructural requirements and heat treatment to desired strength levels.

Mike Reid *has 23 years experience in seeking solutions to vexing forensics issues in propulsions systems. Mike is a recognized authority in a variety of related fields, including deformation mechanics, high-temperature materials, environmental reactions and microstructure/property relationships. Prior to joining the Rocketdyne Materials Department, Mike spent 17 years in the gas turbine industry.*

Forensics Engineering recognizes all five categories as potential origins for problems and proceeds by a series of analytical steps that identify the specific contributors. The process is both methodical and integrative, moving from observation to interpretation and final conclusion. Most often, more than one factor exists and a further subtlety is introduced, which prompts the necessity of describing the degree of contribution or significance of one factor against another. For example, an environmental problem may also be mixed with machining defects, so the question naturally arises as to whether the factors are synergistic (working together, mutually interdependent) or whether one factor predominates to the exclusion of all others, thereby becoming the primary issue. Rarely does an analysis ever reduce to the simplicity of a single variable. Thus, the more complex discrimination required of a multiple-factor anomaly requires the integration of a great deal of objective data across the five categories. Nevertheless, all data in any forensic effort ultimately provide answers to the nature of the actual mechanism, the contributing factors and the rate of propagation. Effective recurrence control is only possible when the mechanism and its factors have been identified.

To illustrate forensics engineering in action, we selected a real case study involving cracking of the flange of a titanium high pressure fuel turbopump duct used in high pressure liquid hydrogen transport from a storage tank to the Space Shuttle's main engines. The ducting is fabricated from Ti-5Al-5Sn alloy, with a wall thickness of approximately 1.2 inches. During a mission, the operating temperature of the duct is that of the liquid hydrogen, -423°F.

The turbopump duct analysis provides an excellent platform for demonstrating methodology as data are accumulated and integrated from each of the five basic categories.

When the component was received for analysis, the fracture surfaces had not yet been cut open or cleaned (the preferred state) and the entire assembly was relatively intact with little damage or alteration. Low magnification analysis at this initial stage of inquiry focused on three fundamental planes or areas of observation: the relation of the flaw to the component geometry as a whole, the specific surface conditions in relation to the cracks and the crack characteristics themselves.

The flaw was located in the fillet radius of the turbopump flange. Although the flange is welded to the body of the duct, the crack location was displaced too far to suggest any influence from the weld process. But radii geometrically may become regions of stress concentration, particularly in this case where misalignment may have occurred during torquing of the flange to the mating assembly. The surface finish was evaluated under low power magnification. There were no indications of improper fabrication and there was no visible evidence of corrosion.

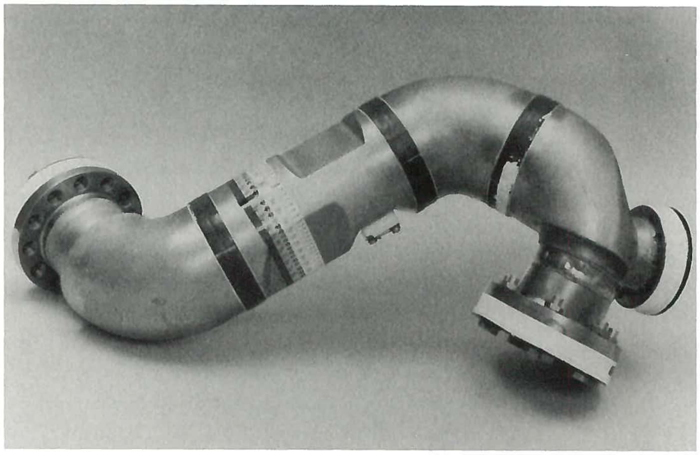
With respect to crack characteristics, the opening was significant: It was easy enough to see without visual aid and was as much as 0.008 inch in width, a reflection of significant strain. A qualitative sense of the assembly and/or operating strain level is one of the most important variables to define in the course of a forensics effort, and the measure of unwanted or excessive levels of strain can manifest itself in a variety of ways, including, at this early stage, the crack width. Other observations gathered during the course of the analysis would add support to this early suggestion, ultimately leading to the conclusion that significant stresses were operative in the radius portion of the flange during crack propagation and that assembly preload was a contributing element.

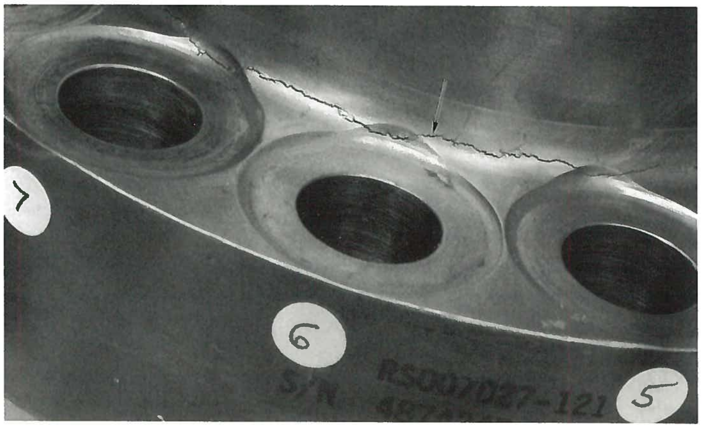
The actual fracture surfaces are the most prolific source of data on a flaw mechanism, and once all possible information had been gleaned from the duct in the as-received condition, effort was turned toward cutting the cracks from the flange, care being taken to prevent any burning or subsequent damage.

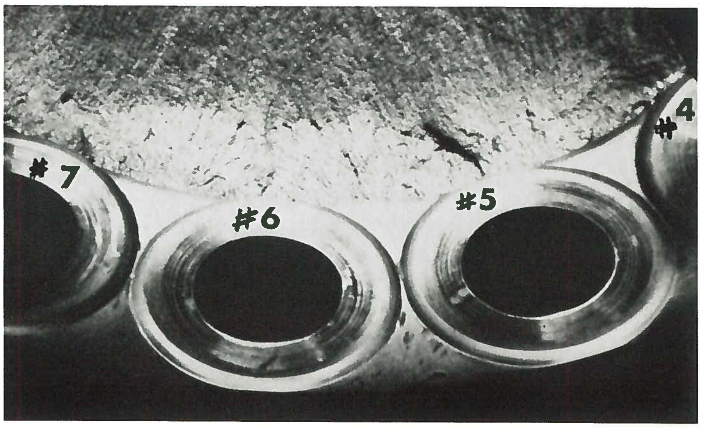
Although detailed knowledge of the mechanism would await use of the scanning electron microscope, understanding continued even at the low magnifications. Dimensional considerations such as depth and aspect ratio, presence of arrest lines and texture changes across the crack depth, origin placement and direction of propagation, surface conditions, environmental interaction in the form of oxidation or corrosion, crystallographic characteristics, temperatures and incidence of secondary cracking are the types of features that may become apparent. Depth was significant. Also, crack initiation was not single-origin, but clearly multiple-origin in nature, a reflection of either relatively high stresses or a degraded surface condition. There were also indications of a change in the propagation mechanism across the one-inch depth, although definition of such was impossible to make at this stage.

Along with this low magnification input, material was cut from the flange for chemistry and microstructural analysis which, along with the supplier's certification, would provide a basis for assessing material integrity. The resulting chemical analysis, suppliers tests (tensile properties at room temperature and -423°F) and metallographic cross sections all met specification requirements. However, the same cross sections that validated the microstructure revealed a thin, precracked surface zone of 0.000050 inch average thickness across the fillet radius. The zone reflected an oxygen-enriched layer that formed during an 1150°F, post-weld stress relief anneal which, because of titanium's natural reactivity, must be done in argon or a vacuum to prevent contamination at temperature. The consequence of the oxygen enrichment is a low ductility, relatively brittle character imparted to the surface, an affect that was demonstrated by the precracked condition observed in the metallography. Although crack dimensions this small evaporate in significance from a fracture mechanics perspective, they assumed a growing level of importance as the mechanism was identified and understood, in the end becoming, along with preload strain, a contributing element to crack initiation.

Up to this point, nothing has been said about the actual crack mechanism, only the exposition of factors that contributed to its initiation. The reason is that the data most explicit of that mechanism quite naturally reside on the fracture surfaces themselves. Direct detailed examination of that surface requires instrumental analysis of a sophistication exceeding prior operations, specifically, the scanning electron microscope (SEM). The SEM is an instrument capable of direct viewing at very high magnifications in a vacuum chamber (up to 35,000X with no surface enhancement preparation). A stream of electrons "illuminates" the object (rather than light), with a resulting depth of field and resolution far superior to that of a standard light source. Because of the SEM's capabilities, the next stage in the analysis—fractography—becomes the most comprehensive and productive of all the phases in a forensics methodology.







Top: View of high-pressure fuel duct showing fracture location in as-received condition. Middle: Flange view showing radius cracking. Bottom: Opened fracture at radius location.

Fractography is the science of interpreting fracture detail, with the goal of conclusively resolving the identity of the mechanism, be it mechanical (fatigue, stress, rupture, creep, overload), environmental (corrosion, stress corrosion, intergranular oxidation, hydrogen embrittlement) or a combination of the two. It is interdisciplinary in nature, combining crystallography, deformation mechanics, physical metallurgy and physical chemistry. The field is made possible not only because of the unique set of variables that comprise each of the major categories, but also because of the ability of metals to deform plastically and translate those variables into visible characteristic "signatures." The amount of detail comprising that signature can be incredible in scope. And with the SEM new aspects of the fracture process come into view by increasing the level of magnification, with the ceiling level limited only by one's ability to interpret what he sees.

With some mechanisms—such as hydrogen embrittlement in nickel alloys—the mechanism of crack propagation may not become visible until analysis reaches magnifications of 10,000X. But it is this very capability that also requires a strict methodology; indeed, in fractography, methodology and patience make up half the required skill. In fact, many errors in this field, especially as applied to forensics, arise not from a lack of interpretative ability, but from a failure to adopt an ordered and methodical approach to the analysis. At 10,000X, for example, a one-inch-long crack surface suggests a real-world length of over 833 *feet* ! With that kind of visual expansion and magnified surface area it's possible to waste a good deal of time going nowhere or covering only a limited portion of the crack history. Thus, we begin scans at clearly defined origins and trace their way along single vectors that proceed from those origins to the fracture perimeter, thereby covering all stages (and changes) in the propagation mechanism. Magnification along a vector is increased in stages from low (up to 1000X), to medium (1000 to 5000X), to high magnifications (5000 to 20,000X or higher, as need and resolution permit). As the magnification is increased, the amount of detail present to the observer becomes considerable, so there is a need to categorize the detail that may be present on the fracture. This trains one to specifically look for features, so that when combined with a patterned scan, nothing is missed. Those categories of detail include overall fracture profile, magnitude and nature of plasticity, defect structure, microstructural detail, secondary cracking (does it exist, and what type), propagation characteristics, nonmetallic residue and arrest lines. To one degree or another, this is the detail that may be present during viewing and, when properly interpreted and integrated with other analyses, contribute to a final answer.

With magnifications of 3000X and higher, details finally appeared that suggested the mechanism. A mixed plastic/brittle mosaic characterized the surface structure, with the plasticity outlining a lens-shaped or platelike phase that averaged only a micron in size (0.000040 inch) and was consistently ordered in a crystallographic pattern. The features were not only reflective of a solid-state precipitation process but also of a process that occurred in the assembled state: in other words, a strain-induced precipitation. The features could not be explained by any constituents normally resident within the material microstructure since earlier metallography failed to reveal any discontinuous phase that even approached the characteristics of the fracture. Examination of applicable literature and of lab samples tested under controlled conditions, however, confirmed that the features reflected a brittle titanium hydride phase. The mechanical properties of any alloy system are a reflection of the microstructure and its constituents, and the appearance of the brittle hydride within a plastic matrix set into motion a crack propagation that was not possible beforehand. The actual crack advance was commensurate with the localized appearance—and subsequent cleavage fracture—of the hydride plates. What was surprising and unsuspected was the elusive nature of the phase. The phase was stable (and therefore visible) only in the immediate locale of the crack tip. As the crack proceeded into the duct wall, the hydride phase left in its wake would soon become unstable and dissolve back into the microstructure, leaving only a thin, lens-shaped plastic frame to evidence its prior existence. Much like a shoe size, the frame fit the dimensions and shape suggested by the literature and the lab samples, leading to confirmation of the fracture mechanism.

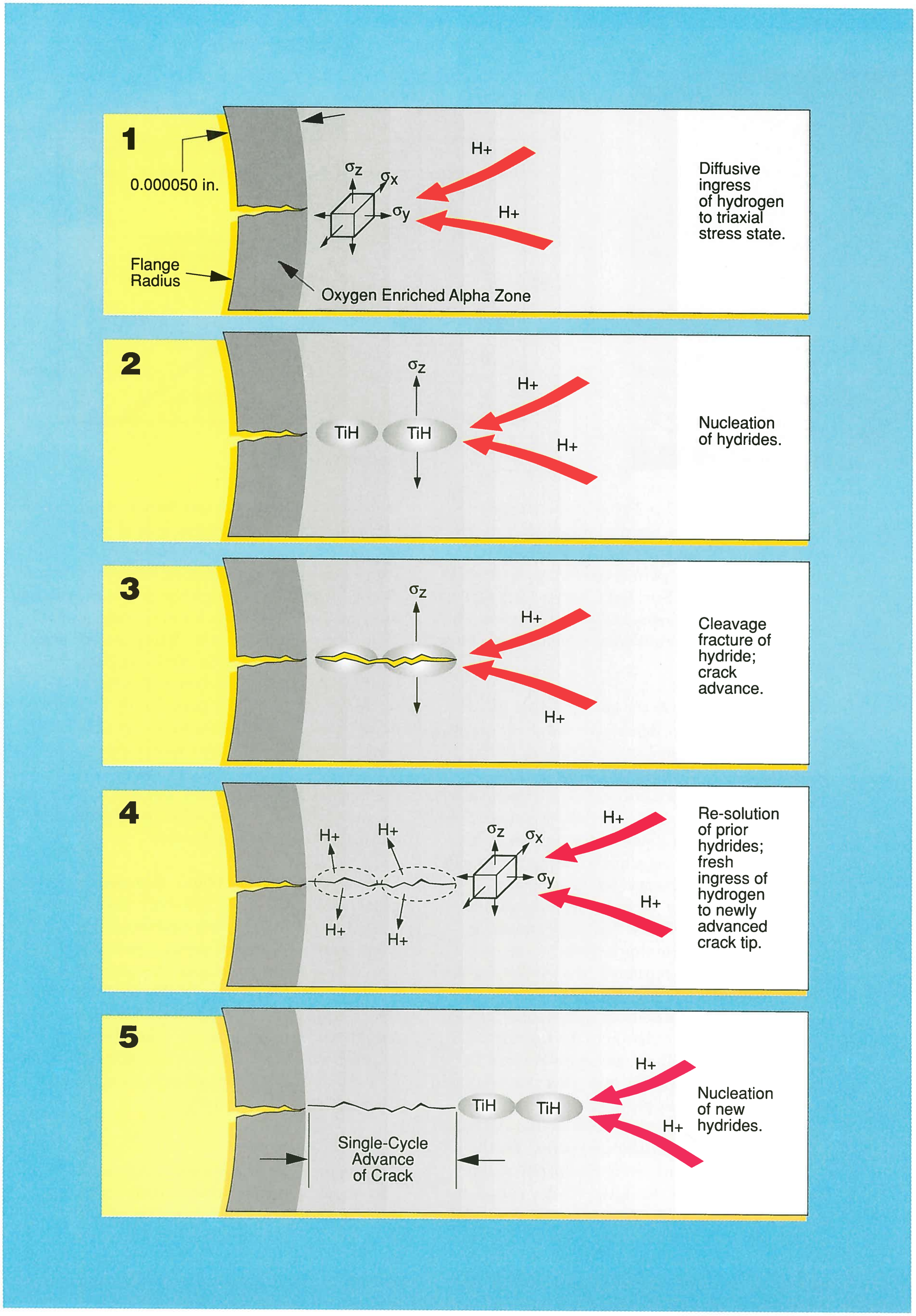
The following statement was drawn from the conclusions section of a report on the matter and very concisely draws together the results of the forensics effort:

"Scanning Electron Microscope analysis in conjunction with literature and exemplar fractography from lab simulation tests conclusively identified the fracture mode of the Ti-5Al-2.5Sn HPFTP duct S/N 4872885 F-5 flange as sustained-load, internal hydrogen embrittlement. The fundamental operating mechanism in crack propagation was strain-induced precipitation and subsequent cleavage fracture of brittle titanium hydride phase, contributed by high-preload strain from duct installation. Propagation was a function of calendar time, assembly preload and ambient temperature conditions, growth continuing throughout the 246 days (0.67 year) of installation time."

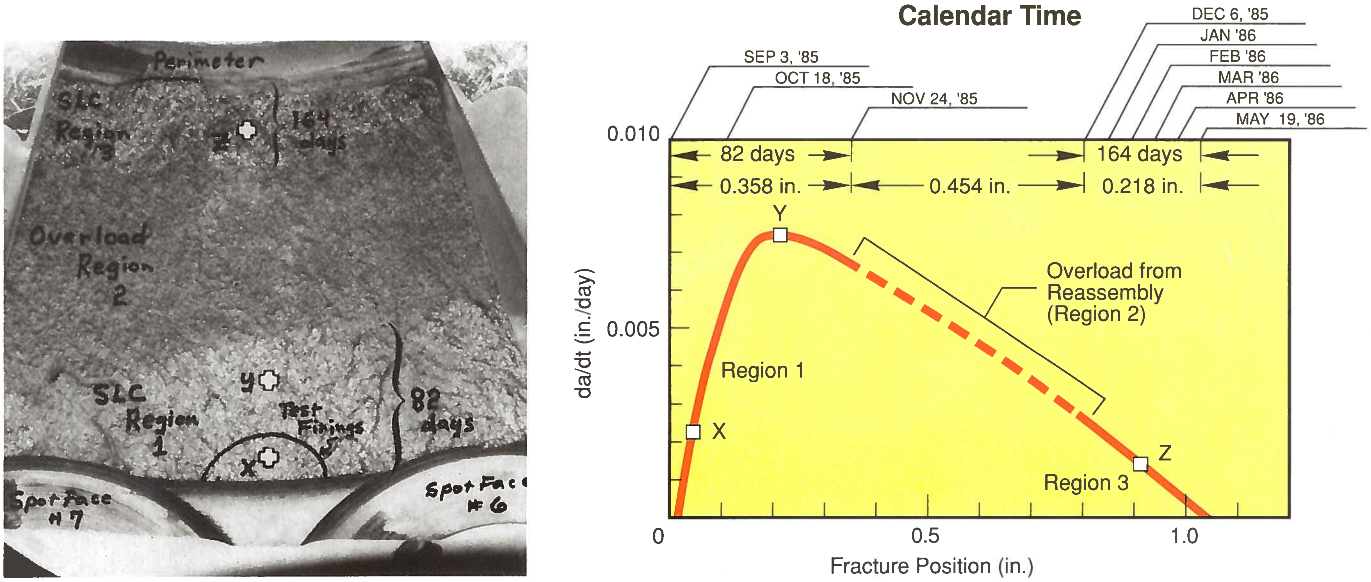
The nature of the mechanism as hydrogen embrittlement also explained the role of the precracked, oxygen enriched zone noted earlier. The cracks acted as trapping sites for localized hydrogen buildup and subsequent multiple-origin crack initiation.

One major effort remained. It now became evident that inspection of ducts in the field would benefit from our new knowledge of crack growth rates for the sustained load mechanism. There was no guarantee that lab testing alone could generate data in time to meet launch schedules. Fortunately, the advantage of rate data taken directly from the fracture was that all of the potential factors already existed in the component, with resulting rates and trends that represented a natural (operating) environment, as opposed to the possible deficiencies intrinsic to a lab simulation.

Such analysis is possible from a fractographic perspective because changes in the operating history or assembled state of a component tend to translate such action directly onto the fracture surface—either as a change in the actual propagation mechanism or as topographical steps or delineations



A history of fracture propagation is illustrated in the following series, from initial hydrogen buildup at a precrack location to cleavage fracture of the brittle hydride phase.



Identification of fracture characteristics allows translation of detail into calendar time—shown at right. Note that the crack growth tends to accelerate rapidly within the first 82 days of assembly, and then decelerates within the remaining 164 days of installation.

called arrest lines. Correlation of specific arrest lines with the history permit growth rates in the form of crack advance per unit time (da/dt); multiple data points permit trends (acceleration or deceleration) to be identified. Arrest lines that can be correlated with history thereby enclose known periods of operating time from which growth rates can be calculated.

The calendar history of the analyzed duct divided itself into three main stages: An initial, 82-day-long preload or torqued state; a middle, 12-day period of disassembly (no preload strain); and a final reinstallation for 164 additional days of preload. Thus, a total of 246 days of preload strain occurred, with a single, near-midpoint interruption. This three-stage calendar sequence corresponded exactly with the fracture sequence, forensics having identified three principal stages of propagation: two areas of sustained load hydrogen embrittlement, one at the beginning and one at the end of the 1.03-inch crack, separated by a middle region of tensile overload. The tensile overload region was the product of the reassembly and became the key event, permitting correlation of the fracture with the two stages of preload. So expressive was the fracture of this one specific operation that one could even identify the multiple advances by overload that resulted as the thirteen bolts around the flange circumference were torqued into place. Further, two separate test firings were conducted almost within the middle of the initial 82-day period of preload, four days apart. Over the course of many weeks, low magnification analysis of the fracture had identified a small "band," almost a perfect semi-circle in shape, that was finally seen as two arrest lines spaced close together (and almost unresolvable as such at low magnification), representing the double test firings. Our analysis confirmed that the band was, indeed, two individual arrest lines spaced 0.009 inch apart. Each of the two lines evidently formed when the stress of the hydrogen flow through the duct during firing was translated to the crack tip, forming a small delineation on the fracture. Using growth rates taken from the earlier described mapping, the 0.009-inch distance between the two arrests converted into a 3.9-day period, only 1/10 of a day difference from the actual 4 days of calendar time. That correspondence was far-reaching in its significance, not only with respect to verifying the placement of the test firings, but also in affirming the dependence of propagation on calendar time (day/night ambient conditions).

