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DESIGN CRITERIA
(CHEMICAL PROPULSION)

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LIQUID ROCKET ENGINE FLUID-COOLED COMBUSTION CHAMBERS

APRIL 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, part of the series on Chemical Propulsion, is one such monograph. A list of all monographs issued to date can be found on the final pages of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, eventually will provide uniform design practices for NASA space vehicles.

This monograph, "Liquid Rocket Engine Fluid-Cooled Combustion Chambers," was prepared under the direction of Howard W. Douglass, Chief, Design Criteria Office, Lewis Research Center; project management was by Harold W. Schmidt. The monograph was written by Dr. N. E. Van Huff and David A. Fairchild of the Aerojet Liquid Rocket Company, and was edited by Russell B. Keller, Jr., of Lewis. To assure technical accuracy of this document, scientists and engineers throughout the technical community participated in interviews, consultations, and critical review of the text. In particular, Dr. C. D. Coulbert of the Jet Propulsion Laboratory, California Institute of Technology; John Campbell of the Rocketdyne Division, North American Rockwell Corporation; A. R. Eberle of the Space Division, North American Rockwell Corporation; T. F. Reinhardt of Bell Aerospace Company; and W. G. Anderson of the Lewis Research Center collectively and individually reviewed the monograph in detail.

Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Lewis Research Center (Design Criteria Office), Cleveland, Ohio 44135.

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GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in design, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into two major sections that are preceded by a brief introduction and complemented by a set of references.

The State of the Art, section 2, reviews and discusses the total design problem, and identifies which design elements are involved in successful design. It describes succinctly the established technology relevant to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Design Criteria* and Recommended Practices.

The *Design Criteria*, shown in italics in section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to assure successful design. The *Design Criteria* can serve effectively as a checklist of rules for the project manager to use in guiding a design or in assessing its adequacy.

The Recommended Practices, also in section 3, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The Recommended Practices, in conjunction with the *Design Criteria,* provide positive guidance to the practicing designer on how to achieve successful design.

Both sections have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the Contents displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the designer.

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1. INTRODUCTION

The walls of the combustion chamber and nozzle of a liquid rocket engine must not be heated to temperatures that endanger the structural integrity of the chamber or nozzle. Several methods exist for cooling the walls so that the temperature is maintained at a safe level:

Regenerative cooling - One or both propellants are circulated as coolants around the outer surface of the wall to be cooled.

Transpiration cooling - A porous inner wall is cooled by forced flow of coolant fluid through the porous material.

Film cooling - A thin layer of cooling fluid is maintained over the inner surface of the wall.

Coatings - A layer of low-conductivity material is deposited as a thermal barrier on the inner (gas) side of the wall.

This monograph concentrates on regenerative cooling because it represents the cooling technique used for current operational flight-weight fluid-cooled combustion chambers. Transpiration cooling, film cooling, and coatings, certainly demonstrated as effective cooling methods, cannot be regarded as operational as of the beginning of 1970. However, because the development work to date has demonstrated significant potential for transpiration cooling, this method is discussed in sufficient detail to portray its current status and to guide future work. Film cooling and coatings are treated as practical supplemental methods to achieve thermal and chemical compatibility between the injector and regeneratively cooled chambers.

Regeneratively cooled chambers began as fairly sturdy double-wall or channel-wall assemblies. As larger light-weight chambers and higher chamber pressures were required, the coolant tube became the dominant chamber component. This development presented a series of major design problems in fabricating and shaping large thin-wall tubes, brazing hundreds of these tubes together into a gas-tight structure, and attaching heavy components to this thin-wall structure. These problems have been solved, as evidenced by the tubular-wall rocket engines used on the Saturn V vehicle, the Centaur stage, and the Titan and Atlas vehicles. During 1968 and 1969, a resurgence of the channel-wall concepts occurred in the form of non-tubular regeneratively cooled chambers. Fabrication methods such as spinning, electroforming, electrodeposition, and casting are employed to form unitized chambers that can provide extremely small, complex flow passages not possible with tubes. This effort is in its development stage and therefore is not covered in detail in this monograph.

Five major yet common problems that arose during many engine development programs appear to be the problem areas in chamber cooling that will continue to arise no matter what design concept is selected:

- Injector/chamber incompatibility. - Variations in combustion around the periphery of the injector generate chemical and thermal streaks that damage the chamber wall near the injector.

- Coolant-passage design complexity. - Optimum utilization of the coolant within practical pressure drop constraints requires local tailoring of the coolant passages, the result being a complex component with variable wall thicknesses, variable coolant velocities, and multipass requirements.

- Chamber-wall lifetime. - Chemical attack and thermal fatigue produce erosion and cracking of the combustion-side wall, the damage leading to an end to chamber usefulness.

- Attachment of heavy components. - Inadequate brazing, large variations in thermal expansion, and excessive loads generate leaks and cracks at thick-to-thin interfaces that can produce chamber failures.

- Transient behavior. - Improper design for the pressures, temperatures, and force imbalances that exist during engine startup and shutdown can cause catastrophic chamber failure.

This monograph treats primarily the individual components of the hardware for cooling the chamber (passages, flanges, manifolds, etc.), and focuses on the solutions to the five problems listed above. However, due recognition is given to the following additional elements that are involved in successful thrust chamber designs:

- Proper use of well-developed analytical procedures provides an accurate evaluation of the thrust chamber design and leads to major initial success.

- Selection of a design based on existing facilities and capabilities enables a development to proceed with lower costs and fewer major problems.

- Carefully conducted experimental studies can establish successful design in critical areas where analytical capabilities are inadequate.

- High-quality brazing is achieved at less expense when brazing is viewed as a major problem area, and task group assignments and studies are made early in the development program.

- The quickest successful resolution of the injector/chamber incompatibility problem is achieved when interaction between the injector and chamber designers is required.

2. STATE OF THE ART

Basic features of the major production engines that use fluid-cooled thrust chambers are displayed in table I. All the engines use regenerative cooling as the primary means of thermal control. As shown, the use of fluid cooling is limited to relatively large boosters, upper stages, or sustainer operation, and in one case to vernier control. The X-15 is the only engine with throttling capability, though others have been operated at throttled conditions; the Agena, J-2, and RL 10 have restart capability. Thrusts range from 1000 to 1.5 million pounds (4.45 to 6672 kN), and maximum chamber pressure is 1000 psia (6.90 MN/m^2). All the engines employ cylindrical or conical combustion chambers, contoured contraction and expansion sections, and round throats. Thus, the state-of-the-art fluid-cooled thrust chamber may be characterized as regeneratively cooled, with a fairly high thrust and classical contour; normal operation is at a single thrust level, and restart capabilities are limited. It is within this definition that the state-of-the-art section is written.

The industry has been engaged in developing fluid-cooled chamber designs other than those represented by table I, but the state of development of these concepts has not been advanced sufficiently to include in detail here. Some of these development designs are listed below for information purposes with the added note that many of the design problems discussed in this monograph are or were evident in these more advanced chambers.

Designation	Unique Aspect	Reference
Aerospike	Annular design	1
Titan IIA	Metallized propellant	2
ARES	High pressure	3
FLOX[1]/Methane	Methane cooling	4, 5, 6, and 7
Non-Tubular	Channel walls	8, 9, and 10
Stacked Wafer	Transpiration cooled	11

There has been considerable effort in recent years to produce a channel-wall chamber using copper or its alloys or nickel for the thermal wall. The high thermal conductivity of these materials combined with the integral nature of the coolant passages and the wall provides a capability to transmit heat at a rate several times higher than that of the production tubular chambers. The channel-wall design appears to be suitable for a wide variety of applications, especially those involving high heating rates and high chamber pressures.

[1] Terms, symbols, and materials are identified in the Glossary.

TABLE I. – Chief Features of Major Production Regeneratively Cooled Thrust Chambers[a]

Designation	Use	Thrust[b]		Chamber Pressure		Propellants	Cooling Design	Cooled Materials	Reinforcement[c]
		10^3 lbf	kN	psia	MN/m^2				
Aerobee	Sustainer	4.70	20.9	324	2.234	(IRFNA/aniline)/ furfuryl alcohol*	Double walled; helical single pass	CRES 347	Welded outer shell
Agena	Upper stage	15.80	70.3	504	3.475	IRFNA*/UDMH	Drilled passage-way 1½ pass	6061-T6 Al	Integral wall
Atlas Thor	Booster	165.00 185.00	733.9 822.9	575 640	3.965 4.413	LOX/RP-1*(RJ-1: Thor alternate)	Hand-brazed tubular; 2 pass	Nickel A	Welded bands
Atlas	Sustainer	80.00	355.8	700	4.827	LOX/RP-1*	Brazed tubular; 2 pass	CRES 347	Welded bands
Atlas/Thor	Vernier	0.67	3.0	265	2.517	LOX/RP-1*(RJ-1: Thor alternate)	Double walled; helical single pass	4130 Steel	Welded outer shell
Delta	Upper stage	7.89	35.1	307	2.117	IRFNA*/UDMH	Welded tubular; 1½ pass	CRES 347	Unbrazed square-wire wrap
F-1	Booster	1522.00	6770.0	960	6.619	LOX/RP-1*	Brazed tubular; 2 pass, 1 bifurcation	Inconel X	Brazed shell
H-1	Booster	205.00	911.8	632	4.358	LOX/RP-1*	Brazed tubular; 2 pass	CRES 347	Brazed shell
J-2	Upper stage	230.00	1023.0	686	4.730	LOX/LH_2*	Brazed tubular; 1½ pass	CRES 347	Brazed shell
NERVA	Nuclear	75.00	334.0	450	3.103	H_2*	Brazed U-tubes; 1 pass	Hastelloy X	Outer shell
RL 10	Upper stage	15.00	66.7	300	1.069	LOX/LH_2*	Brazed tubular; 1½ pass	CRES 347	Glasswrap; welded shell