Little remained at this point. Sustained load crack growth across the 1.03-inch crack was distilled into three data points, yielding a parabolic rate curve when plotted relative to depth, a profile that agreed very well with the stress intensity plot which was also parabolic (a reflection of the synergism between the mechanism and strain). The maximum growth rate, 0.007 inch/day, was the value then used to establish inspection intervals for ducts in the field for positive assurance of safe operation, even with the potential crack anomaly.

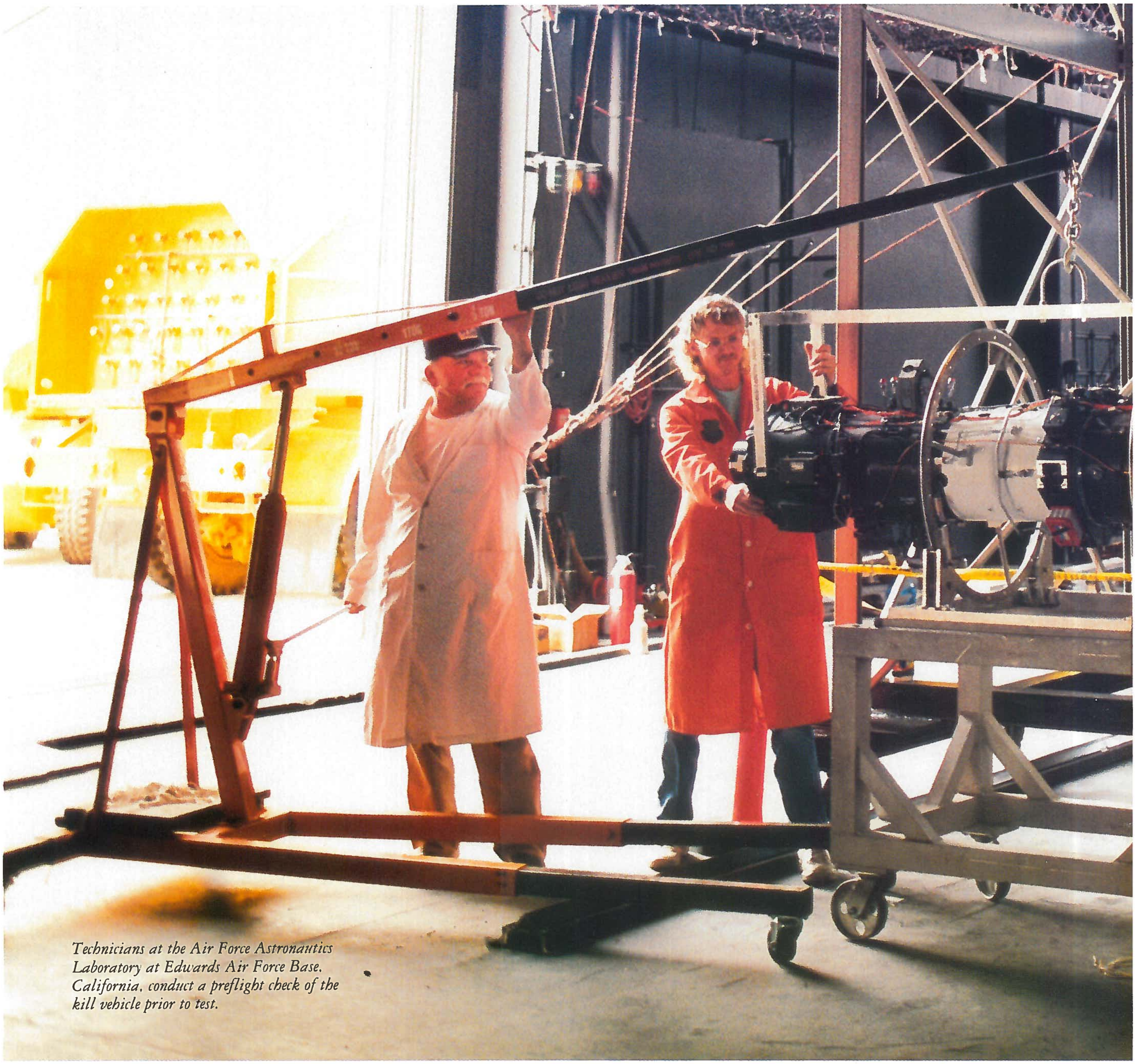
The previous discussion elaborates on a forensics exercise that actually took many months to complete and, in reality, did not always flow as well as might have been suggested. Environmental mechanisms, particularly hydrogen embrittlement, can be very deceptive and often are extremely difficult to analyze. The present case was no exception. But the success of the results demonstrates the viability of the discipline from a number of perspectives.

First, intelligent and effective recurrence control is possible only when the mechanism and its contributing elements have been identified. In the case of our duct, both preload strain and the precracked oxygen-enriched zone were contributors. The problem of the zone on future ducts was resolved by committing post-weld stress relief to a vacuum heat-treat, not an argon atmosphere with its potential for introducing contamination. Preload strain, the other contributing factor, was reduced and since application of this requirement to the duct assembly, flange cracking has been all but eliminated. Oftentimes, however, a short range solution is needed because of what may be a significant turnaround time to effect design or manufacturing changes. In these cases, the contributing factors, in whole or part, and the potential for cracking remain, and continued hardware usage may now be based on inspection intervals so scheduled as to preclude growth reaching a depth or size before launch that would impede performance. In the case of the duct, structural analysis had determined the minimum depth of circumferential crack needed to effect hydrogen leakage through or across the flange seal from preload loss. With maximum growth rates taken directly from the fracture it was possible to calculate the number of days required to reach that critical size (along with a safety factor). That period defined the required inspection interval, the maximum number of days before launch allowed for part inspection. Propagation of any cracks initiating between that last inspection and the launch would therefore represent a subcritical size.

Forensics, thus, not only serves a long-range solution by eliminating factors behind anomalies but can also deal with the more complex, short-range issues created by production and operation schedules. This is one example of how forensics engineering has led to long- and short-term solutions to complex issues—through thorough understanding of all aspects of the phenomenon. Similar approaches are applied daily to both simple and complex issues arising in the kind of hardware that we work with every day. Significant environmental considerations, severe and variable load conditions, and superalloys with little or no general industrial use continually provide opportunities for innovative application of available investigative tools and analytical techniques. It's never less than challenging. ■

PROOF OF PRINCIPLE: THE KINETIC KILL VEHICLE

by W. G. Burns



Technicians at the Air Force Astronautics Laboratory at Edwards Air Force Base, California, conduct a preflight check of the kill vehicle prior to test.

Against formidable technological odds, Rocketdyne engineers have designed, built and flown a prototype "kinetic kill vehicle" that could be a key element in a space-borne missile defense system. In the process, Rocketdyne has demonstrated an ability to construct complete spacecraft systems and effect stunning new miniaturization in propulsion design, all at a fraction of projected costs.

AN EFFECTIVE DETERRENT against a space-based weapon, military satellite or ballistic missile system, regardless of the point of origin, remains a major concern of military and governmental agencies. While the reality of an active threat from traditional Cold War adversaries has seemingly lessened in recent times, there is still ample reason to maintain American vigilance, especially in view of the potential for incursions from Third World factions. To mount such a deterrent, the Strategic Defense Initiative Office and other Department of Defense agencies are now developing several defensive technological schemes, including both ground-based and space-based weapons that can be characterized as directed energy or kinetic energy systems. Simply stated, directed energy systems employ lasers, particle beams or other similar energy forms to defeat a given threat target. Kinetic energy weapons—the subject of our discussions here—employ a "kinetic kill vehicle," or KKV, to strike and thereby destroy the threat target. A KKV, depending on the target to be addressed, may reside on a space-based platform orbiting the earth, or on a ground/sea-based missile which could be launched to a point in space where the KKV would be separated to travel to target impact. In a space-based scenario the KKV would separate from its platform and maneuver to position itself to impact the target, thus destroying it without the use of conventional or nuclear explosives.

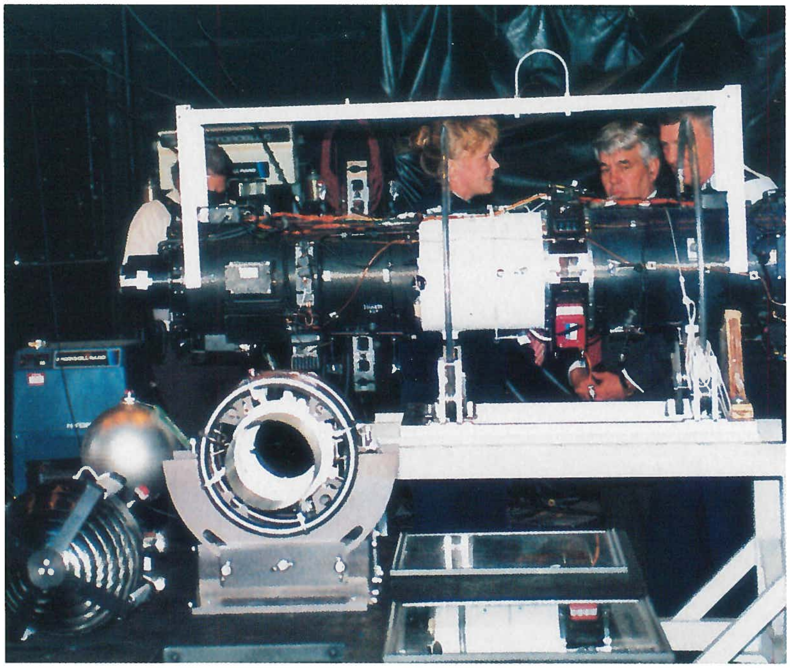
What we will describe here are not projections for the future. They are prototypes that exist, that work and that are flying today, thanks largely to an especially focused and dedicated group of engineers who believed—in the face of considerable skepticism— that the job could be done, and then set about doing it.

***Bill Burns** brings more than two decades of missile development and design to his position as KHIT Program Manager at Rocketdyne. Along with his extensive experience in Air Force defensive hardware systems. Mr. Burns has also served as an instructor in aerospace studies at Georgia Tech.*

Former SDIO chief Gen. James Abramson and staff are briefed early in May of 1989 on vehicle technology just prior to a test flight.

The working vehicle that we know as KHIT—for Kinetic Kill Vehicle Hover Intercept Test program—is the proof-of-principle of technological requirements first advanced as a part of the SABIR program. SABIR—for space-based interceptor—calls for an orbiting mechanism that can not only perceive the appearance of an approaching missile, but identify it as friend or foe as well...and then automatically take action. If friend, do nothing; if foe, destroy it, simply by flying into it at full speed. Given the tremendous velocities involved—perhaps a combined speed of 30,000 miles per hour—there would be no need for a warhead of any kind.

Much is involved in achieving intercept, especially in maintaining the stability of the vehicle; or, as it is expressed, creating a "stable three-axis platform." Essential to the success of the space-based vehicle is the ability to "see" an approaching missile over great distances in the "plume" stage of ascent. By necessity, the "eye" or seeker of the kill vehicle has a very narrow field of vision in order to see thousands of miles, so maintaining precise direction and attitude is paramount. According to SABIR specifications, movement over three axes—pitch, roll or yaw—of the "platform" must be limited to ±4 mradians, or one-fourth of one degree. Only then could the seeker function well enough to ensure target acquisition and allow the vehicle to race across the fringes of space and collide with the assailant. To create a kill vehicle that could do that required not only the development of the individual components, but their integration into a complete and reliable system as well.



Air Force Lieutenant Sue Hall and AFAL facility director Dr. Richard R. Weiss confer near vehicle.

In June 1985 Rocketdyne initiated the Kinetic Energy Weapon (KEW) Divert Propulsion Technology Verification and Risk Reduction program. Undertaken for the Air Force Astronautics Laboratory (AFAL) at Edwards AFB in California, this effort identified critical propulsion parameters and technology for KKVs using near-term, low-to-medium-risk technology components. Through a series of mission and system tradeoff studies, critical components were chosen for the KKV system. In addition, critical component design requirements were established, such as engine thrust, chamber pressure and response, mission duty cycles, system configuration, center-of-gravity (cg) control and propellant loads.

Early consensus was that the vehicle would require eight separate thrusters: four thrusters for divert maneuvers and four ACS thrusters for attitude control purposes—a totally original design. A structure and new propellant tanks capable of holding storable hypergolic propellants for long periods of time were also needed, along with a pressurant tank and valves. Working from Rocketdyne design performance specifications, the components were prepared by several vendors.

Under the Technology Program, Rocketdyne started to design and build the individual components. As the first of its kind, the kinetic kill vehicle would develop and emulate SABIR-specified flight control laws, with form very much following function. From the outset a lightweight system has been a primary requirement, especially with regard to deployment and actual performance, so components were designed with size as a key parameter. And again, the high impact velocities that would be encountered suggest that a projectile no larger than a golfball could do the job.

The components selected for development and technology advancement were a 400-pound thrust bipropellant divert engine, a 5-pound thrust bipropellant ACS engine, spherical aluminum diaphragmed propellant tanks and a 10,000 psig storage, regulated helium pressurization system. Then a system testbed was used to verify the critical system component interactions, with key emphasis on light weight, while at the same time using low-to-medium-risk technology. The components selected were actually designed and fabricated in both heavyweight and flightweight versions, and were tested in configurations that involved combinations of both. Now came the critical Rocketdyne task: putting everything together into a kill vehicle that could fly—a feat that had never before been accomplished.

Evolving from this risk-reduction technology program in 1987 was KHIT, the kinetic kill vehicle hover intercept test program. Emphasis in the program focused on the design and fabrication of an experimental vehicle using the propulsion components designed and developed under the basic technology program. The remainder of the kill vehicle's components were "off the shelf," all to create a vehicle that would be reusable as a basic test article. A breadboard avionics system was designed and assembled, including an on-board control inertial reference unit (IRU), as well as a flight control ground station. And equally important, Rocketdyne developed and activated the first KKV flight test facility for and with the Air Force Astronautics Lab at the AFAL site to conduct the flight test program, which would include actual required ground and in-flight KKV operations. The solid and cohesive Air Force-Rocketdyne team that evolved from this cooperative effort, it should be said, was the key ingredient to the success of KHIT.

The 150-pound workhorse KKV, unlike the expendable space application, is a basic test device capable of multiple uses, exhibiting serviceability, and flexibility for multiple test objectives. A modular approach has been implemented which enables easy replacement of the major components; i.e., the structure assembly, a propellant module, a pressurization module and an avionics "suite." Further, all of the modules, engines and other components are interchangeable between separate vehicles and positions. In addition, the propulsion system contains a pressurant tank and extra service and pyrotechnic valves, as required for test operations.

In typical operation, the KKV is loaded with propellants (nitrogen tetroxide/monomethyl hydrazine) and helium pressurant and installed on a launch cradle platform at a 10-foot elevation. The position and alignment of the kill vehicle's IRU to the test building coordinates are precisely controlled and measured using an electronic leveling device, while an umbilical provides electrical power and controls for pretest system integration checks. A separate umbilical provides gaseous nitrogen preflight cooling for the avionics, particularly the IRU and power supply.

Initial test profiles have consisted of a set of programmed intercept maneuvers, including liftoff, horizontal divert-controlled translation, ACS stabilization and set-down. Action begins with a signal to fire the isolation valves to allow pressurization of the propellant tanks, and then opening the propellant lines to the engine system. The power umbilical is released and the vehicle is switched from ground to on-board battery power, while the cooling umbilical is remotely disconnected. The vehicle lifts off the launch cradle by firing the bottom divert engine in a pulsing mode (a series of 50 millisecond on-time pulses), rising to a position about 13 feet above the launch point.

At the same time the launch cradle retracts downward from the capture net. The IRU data are downlinked to the ground console, and the engine valve commands are uplinked to the vehicle. The ACS will correct for thruster misalignment and cg migration. A lateral divert translation is accomplished by a single roll of the vehicle and divert thruster action, a method of correcting for axial position. Near the end of the flight the vehicle is brought down to a position seven feet above the net and is allowed to drop into it. Then the vehicle is secured remotely via telemetry by closing the valves that isolate the propellant feed lines and venting the helium pressure from the pressurant and propellant tanks. The unpressurized vehicle is then safe for handling.

Postflight test servicing of the vehicle is accomplished by decontaminating the propellant systems and removing the propellant and pressurant modules. The pressurant module is serviced by replacing two isolation valves; the expendable propellant module is replaced; and the engines are inspected and serviced or replaced as required. Thus, the vehicle can be rapidly prepared to support the next flight.

The current KHIT program was initiated on September 15, 1987. The first nine months of effort centered on developing the KKV propulsion/structure and avionics hardware systems configuration, formulating and validating system software, constructing the test facility and preparing ground static and flight test operating procedures.

During the period from mid-June to early October 1987, a series of three static firings of the KHIT vehicle was conducted in preparation for the planned first flight in November 1988.

The first static firing employed the propulsion system only, using heavyweight facility propellant tanks. Designated as the Facility Activation Test, each divert and ACS engine was cycled for a one-second burn. In addition, various combinations of simultaneous divert/ACS firings were accomplished. This served to activate the test facility, validate ground static test procedures, while providing initial data relative to simultaneous/multiple engine firings.

In late July, a second static propulsion test consisted of a complete 26.7-second mission duty cycle firing. A complete success, this test confirmed that all engines fired as commanded—and as they would be required to do in flight.

The static series culminated in a complete systems integration test conducted in early October. The test configuration employed both flightweight propellant tanks and avionics for the first time; the system was complete essentially as it would be for flight except that facsimile IRU data were employed for engine valve command. The KHIT system performed flawlessly during this test, thus providing the margin of confidence needed to proceed forward to freeflight testing.

The first KHIT freeflight tests were conducted in November and December 1988—and quickly revealed problems in the control systems. Though scheduled for a flight duration of 21.6 seconds, the test was aborted early on. Yet even at that, the primary objective was still attained: the achievement of "hover," to the cheers and shouts

The entire AFAL/Rocketdyne testing crew at the Edwards AFB site. The occasion was the successful conclusion of the first test flight.

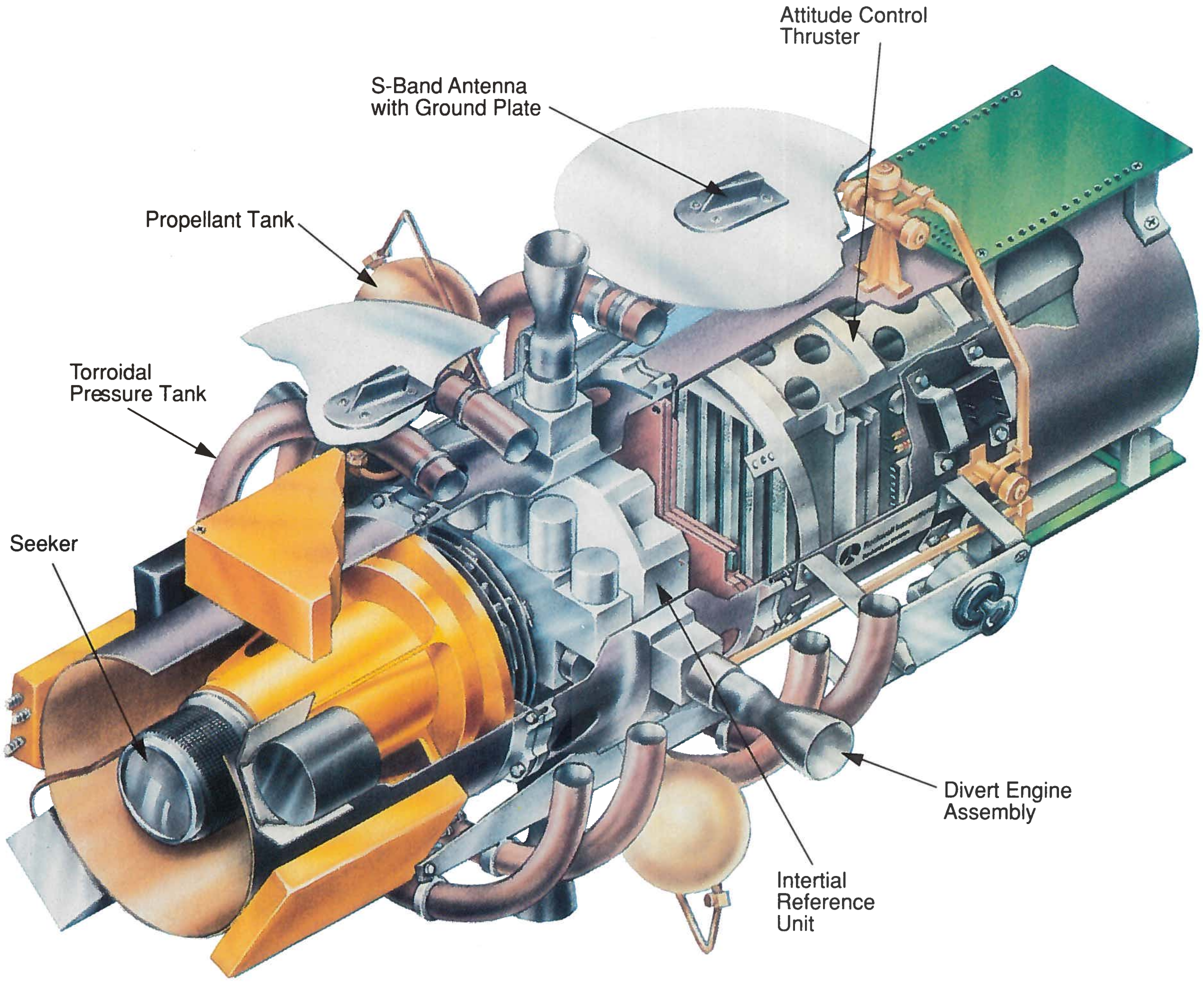
of crew and onlookers. Equally important, these short-duration tests provided valuable data in the diverse areas of KHIT platform stability, cg migration, divert engine thrust vector misalignment and avionics command telemetry performance, as well as video contrast tracker position location and IRU performance.