TABLE I. – Chief Features of Major Production Regeneratively Cooled Thrust Chambers[a] (concluded)

Designation	Use	Thrust[b]		Chamber Pressure		Propellants	Cooling Design	Cooled Materials	Reinforcement[c]
		10^3 lbf	kN	psia	MN/m^2				
Titan I	Booster	149.00	662.8	675	4.654	LOX/RP-1*	Welded and brazed tubes; 2 pass, 1 bifurcation	CRES 347	Wirewrap
	Sustainer	80.00	355.8	784	5.407	LOX/RP-1*	Welded and brazed tubes; 2 pass	CRES 347	Wirewrap
Titan II/III	Booster	214.00	951.9	820	5.654	N_2O_4/A-50*	Brazed tubular; 2 pass; 1 bifurcation	CRES 347	Wirewrap
	Sustainer	100.00	444.8	832	5.737	N_2O_4/A-50*	Brazed tubular; 2 pass	CRES 347	Wirewrap
Titan III Improved	Booster	220.00	978.6	817	5.633	N_2O_4/A-50*	Brazed tubular; 2 pass	CRES 347	Wirewrap and cylinder shell
	Sustainer	100.00	444.8	825	5.688	N_2O_4/A-50*	Brazed tubular; 2 pass	Hastelloy X	Brazed square-wire wrap and wire overwrap
X-15	Aircraft	15.00 to 50.00	66.7 to 222.4	Not Available		LOX/NH_3*	Welded tubular; 2 pass	CRES 347	Wirewrap

[a] Reference 12 includes concise descriptions of these liquid propellant thrust chambers; reference 13 describes the NERVA chamber.
[b] Rated thrust at altitude of major use.
[c] For combustion and throat zones only.
* Coolant

Notes:
Agena chamber had aluminum oxide coating at forward end.
Atlas and Thor vernier had nickel-plated exterior.
F-1 chamber used regenerative cooling to 10:1; Hastelloy C to 16:1 cooled by turbine exhaust gases.
NERVA chamber is still in development.
X-15 chamber had Rokide coating.

2.1 Regenerative Cooling

The fundamental problem of regenerative chamber design is to provide adequate cooling within the limits of the available coolant and the allocated pressure drop (underlines represent imposed constraints). Early in the design phase, the limits for cooling are defined in terms of allowable wall temperatures, coolant bulk temperature, and heat fluxes. Then the coolant system is designed to operate within these limits and within the constraints of the system. Ultimate adequacy of the coolant system can be verified only by testing.

Other goals that influence the design include structural integrity of the engine configuration; satisfaction of envelope, interface, and duty-cycle requirements; operational stability; minimum weight; and ease of fabrication and maintenance. Together with the cooling requirements, these goals define the physical problem of chamber design; and the chamber design proceeds through the steps of compromise and iteration to the final optimized thrust chamber.

Coolant passages for the operational chambers include tubular, double-wall, or drilled passageway configurations (table I). An important observation from the table is that all of the large thrust units use multi-pass, tubular-wall construction, because it provides a viable, light-weight thrust chamber. The single exception is the NERVA engine. Though it is classified as tubular, the tubes in this development-phase chamber actually are U-shaped in cross-section, being brazed to a heavier outer shell along the open side, with the coolant flowing in a single pass. This configuration evolved from the need to provide cooling for the structural jacket because of nuclear heating. The Atlas vernier, the Aerobee, and the Agena use cooling configurations other than tubular: the Atlas vernier and the Aerobee are double walled, and the Agena uses drilled passageways.

In view of design and performance limitations identified with each cooling concept, an order of selection has necessarily evolved. Generally, with the need for more effective cooling at higher chamber pressures and larger physical size, tubular-wall construction has been the only economical method of producing tailored, uniform cooling. With tubular construction, walls that are exposed to combustion gases are controlled to specific thicknesses throughout the interior of the chamber, and the coolant passages are sized to tailor coolant velocities according to specific needs at each longitudinal station. In addition, the composite tube bundle has proven to be an adequate frame about which structural reinforcement can be attached, independent of physical size. Thus, in the overall view, the tubular configuration provides the means to meet the constraints and requirements and achieve the goals of optimum chamber design.

For smaller chambers with low heat loads, the double-wall chamber or one with drilled coolant passages is preferred over the tubular construction because of the significant cost savings derived from simplicity and because coolant tubes become restrictively small in low-thrust units. However, these simpler designs have been used only when the heat load is low, where cooling can be effected using heavier, nontailored walls and coolant passages.

The prominent means available for constructing coolant passages are summarized in table II, together with a subjective evaluation of their usages and limitations. It is readily seen that the coolant tube is the most versatile configuration with the highest operational capabilities and greatest production use. None of the designs is considered easy to fabricate. The channel-wall concepts using machined slots and electroformed passages offer cooling advantages over the double-wall and the drilled-passageway concepts, but as pointed out above, these configurations are regarded as development concepts at this time.

2.1.1 Coolant Passages

2.1.1.1 BASIC REQUIREMENTS

Satisfactory coolant flow has been achieved in fluid-cooled combustion chambers using either tubular or channel-wall construction. However, no rigorous optimization process has been universally employed in selecting the cooling configuration. Rather, each designer has built on his prior experience, with some innovative improvements, to produce each new chamber design. As a result, two designers, faced with the same requirements, but using unique skills and experience bases, might well have produced significantly different chamber designs. The two designs could be equal in capability, cost, and weight. Therefore, the current state of the art suggests that the most important factor in selecting a cooling configuration in response to a set of requirements is the sum total of individual differences in design and fabrication knowledge and experience.

The operational requirements of thrust, available coolant, pressures, and heat loads are, of course, of major importance in the selection of a cooling configuration. Fluid-cooled, low-thrust units have not been tubular, because the requirements have resulted in tubes that would be too small. Large chambers have been of tubular construction because of weight and tailored-cooling advantages. With the current trend toward higher heat loads, advanced designs using channel-wall construction with high-conductivity materials are emerging as prime concepts for configuration of chambers; the coolant channels are integral with the thin, high-conductivity liner to provide maximum effectiveness of regenerative cooling. For very high thermal loads, some form of transpiration cooling appears to offer the greatest capability.

Coolant passage selection has been, then, a process of building on established technologies and fabrication experience to meet the operational requirements. The requirements, including usually the definition of the coolant, are prescribed by the component specification against which the hardware is to be developed. The number of coolant passes, the type of construction, and special considerations, such as supplemental cooling and thermal insulation (coatings), usually are defined by the chamber designer.

TABLE II. – Qualitative Comparison of Methods of Coolant-Passage Construction

Type of Construction	Large-size capability	Low weight	Low cost	Cooling capability	Current fabricability
PRODUCTION CONCEPTS					
Brazed tube	G	G	F	G	F
Welded tube	F	G	F	P	F
Double wall	F	P	G	P	G
Drilled passageway	F	F	G	P	G
DEVELOPMENT CONCEPTS					
U-tube	G	F	P	F	F
Channel wall (refs. 8, 9, & 10)	P	F	G	G	F
Stacked plates (ref. 11)	P	F	F	G	F

Key: G - Good
F - Fair
P - Poor

2.1.1.2 NUMBER OF PASSES

An initial consideration is the proper selection of the number of coolant passes, since this impacts all of the design goals. Three methods have been used: one pass with the coolant flowing forward from the expansion section; one-and-a-half passes with the coolant introduced in the expansion section, flowing down and then up to the injector; and two passes with the flow proceeding down from the injector and returning up through alternating passages.

The one pass (or single pass) is the simplest concept, but it can require the use of very small flow passages at the high-heat-flux regions as well as a fairly large manifold at a high expansion ratio. Heavy masses at the aft end of the chamber aggravate gimbaling requirements and reduce the engine natural frequency; most flight systems require high natural frequencies for the engine. One-pass cooling has tended to be used with the smaller chambers only.

The term one-and-a-half pass should not be taken literally, because the "half" actually represents a partial pass starting below the throat. The one-and-a-half pass is used with coolants that must be heated before they become effective. Liquid hydrogen, for example, is introduced in the expansion sections of the RL 10 and J-2 engines, since it must be gasified before it can accommodate the high heat fluxes at the throat. The extent of the partial pass is derived from a tradeoff between thermal and gimbaling considerations with the desire to keep the inlet manifold forward.

The popular two-pass design tends to complicate the forward manifold, but it does permit higher coolant velocities with larger diameter tubes than the one-pass design. Furthermore, it minimizes gimbaling problems because the weight of the turnaround manifold is small. Although more than two passes have been considered when limited coolant was available, the additional pressure drop and complicated manifolding have made this an undesirable selection.

2.1.1.3 TUBES

The design of the coolant tube is the predominant problem in tubular combustion chambers. Large numbers (usually hundreds and in some recent designs even thousands) of tubes are required per chamber. Although the design process is difficult in itself because of the combined thermal, hydraulic, and stress requirements, fabrication, in the final analysis, actually sets the design limits. Over the years, continual optimization within the fabrication limits has resulted in a costly, complex piece of hardware with tapered flow passages, uniform or tapered walls ranging in thickness from 0.010 to 0.040 in. (0.254 to 1.02 mm), controlled inner and outer surface roughness, tube joints and bifurcations, and close tolerances. Table III displays materials, typical wall thicknesses, and propellants that have been used in tubular chamber development programs. Figure 1 shows the basic configurations of state-of-the-art double-taper coolant tubes.