The next KHIT flight test was conducted on April 22, 1989, and went the entire scheduled 21.6 seconds, with the planned/simulated flight profile correlating extremely well with the actual flight path. Divert engine thrust was calculated at 325 foot-pounds, while that of the ACS was 5.0 foot-pounds. Most importantly, vehicle stability was 3 mradians—actually exceeding the SABIR requirement.

Two subsequent, highly successful flight tests were conducted during the summer of 1989. The KKV configuration for these flights included a seeker and its associated electronics. Valuable data gained from these tests included KKV platform stability improvement to 1 mradian and confirmation of the ability of seeker algorithms to translate from missile plume tracking to missile hardbody tracking, a critical technical advancement to weapon system development and eventual deployment.

And that, in the strictest sense, describes the early flights of the KHIT test vehicle. Yet it hardly does justice to the emotional impact that bouyed KHIT into the air at the AFAL test facility. Indeed, those who have been fortunate enough to see the videotapes of the flights are struck by the chorus of encouragement from seemingly staid, serious technicians off camera. But then it's worth reiterating that this was a project that was initially greeted by a refrain of, "It can't be done." So small wonder, then, at the enthusiastic response from the people who made it happen, from actual inception to working hardware.

AHIT Hover Vehicle



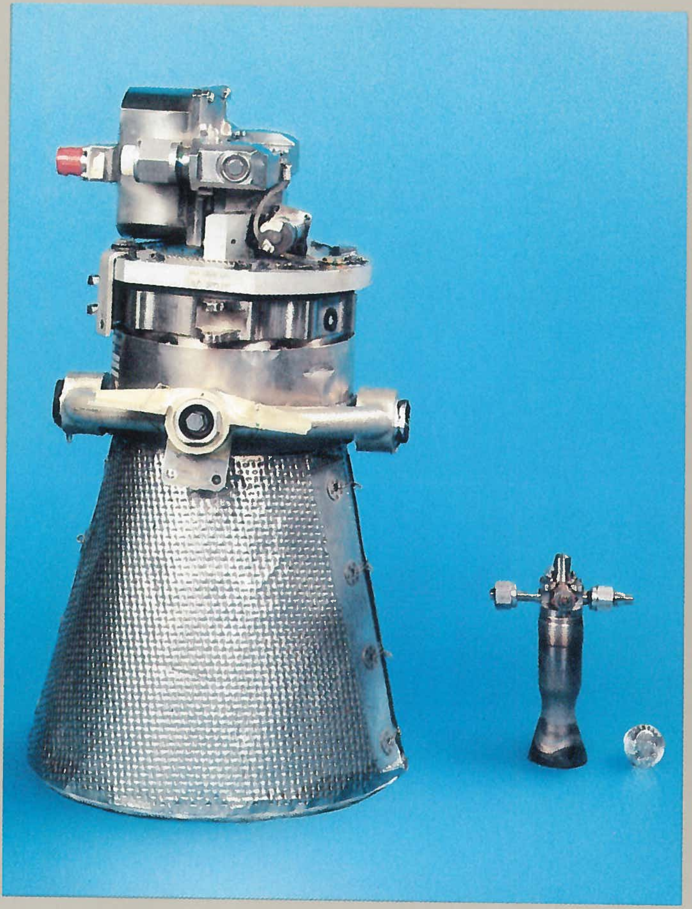
The AHIT hover vehicle is the next generation kill vehicle and is significantly smaller—roughly one-half the size of the original testbed vehicle—with further reductions foreseen for future iterations.

The basic KHIT vehicle design with its modular approach forms a basic workhorse vehicle to support several applications. As is, it can be used to carry Guidance and Control (G&C) test components, including target seekers. For any new application, a new structural shell will be fabricated, along with a new set of divert and ACS engine mounting assemblies—a relatively rapid and low-cost fabrication process. The positioning of mounts and other modules is then tailored to correctly mass balance the desired components, as well as to provide their correct structural mounting. Existing modules and engines can then be installed and a test can be accomplished with a minimum of facility modifications.

In the G&C seeker-related flights—as in the summer, 1989 tests—simulated targets will be provided for the seeker to view through an open test-facility side door. In ground tests, satellite images have already been tracked across a large mirror scene generator in order to demonstrate capabilities relative to enemy satellite negation. Similar hover flight test programs are scheduled throughout 1990.

Meanwhile, Rocketdyne will continue to pursue the component miniaturization technology that has been the backbone of our advancements in the KEW arena. Specifically, the Rocketdyne-developed 1200:1 thrust-to-weight divert propulsion engine is being used as the basis for a new lightweight KKV,

Engine Miniaturization



Significant technology strides have been made in small rocket engine size and weight, with new, extremely lightweight high-performance propulsion systems that can be built for a fraction of previous costs.

Improvements can be measured by comparing engine thrust-to-weight. Engine thrust is divided by engine weight, yielding an equivalent pound of thrust per pound of engine weight (T/W ratio). Rocketdyne has been able to take state-of-the-art technology with a T/W ratio at 20, and by using innovative ideas, produce T/W = 200, T/W = 400, and finally, T/W = 1200 engines.

Along with these dramatic weight improvements, the new engines and propulsion systems show a decrease in cost as well. Whereas the significant MM III thruster on the left (314-pound thrust) costs about $150,000, it is estimated that in production the T/W = 1200 thruster on the right will run about $3,000 each—1/50 of the MM III cost.

Although developed for SDI programs, this lightweight, low-cost propulsion system technology has potential for application to other projects as well. One example is space attitude control and maneuvering propulsion, where a strict propulsion systems budget is required. If the propulsion hardware weighs far less, the amount of on-board propellants can be increased to allow a more stressing or longer mission.

the Advanced Hover Intercept (AHIT) program. This KKV, to weigh in at only 37 pounds, is currently being assembled at Rocketdyne, with a first flight scheduled for May 1990.

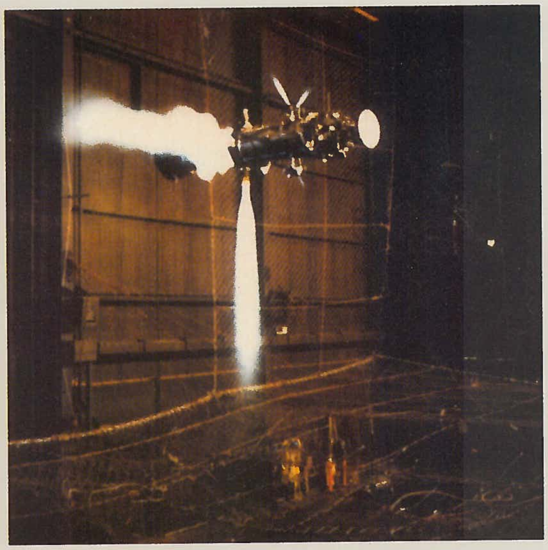
The KHIT program team has supplied early data on the G&C and propulsion system dynamic interactions that directly support the KEW programs. This basic vehicle and facility are now in use and will continue to serve other programs to obtain early data with a relatively low-cost ground-based/flight test program, as compared to space flight programs. Actual operating data from the propulsion system can then be compared to simulation data. This will validate technical approaches and hardware performance so as to enhance the success of subsequent space flight tests.

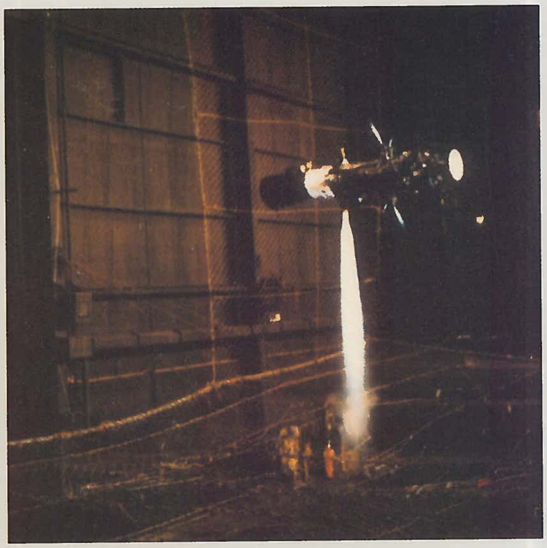
In short, Rocketdyne's effort has demonstrated that the KEW concept is viable. KHIT is a demonstrated working vehicle for lower than anticipated cost (just 10% of the original estimate); a less complex propulsion configuration (four ACS engines instead of eight); and platform stability significantly better than called for. And on top of that, the program has resulted in significant advancements in component miniaturization and modular flexibility, all of which bodes well for the still greater challenges in ground/sea and space-based defense that lie ahead. ■

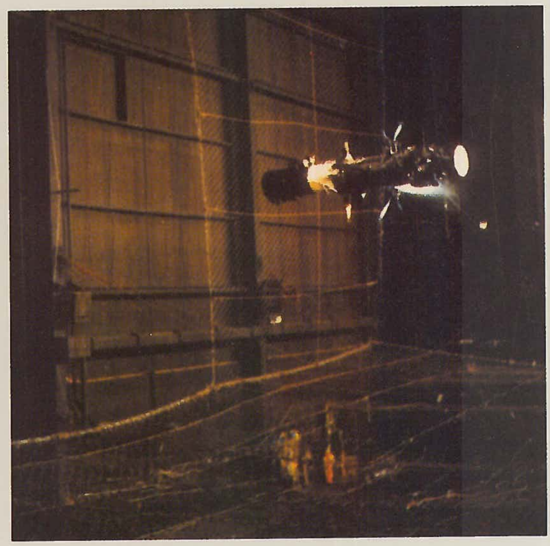
Overleaf: The KKV in action. Reading counterclockwise from the bottom right-hand photo, the KKV ascends, maneuvers and finally drops to the net below after a flight duration of 28 seconds.

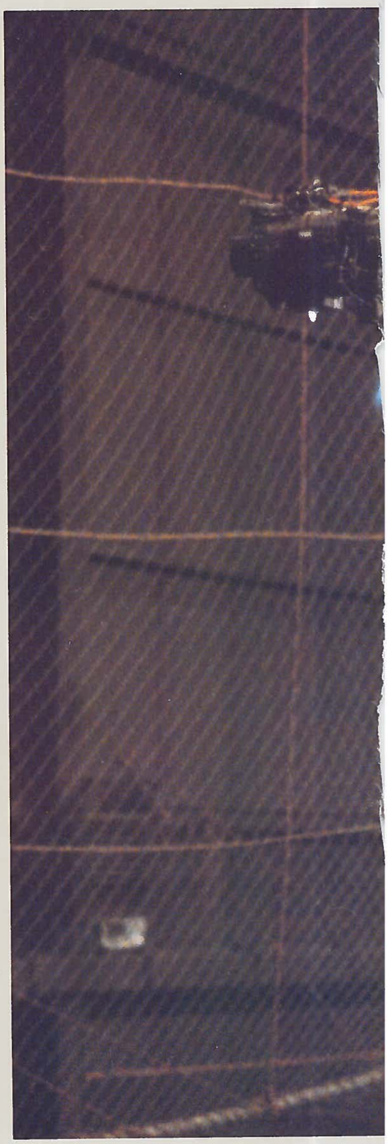
Test Flight of the Kinetic Kill Vehicle

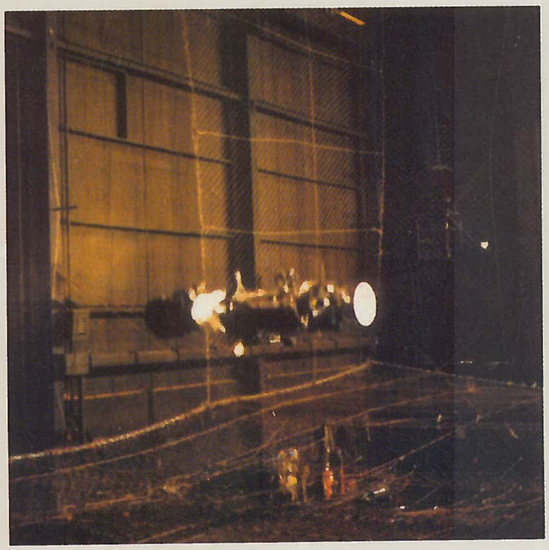
Air Force
Astronautics
Laboratory,
Edwards
Air Force Base,
California

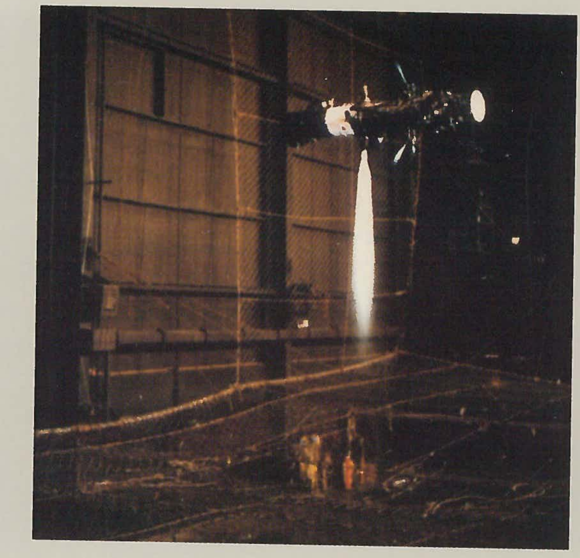


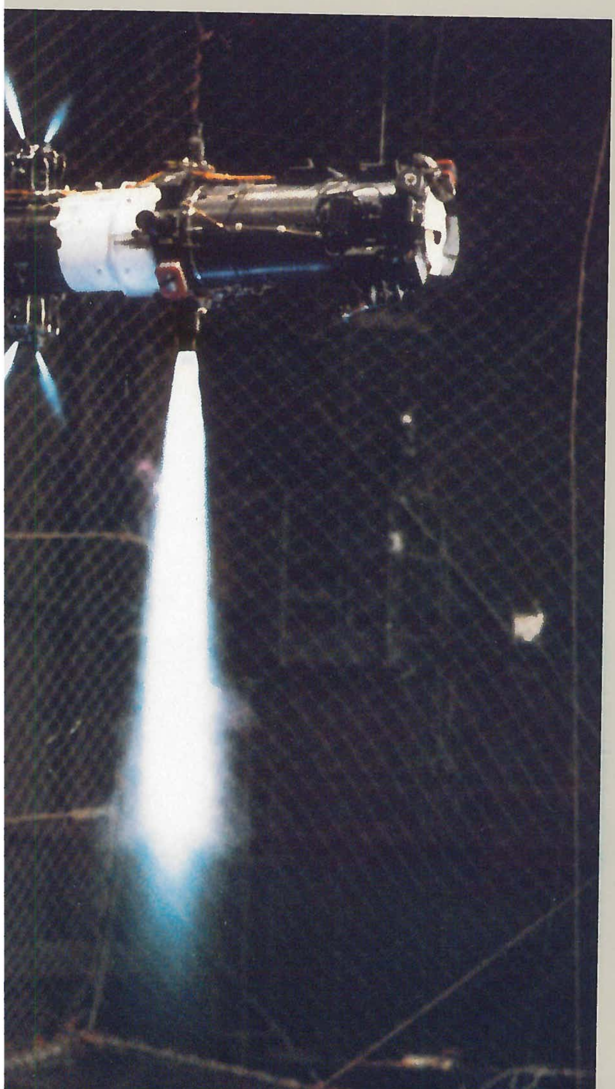


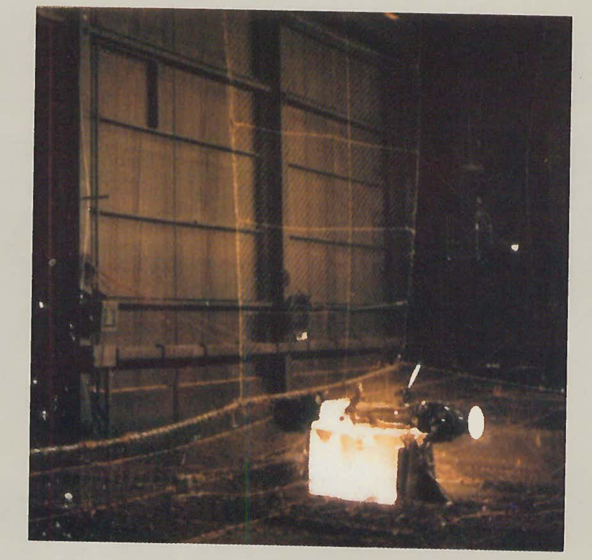


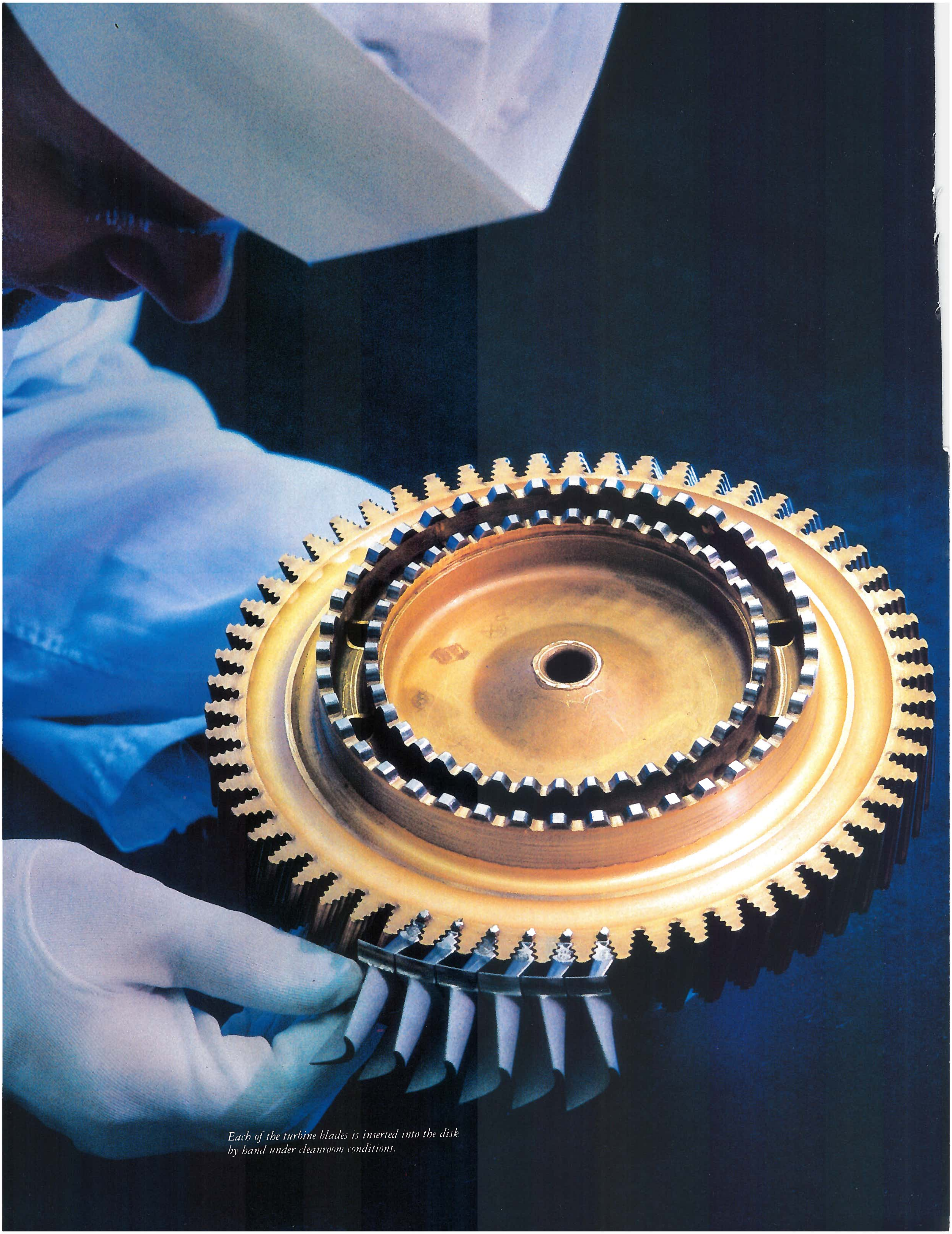












Each of the turbine blades is inserted into the disk by hand under cleanroom conditions.