TABLE III. – Tube Materials and Propellant/Coolants Used in Tubular Combustion Chambers

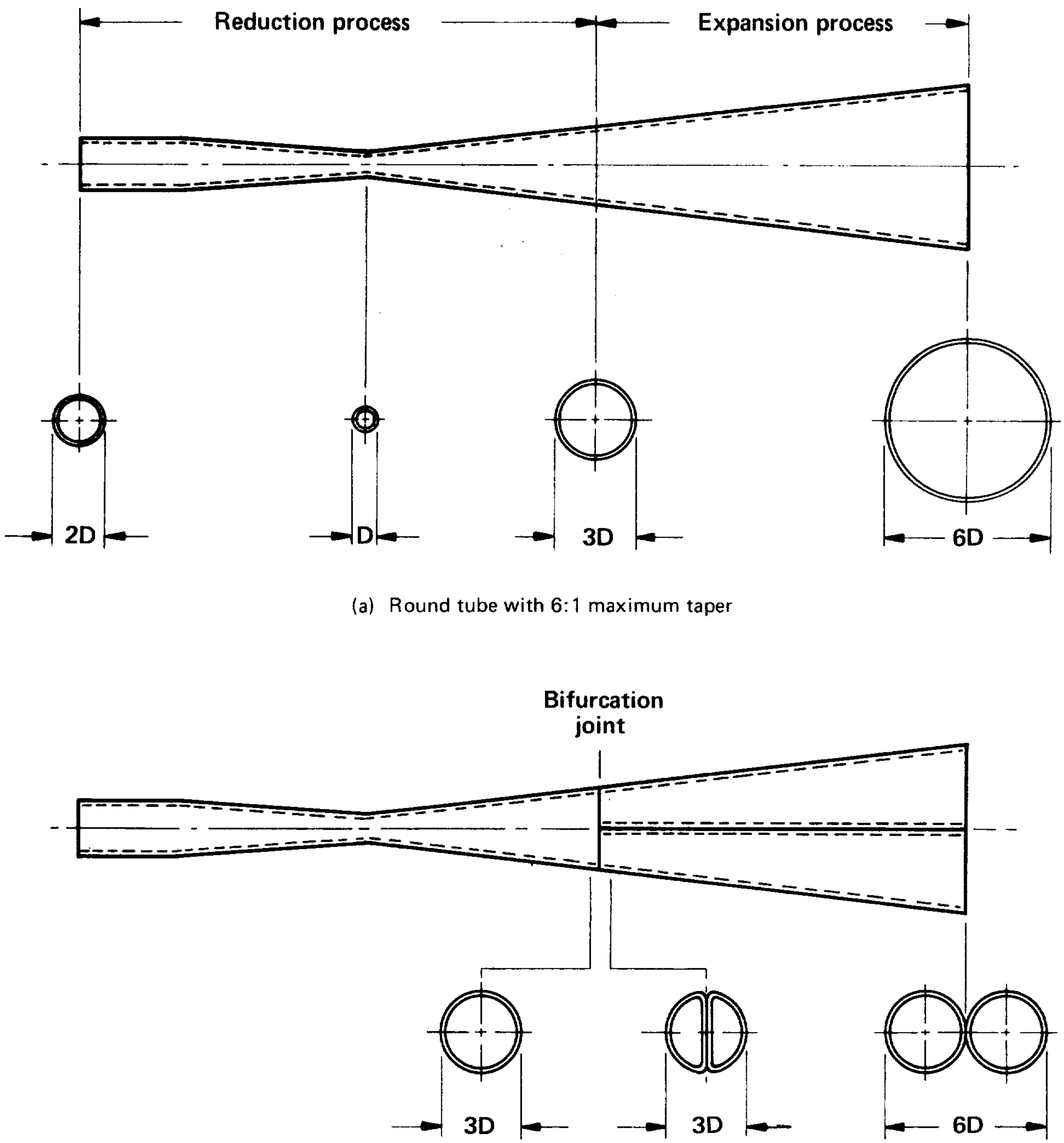
Material	Wall Thickness		Propellants	Programs
	in.	mm		
CRES 347	0.010 to 0.040	0.254 to 1.016	LOX/LH_2*; N_2O_4/A-50*; IRFNA*/UDMH; LOX/RP-1*; LOX/NH_3*; LF_2/LH_2*; FLOX/LPG*	J-2, RL 10; Titan II/III/Delta; Titan I, H-1, Atlas, X-15; Fluorine RL 10 (ref. 14); Light Hydrocarbons (refs. 4 through 7)
Hastelloy X	0.015	0.381	H_2*; N_2O_4/A-50*	NERVA; Improved Titan III
Hastelloy N	Not available		LOX/LH_2*	RL 10
Inconel X	0.018	0.457	LOX/RP-1*	F-1
Inconel 718	0.012	0.305	N_2O_4/A-50*	Mansa (ref. 15); ARES (ref. 3)
Nickel 200	0.017	0.432	LOX/LH_2*	NERVA (simulation testing)
Nickel A	0.040	1.016	LOX/RP-1*; FLOX/RP-1*	Atlas, Thor; Atlas/FLOX (ref. 16)
Al 5052	0.035	0.889	IRFNA*/UDMH	Ablestar (ref. 17)
321 SS	0.022	0.559	LOX/RP-1*	E-1 (ref. 18)
304 SS	0.022	0.559	LF_2/LH_2*	Experimental H_2/F_2 engine (ref. 19)

*Coolant

Notes: LPG – liquified petroleum gases (methane, propane, etc.)

Underlined propellants are in use in operational chambers.

Tubes also have been formed from TD Nickel and 29-20 SS (J-2), Inconel 625 (F-1), and Waspaloy (F-1).



(a) Round tube with 6:1 maximum taper

(b) Top view of bifurcated tube with 3:1 maximum taper

Figure 1. – Coolant tube configurations

Individual tubes are formed from a single, large cylindrical tube during alternating working (swaging, spinning, drawing, or expanding) and heat-treating steps. The tube depicted in figure 1(a) is a simple double-taper tube with a maximum cross-section variation of about 6:1 on the diameter. It is achieved by combining reduction and expansion processes, because a pure reduction process beyond 3½:1 has caused significant variations in surface roughness and flow area and thereby resulted in excessive flow losses. Although expansion processes have not been used specifically for coolant-tube fabrication, they have been demonstrated beyond 2:1 for other commercial applications. Thus, a maximum taper of 6:1 is achievable by combining a 2:1 expansion with a 3:1 reduction.

The tube is bent to the contour of the thrust chamber after tapering. It is then "spanked" or pressed to the required design cross-section at each longitudinal position. Round cross-sections are shown in figure 1(a), although oval shapes have been used extensively.

Bifurcation joints in expansion nozzles, as shown in figure 1(b), have been used to maintain reasonable coolant velocities with state-of-the-art tubes. Although these joints are in operational use (e.g., the Stage I Titan II and F-1 engines), they have been persistent trouble spots because of fitup difficulties. In addition, excessive dropthrough has occurred when joints were welded; and the center wall of the two-tube side has deformed, causing flow maldistributions and locally low coolant velocities leading to overheating and premature tube failures.

Tube wall thicknesses are an integral part of the thermal management and as such must produce and maintain a specified resistance to heat transfer. Wall thicknesses as low as 0.010 in. (0.254 mm) have been used, and many chambers have been produced with 0.012-in. (0.305 mm) walls. Pinholing was a problem in early 0.010-in. (0.254 mm) walls, but this degradation occurred with carburizing propellants and imperfect tubes. Destructive carburization ceased to be a problem when the wall thicknesses were increased to 0.016 in. (0.406 mm) and the imperfections in the tubes were eliminated. Normally, a constant thickness over a length of tube simplifies the fabrication; however, this condition is not always desirable, as illustrated with the newest Stage II Titan when burnouts occurred in the combustion zone, 4 in. (10.2 cm) from the injector face. The cause of the burnouts was insufficient cooling for the local heat flux, and the most desirable way to lower the heat flux to the coolant was to thicken the walls of the tubes in the overheated area from 0.024 in. (0.61 mm) to 0.037 in. (0.94 mm). The transition from the thin to the thick wall is accomplished over a 2-in. (5.08 cm) length. This tapered wall combined with a 3½:1 diameter ratio represents a significant increase in the technology of tube forming over earlier Titan systems. It also indicates the extent of sophistication in tube design, because these modifications were made to retailor the coolant velocity and the thermal conductance of the wall to provide a greater overall margin of safety.

Fabricated tubes when stacked have produced unbrazeable gaps or extremely tight fits due to tolerance build-up. These variations have been overcome to a large extent by distributing and filling gaps with shims, preferential use of over- and under-size tubes, peening, and continuous quality control interactions with the vendors. Round or slightly oval tubes have been easier to fit up because gaps can be detected visually with little difficulty.

2.1.1.4 CHANNEL WALLS

The channel-wall production configurations have been either double walled or drilled passageway. Double-wall construction has proven useful for low-cost, low-thrust systems where an intermediate level of heat load exists. The simplest operational approach, as exemplified by the Atlas vernier and the Aerobee chambers, is to assemble two concentric shells with an annular space between them to form a single-pass cooling passage. The coolant is directed about the annulus in a helical fashion, instead of in the preferred axial direction, so that higher coolant velocities are produced. The inner wall is not connected structurally to the outer wall (or, if so connected, the connections are widely spaced), with the result that the inner wall is under a collapsing pressure exerted by the coolant and therefore must be of sufficient thickness to remain structurally stable at operational temperature.