BUILDING A BETTER BLADE

by L. G. Fritzemeier and J. W. Brockmeyer

As key components in a liquid propellant rocket engine, turbine blades encounter an extrememly harsh and demanding operating environment. Recent developments in materials reasearch offer provocative new choices that portend extended blade life and improved performance.

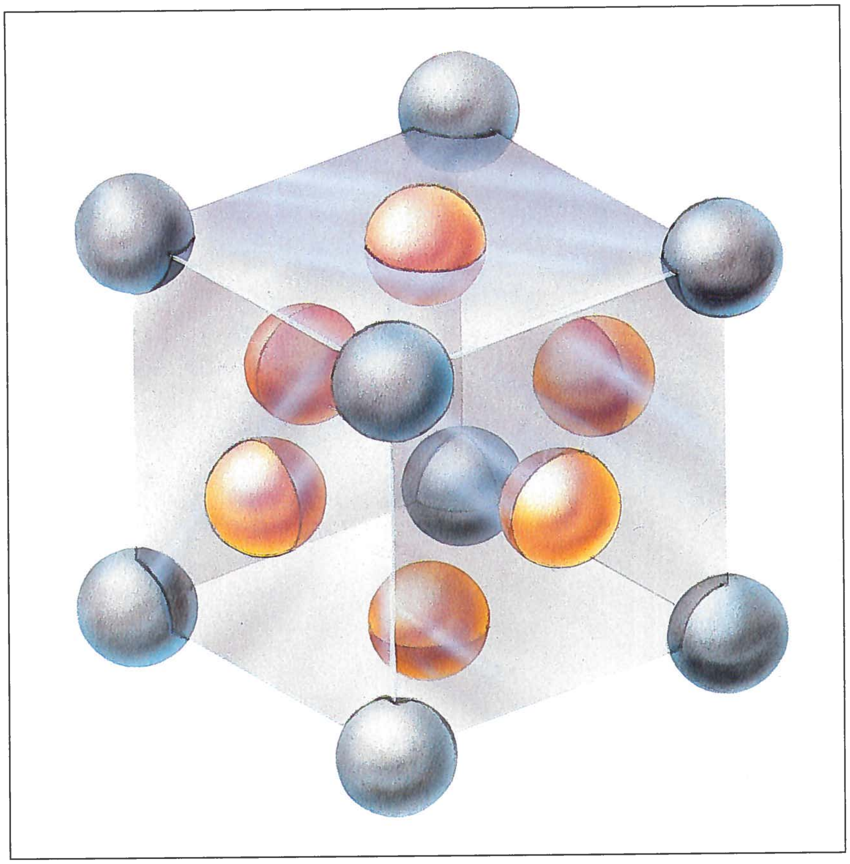
TURBINE BLADES ARE ARGUABLY the most highly stressed, and distressed, components in a liquid rocket engine, operating in an environment that has rightly been described as Dantean: Where hot, noxious gases continually bombard the materials; where the high rotational speeds impart high mean stresses; where starts and stops introduce thermal fatigue cycles; and where high-cycle fatigue loading can be imposed by a number of sources.

Liquid rocket engine turbines are driven by the hot combustion products of the rocket engine propellants. Although a variety of propellants is used, the hydrogen-rich steam combustion gases produced by the fuel-rich combustion of liquid oxygen and hydrogen are the most severe in contemporary earth-to-orbit rocket engine turbines, such as those of the staged-combustion-cycle Space Shuttle Main Engines (SSMEs). In this demanding environment, which combines high temperatures, reactive gases and high flowrates (with potential for erosive wear), the materials that can be successfully used for turbine blades are very limited. The turbines operate at very high rotation rates with high turbine blade-tip speeds, resulting in high centrifugal stresses; the blades face cyclic stresses, making both low- and high-cycle fatigue resistance significant.

Dr. Fritzemeier *is principal investigator for advanced metallic materials development at Rocketdyne and holds two patents for the industry's first viable commercial single-crystal hot isostatic pressing process. In 1989 Dr. Fritzemeier was honored as the Rocketdyne Division's Engineer of the Year and as a Rockwell International Engineer of the Year.*

Jerry Brockmeyer *holds six United States patents, all related to ceramics materials. Mr. Brockmeyer is Rocketdyne's principal investigator for a NASA-Lewis Research Center contract for exploration of the feasibility of using ceramic composites in rocket engine turbomachinery.*

Low-cycle fatigue results from the thermal cycling of engine start-ups and shutdowns. The near-explosive start in engines such as the SSME thermally shocks the blade surface. High-cycle mechanical fatigue occurs from the cyclic stresses as the blades rotate past wakes generated by stationary turbine nozzles and other gas-path elements.



Atoms in a superalloy crystal are arranged at the corners and face-centers of an imaginary cube and are repeated in three dimensions to compose the entire part. For strengthening properties, the corner atoms are aluminum, while those in the face-centers are nickel. The cube axis of a single crystal is oriented along the edge of the cube, which is the natural growth direction, as well as the low elastic modulus orientation. By contrast, the stiffest orientation for the cube is from corner to corner.

The search for materials capable of surviving in these conditions has been continual since the advent of the gas turbine engine. Early on, the most exotic materials utilized as turbine blades were conventional cobalt-based or nickel-based superalloys, with elements such as chromium, titanium and aluminum added for improved resistance to corrosion and for high strength. Such alloys are "super" because they retain excellent strength to significant fractions of their melting points. The superalloys were adequate for turbine blade applications in early rocket engines due to the expendable nature of the engines and to the use of petroleum fuels, the environment for which the alloys were developed in the gas turbine industry.

The development of the SSME, however, involved the use of hydrogen as a high-efficiency fuel and, simultaneously, the reusable, long-life engine system. Both of these developments had significant impact on the requirements for turbine blade materials. Hydrogen environment embrittlement (HEE) had recently been identified as a concern for metallic materials because of its degrading effect on metallic properties. Low-cycle fatigue and thermal shock resistance were also considerations due to the multiple starts and stops anticipated during the engine life cycle. Consequently, turbine blade materials for these new engine systems were sought which would be capable of surviving in the higher temperature, more aggressive environment.

In the early 1970s, directionally solidified (DS) superalloys were the state-of-the-art choice for the SSME application. These alloys were intended primarily for military jet engine applications and were developed for improved high-temperature creep (deformation under a constant load) resistance, relative to conventional superalloys.

Conventionally cast superalloys are composed of a number of small grains, or crystals. The boundaries between the grains are weaker than the grain interiors under creep conditions. By controlling the withdrawal of heat from the solidifying turbine blade casting, the grains in DS superalloys are columnar and aligned with the major stress axis, thus eliminating the weaker regions of the conventionally cast materials. Directionally solidified MAR-M246®* was chosen as the optimum alloy available for SSME turbine blade application, based primarily upon superior creep resistance relative to other candidate alloys.

As early experience was gained with the SSME, cracking was observed in the turbine blades of both the high-pressure fuel turbopump and the high pressure oxidizer turbopump. High-cycle fatigue, low-cycle fatigue and thermally induced steady-state strains, all assisted to some extent by hydrogen embrittlement effects, were identified as causes for these cracks. Carbides, which are inherent in the DS alloy and necessary to stabilize the columnar grain boundaries at elevated temperature, were identified as initiation sites for many of the cracks. Improvements have been incorporated which have extended turbine blade life, demonstraed to a 20,000-second range, with no cracks in over two years of extensive testing. Thus, efforts to extend the life of the SSME and enhance the designs of new engine systems, such as the Advanced Launch System (ALS), single-stage-to-orbit engines and the proposed supersonic civilian transport system, have guided further efforts to identify and evaluate materials for improved turbine blade capability. Longer life, increased turbine operating temperatures, improved reliability and economics are all considerations for these applications.

---

* *MAR-M246® is a trademark of the Martin-Marietta Corp.*

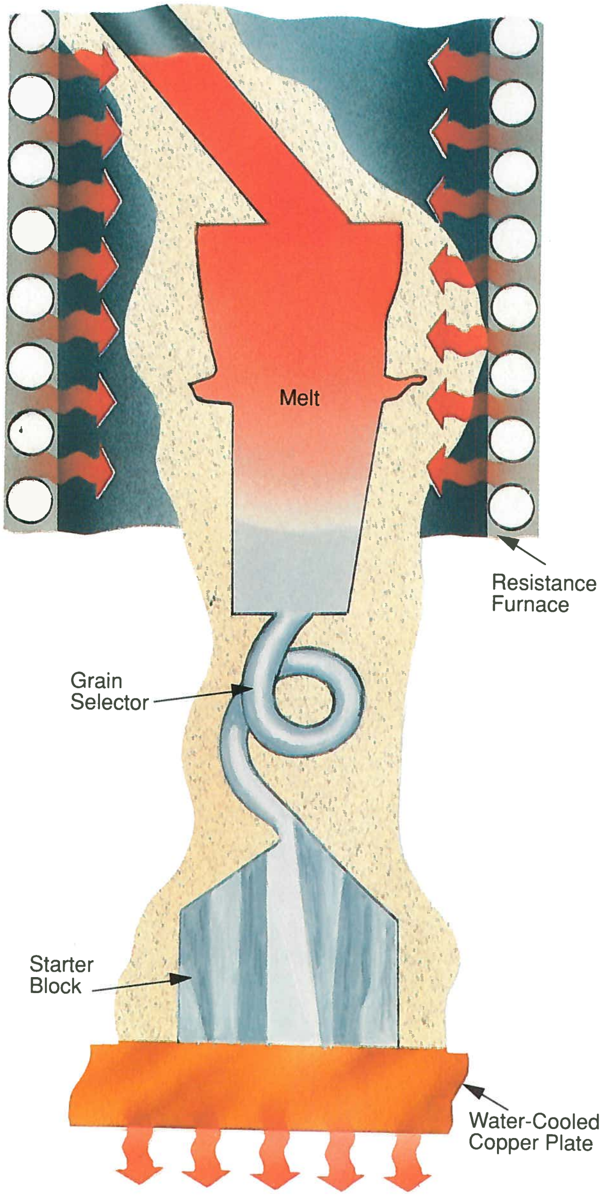
A 1984 Rocketdyne report to the National Aeronautics and Space Administration identified several materials systems for near-term and long-term development as improved turbine blade materials for advanced hydrogen fueled rocket engine applications: single-crystal (SC) superalloys, metal matrix composites (MMCs), and monolithic ceramics and ceramic matrix composites (CMCs). The more recently defined requirements for the ALS engines have prompted new looks at hydrogen-resistant versions of the conventional superalloys.

Single-crystal (SC) superalloys have been developed as an extension of the philosophy which led to directionally solidified turbine blade alloys. Removal of the grain boundaries perpendicular to the applied stress allows significant increases in operating temperature and applied stress for the directionally solidified components relative to the conventional superalloy castings. It is expected that additional gains will be realized by removing the remaining boundaries and producing a part consisting of a single grain or crystal. Elimination of the grain boundaries would allow the removal of carbon and the elements used to form carbides, which have been seen as essential to strengthening the grain boundaries. Since carbon reduces the melting point of nickel base superalloys, its removal from the single-crystal components would permit a significant (50°F) increase in turbine blade use temperature, which in turn would increase the efficiency of gas turbine engines. This virtual elimination of carbides would be a significant advantage for rocket engine applications, since SSME turbine blade cracks have initiated at the carbides in DS MAR-M246®.

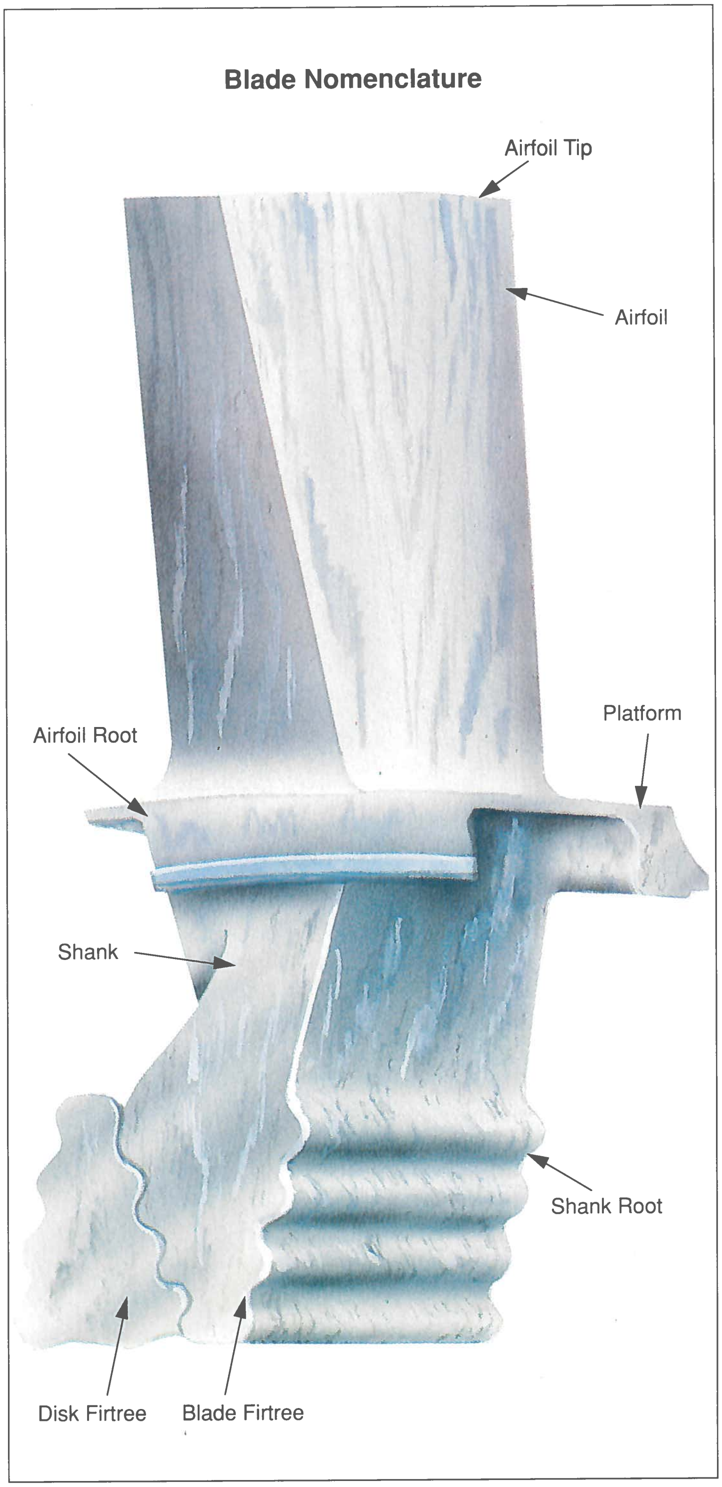
Rocketdyne first began evaluating SC superalloys for the SSME application in 1978 (at about the time the alloys were first scheduled for commercial gas turbine use). Because of difficulties in producing castings of a quality suitable for rocket engine use during the early industry efforts, the Rocketdyne development effort remained at a low level until 1984, when a major initiative was begun. The initial goals of the new program were to identify a SC alloy for direct substitution in the SSME high-pressure turbopump turbines and to evaluate SC processing to determine whether additional improvements in properties relative to the gas turbine engine standards could be obtained. These efforts were soon expanded as the unique attributes of SC components were demonstrated.

More than 15 different SC alloys have been tested for potential application in the SSME. Several of these alloys have been found to be more resistant to hydrogen embrittlement than DS MAR-M246®.

Single-Crystal Casting



Single-crystal casting is an extension of the directionally solidified process employed for current SSME blades. Heat is withdrawn from the bottom of the mold, causing grains to nucleate and grow into the stable block. A grain selector blocks the passage of all but one grain—or crystal—into the mold cavity. The mold is slowly withdrawn from the resistance furnace, allowing the solidification front to progress into the mold, producing a single-crystal component casting.



In particular, the plastic strain that these alloys can sustain prior to the initiation of a crack is higher than that for the DS alloy; i.e., because it is more difficult to initiate a crack in the SC alloys, they should therefore be more capable of surviving in the hydrogen fuel combustion environment. As noted, the SC superalloys can be utilized at higher temperatures than their directionally solidified counterparts. This increased-use temperature capability is equivalent to achieving higher strength at a given temperature in the turbine environment, providing an increased operating margin over lower strength materials in the same application. The high-cycle fatigue and low-cycle fatigue lives—the primary life-limiting factors of the DS MAR-M246® turbine blades—of the SC alloys have been demonstrated to be significantly greater than they are for DS MAR-M246® in SSME operating conditions.

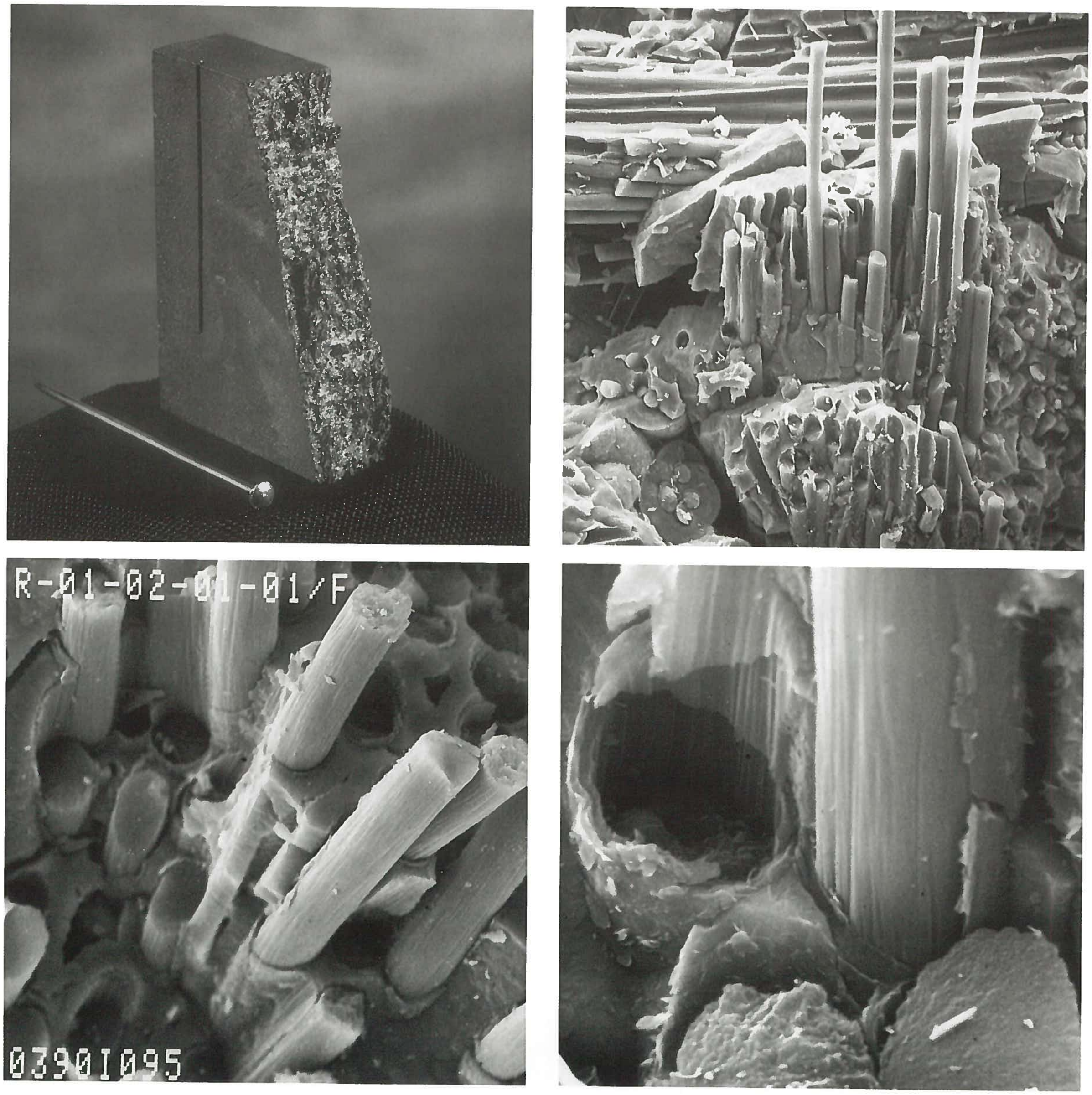
Additional life improvements have been projected through improved processing of the SC castings. A major portion of the SC development effort has been to optimize the processing and properties of these materials specifically for rocket engine applications. The shorter life requirements and substantially different operating conditions of rocket engine turbines, relative to the aircraft gas turbines—for which SC superalloys were initially developed—dictate different property requirements. Specifically, thermal shock, thermally induced low-cycle fatigue, high mean stress high-cycle fatigue, moderate temperature (1600°F), short (less than 10 hours) design life and HEE in the rocket engine turbine contrast with moderate thermal cycles, higher temperatures (1800°F), long (greater than 10,000 hours) design life, and hot corrosion and oxidation in the gas turbine.

When the carbides were removed from SC superalloys, the initiation sites for fracture under both fatigue and tensile loading shifted to a new area of the material: casting porosity and microstructural segregation, known as casting eutectic, which are natural consequences of the casting process. Fortunately, both porosity and eutectic colonies can be virtually eliminated through newly developed processing improvements.

Elimination of the internal casting porosity is simple in concept but difficult in execution. Hot isostatic pressing (HIP) is a primary method of removing internal porosity from conventional industrial castings. Simply described, this method involves high pressures and temperatures which are applied to force material flow, causing the pores to collapse and the interfaces to bond together by diffusional processes. Early attempts by the gas turbine industry to apply HIP for pore closure in SC superalloys were unsuccessful. The application of temperature and high pressure causes local recrystallization in the SC alloys around the closing pores, a phenomenon found to be nearly as difficult a problem as the original casting pores in nucleating fatigue cracks, thus negating the benefits of porosity closure.