Some difficulties have been experienced in attaining the required flow-passage dimensions and in minimizing cross flow from one channel to the next. For the Atlas vernier, these problems were solved by spinning the inner shell to the required shape and smoothness, handbrazing a helically wrapped square wire to the inner shell, and enclosing the structure with a split outer shell. The outer shell was contoured to fit within 0.010 in. (0.254 mm), and the joint welds at the splits pulled the halves snugly against the helically wrapped wire. Distortion of the outer shell between the lines of wire contact was minimal. An attempt to spin the outer shell about the inner shell and wire was comparatively unsuccessful.

For the Aerobee, an inner shell to which a flow guide was welded on the cylindrical portion of the chamber was used. Through the convergent/divergent nozzle, the flow passage was defined bv a helical groove that was cut into the inside diameter of a filler block assembly. The assembly, consisting of four sections, was split longitudinally for installation, bolted together about the inner shell, and separated at the throat plane. Contact between the assembly and the inner shell was maintained by compressed springs. The entire assembly was enclosed by a cylindrical outer shell.

Neither the Atlas vernier nor the Aerobee experienced overheating at the point of contact of the helical guides, but the widths of the guides were designed to minimize heat flow blockage. Neither design exhibited burnouts or excessive pressure drop resulting from (1) potential flow separation (eddy generation) in high-aspect-ratio passages or (2) the decrease in coolant velocity near the corners of narrow, high-aspect-ratio passages. Overheating did occur at the coolant entrance in an early Atlas vernier design and in the convergent section in the Aerobee chambers, but passage redesign eliminated this problem.

Coolant passages drilled into conductive material form what has been called "drilled passageway" construction. This method is used for the Agena and has been used for numerous research projects where (1) design simplicity is desired, and (2) relatively unlimited coolant supplies exist. The Agena is fabricated from aluminum in three sections, with the passages in each section drilled according to the local cooling requirements. The development of the gundrilling technique to drill long, precise passages was the major difficulty in producing the first Agena chambers. The most demanding requirement called for the drilling of holes 0.116 in. (2.95 mm) in diameter and 15½ in. (39.4 cm) in length through a hyperbolic nozzle throat section. Holes were drilled at a 34°skew angle to the centerline of the chamber, so that straight drill paths would follow the inner contour. Hole placement was controlled within 0.005 in. (0.127 mm), while the diameter and straightness could vary up to 0.002 in. (0.051 mm) and 0.025 in. (0.635 mm), respectively, from the required mean values. The remainder of the Agena chamber comprises 0.125-in. (3.18 mm) diameter holes in a forward cylindrical section and 0.172-in. (4.37 mm) diameter holes in the conical expansion nozzle downstream of the throat passages. In this aft section, the coolant flow is two-pass, at a 25°cant angle, with the inlet at the forward end of the cone. From the return pass in the cone, the coolant enters the throat region and flows forward, through the remainder of the chamber, to the injector.

These long ($L/D>125$) cooling holes were produced successfully by developing specialized techniques and equipment that could maintain a constant cut per revolution of the cutting head. Other important factors that contributed to the success were the use of single-fluted gundrills, pressurized and filtered coolants, bushings to support and guide the gundrills, and carbide cutting heads. Gundrilling has progressed to the point where qualified fabricators can produce holes to L/D limits of 250 to 300 and as small as 0.090 in. (2.29 mm) in diameter.

2.1.1.5 SPECIAL THERMAL AND HYDRAULIC CONSIDERATIONS

Every major rocket engine company has developed comprehensive computer models for designing coolant passages. These models often are proprietary, and, although their use is not absolutely necessary, it is extremely difficult to generate an optimum design without one. The design of the passages is basically a thermal and hydraulic problem requiring an accurate understanding of the nature of heat transfer between the combustion gases and the coolant. Optimization requires tailoring and evaluating tradeoffs involving (1) wall thickness as it affects wall temperature and heat flux; (2) flow area as it affects coolant velocity and pressure drop; and (3) effects of the gas-side convective coefficient, the number of coolant passes, the dimensions of the chamber and nozzle to be cooled regeneratively, and the wall material.

The weakest link in the analysis is the analytical description of the gas-side thermal conditions, especially in the region just below the injector. In fact, it is doubtful whether optimization studies are justified unless exact conditions are measured for the injector and chamber contour that will be used. The widely accepted methods for predicting gas-side thermal conditions are derivatives of the simplified Bartz correlation (ref. 20) and the Hatch and Papell correlation (ref. 21) for film cooling. Each of these fundamental approaches must be used with real caution, as confirmed throughout the industry by continuing problems of tube burnouts just below the injector. This burnout indicates that the thermal conditions (sometimes chemical conditions) are not being modeled accurately. During a recent Stage II Titan III product-improvement program, for example, burnouts occurred when fuel film and barrier cooling were reduced. The theoretical predictions of the gas-side heating proved to be non-conservative, and the burnouts reemphasized the value of measuring actual conditions for individual injector/chamber combinations. The inaccuracies in the analytical predictions stem from the absence of a positive definition of the boundary conditions wherein the film coolant and combustion reactants interact; as a result, the transport properties cannot be designated accurately for specific locations. Serious effort is being made to develop more accurate prediction methods, but at the cost of increased model complexity. This complexity has been a deterrent forcing the designer to resort to the more practical method of applying conservative design factors to the simple analytical models.

The liquid-side thermal conditions generally are much better understood and characterized. Table IV lists propellants that have been used as coolants and provides a subjective evaluation of the depth of information. In general, accurate liquid-side convective coefficients are predictable for most coolants. The correlations for hydrogen were not completely consistent until the data from many investigators were treated compositely. The composite data permitted a better interpretation of the critical temperature region, where significant transport property variations have produced results that previously were difficult to interpret. The influence of curvature also has been recognized, and enhancement and degradation effects are now considered. The phenomenon and effects of nucleate boiling also are well understood. The important consideration is that in the regime of nucleate boiling, the liquid-side wall temperature will be at or a few degrees above the saturation temperature of the coolant. This similarity must be accommodated in the theoretical model, and, although wall temperature assumed on this basis is not absolutely accurate (because the wall superheat is a function of the heat flux), such assumed temperature has been sufficient for design purposes, causing at most a 50°discrepancy with a 1500°F base (28 K in 1089 K).

Correlations for the onset of film boiling (burnout) are available for most common propellants. The burnout information has been determined in controlled experiments, in which round tubes are electrically heated to failure while the heat load is measured at specific coolant velocities, temperatures, and pressures. Most of the data accumulated in this manner have a fractional standard deviation of about 0.15. The chambers for the Titan engines have been designed to operate at a maximum heat flux that is 15 percent less than the heat flux that would cause tube failure, although in newer designs the value is kept at least 18 percent below the theoretical burnout level.

Some coolants have formed residues on the liquid side of the heated wall; some have decomposed. RP-1 is noted for coking at wall temperatures above 800°to 900°F (700 to 756 K) and has produced sulfur embrittlement of nickel tubes when the sulfur content exceeded specifications. Furfuryl alcohol has produced resinous deposits on walls at 600°F (589 K) and above. The family of hydrazine coolants will decompose at elevated temperatures; most notably, Aerozine-50 has detonated when in contact with walls above 600°F (589 K). Detonation is avoided by keeping the liquid-side wall temperature below

TABLE IV. – Propellants as Coolants

Propellant/Coolant	ϕ_{crit}		h^1		Limit T_B	Limit T_w	Remarks
	(a)	(b)	(a)	(b)			
Operational:							
Hydrogen	D	D	A^2	A^2	E	E	–
RP-1	B	B	A	A	D	728K	Scale formation noted
A-50	A	A	A	A	422K	589K	Will detonate
IRFNA	B	C	A	A	D	D	Scale formation noted
Ammonia	A	C	A	A	E	E	--
Aniline/furfuryl alcohol	B	D	A	A	D	D	Resinous deposits noted at about 589K
Research:							
N_2H_4	A	C	A	A	T_{sat}	D	Will detonate; material restrictions
N_2O_4	A	B	A	B	E	D	Decomposes endothermically
MMH	A	B	A	B	T	D	Can detonate
MHF-5	B	B	A	B	T_{sat}	D	Can detonate
Methane	B	B	A	A	D	D	Can decompose and leave scale residue
H_2O_2	B	B	B	B	D	D	Decomposes violently; material restrictions
Water	A	C	A	A	E	E	Tap water may form scale

Information on a number of other propellant/coolants is available in reference 34.

Key:

A - Good correlation based on substantial experimental data

B - Good correlation based on limited experimental data

C - Correlation based on meager data or on extrapolation

D - Value or limit poorly defined

E - No limit known

(a) $P < P_{crit}, T < T_{sat}$

(b) $P > P_{crit}, T < T_{crit}$

[1] Forced convection without nucleate boiling; For $T > T_{crit}$ (gases), use reference 22

[2] B rating near critical region

600°F (589 K). For the cases of deposits and residues, minor deposits have been accepted if the longevity requirements can still be met, since the deposits build up slowly over a period of time.

Even though cooling requirements can be predicted accurately, thermal failures have occurred when secondary effects were ignored. Wall burnouts have occurred for a number of reasons:

- Stagnation or recirculation areas existed in coolant passages.
- The total cooled area was increased slightly, thereby increasing bulk temperature and lowering the burnout heat flux margin.
- Coolant velocities were reduced in supposedly safe areas, but the thermal model eventually proved to be inaccurate.
- Film cooling (supplemental to regenerative) was reduced below burnout levels in supposedly safe situations.
- In a double-wall design, the manifold did not transmit the coolant uniformly into a wide passage, and the inlet region burned out.
- Wall thickness of low-conductivity material was excessive at certain areas, particularly at manifold attachments and bifurcations, and these areas overheated.