The solution was to develop a process for pore closure through low-energy creep mechanisms, rather than by the plastic deformation mechanism of the earlier processes, thereby avoiding the recrystallized grains. The benefit of this new Rocketdyne HIP process increases low-cycle fatigue life by 10 times over non-HIP SC casting and increases the high-cycle fatigue endurance strength by 50%. A patent for this technique has been allowed and, in a somewhat rare reversal of technology transfer, a process developed by the rocket engine industry is rapidly being adopted by the gas turbine industry.

Single crystals are also unique because their properties vary with the orientation of the crystal. Nickel-base superalloys are face-centered cubic. Simply put, the atoms in the crystal are located at the eight corners and in the centers of the six faces of an imaginary cube. The elastic modulus, or stiffness, of the component can be tailored by rotating the component relative to the axes of the crystallographic cube. Thus, the elastic modulus of a crystal oriented parallel to the cube axis is about 18 Msi, while the modulus of a crystal oriented from corner to corner of the cube is about 33 Msi. The natural growth direction of a SC superalloy is parallel to the cube axis. The SC SSME turbine blade castings are oriented such that the radial axis of the blade is parallel to this growth direction, and the "firtree"—the attachment point—axis of the blade is parallel to another cube axis. Test and analysis have shown that this blade configuration provides up to a five-fold increase in high-cycle fatigue life, relative to randomly oriented SC blades.



The fracture surface of a carbon-reinforced silicon carbide test item is shown at increasing magnifications to emphasize various features of the composite. Top left: The test piece, with actual size indicated. Top right: At higher magnification, the fabric-like weaving that forms the structure is evident. Bottom left: Still higher magnification shows areas where fibers have been pulled out of the matrix, an energy absorbing mechanism for toughness and less brittleness. Bottom right: Extreme magnification of an interfacial layer provided for environmental protection and matrix integrity.

Control of the stiffness through crystal orientation can also be utilized to tailor the dynamic frequency of the SC component in order to avoid resonant coupling with excitations from other sources within the engine.

Metal matrix composites were originally developed for gas turbine applications and are now being modified and characterized for rocket engine applications. The MMCs developed for turbine blade applications are typically superalloy matrices reinforced by high strength refractory metal-based fibers or ceramic fibers. This class of MMCs is known as fiber reinforced superalloy (FRS) composites. Typical matrix alloys are WASPALOY®* or the INCOLOY®** series of alloys. WASPALOY® is a natural choice since it is the same material from which the SSME turbine disk is fabricated. The INCOLOY® alloys were originally chosen for their compatibility with a high-pressure hydrogen environment. These iron-nickel based superalloys possess the rare attribute of being largely unaffected by HEE. The coefficient of thermal expansion for the INCOLOY® alloys is also closer to the low coefficient of expansion of the materials commonly employed as reinforcing fibers, which aids in alleviating residual stresses from fabrication processes.

The final choice of matrix material is dependent on many factors. For hydrogen-fueled rocket engine applications the matrix material should be HEE-resistant, ductile and sufficiently strong at turbine operating temperatures. The matrix acts to transmit load to the reinforcing fibers, which are the primary load-carrying elements.

The choice of fiber material is dictated by two primary considerations: strength or load-carrying capability at operating temperature and compatibility with the matrix. Carbon and silicon carbide are examples of ceramic fibers which meet the strength criteria. These materials are also low in density, an attractive attribute for rotating element application. Unfortunately, most metals, and especially superalloys, have a high solubility for carbon, so that at the typical FRS application temperature—around 2000°F—diffusion of carbon from the fiber into the matrix degrades the fiber integrity. A significant effort is currently being directed to the development of engineered coatings and interfaces to prevent this degradation.

Refractory metals are considerably more stable at elevated temperatures in the MMC than the commercially available ceramic fibers due to much slower refractory metal diffusion rates in the nickel-based superalloy matrix. Most FRS development has centered on tungsten fiber reinforcement since these fibers are readily available in the form of tungsten lamp bulb filaments. Recent strength improvements in alloyed tungsten fibers and alloyed molybdenum fibers have increased the available strengths of the composites. The advanced molybdenum fibers are particularly attractive because they are lower in density than the tungsten, further reducing the overall composite density and the mass of the finished component.

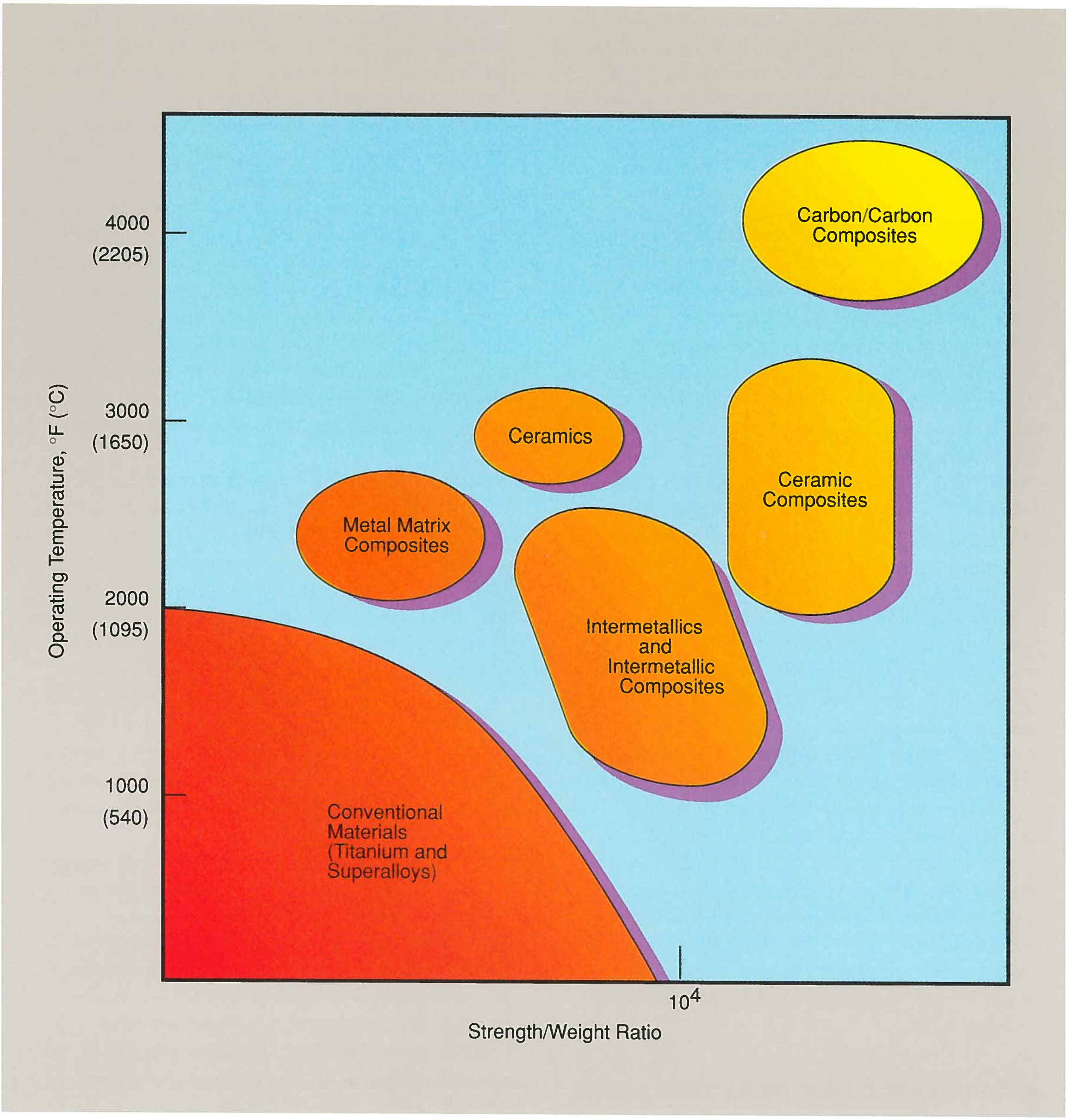
Rocketdyne's involvement in the FRS development effort, sponsored primarily by NASA, has been in the areas of component design, materials characterization with regard to rocket engine specific properties and FRS joining technologies. Through the use of high-density refractory metal as reinforcements, FRS composites are generally more dense than the cast nickel-base superalloys employed as turbine blades. However, the much higher strengths of the FRS at operating temperatures allow the FRS blade airfoils to be hollow, while achieving the same stiffness and physical properties as the solid superalloy blades. The FRS turbine blade can then sustain higher loads with blade mass similar to the superalloy component. Additionally, a lower mass blade can reduce loads translated into the disk or can further reduce engine weight by allowing reduced disk mass. Thermal strains in the airfoil can also be reduced by the use of thin-walled hollow airfoils. The temperature differential between the outer and inner walls is reduced, relative to the temperature differential in a solid airfoil, thereby reducing the thermal strains. Reduction in the amplitude of the thermal strains during start-and-stop transients reduces the low-cycle fatigue strains and increases the blade life.

The thermal shock resistance of the FRS composite has also been demonstrated to be higher than that of either the DS MAR-M246® or SC alloys. Thermal shock tests were conducted by sweeping a defocused beam from one of the Rocketdyne electron beam welding systems across the surface of a sample. Heat fluxes and transient heating times similar to the severe start transients in the SSME were simulated. A notable improvement in thermal fatigue capability of the FRS composites was observed and was attributed primarily to the increased thermal conductivity of these systems, relative to standard superalloy castings. The more rapid heat dissipation reduces the local thermal gradients, thus decreasing the amplitude of the thermal strain and increasing the number of thermal cycles until cracking occurs.

---

* *WASPALOY® is a registered trademark of United Technologies Corp.*

** *INCOLOY® is a registered trademark of the Inco family of companies.*



Materials development for advanced turbine blade applications is based upon increased turbine efficiency through higher turbine inlet temperatures. Improvements in rotordynamics and operating margin are achieved through higher strength-to-weight ratios.

FRS composites are generally less severely influenced by HEE than monolithic superalloys. Testing at relatively low hydrogen pressures has indicated no measurable loss in the FRS notched-bar strength due to the hydrogen environment. Although WASPALOY® suffers some degradation from HEE when tested in unreinforced form, tungsten-fiber-reinforced WASPALOY® was found to be unaffected. A possible explanation arises from the difference in stiffness between the fiber and the matrix. Tungsten is more than one and one-half times stiffer than the typical superalloy matrix. Therefore, for a given strain, the fiber carries more of the load than the matrix. Since the fibers are shielded from the hydrogen environment by the matrix, they are not susceptible to embrittlement and can sustain their typical strength.

Most of the materials under development for turbine blade applications are intended to provide increases in application temperature. Increased turbine temperatures result in increased efficiencies for aircraft engine systems and are also important for rocket engine systems, such as an uprated SSME and the proposed supersonic or hypersonic transport systems. In contrast, the major thrust of the ALS program is for gas generator or split expander cycle engines with turbine inlet temperatures, ranging from -100°F for the split expander to 1100°F for the gas generator. Materials requirements for turbine blades in these low-temperature engines are different from the elevated temperature environments. Hydrogen environment embrittlement effects are generally most significant near room temperature, necessitating the use of

HEE-resistant materials. Thus, primary design criteria for these engine systems are the demonstration of high reliability and low cost. High-strength, excellent fatigue capability and low-cost fabrication processes are dictated. Conventional, cast or forged superalloys are most capable of meeting these requirements.

Rocketdyne has developed several new superalloys specifically to meet the requirements of high strength with improved resistance to HEE. The alloys were developed from several iron-nickel-based superalloys which were known to be virtually immune to HEE. The alloy RIM-D1 was developed for high-strength turbine disk forging applications, but is also ideally suited for the low-temperature blade and vane applications. The very high strength and immunity to HEE of RIM-D1 provide high reliability in the rotating element environment. Forged microstructures are also very low in internal discontinuities where fatigue fractures can occur. This, coupled with the high strengths, results in fatigue endurance strengths which are much higher than those of typical cast turbine blade materials. The proposed method of producing blades from RIM-D1 forging is by electrochemical machining which produces a very fine surface finish, essentially mirror-smooth, and has been shown to provide a significant increase in turbine efficiency, relative to a standard machined finish. Airfoils produced in this manner cost about the same as an equivalent casting. Rocketdyne recently demonstrated the castability of a commercial, HEE-resistant iron-nickel-base superalloy. This alloy could be used in situations where the forging and machining of wrought components were prohibited by configuration.

Conventional and directionally solidified cast superalloys are limited to operating temperatures of 1500°F to 1600°F, and the single-crystal alloys increase these temperatures by about another 200°F. Yet real improvements in turbine efficiency may require still further increases in operating temperature, beyond the capabilities of superalloys or metal matrix composites. Ceramics and ceramic composites are being considered for these higher temperature applications.

Ceramics are known for their resistance to high temperatures but historically have not been considered for demanding structural applications because of their low ductility, low fracture toughness and subsequent low reliability. However, developments of the past 10 to 20 years have significantly improved these traits. First, monolithic oxide ceramics (aluminum oxide and partially stabilized zirconia) gained higher toughness and improved reliability by improvements in the cleanliness of raw materials and close control of processing. These improvements resulted from a detailed understanding of the materials behavior and their sensitivity to inherent flaws. More recently, non-oxide ceramics (silicon carbide and silicon nitride) have been developed with even better structural properties than the oxides. Using these improved materials, air-breathing ceramic engines have been made and have demonstrated the feasibility of using ceramics for critical structural applications. For several years, small automotive turbocharger rotors have been produced commercially from monolithic ceramics in Japan, and plans are in place for the production of a small, commercial ceramic auto engine in the next few years.

Still, even with these improvements, monolithic ceramics are an order of magnitude lower in fracture toughness than most metallic alloy systems. This is due to the monolithic ceramic materials inherent brittleness, or low strain to failure, and sensitivity to surface flaws. By applying advanced composites technology in concert with the advantages of the monolithic ceramic matrices (high-temperature capability and excellent environmental resistance), ceramic matrix composite materials have been developed with many of the advantages of monolithic ceramics, yet with fracture toughnesses much closer to that of traditional metallic alloy systems.

A variety of systems is involved. The composite reinforcement can be either a dispersed phase or a continuous phase. Dispersed phases can be particulates, platelets, whiskers or short fibers. Continuous reinforcements can be either monofilament fibers or multifilament fibers. Either metallic or ceramic materials can be used as reinforcements, provided they are compatible with the processing conditions of the surrounding ceramic matrix. The reinforcement commonly employs an interfacial phase to improve its compatibility with a specific matrix. The matrices may be glass, glass-ceramics, oxides or non-oxides. For liquid rocket engine applications, continuous ceramic or carbon fiber-reinforced ceramic matrix composites (FRCMCs) have demonstrated the best combination of properties for components such as turbine blades.

Continuous fiber reinforcement with multifilament fibers results in various potential benefits. To appreciate these benefits, the FRCMC production process itself must first be understood.

The first step in the manufacturing process is the creation of a fiber preform conformal to the component geometry. The preform can be manufactured from woven fiber layers, laminates, braids, or multiaxial structures. Next, the preform is infiltrated with the ceramic matrix. Infiltration can be accomplished by a number of processes, including hot pressing of ceramic powders, sol-gel infiltration, and chemical vapor infiltration (CVI). For relatively near-term applications, CVI is the preferred process, though slow and expensive. However, the resultant material has superior properties for rocket engine use. Following CVI, a final coating is applied which can consist of matrix material only or can incorporate one or more protective outer layers with properties specific to the application.

As noted previously for FRS composites, the reinforcement fibers are the principal load-bearing element when the component is stressed. Control of the fiber architecture in the preform allows the mechanical properties of the composite to be "tailored" to the axes of highest stresses. For a rotating element, such as a turbine rotor, centrifugal forces produce high stresses in the radial and tangential directions, requiring that the reinforcement be maximized in the plane of the disk. Turbine blades, which are located at the disk periphery, have a maximum centrifugal load at the blade roots. This load is a function of rotational velocity and blade mass. Maximization of the fiber volume in the stressed plane, use of high-strength fibers, and minimization of mass combine to maximize load-bearing ability and minimize stress of the blades. Ideally, then, for a "blisk," the in-plane fibers will be oriented radially and tangentially. This is accomplished by polar weaving of the fiber preform. In practice, polar weaving is a relatively new technology, and more conventional weaving methods give nearly the same in-plane properties as polar weaves. By laying-up a series of conventional two-dimensional weaves and rotating the individual layers, a multilayer structure can be made with nearly isotropic in-plane properties.

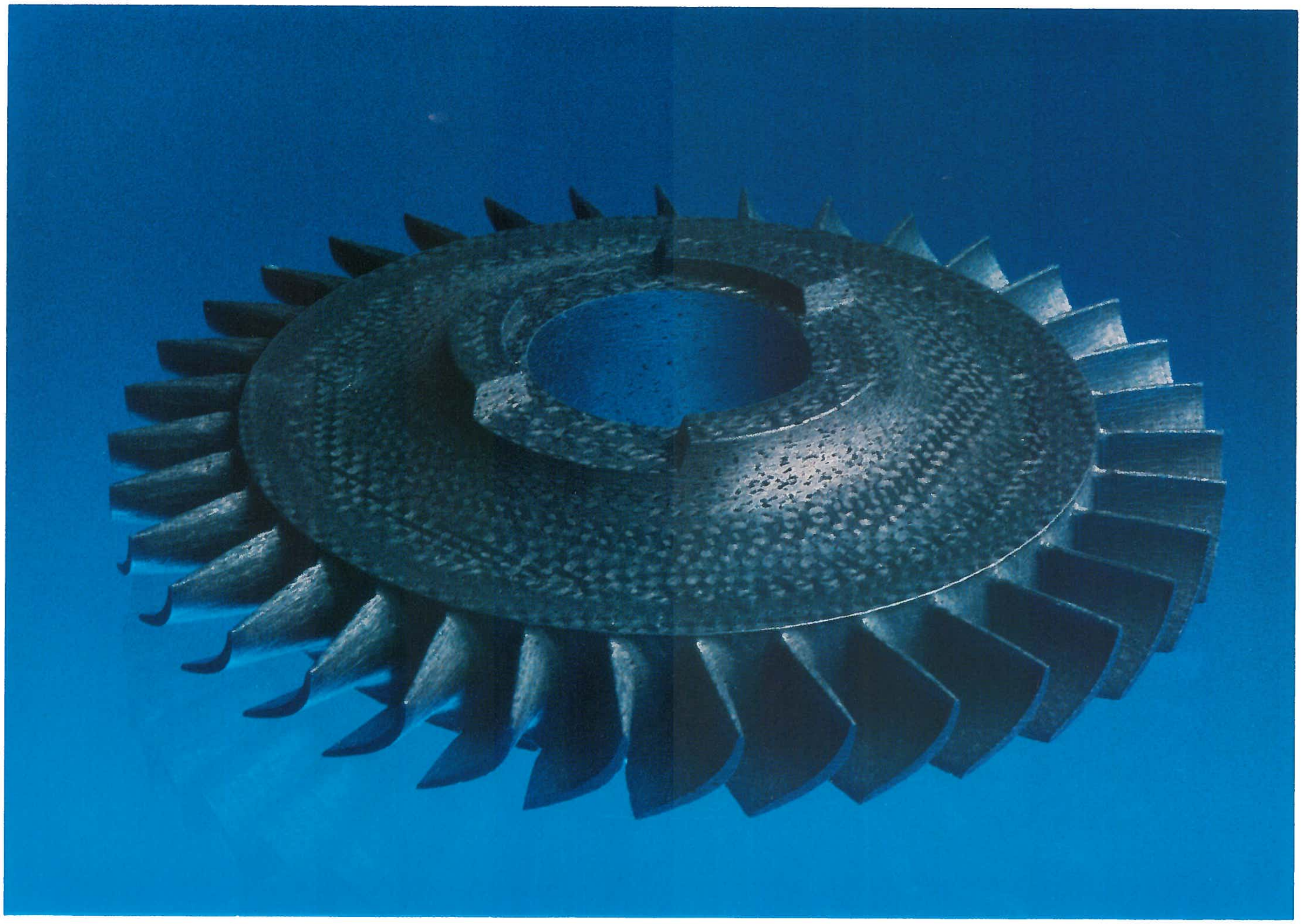
Ideally, the fibers which comprise the preform will be low density and high strength, environmentally stable, and compatible with the matrix and its processing conditions. Commercial carbon fibers are readily available in a range of grades with excellent mechanical properties. Carbon is low density and resistant to very high temperatures (in fact, its strength increases with increasing temperature over a wide range), but it is readily degraded by either oxidizing or hydrogen-rich environments at high temperatures. The more environmentally stable ceramic fibers, such as silicon carbide fibers, are not readily available in grades with mechanical properties comparable to carbon fibers. For applications which require the utmost in strength and strength-to-density ratio at elevated temperatures, carbon fiber-reinforced materials are preferred. It is essential for these materials that the matrix phase and/or the final coating provide environmental protection to ensure that the carbon fiber reinforcement is not degraded in use. For applications which can accept lower strengths, silicon carbide reinforcing fibers are preferred because their environmental stability is better.

Much of the toughness of FRCMCs results from the sliding of the fibers within the matrix as the component is stressed. However, a strong bond between fiber and matrix does not allow this sliding to occur, with the result that cracks propagate much as they would through a low ductility matrix; and brittle, rather than "graceful," failure occurs. Consequently, fibers are coated with engineered interfaces to reduce interaction between the reinforcement and the matrix.