Joints and bifurcations are prime areas for the existence of flow disturbances and resultant failure. Bifurcations particularly are areas of caution because the combination of weld dropthrough or braze accumulation, distortion, and difficult physical fitup leads to flow obstruction. Also, undetected braze voids in these areas act as barriers to efficient heat transfer.

Pressure drop has been predicted accurately by standard procedures for calculating fluid flow. When errors have occurred, they have been caused by ignorance of actual conditions such as surface roughnesses or channel dimensions. Unanticipated flow variations have resulted from tubes worked to 1/5 of the original diameter; the friction factor was increased significantly by this amount of working and the wall thicknesses were erratic. Excessive pressure drops also have occurred when velocities of liquid coolant exceeded 200 ft/sec (61.0 m/sec). For liquids, the dynamic head at high velocities magnifies the effect of any local flow disturbance. For gases, the standard procedure is to limit the velocity to Mach 0.3 to avoid potential sonic choking.

2.1.2 Manifolds

The primary role of the manifold is to distribute the coolant uniformly to the flow passages, so that no passage will receive inadequate coolant flow. The degree of uniformity established is related to the thermal margin of safety required for the specific combustion chamber. Smooth flow must be provided at each passage inlet to preclude stagnation or recirculation in regions of transitory detached flow.

Three kinds of coolant manifolds are used in regeneratively cooled chambers: inlet, outlet, and turnaround. Design complexity depends on the number of coolant passes and the extent of integration with structural support features. In some cases the manifolding is integral with structural supports and interface flanges. For some two-pass systems, the inlet manifold is integral with the forward flange. When a nozzle extension is bolted to the aft end of a regeneratively cooled chamber, the turnaround manifold is integral with the aft flange. The outlet manifold is always integral with the forward flange.

2.1.2.1 FLOW DISTRIBUTION

Virtually all inlet manifolds have required design iterations to overcome problems of flow maldistribution. The inlet manifold must distribute coolant from a single source to the coolant passages around a circumference. Inlet manifold design thus is critical because it has prime control of the coolant distribution in the first pass of a coolant system. Flow variations up to 20 percent have been tolerated in the first pass of a multi-pass configuration, because the coolant is at its lowest bulk temperature and usually the thermal margin near the inlet is wider than that near the outlet. Normally, this variation must be reduced prior to the final pass. This reduction has been accomplished by using the inherent balancing benefits derived from common manifolds at turnaround and transition areas. When large flow variations have not been tolerable in the first pass, extensive analytical balancing, coupled with flow tests, has been used. As a result, manifold shapes have been modified, and the inlets to the coolant passages have been tailored for uniform metering of the flow.

The degree of flow imbalance in parallel-circuit flow as a function of inlet and outlet manifolding is amenable to reasonably precise analysis. For hydrogen-cooled systems, where large density variations exist, flow uniformity is achieved almost exclusively by analytical methods. Parallel circuits are designed precisely in response to the properties of the hydrogen at each station, and the manifolding is an integral part of the flow model. For storable coolants, the design problem is not as complicated, since changes in coolant density are not as pronounced.

The inlet manifold for fluid-cooled chambers invariably is formed in a toroidal shape. Two theories of torus design guide the designer: (1) variable area with constant flow velocity and (2) constant area with variable flow velocity. The advantages for the tapered torus are that the velocities at the inlet to each coolant passage are equal and the inlet characteristics do not vary; the physical size is small, thereby minimizing trapped propellant volume (adverse mass properties and adverse dynamics) and minimizing structural loads; and stagnant flow areas are avoided. The disadvantages include potential adverse flow distribution due to pressure drop around the torus, and a more complex shape for fabrication. In comparison, the main advantage of the constant area torus is that pressure losses around the torus are minimized; however, maldistribution still results because the inlet velocities to the coolant passages near the inlet of the torus are higher than they are opposite the inlet. Flow splitters at the inlet to a torus have improved the flow distribution in coolant systems. Torus design today is a compromise between two extremes, and smooth turns combined in many cases with smooth vanes are used to achieve the required degree of flow uniformity.

For double-wall chambers with helical coolant flow, flow uniformity with an inlet torus has been achieved by keeping the flow velocities low and providing smooth streamlines of flow at the entrance to the coolant flow section.

Turnaround manifolds collect the coolant at the end of a tubular pass and direct it into the next pass. Generally, this flow reversal is accomplished at low velocities, which is possible because the location is always in the expansion nozzle where the heat loads are lowest. The turnaround manifold is either a common annulus to all tubes, or it contains passages to collect flow from one tube and direct it to a specific adjacent tube. The common annulus is preferred for storable coolants because it can even out flow distribution prior to the final critical pass. Discrete passages are preferred for hydrogen because of the need to balance the flow resistances for each channel separately as a function of the local coolant properties.

Outlet manifolds simply provide a means of directing all of the coolant uniformly to the injector. These manifolds are made integral with the forward attachment flange; usually they consist of a collection annulus and a ring of holes to match either holes or an annulus in the injector. Smooth transitions within this manifolding are used to reduce undesirable pressure losses. If the chamber is welded to the injector, an annulus is provided within the injector to collect the flow prior to distributing it to the injector manifolding.

In spite of precautions in design, flow variations will exist. Redesigns have been most effective when the flow distributions were measured and studied in a cold-flow facility using either liquid or gaseous simulants. Removal of the turnaround manifold has facilitated the evaluation of the first pass of a multi-pass system. Errors in cold-flow evaluations largely have been eliminated by flowing to back pressure and simulating the operational inlet conditions.

2.1.2.2 STRUCTURE

The structural design of toroidal parts has been accompanied by small problems, but the fabrication is well proven, with many rolled and forged parts in use. Generally, two shell halves are welded together to form the torus; care is taken to eliminate stress concentrations the cause of leakage cannot be assigned exclusively to the higher loads that exist in the brazed joints of these chambers. The class of chambers that incurred more leakage not only was less rigid but was also dependent on early brazing techniques. The advancement of the art of chamber fabrication has provided both stronger chambers and stronger brazed joints. The accompanying reduction in leakage, though brought about by both of these improvements, probably is creditable more to new brazing techniques (sec. 2.7) than to the reduction in joint loads.

2.1.3.1 THROAT REINFORCEMENT

There are several operational means (table I) for reinforcing regeneratively cooled nozzle throats against buckling. Major methods are depicted in figure 2 and include cylindrical shells (Aerobee, Stage I Improved Titan), one-piece brazed jackets (J-2, F-1, H-l), brazed wire jacket (Stage II Improved Titan), bolt-on corsets (Stage II Titan III), weld-on corsets (RL 10), banded (Atlas booster and sustainer), integral shell (NERVA [U-tube], Atlas vernier [double wall] and Agena [drilled passageways]). The Titan II, X-15, and Delta chambers are wirewrapped for hoop support only and rely on the inherent strength of the tube bundle to resist buckling.

For tubular chambers the major problem of structural support in the throat has been to support the tubes rigidly and positively. The best (strong, low weight, uniform restraint) support is achieved through an intimate attachment of the support structure to the tubes. The loads are transmitted in shear from the tube bundle to the support through a brazed joint. A high degree of intimacy is achieved with the brazed-jacket design, wherein the jacket is brazed to a large portion of the lengths of the jacketed tubes. With this design, the major problem has been to achieve positive attachment between the jacket and the tubes. During brazing of the one-piece-jacket design, the coolant tubes are pressed against the jacket by a pressurized bag. This procedure was used to fabricate the F-1, J-2, and H-1 chambers, but the development of the tooling and procedures was costly and difficult. The brazed-wire-jacket technique (Improved Titan sustainer) uses square wire spirally wrapped about a brazed tube bundle to form a continuous shell. The wire strands are brazed to each other and to the tube crowns. Contact between the wire and the tubes is achieved by wrapping the wire under considerable tension about a brazed tube bundle whose roundness has been preserved during the earlier tube-to-tube braze cycle. The tension is decreased in decrements during wrapping to limit the shrinkage of the tube bundle.

The brazed jacket can be tapered for optimum strength and weight, and age-hardening can provide maximum strengths for ageable materials. No critical jacket failures have occurred unless the jackets were loaded beyond the design ultimate or the hardware contained some deviation from the required configuration. For the brazed wire, fatigue failures have occurred in the tube crowns between wires that were not brazed together adequately during early development. For production hardware, quality control procedures guarantee the absence of voids in the wire-to-wire joints. For all brazed-jacket concepts, fatigue failures have also been experienced at the tube crowns when there was insufficient braze contact at the weld joint by penetrating the entire shell thickness with the weld. Torus fabrication has been bothered by distortion due to welding, but step welding, peening, and mechanical pressing have been used successfully to minimize distortion or to return the part to the required form. Occasionally, the internal configuration has been distorted when light structural areas were peened excessively. When intolerable distortion could result, only light peening, if any, has been used, and inspection by sectioning test pieces has been used to verify acceptability.