In addition to overall architecture and fiber chemistry, the fiber tow count (number of filaments per strand) and filament diameter are varied to achieve the desired properties. For structures which require fine detail, such as the small radius leading and trailing edges of blades needed for aerodynamic performance (and which need a smooth-surface finish), small-diameter strands with relatively low tow counts are preferred. This must be balanced against other constraints. Use of fine strands increases processing time (and cost) for the preforms. Also, the interstices within the lower tow-count structure are smaller than in coarser filament structures, which makes the chemical vapor infiltration process more difficult, slower and more expensive.

For rocket engine turbine blades, non-oxide matrices combine good mechanical properties, resistance to high temperatures, acceptable stability in the operating environment and very good resistance to thermal shock. Both silicon carbide and silicon nitride have been used to fabricate FRCMC structures, and silicon carbide has been demonstrated to be particularly suited to the fabrication of complex structures using existing processing methods.

The presence of distributed, fine (typically less than 0.002 inch) porosity is inherent in the CVI process and is not generally detrimental. Surface-connected porosity results in surface defects that can have detrimental aerodynamic effects and must be considered. Larger pores are indicative of delaminations between the fiber layers and would be cause for rejection of critical parts. Detection of delaminations, especially internal delaminations, relies upon non-destructive evaluation methods such as X-ray, ultrasound, computer-aided tomography and laser interference holography.



A fiber-reinforced ceramic matrix composite turbine blisk fabricated by DuPont for an expendable turbine engine. Photo courtesy of DuPont Composites Division.

With this background, and an understanding of the many phases (fiber, interface, matrix and porosity) that comprise a "real-world" FRCMC component, the application of FRCMCs to rocket engines and, specifically, to turbine blades can be evaluated. First, as noted above, ceramics offer potential increases in operating temperature. For selected engine cycles, increasing the turbine temperature can result in considerable efficiency improvement. Several seconds of specific impulse (I_s) gain have been shown to be achievable by increasing the turbine inlet temperature of a gas generator cycle engine to 2200°F, a reasonable operating temperature for current generation FRCMCs. For an earth-to-orbit engine this would result in increased payload or would allow reconfiguration of the vehicle and propellant tanks to reduce launch weight. With launch costs currently on the order of several thousand dollars per pound, this advantage translates into a considerable cost benefit.

Further benefit can be gained by increasing the life of turbine blades which yields major benefits in terms of reduced maintenance and refurbishment costs. Pitch-line velocity limits calculated for FRCMCs, based on their ultimate mechanical properties, are substantially higher than those for metallic blades. This is due to the higher strength-to-density ratio of the FRCMC. The higher strength-to-density ratio of FRCMCs reduces the effective driving forces for fatigue and thereby increases operational life. Fatigue data are limited; and life improvements have not yet been confirmed; but the data that are available are promising. Thus, FRCMCs have the potential to increase performance in advanced engines by increasing operating temperature and blade speed, or they can benefit existing engines by increasing component life. Finally, FRCMC components would be lighter than their metallic equivalents. Not only would this reduce engine weight, but it would also improve the rotordynamics of rotating components.

For relatively small rotors, up to about 12 inches in diameter, FRCMC blades would probably be made integral to the disk (i.e., a "blisk"), eliminating the complications of mounting and joining, as with the use of firtrees. Use of a preform with dimensions similar to the final component geometry allows the manufacture of near-net shapes by CVI, but allowances are necessary in the preform geometry for interim and final machining.

The FRCMC would first be produced as a solid disk (like a hockey puck) or would be manufactured with a bore hole for attachment to the shaft. The turbine blades would then be machined onto the periphery of the disk.

FRCMC turbine blades and blisks have been produced and tested. To meet the demanding stresses of liquid rocket engine use, carbon fiber reinforced silicon carbide (C/SiC) was selected as the material system to demonstrate feasibility. Rocketdyne is currently engaged in work with NASA to demonstrate FRCMC components in rocket engine turbomachinery. In the first phase of this program, the feasibility of manufacturing critical elements, specifically turbine blades, has already been demonstrated. The properties of C/SiC for a specific engine application were shown to be compatible with higher performance requirements (higher temperature and higher tip speeds). In a following phase, the plan is to demonstrate a complete ceramic component under simulated rocket engine turbine conditions.

Turbine blade materials developments have been driven by the requirements of existing and proposed engine designs. Improved life, increased operating margins, extremes of temperature, aggressive atmospheres and increasing economic pressures have all contributed to the definition of material requirements. It is obvious that no single material or class of materials can meet the demands that the turbine environments make. Nevertheless, the breadth of the materials systems available today is more extensive than ever before, allowing the material choice to more closely fit the application. Further developments will improve the materials menu and allow future engines to keep spinning—hotter and faster. ■

RHYFL - A TOOL FOR ATTAINING HYPERSONIC FLIGHT

by P. M. Hurdle and A. D. Rolland

Even the testing procedures for the National Aero-Space Plane will require exotic new facilities that will surpass anything yet built. Rocketdyne's new hypersonic test laboratory will be able to duplicate the severe environmental stresses and properties of Mach 24.

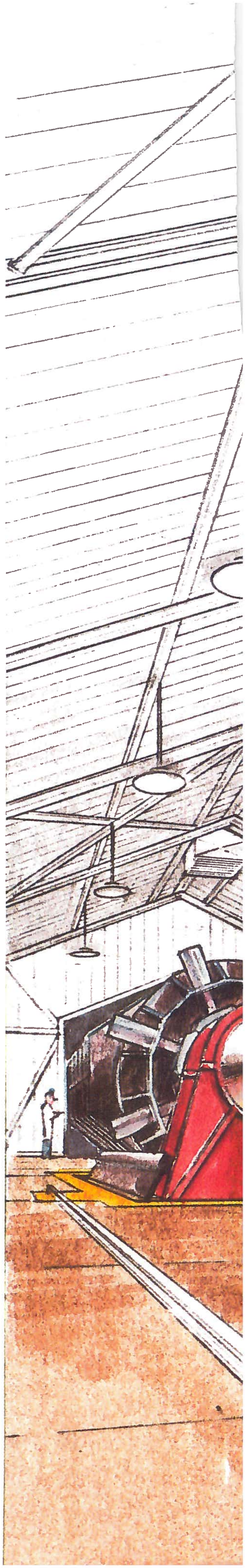
Dr. Patrick Hurdle *is the Chief Project Engineer for the RHYFL project, with a background in fluid mechanics and acoustics that covers nearly 25 years. During his career, Dr. Hurdle has worked in the areas of underwater acoustics, aerosonics, lasers and gas dynamics.*

Al Rolland *joined Rocketdyne in 1957, and in the succeeding three decades has been a key contributor to a diverse array of programs, including Apollo, Lance, Minuteman, Atlas, the Space Shuttle Main Engine and Peacekeeper. As the Associate Manager of Development Projects, Mr. Rolland worked on the NASP program for three years.*

ON FEBRUARY 24, 1949, in the New Mexico sky over White Sands Proving Grounds, a a new era began. On this day a man-made object attained speeds in excess of five thousand miles per hour, moving for the first time, into a velocity regime known as hypersonics. From this two-stage rocket, composed of a V-2 as the first stage and a WAC Corporal rocket as the second stage, it would be more than 12 years later before a manned vehicle would again reach hypersonic speed. The feat was accomplished when Major Yuri Gargarin of the USSR reached a velocity in excess of 25 times the speed of sound on April 12, 1961 in Vostok I, approximately 17,000 miles per hour.

During the 1960s and early 1970s there was considerable research undertaken in the United States to investigate air-breathing propulsion systems capable of sustaining hypersonic flight, followed by a second, sustained effort in the middle 1980s. In a strongly targeted approach, the United States began a major program to develop a vehicle that would be capable of taking off from a runway, attaining hypersonic velocity based on a combined air-breathing/rocket propulsion system, reaching earth orbit, and returning to the earth surface under power for a conventional landing. This effort is known as the National Aero-Space Plane (NASP) program, and is a direct response to the challenge of hypersonic flight.

First, a description of the dynamics of hypersonic flight and what's involved.



An artist's rendition of a portion of the Rocketdyne Hypersonic Flow Laboratory (RHYFL), looking from the compression tube launch segment toward the high-pressure end of the tube. The window section indicates the location of the control room.

When a hypersonic vehicle first leaves the runway it will be traveling at a speed in the range of 300 miles per hour (440 ft/sec). Since the speed of sound near the earth's surface is on the order of 1100 ft/sec, the vehicle is said to be traveling at subsonic speed. As the vehicle starts to climb and accelerate, it will eventually reach a velocity equal to the sound speed. At that time, the vehicle is said to be traveling at transonic speed. Once having attained the speed of sound, if the vehicle continues to accelerate it will be flying at supersonic speeds. As the velocity of the vehicle continues to increase, it will eventually attain hypersonic speeds.

The lines of demarcation are well defined for the subsonic, transonic and supersonic regimes, with the initial formation of shock and expansion waves as the vehicle exceeds the speed of sound. However, this is not the case for the hypersonic regime. There are no distinct physical phenomena that occur all of a sudden at a given velocity, which one can point to and state that above this speed the vehicle is flying at hypersonic speeds. Hypersonic is best defined as the velocity regime where certain physical phenomena become progressively more important as the Mach number is increased. The general consensus is that hypersonic flight commences when a vehicle reaches a velocity somewhere between five and eight times the speed of sound (Mach 5 to Mach 8).

These physical phenomena are thin shock layers, large entropy layers, strong viscous interactions and high temperature effects. As the Mach number increases for a given flow deflection angle, the shock angle becomes smaller. At hypersonic speed, the shock angle can become so small (i.e., thin shock layer) that the shock will merge with boundary layers. The entropy of the flow increases across a shock wave, and the stronger the shock wave, the larger the entropy increases. Since the shock wave strength is proportional to the Mach number square, a vehicle flying at hypersonic speed will experience a very strong entropy gradient in the vicinity of its nose. This entropy layer flows over the body, and the boundary layer along the surface of this vehicle grows inside this layer and is affected by it.

For a vehicle flying at hypersonic speeds, the flow, with respect to the vehicle, contains a large amount of kinetic energy. When this flow is slowed down by viscous effects within the boundary layer, the loss of kinetic energy results in an increase in the internal energy of the flow. This increase in internal energy of the gas in the boundary layer raises the temperature within this layer. And since viscosity increases with temperature and the boundary layer thickness increases with viscosity, at hypersonic velocity the thickness of this layer can be quite large. This thick boundary layer displaces the inviscid flow outside the layer, and gives the vehicle the appearance of being larger than it actually is. This change in the flow field outside the boundary layer will react with this layer, affecting its growth. This effect is called viscous interaction and influences the surface pressure distribution (i.e., lift, drag and stability) on the vehicle.

Of the physical phenomena characteristic of hypersonic flight, the most critical are the high temperature effects. When the velocity is reduced, for example, behind a strong shock or in the boundary layer, the reduction in the kinetic energy of the gas is transformed into internal energy, resulting in extremely high temperature on the orders of thousands of degrees Rankine. These temperatures can be of sufficient amplitudes to cause dissociation of the gas molecules, and in extreme cases, even ionization of various atoms. When this occurs, the gas can no longer be treated as a calorically perfect gas, but rather as a chemically reacting mixture.

For chemical reacting mixtures, three different kinetic processes can occur. The flow can be assumed to be frozen, in equilibrium, or in non-equilibrium. This added characteristic of the flow significantly increases the complexities of the problem.

While the high temperature and chemical reacting properties of the gas will influence the flight properties (lift, drag and moments) of a vehicle traveling at hypersonic speed, their dominant effect will result in an extremely high heat-transfer rate to the surface of the vehicle. Not only will the vehicle experience heating by means of convection from the boundary layer, but also from thermal radiation.

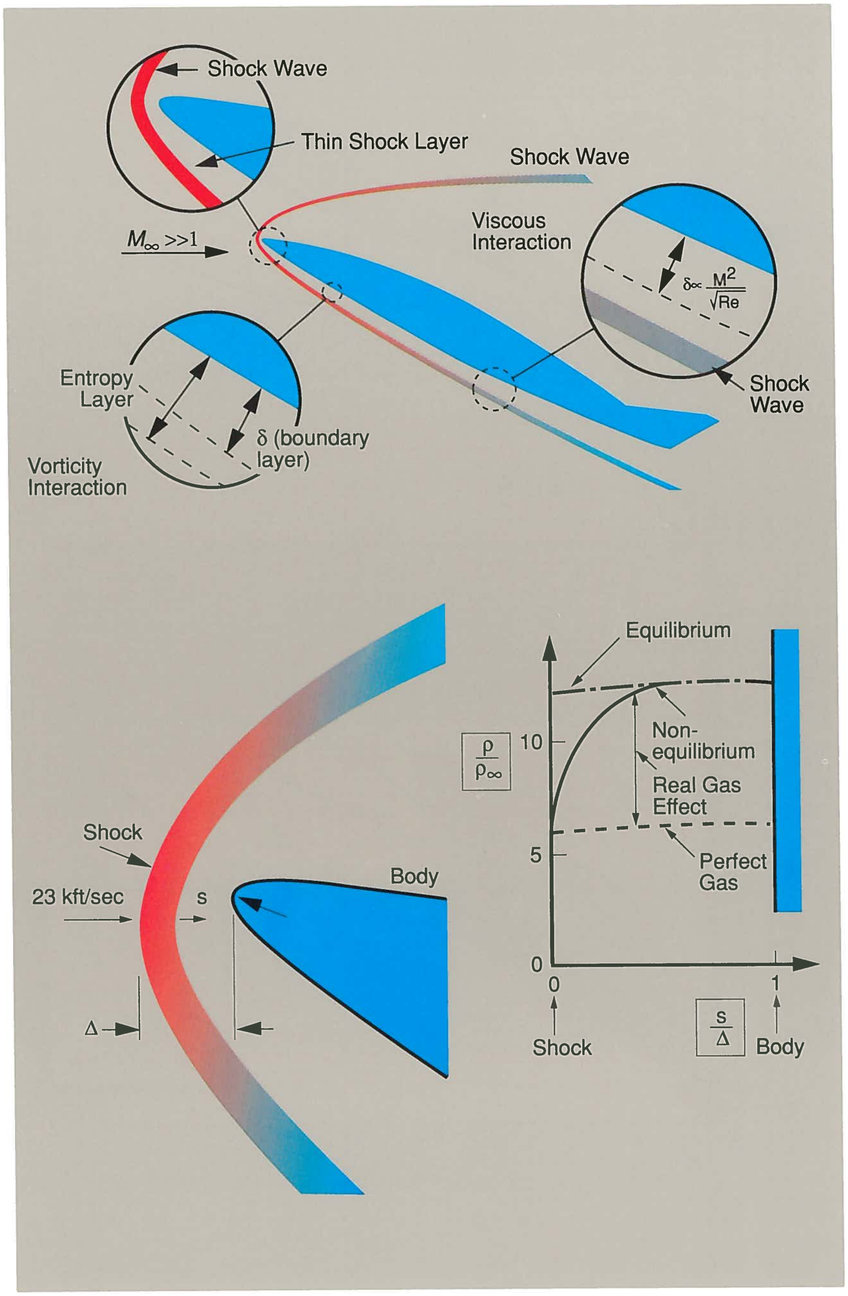
When one considers these various physical phenomena—that progressively become more important as the vehicle attains higher and higher velocities in the hypersonic flight regime—it is clear that vehicles flying at these speeds will have to be designed differently from the aircraft of today. The propulsion systems will have to be an integral part of the airframe, and special materials and coolant systems will have to be fabricated to cope with the extremely high heat-transfer rate experienced by the surface of the vehicle. Equally important—due to the very high speed of the aircraft—is the necessity for the control systems to react almost instantaneously. These requirements pose significant technical challenges that must be overcome before hypersonic flights become "routine."

Development of airbreathing hypersonic flight vehicles will require a major expansion over the flight envelopes of today's jet aircraft and rocket-powered launch vehicles. Since experimental verification of adequate engine and engine-airframe performance is key to a successful design and flight test program, this expansion has already had a profound impact on facilities for ground test simulation.

The upper limits of today's advanced jet engine flight envelope are altitudes of 80,000 to 90,000 feet and Mach numbers of 2.5 to 3.0. The flight envelope of hypersonic vehicles will require that the engine function at Mach numbers ranging from 0 to 24 at altitudes ranging from 0 to over 200,000 feet. Even within the altitude and Mach range of today's jet engines, the hypersonic airbreathing vehicle will follow a different flight path. In single-stage-to-orbit (SSTO) missions such as that contemplated for the NASP, it is essential the vehicle be capable of higher speeds at low altitudes.

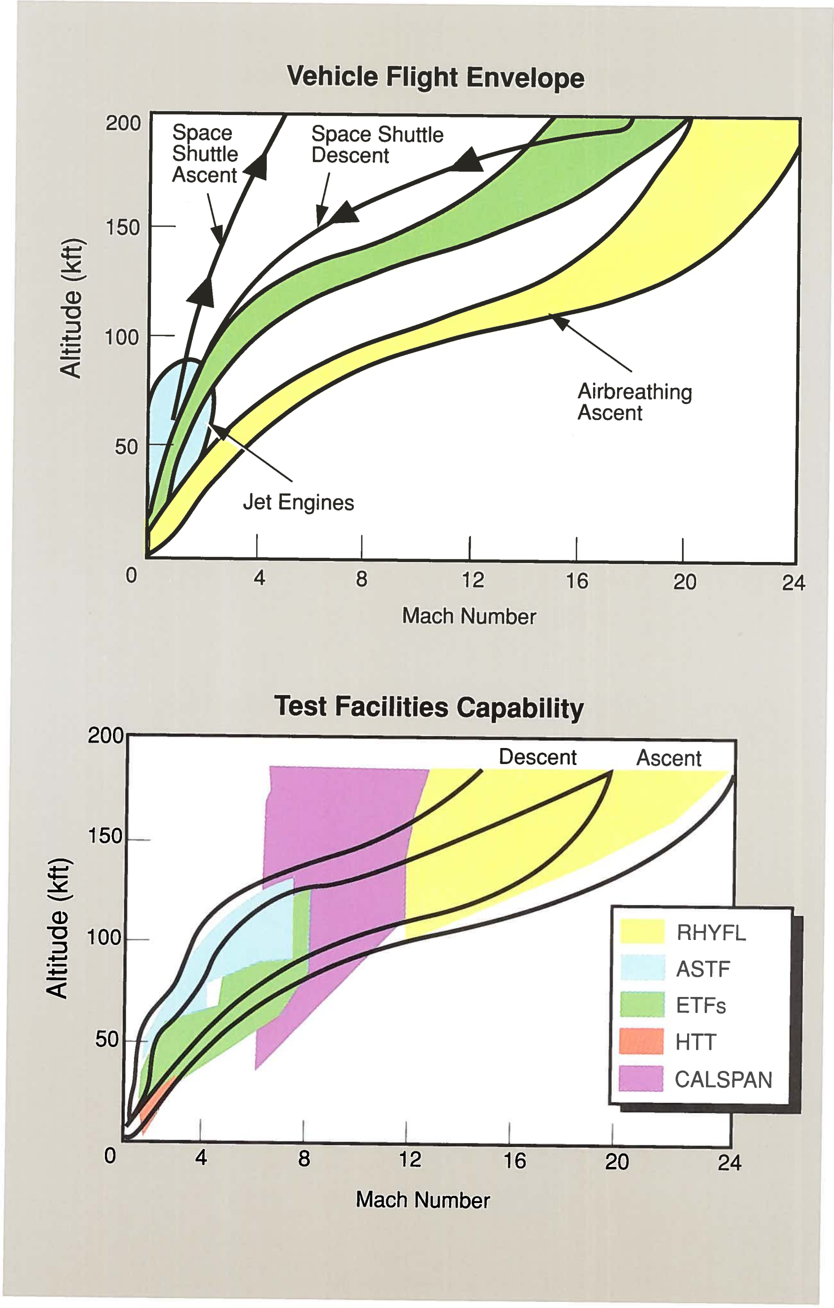
Comparison between the hypersonic airbreathing flight envelope and the Space Shuttle ascent flight envelope reveals the dramatic departure from today's flight experience that the NASP SSTO vehicle represents. The Space Shuttle flies at hypersonic speeds and at high altitudes. However, being a rocket-powered vehicle that carries both its fuel and oxidizer, the Shuttle's most efficient trajectory is one of quick ascent through the atmosphere in order to minimize drag and gravity losses and the design complications of sustained aeroheating. On the other hand, the airbreathing SSTO vehicle will accelerate within the lower atmosphere in order to provide the large quantities of air (oxidizer) required by its engines to attain the high specific impulse so important to SSTO capability. Speeds as high as Mach 16 may be reached at altitudes as low as 125,000 feet.

The marked difference in flight envelopes suggests that facilities designed to simulate advanced turbojet and rocket-powered flight environments may not be suitable for hypersonic airbreathing propulsion systems. Indeed, the early planners at the NASP Joint Program Office found this to be the case. At the start of the NASP program, there were no facilities in the United States capable of testing a large-scale engine module in the critical regime between Mach 5 and Mach 8. Proper simulation of flight at these Mach numbers requires a wind tunnel which can provide the corresponding stagnation pressures and temperatures. As a part of the overall NASP program, the JPO funded the development of two facilities known as the Engine Test Facilities (ETFs), one at the Marquardt Company in Van Nuys, California, and the other at Aerojet TechSystems in Sacramento, California. These facilities provide relatively long duration test capabilities in the Mach 5 to Mach 8 range, and can simulate flight altitudes representative of a NASP ascent trajectory. They provide essential test coverage in the range in which the engine must transition between the ramjet and scramjet modes of operation.