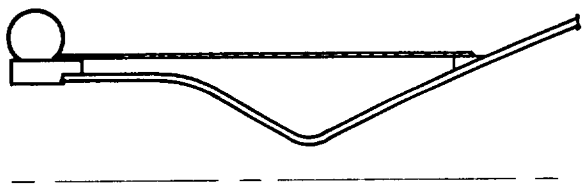
Manifolds usually are welded or brazed to other chamber components. Stress concentrations and leak paths at brazed joints are avoided by maximizing the area of braze contact. When parts are welded, the edges of the parts are prepared for fully penetrating groove welds, and the heavier pieces are tapered to provide a smooth stress flow from one piece to the other. When manifolds have been tack welded to tubular chambers prior to brazing, the fit of the brazed joints often has been degraded. This problem has been avoided by locating tack welds at a position that did not distort the gaps to be brazed or by distributing the welds to eliminate local distortion problems.

2.1.3 Chamber Reinforcement

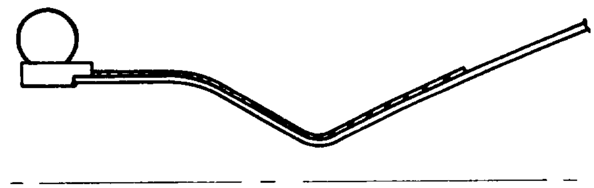
The major problem of providing structural support to fluid-cooled chambers is to transmit to heavy structural members the loads that originate at thin-walled surfaces; this transmission must be made without degrading the performance of the cooling mechanism and without structural failure. The three areas of structural concern are the hoop support about the combustion chamber, the support at the nozzle throat to resist bending and buckling, and hoop support about the expansion nozzle to resist collapse from hoop compression. The last condition occurs during operation at sea level, where jet separation occurs during start and shutdown and the nozzle runs overexpanded during steady-state operation.

For structural design, limit loads and factors of safety (sec. 2.1.6) are specified to the designer. Normally, limit loads are derived by summing maximum discrete loads. Two factors of safety then are applied to these loads. The yield safety factor usually ranges from 1.0 to 1.32; it establishes a load level below which no plastic or elastic deformation can be tolerated. The ultimate safety factor (1.3 to 1.8) is applied to establish the load level below which structural failure is unacceptable. These factors are applied to the physical limit loads but not to the accompanying environmental thermal, shock, and vibratory loads. Hence, combustion chambers are designed to withstand simultaneously the sum of the ultimate loads plus the environmental load phenomena.

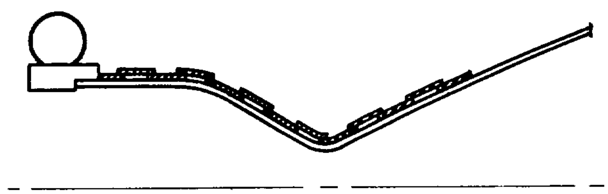
One of the reasons for "retiring" tubular chambers during development programs has been hot-gas leaks (tube-to-tube joints). On many of the programs, such leaks have developed after large numbers of tests (more than 15). Though leaks have been more prevalent in chambers that had less rigid structural support (banded, cylindrical shell, wirewrap only),



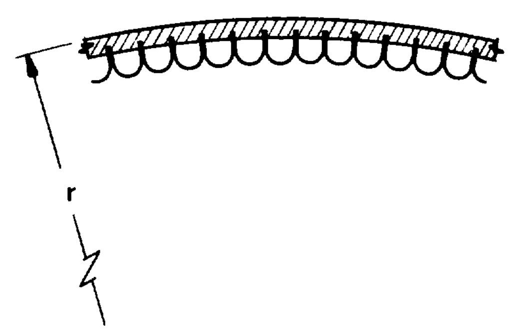
(a) Cylindrical shell



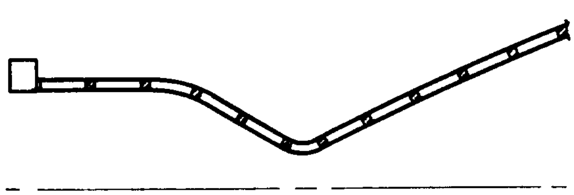
(b) One-piece brazed jacket; brazed wire jacket; bolt-on and weld-on corsets



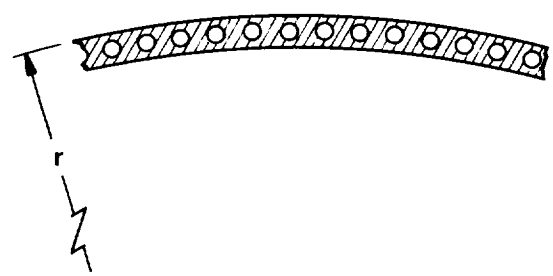
(c) Banded



(d) U-tube, integral shell



(e) Double-walled, inherent integral shell



(f) Drilled passageway, inherent integral shell

Figure 2. – Methods of reinforcing nozzle throat zones

between the jacket and the tubes. Sufficient contact is guaranteed by quality control procedures in response to the design requirements, and no failures have been experienced with flight-configuration hardware.

A problem that has been experienced with brazed jackets is fatigue failure of the tube crowns at the aft end of the jacket (fig. 3). At this point, cyclic loads from structural resonances of the expansion nozzle can be significant, and the stress discontinuity leads to fatigue failure. The problem has been eliminated by altering the resonance characteristics of the nozzle and by reducing the severity of the stress discontinuity at the joint. The resonance characteristics have been altered by adding damping bands to the expansion nozzle; peak stresses at the discontinuity have been reduced by achieving a high degree of braze contact between the jacket and the tubes in the aft 1 to 2 in. (2.54 to 5.08 cm) of the jacket, and by tapering the thickness of the jacket in this area.

A cylindrical shell transmits loads directly from the expansion nozzle to the forward end of the chamber and thereby reduces the loads normally carried through the throat. The major problem is to attach the shell rigidly to the tube bundle without inducing intolerable stress concentrations and without adversely restricting the extension of the tube bundle contained within the shell. In the Improved Stage I Titan, such a problem was precluded by contacting the tubes at the aft end over a length sufficiently long to keep the local stresses low.

A shell that is integral to the coolant passages can be the simplest and surest support structure. The NERVA U-tube concept encloses the coolant passages with a heavy structural shell, but the fabrication is complicated by the need to ensure complete closure of the coolant passage. The drilled-passageway concept of Agena is limited thermally by the physical placement and shape of the drilled holes. However, the structure can be made as thick as necessary.

The standard Titan sustainer and the RL 10 use specially attached corsets; because of the lack of integral construction between these jackets and the coolant tubes, the jackets are heavy. The Titan sustainer uses a split, form-fitting shell that is bolted together at the seams and welded to the forward end of the chamber at the mounting flange. The space between the shell and the wirewrap is filled with epoxy to distribute the loads and provide some shear-carrying capability. The Titan sustainer has flown with and without this corset, but the structural contribution of this corset has been demonstrated by ground tests. During the termination of a simulated altitude test (firing into a diffuser), asymmetric jet separation can cause loads up to 1.4 times the limit load conditions. The major load element is a dynamic side load, which has buckled the chamber in the throat region when the corset was not attached. The subsurface wirewrap embedded in epoxy offers no capability for carrying meridional loads. For the RL 10, an external corset is attached by welding six segments of rolled sheet together about the tube bundle. No undercoating of epoxy is applied, since problems have been experienced with cracking and degradation of epoxy in contact with cryogenically cooled surfaces. The weld-on corset uses weld shrinkage to increase the contact of the shell and the coolant tubes.

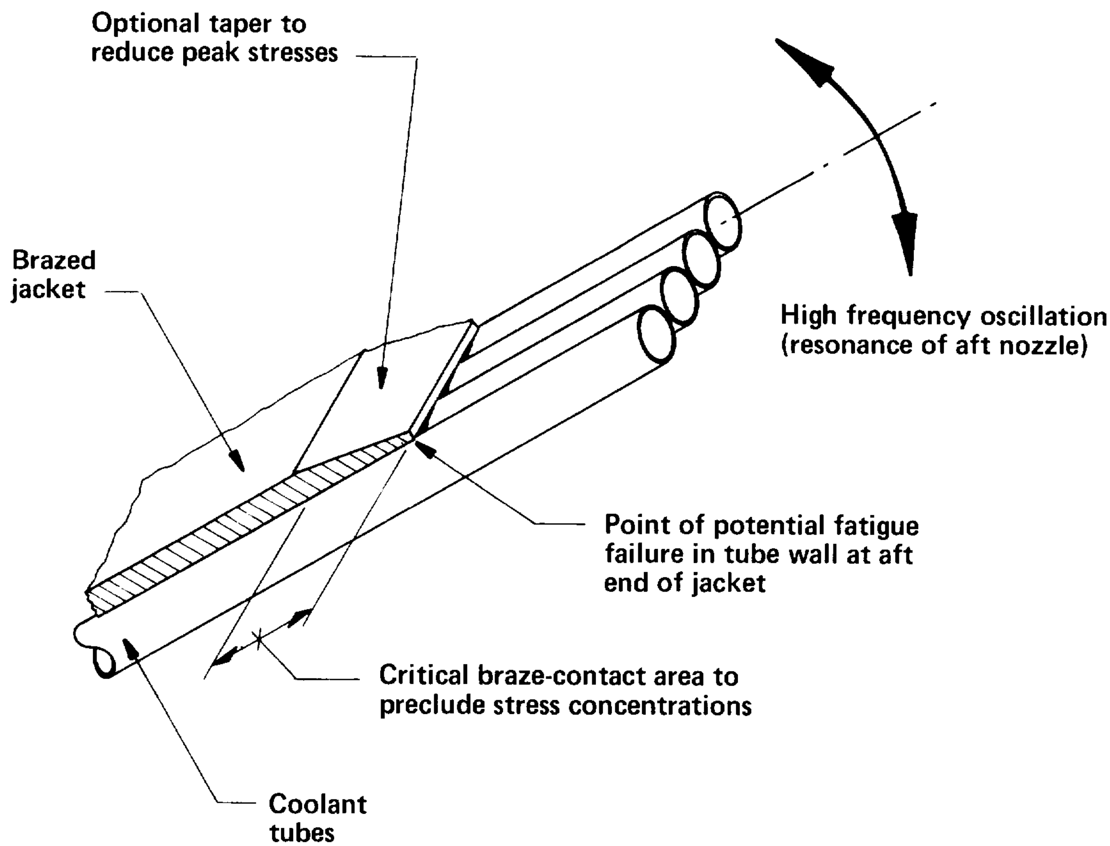


Figure 3. – Critical stress point in jacketed-chamber construction

The Atlas and Thor chambers use primary bands that are spaced a few inches (several centimeters) apart and are handbrazed in place. Secondary bands are welded to the primary surface bands, bridging the gaps between them. The resultant jacket is an effective structure, but like the welded and bolt-on jacket, it is heavy.

The Titan II booster, which has also flown on a large number of Titan III flights, does not require supplemental structural support at the nozzle throat to resist buckling. The low 8:1 area ratio of the nozzle generates relatively low side loads at ignition and thrust termination. Because of the large physical size of the throat, these loads are withstood successfully by the tube bundle alone.

Advanced work is being done with integral-shell coolant-passage construction. Reference 9 presents an evaluation of channel-wall construction where the coolant passages are integral with the inner shell, and the outer shell is electroformed nickel. The primary purpose of this effort was to develop efficient cooling with low-cost construction.

2.1.3.2 HOOP REINFORCEMENT

No serious hoop support problems have been encountered in any of the chamber development programs. This absence is attributed to the simplicity of analyzing hoop loads and designing simple support systems. Hoop support has been provided by shells in contact with the tube crowns, wirewrapping, banding, or integral-shell coolant-passage construction. In the cases of the shells and integral structure, hoop and throat reinforcement usually are carried by the same structure. High-strength round wire is used for Titan and the X-15, and square wire for Delta. For Titan, the round wire is cold drawn, deriving added strength from working, and is imbedded in a resin adhesive about the tube bundle to distribute the hoop loads evenly. The major wire problem with Titan has been to keep the wire in place during operation. This has been accomplished by wrapping clean wire under considerable tension in a heavy bed of epoxy resin. An epoxy bed was used also for the X-15. As noted, Delta uses square wire, for which no epoxy is needed since adjacent strands will not roll over each other.

Maximum tensile strength is derived for each support method by taking advantage of the metallurgical properties of each material. Hardenable materials often are used for jacket designs, where, after brazing, the strength can be increased considerably by agehardening. Non-agehardenable materials are applied after brazing if their strengths are reduced by the brazing environment. The cold-worked steel wirewrap is applied after brazing; the only precaution necessary is to maintain the full tensile strength of the wire where it attaches to the wrapped segment. This is accomplished by constraining the ends of the wire with friction forces that are derived by laying the initial and final wraps of wire in V-shaped grooves in a circumferential band. The extreme ends of the wire then can be welded to the band. As the hoop loads are absorbed, tension pulls the end wraps of wire into the V-grooves, thus increasing the resisting friction forces.

A case where the absorption of hoop loads results in a secondary-stress consideration is the banded chamber; it is designed to withstand bending stresses in the tube spans between the support bands. The double-wall chamber with an annular coolant passage is designed to withstand hoop stresses with minimum deflection so that the inner and outer walls do not separate. These walls need not be rigidly attached to each other if the fitup is fairly tight and the deflections are minimized. Tight fits have been achieved by welding the seams of a split outer shell over the inner shell and helical guide. The longitudinal welds pull the halves together snugly about the inner shell structure. Early problems of gaps formed by thermal expansions (the Aerobee) were solved by forcing the parts together with springs.

2.1.3.3 NOZZLE REINFORCEMENT

The expansion nozzle is designed both to withstand hoop tension during operation in a vacuum environment and to prevent collapse from external pressures that are greater than the static pressures developed within the nozzle during sea level testing. Hoop tension occurs within the nozzle wherever the static pressure of the exhaust gas is greater than the ambient pressure; an underexpanded nozzle thus operates entirely in hoop tension. Collapsing forces exist within overexpanded nozzles, particularly those that are designed to operate in a vacuum environment but are ground-tested at sea level conditions. In this latter case, the ground-test conditions usually dictate the configuration of the support structure for the expansion nozzle.

Collapse of the expansion nozzle under start-transient and shutdown loads at finite ambient pressure has occurred infrequently. It has been prevented by brazing rings firmly to the exterior of the nozzle. In some cases the rings have been first welded to the tubes, but subsequently these joints have been brazed to reduce stress concentrations. The aft end of a regeneratively cooled nozzle contains a coolant manifold (in some cases, this manifold is integral with an attachment flange for a nozzle extension), which inherently provides considerable ring stiffness.

Since the support rings can resist nozzle collapse while being spaced apart from each other, the stresses in the unsupported spans of the nozzle wall are considered. These spans act as beams, and the bending stresses in these spans together with the nozzle forces dictate ring spacing. In some cases, oscillation in the unsupported spans caused eventual fatigue failure at the junctions of the tubes with the rings. This problem has been solved by reducing the cyclic loads with damping bands or by increasing the physical area of the joints of the rings and the tubes.

2.1.4 Interface Flange

Interface flanges attached to regeneratively cooled thrust chambers include coolant inlet and outlet flanges, skirt mounting flanges, injector mounting flanges, special peripheral mounting points, and flanges for tapoff of fluid or hot gas. These flanges often contain internal flow passages, are exposed to heat, and are sources of stress concentration.

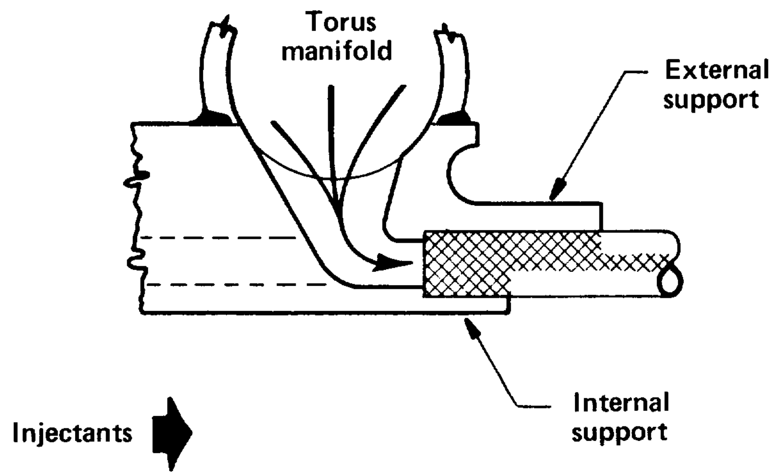
The injector mounting flange generally has the greatest number of design requirements and constraints. For a regenerative chamber, this flange submits to some or all of the following: (1) internal coolant manifolding that feeds fuel to the injector; (2) partial exposure to the combustion gases; (3) integral seal joints for the coolant and the combustion gases; (4) provision for attachment to the injector either mechanically (bolting) or physically (welding); (5) provision for attachment to the coolant-passage structure of the combustion chamber; and (6) for 2-pass cooling, integration with inlet manifolding that feeds fuel into the first pass of the coolant flow channels.

Injector mounting flanges currently are designed to attach securely to the coolant passage structure with minimum geometrical discontinuity at the joint. The secure attachment is achieved by long, brazed shear joints; geometrical discontinuities are minimized by attaching the forward flange to the coolant passages over a longer length on the exterior than on the interior (hot-gas side) surface of the passages (fig. 4). This kind of attachment forms a transition zone with a broad distribution of transition stresses. The thermal loads to the surfaces that are exposed to the hot gases are limited by keeping the exposed length short and as close to the injector face as possible. The exposed surface usually is protected by fuel film or barrier cooling. If the flange erodes, the injector invariably is altered. The internal manifolding (inlet or outlet), seal grooves, and threaded holes are integrated while maintaining adequate design structure.

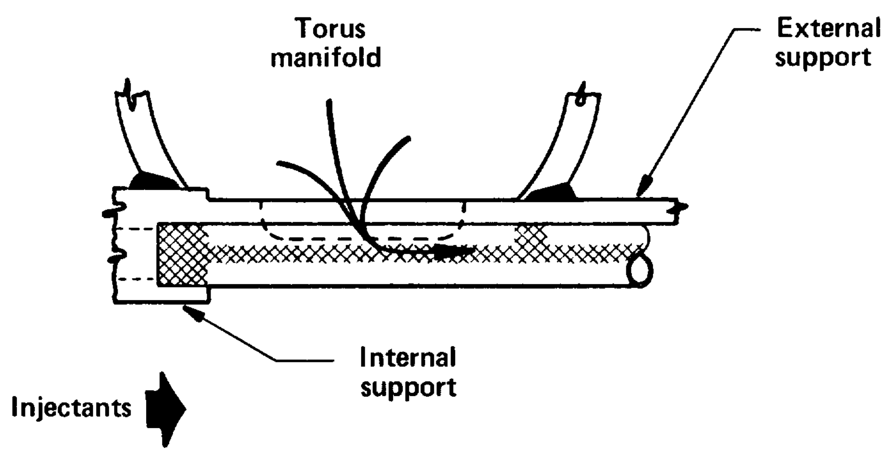
Skirt mounting flanges often contain coolant manifold passages; hence, these flanges submit to some of the same constraints as the injector mounting flange. Skirt mounting flanges are machined true to forward flanges so that the thrust vector alignment can be controlled. Since these aft flanges cannot be mounted to the required trueness, and the position cannot be maintained during chamber braze cycles, the required trueness is achieved during a final machine operation. Precautions are taken to ensure that this final machining does not penetrate into the coolant manifolding. These flanges have not been subject to problems other than minor erosion. When erosion has occurred, the erosion pattern has been used to establish additional machining requirements; i.e., heavy or exposed areas that are damaged by the hot gases are machined off. When heat flux at the exit is relatively high, the tubes are shaped to place the manifold out of the hot-gas stream (e.g., in the design for the J-2 engine).