Physical phenomena associated with hypersonic speeds, are thin shock layers, large entropy layers, strong viscous interactions and high temperature effects. The chemical reactions (real gas effects) experienced in hypersonic flight cause a greater increase in gas density across a shock than predicted when the medium is assumed a prefect gas (ρ_∞ is the freestream density just before the shock).

Yet there remained a gap in ground test capability at the highest Mach numbers that the engine-



NASP will fly faster at lower altitudes than present-day aircraft. Test facilities capable of supporting the development of this vehicle are the 48-inch/96-inch tunnel at CALSPAN; the High Temperature Tunnel (HTT) at NASA-Langley; the two Engine Test Facilities (ETF) at Marquardt Company and Aerojet TechSystems; the Aeropropulsion System Test Facility (ASTF) at AEDC; and RHYFL

airframe combination would encounter. This was particularly true of facilities needed for testing of large-scale components. At higher flight Mach numbers (M>10), the airstream energy is so great that, on the ground, conditions can only be simulated for periods measured in milliseconds using a shock tube facility. Even in such short test durations, however, significant amounts of valuable data for characterization of engine and airframe component performance can be acquired. So in order to fill this void in test capability, Rocketdyne, late in 1987, embarked upon the design and construction of the Rocketdyne Hypersonic Flow Laboratory (RHYFL).

Proper simulation of air pressure and temperature at high Mach numbers was not the only requirement to have a major impact on RHYFL. The ability to reproduce these conditions using full-scale test hardware—for the engine combustor, in particular—was considered paramount. Whereas it is generally accepted that aerodynamic phenomena can be adequately simulated with subscale models by matching the Reynolds number based on a selected characteristic length, almost no one is willing to accept subscale test results as design validation when combustion kinetics and reacting flows are present. Thus, Rocketdyne's NASP managers came to believe that an engine concept based on high-speed performance validated with full-scale hardware was mandatory if government decision makers were expected to eventually support go-ahead for detail design and fabrication of the X-30 experimental aircraft.

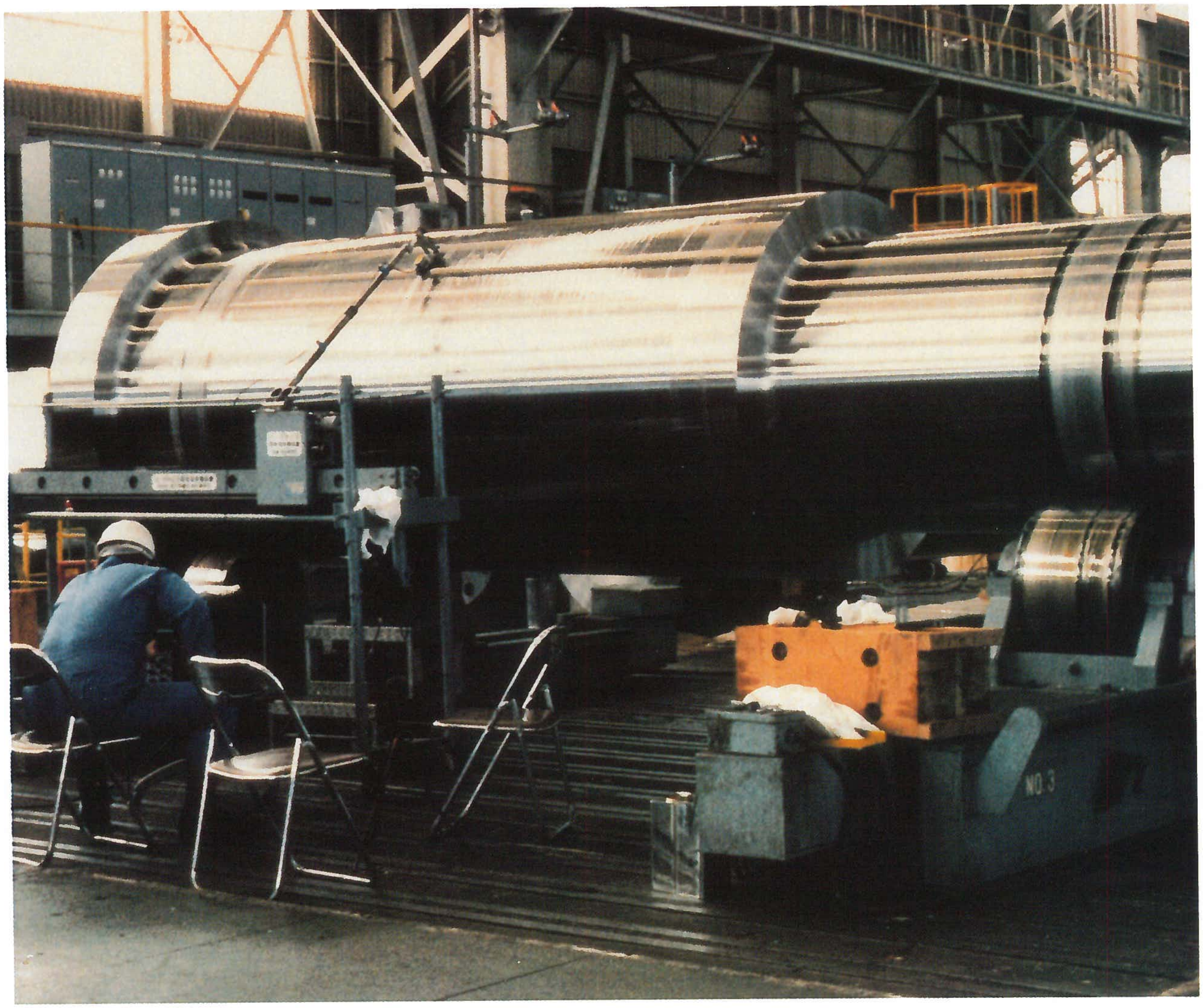
The energy levels required to deliver the mass flow at the proper conditions, and its consequent size, are what makes RHYFL unique. At its maximum operating pressures, RHYFL will generate 33 megajoules. This is more than 30 times greater than the largest free-piston shock tunnel in operation today, the T-4 facility at the University of Queensland in Brisbane, Australia.

The heart of RHYFL, as designed and constructed by WBM-Stalker-Bechtel, will be a free-piston shock tunnel operated in a shock reflection mode. Additional systems that make up RHYFL will be gas feed and vacuum systems, diagnostic systems and a data acquisition system.

The free-piston shock tunnel will consist of secondary reservoirs, launch manifold, compression tube, inertial mass, shock tube, nozzle, test section, dump tank, positioning system, translation system, diaphragm handling system, piston handling and inspection system, and a control system.

The two secondary reservoirs will contain the gas (pusher gas) to propel the piston down the compression tube. For most tests the pusher gas will be nitrogen at pressures up to 3500 psi. The launch manifold will provide the interface between the secondary reservoirs and the compression tube and will contain the launch capsule. The launch capsule will hold the piston in the ready mode just prior to firing the shock tunnel.

The 153-foot, 24-inch diameter compression tube will house the piston and the helium driver gas. The strength of the shock wave generated in the shock tube is dependent on the pressure and temperature of the driver gas at the time of



This forged and machined hardware will be matched with other components to complete the RHYFL shock tunnel.

diaphragm rupture. The end of the compression tube, where a burst diaphragm will be housed, is designed to operate at pressures up to 37,000 psi. The six-foot-long piston will weigh 4400 pounds.

The shock tube will be separated from the compression tube by the burst diaphragm and will contain the test gas, which typically will be air. It will be 103 feet in length, with an internal diameter of eight inches. A thin mylar diaphragm will separate the shock tube from the nozzle.

RHYFL will initially be used to conduct full-scale direct connect combustor experiments. To accommodate the rectangular inlet geometry of the combustor, a two-stage nozzle will be employed. The first stage will be an axisymmetric nozzle, and the second stage a rectangular nozzle that expands in two dimensions. The throat of this stage, positioned inside the exit of the axisymmetric stage in a cookie-cutter fashion, will allow for the removal of the boundary layer. In addition, boundary-layer bleed slots will be included on two of the sidewalls of the second stage to mitigate the generation of boundary layer bulge due to the two-dimensional expansion of this stage. The variations in the throats of the two stages will allow the area ratio of this nozzle to vary from approximately 90 to about 400. When the tunnel recoils, the first stage of the nozzle will move with the shock tube while the second stage will remain fixed to the test section.

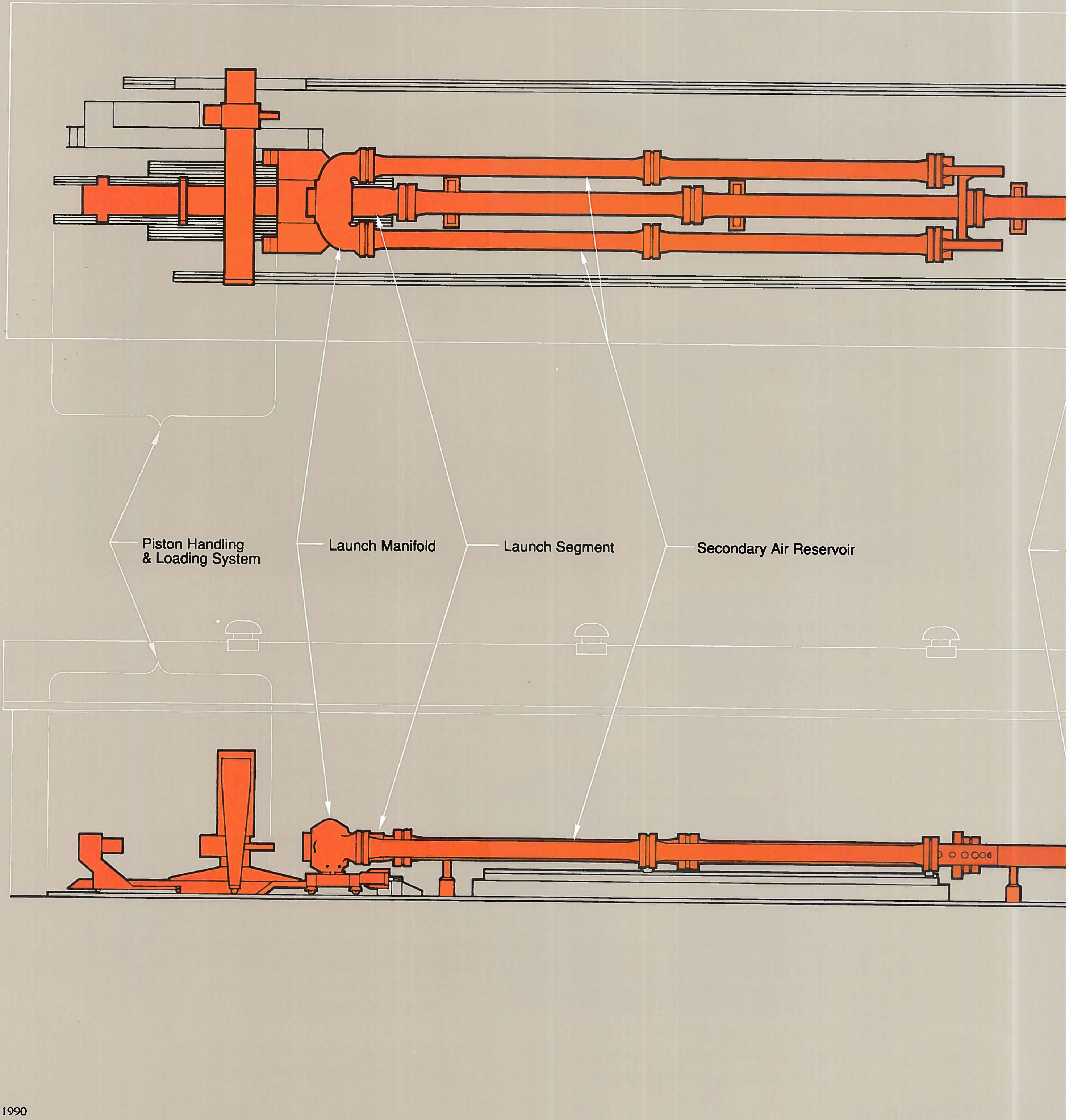
For the NASP combustor tests, the test section will be a full-scale scramjet combustor including a transition section and an internal nozzle. This test section will interface to the dump tank, which will be 33 feet long with an internal diameter of 13 feet. The opening to this tank will be a circular opening with a diameter of 6.5 feet. The tank will be equipped with a number of access ports to allow test hardware to be located inside this tank.

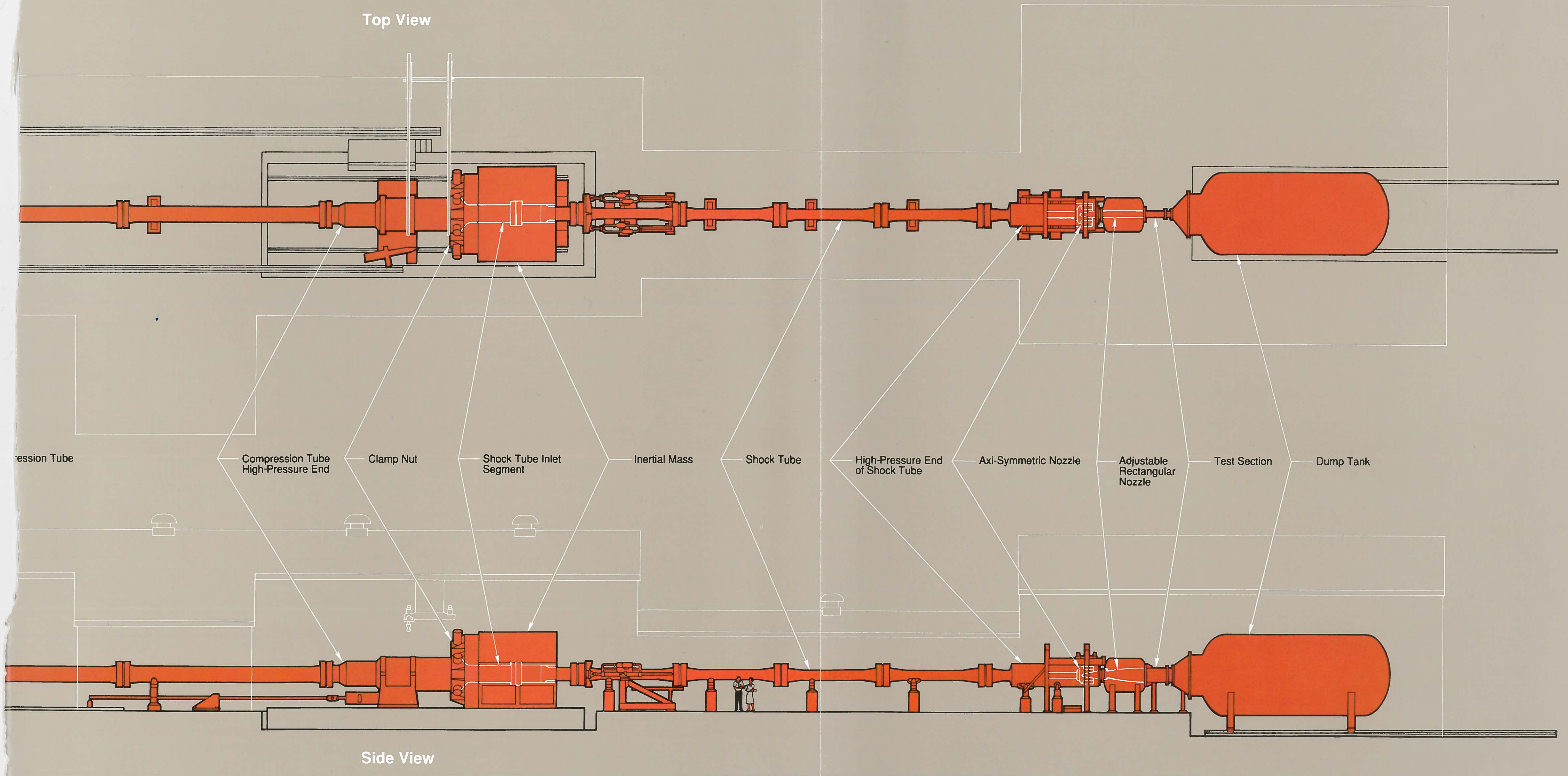
Even though RHYFL will initially be used to conduct full-scale combustor tests, the facility has

RHYFL

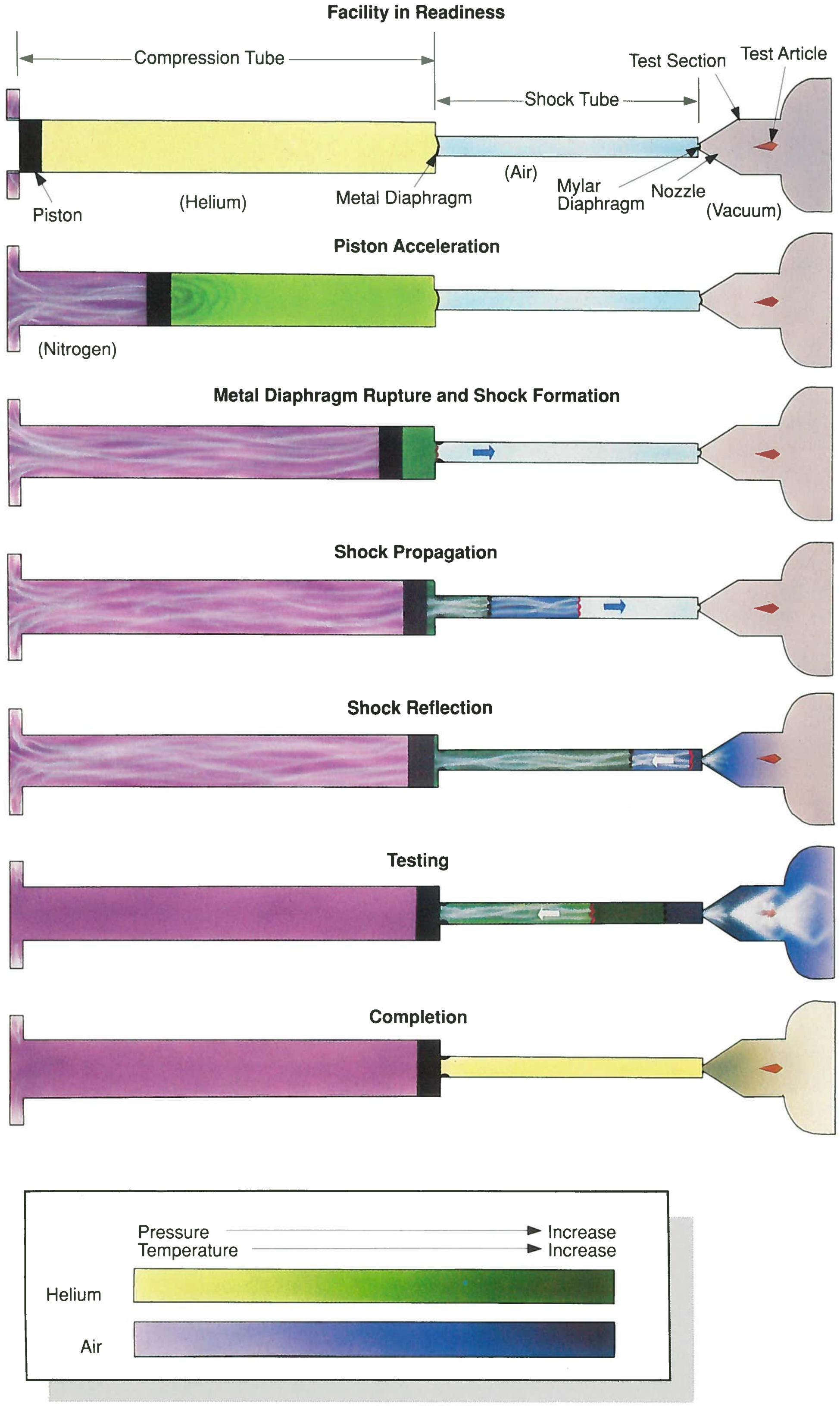
Rocketdyne Hypersonic Flow Laboratory

The heart of the Rocketdyne Hypersonic Flow Laboratory is a free-piston shock tunnel operated in a shock reflected mode. This facility will provide test conditions simulating inflight characteristics for a full-scale combustor for the National Aero-Space Plane (NASP) over the Mach number range of 12 to 24. The tunnel will be slightly longer than a football field and weigh approximately 1.6 million pounds.




Top View
ession Tube
Compression Tube
High-Pressure End
Clamp Nut
Shock Tube Inlet
Segment
Inertial Mass
Shock Tube
High-Pressure End
of Shock Tube
Axi-Symmetric Nozzle
Adjustable
Rectangular
Nozzle
Test Section
Dump Tank
Side View

RHYFL Testing Sequence



Shock reflection at the end of the shock tube provides test gas with the correct stagnation enthalpy to simulate hypervelocity flight. Test times available are on the order of milliseconds, but are sufficient to measure performance of a full-scale combustor for NASP.

been designed to accommodate airframe tests. For these types of tests it is anticipated that a much longer nozzle will have to be used; therefore, the dump tank will be built such that it can be moved approximately 33 feet downstream of its initial position. This will provide room for the added nozzle length and a test section with an internal diameter up to 6.5 feet and a length of approximately 10 feet.

When the pusher gas exerts a force on the piston, an equal and opposite force will be applied to the launch end of the compression tube. To compensate for this, the free-piston shock tunnel up to and including the first stage of the nozzle will be allowed to recoil. This will ensure that the center of mass of the tunnel essentially remains at a constant position. Since the piston weighs about 4400 pounds and moves a distance of approximately 150 feet, the tunnel with a weight of slightly less than 800 tons will move about 5 inches.

The controls necessary to operate the tunnel and the associated gas systems will be fully automated using a computer system. It will include two monitoring subsystems to provide totally independent assessment of the tunnel operating conditions.

The diagnostics for RHYFL will consist of both intrusive and nonintrusive systems. In addition to the wall-mounted pressure transducers, heat-transfer gauges and pitot-static pressure rake, RHYFL will be equipped with four diagnostic systems being developed under the NASP program. These are a Planar Laser Induced Fluorescence (PLIF) system, a high-speed Schlieren system, a 3-D holographic system and a time-of-flight (TOF) mass spectrometer. The first three systems will be nonintrusive, while the TOF mass spectrometer will be housed in the entrance to the dump tank. The PLIF system will be capable of providing either two-dimensional (sheet) frozen images of OH and/or NO concentration profiles, or a two-dimensional profile of the static temperature using the ratio of the two OH images. The Schlieren system will provide an integrated map of density variations in the flow. This system can take 80 photographs per test at a rate up to 20 kHz. The holographic system using a ruby laser will provide three-dimensional information of strong flow field perturbation (e.g., shock wave) and multiple views of line-of-sight of integrated flow features (e.g., shear layer). The TOF mass spectrometer system will monitor the relative concentration of the major species (H_2, O_2, N_2, H_20, NO, etc.) at a single point in the flow field throughout a test. This system will provide an updated spectrum every 50 microseconds. To record the sequence of events and the pressure and heat transfer data, RHYFL will be equipped with a 300-channel data acquisition system. This system will be capable of sampling rates up to one million samples per second.

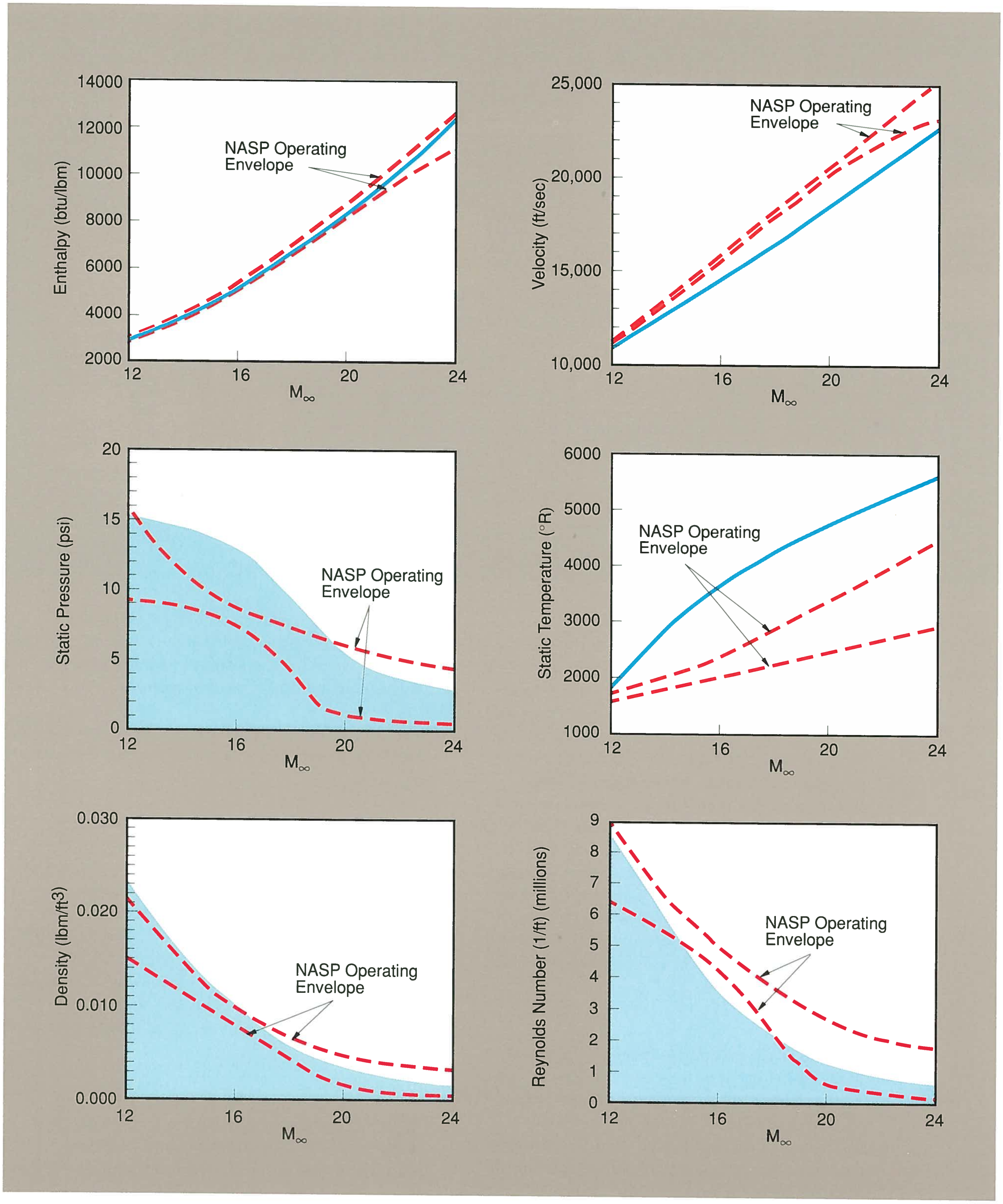
The operation of RHYFL can be broken down into seven steps:

Facility Readiness :
The secondary reservoirs are filled with high-pressure pusher gas, typically nitrogen. With the metal and mylar diaphragms in place, the compression tube is filled with the driver gas, helium. The initial pressure in this tube will be somewhere between one-half and two atmospheres. The test gas, air, is placed in the shock tube at a pressure in the neighborhood of one-half to one atmospheres. The nozzle, test section and dump tank are evacuated to a pressure of 0.1 torr.

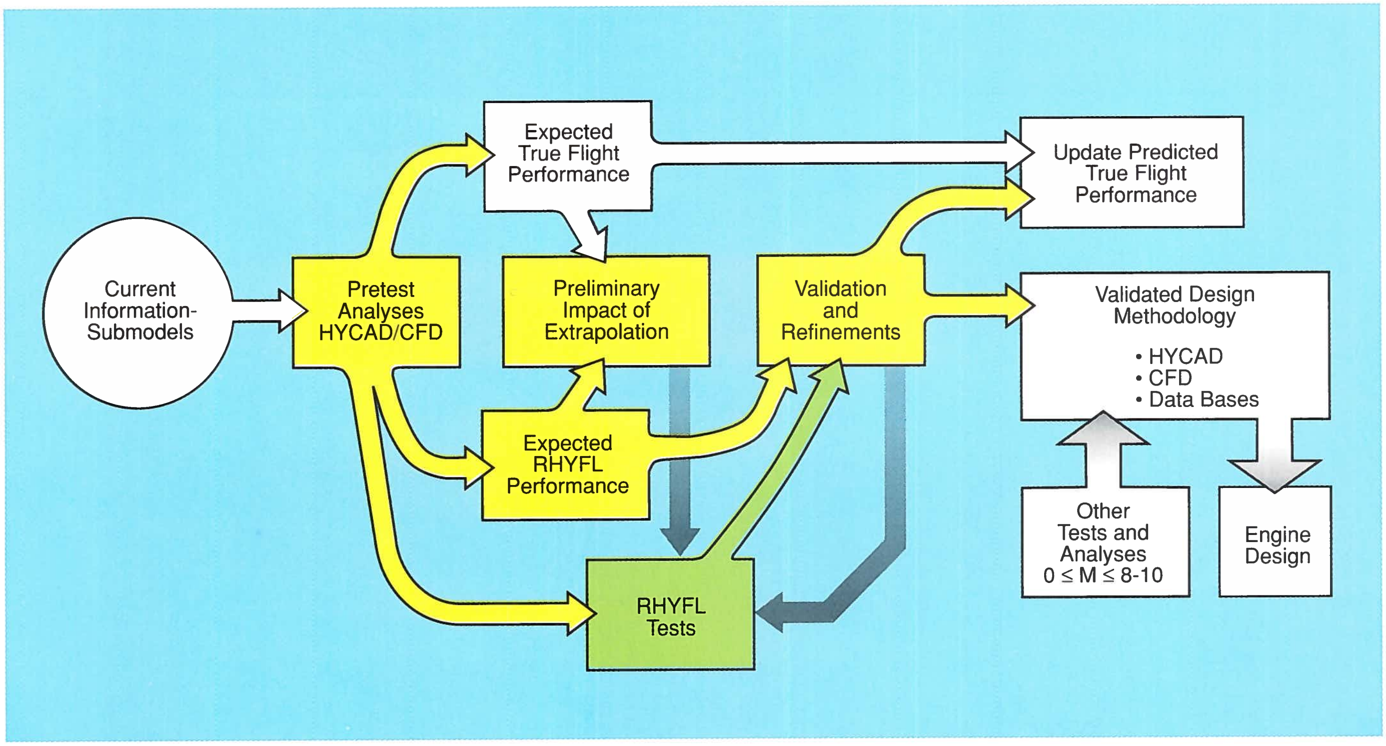
Piston Acceleration :
The pusher gas is introduced to the rear face of the piston through the launcher manifold. The piston begins to accelerate and compress the driver gas, helium. The piston can accelerate to velocities approaching a thousand feet per second. Due to the very short time (a fraction of a second) involved in the compression of the driver gas, this process can essentially be considered adiabatic.

Metal Diaphragm Rupture and Shock Formation :
As the driver gas is compressed, there is a significant rise in its pressure and temperature. Depending upon operating conditions, the pressure and temperature of this gas can attain values approaching 37,000 psi and 9,000°R. When the differential pressure across the metal diaphragm equals its burst pressure, it will rupture, and a shock wave will be propagated in the shock tube. This will occur when the piston is anywhere from approximately 30 inches to 15 inches from the end of the compression tube. Once the diaphragm has ruptured, the piston will continue to move forward, thereby keeping the driver gas at nearly a constant pressure.

Shock Propagation :
As the shock wave propagates down the shock tube, the test gas that it traverses is accelerated to a high velocity and experiences a significant increase in pressure and temperature.



Predicted design characteristics for RHYFL at the nozzle exit as a function of in-flight Mach number (M_∞) for a full-scale combustor test. These predictions were made assuming equilibrium conditions in the shock tube and nonequilibrium flow in the nozzle.



RHYFL will be an integral part of the NASP program, providing invaluable data to assist in the design of airbreathing engines and Computational Fluid Dynamic Code validation for in-flight Mach number ranges from 12 to 24.

Shock Reflection :
When the shock reaches the end of the shock tube, two events will occur: one, the mylar diaphragm at the entrance to the nozzle will rupture; and two, due to the fact that the throat of the nozzle is considerably smaller in diameter than the shock tube, the shock will be reflected and begin to propagate upstream. As the reflected shock traverses the gas that is moving downstream, a reverse velocity component is imparted to the test gas essentially bringing it to rest, resulting in the gas attaining its stagnation properties (enthalpy, pressure, temperature, etc.). The rupturing of the mylar diaphragm will allow the test gas to enter into the nozzle. From this step forward, the free-piston shock tunnel basically acts as a blow-down tunnel.

Testing :
As the test gas propagates through the nozzle, it will be accelerated to hypersonic velocities (up to 25,000 ft/sec). This condition will last long enough (milliseconds) to attain steady-state conditions in the test section. During this time, a test article in the test section will experience the physical phenomena (e.g., high temperature effects, viscous interaction) that are characteristic of hypersonic flight.

Completion :
As soon as the driver gas, helium, is introduced into the test section, the test is completed. At that time the piston, having surrendered its kinetic energy to the driver gas, is at the end of the compression tube. The shock tube is filled with helium, and the nozzle, test section and dump tank are occupied with a mixture of test gas and helium.

The period from the time the piston begins to move until the time that the test is completed is less than one second.

Beside the test gas properties at the exit of the nozzle, the other important characteristic of the facility is the available test time. If the data are to be valid, the combustor must experience steady-state conditions during the test. Due to its size, RHYFL will provide test time sufficient to ensure steady-state conditions for a full-scale NASP combustor over the Mach number range of interest. In fact, for Mach numbers 20 and below, this facility will provide test time significantly greater than required.

RHYFL has been designed to test combustors for the X-30 engines at or near full scale. Since the entrance velocity is closely simulated, the residence time within the combustor will be a good simulation of flight conditions. Air density will be lower than flight conditions, but injectant density can also be proportionately reduced so that the dynamic pressure ratio $(\rho_f u_f^2/\rho_a u_a^2)$, important in the study of transverse jet penetration and mixing, provides good simulation, where the subscripts f and a correspond to fuel and air, respectively.

At simulated flight Mach numbers above 18, detail differences in the combustion process can be expected because of the air dissociation and elevated temperature influence on the kinetics of the combustion process. This will primarily be felt in the chemical kinetics of ignition and the level of nonequilibrium flow in the aft body/nozzle. However, over much of the operating range of the X-30 engine, the overall rate of reaction is limited by mixing rather than by kinetics; therefore, the effects of dissociation and increased static temperature on the simulation will not seriously affect test results.

Finite-rate air dissociation kinetics calculations can be used to address the differences between RHYFL and those of actual flights. While initial estimates can be made using one-dimensional kinetics calculations, more detail assessments will require 2-D and 3-D calculations to examine the effects of boundary layer and mixing phenomena. Rocketdyne, under the NASP program, has developed a number of computational tools to address these differences. These include the HYCAD combustor analysis code and a finite-rate chemistry version of the sophisticated USA computational fluid dynamics (CFD) code. Initial calculations for a generic combustor geometry have been conducted using the HYCAD code. The results showed that significant differences would occur in the measured net internal thrust between tests conducted in RHYFL and the flight engine. However, when the net internal thrust was normalized by the correct dynamic pressure of the fuel to obtain the specific impulse of the engine, the results between RHYFL and the engine showed excellent agreement up to about Mach 20. Above this Mach number, RHYFL showed a higher specific impulse, which is probably due to the higher gas dissociation in RHYFL, producing additional heat from recombination.

The results of full-scale combustor tests in RHYFL, coupled with CFD calculations, will prove to be invaluable in the design of the scramjet for the NASP X-30 aircraft.

Detail design of the facility is complete. Procurement of tunnel components is progressing satisfactorily with many major components already delivered. Actual construction at the Burro Flats site at SSFL is scheduled to begin in July 1990, with completion anticipated in May 1991. Testing in support of the NASP program is expected to begin in late 1991, following a six-month commissioning period during which the facility will be brought up to operational status. This schedule will permit ample time to acquire the high-speed engine and airplane component performance data so critical to the decision to build the X-30 airplane.

When completed, RHYFL will be the largest and most advanced facility of its kind in the world. More important, RHYFL will represent a unique asset to Rocketdyne, and indeed, the country in the development of systems for affordable access to space. ■

ACKNOWLEDGMENT

The RHYFL project is the result of the efforts of a number of Rocketdyne personnel, including Dr. J.A. Blauer, J.F. Pavlinsky, S. Fischler, P.A. Neff, R.L. Pappan, C.H. Shoji and T.A. White. In addition, the authors are grateful for the assistance of S.A. Munjee and Dr. J.A. Blauer in predicting the operating characteristics of the RHYFL free-piston shock tunnel.

FOR ADDITIONAL READING

The Industrial Revolution, Part II

THE DEMING ROUTE TO QUALITY AND PRODUCTIVITY: ROAD MAPS AND ROAD BLOCKS, William Scherkenbach, Quality Press.

WHAT IS TOTAL QUALITY CONTROL? THE JAPANESE WAY, Kaoru Ishikawa, Prentice-Hall.

INTRODUCTION TO QUALITY ENGINEERING, Dr. Genichi Taguchi, ASI Press.

OUT OF THE CRISIS, W. Edward Deming, George Washington University.

QUALITY IS FREE, Philip Crosby, NAL.

QUALITY FUNCTION DEPLOYMENT, ASI Press.

THE DEMING MANAGEMENT METHOD, Walton, Dodd, Mead & Company, New York, 1986.

BETTER DESIGNS IN HALF THE TIME: IMPLEMENTING QFD, GOAL/QPD, Mathuen, Massachusetts, 1988.

GUIDE TO QUALITY CONTROL, Kaoru Ishikawa, Quality Resources, White Plains, New York, 1968.

Forensics Engineering

MODEL OF SUSTAINED LOAD CRACKING BY HYDRIDE GROWTH IN TITANIUM ALLOYS, W.J. Pardee and N.E. Paton. Met.Trans., Vol.IIA, pp.1391-1400, August 1980.

HYDROGEN EMBRITTLEMENT OF ALPHA TITANIUM: IN SITU TEMP STUDIES, D.S. Shih, I.M. Robertson and H.K. Birnbaum, Acta. Met., 36, No.1, pp.111-124, 1988.

MECHANISMS OF HYDROGEN-INDUCED DELAYED CRACKING IN HYDRIDE FORMING METALS, R. Dutton, K. Nuttall, M.P. Puls and L.A. Simpson, Met.Trans., Vol. 8A, pp. 1553-1562, October 1977.

HYDROGEN EMBRITTLEMENT OF Nb I-MACROSCOPIC BEHAVIOR AT LOW TEMPERATURES, S. Gahn, M.L. Grossbeck and H.K. Birnbaum, Acta. Met., 25, pp.125-134, 1977.

LOW-TEMPERATURE HYDROGEN EMBRITTLEMENT OF NIOBIUM II - MICROSCOPIC OBSERVATIONS, M.L. Grossbeck and H.K. Birnbaum, Acta. Met., 25, pp.135-147, 1977.

METALLOGRAPHIC OBSERVATIONS OF THE INTERACTION OF HYDRIDE, STRESS AND CRACK GROWTH AT 600°K IN A Zr-2.5% Nb ALLOY, K. Nutall, A.J. Rogowski and F. Havelock, Scripta Met., 10, pp.979-982, 1976.

GASEOUS HYDROGEN-INDUCED CRACKING OF Ti-5Al-2.5Sn, D.Williams, H.G. Nelson, Met.Trans., 3, pp.2107-2113, 1972.

MICROSTRUCTURAL ORIGIN OF FLUTES AND THEIR USE IN DISTINGUISHING STRIATIONLESS FATIGUE CLEAVAGE FROM STRESS CORROSION CRACKING IN TITANIUM ALLOYS, D.A. Meyn and E.J. Brooks, ASTM STP 733, pp.5-31, 1981.

SUSTAINED LOAD TESTING OF Ti-5Al-2.5Sn (ELI), J.T. Staley, Jr., MPR-89-0682, June 28, 1989.

Proof of Principle: The Kinetic Kill Vehicle

KINETIC ENERGY WEAPON DIRECT PROPULSION TECHNOLOGY VERIFICATION AND RISK REDUCTION PROGRAM, L.L. Tignac, Rocketdyne, January 1987.

KINETIC ENERGY WEAPON DIRECT PROPULSION TECHNOLOGY VERIFICATION AND RISK REDUCTION PROGRAM - KEW HARDWARE DEVELOPMENT, L.L. Tignac, Rocketdyne, March 1988.

KINETIC KILL VEHICLE FLIGHT TEST PROGRAM, W. Burns, L. Tignac, T. Massmann and S. Nestlerode, Rocketdyne, July 1988.

KKV PROPULSION SYSTEM TECHNOLOGY ACHIEVEMENTS, Rocketdyne BD 88-150.

Building a Better Blade

MATERIALS FOR ADVANCED ROCKET ENGINE TURBOPUMP TURBINE BLADES, W. T. Chandler, NASA-LeRC Contract NAS3-23536, Final Report, November, 1983.

NASA PROBES CERAMICS FOR THE 21ST CENTURY, Ceramic Industry, April, 1988.

SUPERALLOYS, SUPERCOMPOSITES AND SUPERCERAMICS, John K. Tien and Thomas Caulfield, Eds., Academic Press, San Diego, CA, 1989.

RHYFL: A Tool for Attaining Hypersonic Flight

HYPERSONIC AND HIGH TEMPERATURE GAS DYNAMICS, John D. Anderson, McGraw-Hill, Inc., New York, New York, 1989.

CHALLENGES FOR HIGH-ENTHALPY GAS DYNAMICS RESEARCH DURING THE 1990s, H. Hornung and B. Sturtevant, Graduate Aeronautical Laboratories, California Institute of Technology, FM 90-1, January 1990.

HYPERVELOCITY AERODYNAMICS WITH CHEMICAL NONEQUILIBRIUM, R.J. Stalker, Annual Review of Fluid Mechanics, 21: 37-60, 1989.

DEVELOPMENT OF A HYPERVELOCITY WIND TUNNEL, R.J. Stalker, Aeronautical Journal of Royal Aeronautical Society, pp.374-384, June 1972.

First delivered to the field in 1972, the highly mobile Lance surface-to-surface missile was designed as long-range artillery support. The Lance is still deployed in key areas around the world and uses an innovative "chamber-within-a-chamber" annular bell thrust chamber configuration.

Rockwell International

...where science gets down to business

Pub. 571-K-81 Rev. 7-90