Special flanges often are attached to the coolant structure for mounting components, for attaching mounting struts or gimbal actuators, or for achieving gas tapoff. The local nature of the applied loads requires special reinforcement to be used in the area of attachment. Stress concentrations are limited by this reinforcement and by the attachment of the flanges to the main chamber body or manifold in a geometrical configuration that provides for smooth, continuous lines of load transfer.

Note: Cross-hatched area shows braze contact



(a) Integral flange/manifold



(b) Adjacent flange/manifold

Figure 4. – Injector mounting flange designs

2.1.5 Materials

Every major chamber development program has included material evaluation studies. Many metallurgical problems have been experienced during these programs: chemical compatibility with the propellants and coolants, brazeability, weldability, formability, and maintenance of design structural properties after fabrication. These problems were not necessarily resolved by changes in materials or by metallurgy. Table III shows the materials ordinarily used for chamber tubes; mechanical and physical properties for these common materials are readily obtained from sources such as MIL-HDBK-5 (ref. 23).

Since fluid-cooled chambers normally involve cooled walls with thicknesses in the range of 0.010 to 0.040 in. (0.254 to 1.02 mm), degradation of the material composing these thin walls is intolerable. Material degradation results from chemical attack (corrosion), incipient melting (erosion), overheating and resulting grain growth of the base metal, and thermal cycling. In addition, material physical properties are degraded by diffusion of some braze alloys and the constituents of some weld materials. Every chamber is subjected to thermal cycling, and every program has experienced forms of wrinkling of cooled walls and, eventually, fractures resulting from fatigue. Thermal fatigue has been minimized by employing ductile materials and by reducing wall temperatures in troubled areas.

For each chamber design, basic material compatibility with the propellants, reactants, and coolants is achieved by selecting materials with excellent compatibility ratings, rather than by compromising with materials whose compatibilities are ranked as being fairly good. This means simply that when a compatibility problem can be avoided by material selection, it is so avoided. In no instance is a material with questionable compatibility used. For example, because of their high thermal conductivity, copper alloys are often considered for use in regions where heat flux is high or where heat-sink cooling is important. These alloys have been used successfully with liquid-oxygen/liquid-hydrogen and liquid-oxygen/kerosene systems, propellant combinations with which they are completely compatible; however, copper alloys are not used with nitrogen tetroxide, other than in research studies, because any moisture will produce nitric acid, which attacks the alloys. Similarly, series-200 nickel has been considered for cooled surfaces that require relatively high thermal conductivity, but because of chemical incompatibility this alloy has not been used in contact with hydrazine or hydrazine blends.

Data on compatibility are stored by rocket engine manufacturers, but in some instances problems associated with special uses are not documented. For example,

- Although CRES 347 basically is fully compatible with hydrazine blends, operation at temperatures in excess of 1600°F (1144 K) has resulted in carburization of the material. This process of carbide formation within the material, at the grain boundaries, reduces the corrosion resistance and the ductility of the base metal. Rapid, intergranular corrosion and cracking ensue. Carburization has been deterred by keeping material temperatures below 1600°F (1144 K).

- The corrosion resistance of some high-carbon stainless steels (e.g., CRES 316) is reduced by sensitizing. Sensitizing results from the precipitation of chrome carbides at the grain boundaries when the material is held at temperatures in the range of 800°to 1500°F (700 to 1089 K). The loss of pure chrome in the grain structure reduces the corrosion resistance of the material. Often during fabrication and operation, the coolant passage materials are heated to or through 1200°F (922 K) (brazing, annealing, welding, and hot-firing). Materials that can be sensitized simply are not used for applications near 1200°F (922 K). When they are used and a braze or anneal cycle heats the material through the sensitizing range, the duration within this range is kept to a minimum.

- Sulfur contamination of nickel, even in slight amounts, can produce intergranular attack or embrittlement at brazing temperatures. The contamination can come from a variety of sources (grinding wheels, rubber goods, atmosphere, etc.) during the manufacturing process. Likewise, high sulfur content in the hydrocarbon coolant causes progressive intergranular cracking of the hot-gas-side walls during operation.

Many unanticipated problems with new materials and new conditions have been experienced by all designers; consequently, most designers continue to use materials with which they are familiar.

The choice of materials for components that attach to the coolant system is based on the need for physical compatibility with the coolant system as well as on the structural and thermal requirements. In almost all tubular systems, the structural support bands and jackets are made from the same material as the coolant tubes. When the materials are different, weldability and brazeability have to be established. Furthermore, when dissimilar materials are brazed, materials with similar thermal expansion coefficients produce better results. When the use of such materials is not possible, special design provisions are made. For example, to reduce cost, the forward and aft flanges of the Improved Stage II Titan are made from CRES 347, although the coolant tube material is Hastelloy X. Though the CRES 347 expands more with temperature, the parts are retained in intimate contact for brazing by welding the tubes discretely to the flanges prior to brazing. Also, at the aft end, the tubes are welded to each other to prevent gaps from forming between the tubes. At the forward end, the tube bundle during brazing is banded around the exterior near the flange so that gaps do not form as a result of thermal growth.

Generally, materials with high ductility are chosen, because it has been found that local yielding must be tolerated, and a ductile system can redistribute the stresses without local failure. Local "crippling" (plastic instability resulting in rippled surface) in the hot-gas walls of regenerative systems normally occurs during a firing; the cause is excessive compressive strain induced in the hot-gas walls by the combination of mechanical loads and thermally induced stresses. Excessive crippling is avoided by proper design, but local minor crippling is tolerable if the tube material has a high ductility and will not strain harden at operating temperatures.

Precautions are taken with the materials used for coolant systems to ensure that the strength properties are equal to or better than those reported in the literature. The coolant passages are shaped from or within specially worked materials. Coolant tubes, for example, are exposed to many successive drawing and swaging cycles, with each cycle culminating in a heat treatment. This heating is standard procedure; it relieves the residual stresses, recrystalizes some of the strained grains, and reorients the grain matrix. However, the thin-wall material can be subjected to adverse conditions during assembly if, for example, the tubes are brazed at temperatures at which grain growth occurs. As grain size increases, material is less ductile and more susceptible to low-cycle fatigue.

2.1.6 Structural Analysis

The problem of structural analysis of a fluid-cooled chamber or of any load-carrying structure is to (1) define the maximum applied loads and environments and then (2) configure the structural member so that it will remain within allowable stress limits for all failure-mode conditions. Stated another way, the design of a structure or structural component usually is defined on the basis of the relation between the loading conditions that will be imposed on the structure and the capability of the structure to withstand these loads. Limit load, design load, allowable load, nominal pressure, MEOP, design safety factor, and margin of safety are basic terms that are used to define the relation between structural loading and structural loading capacity. These terms are defined as follows:

Limit load: Maximum expected load that will be experienced by the structure under the specified conditions of operation, allowance being made for statistical variation.

Design load (or stress): Product of the limit load (or pressure) and the design safety factor.

Allowable load (or stress): Load (or stress) that, if exceeded, produces structural failure. Failure may be defined as buckling, yield, or ultimate, whichever condition prevents the structure from performing its function.

Nominal pressure: Maximum pressure to which structure is subjected under steady-state conditions.

MEOP: The maximum expected operating pressure at any time including engine transient condition, or 1.1 x nominal, whichever is greater.

Design safety factor: An appropriate arbitrary multiplier greater than 1 applied in design to account for design contingencies such as slight variations in material properties, fabrication quality, load magnitude, and load distributions within the structure. The magnitude of a safety factor is a reflection of the degree of confidence in material properties, production processes, and the validity of the predicted usage conditions.

Margin of safety (MS): Fraction by which the allowable load (or stress) exceeds the design load (or stress):

$$MS = \frac{1}{R} - 1$$

where R is the ratio of the design load (or stress) to the allowable load (or stress).

Acceptance of a structure is based on the achievement of positive margins of safety under ultimate (failure) and yield (adverse yield or deflection) load conditions that are established by factors of safety applied to the maximum predicted loads. If the stress levels exceed the allowable values, redesign is necessary. Some permanent local yielding generally is allowable.

2.1.6.1 GENERAL REQUIREMENTS

The maximum applied load is derived by summing numerous discrete loads (see Table V, Load Sources). The basic problem is to include all important loads in the analysis, represent each individual load accurately, and consider appropriate time-phase characteristics. Although some loads have been inaccurately represented for some systems (notably, the thermal, transient, and vibration loads), no gross failures have occurred in prototype hardware. Failures have been local and have involved improper design practice (e.g., stress concentration) or fabrication discrepancies (e.g., brittle weld, wall thickness deviation). The absence of gross failure apparently is a measure of the generally conservative nature of the design analysis and the effectiveness of the applied safety factors.

2.1.6.2 DESIGN ANALYSIS

Analyses are oriented to the specific structural failure modes peculiar to regenerative chambers. Typical failure modes together with the location where they normally occur are presented in table V. The modes are imposed on an analytical model that represents the chamber structure, and required wall thicknesses are determined for the important structural members. A universal problem in the past has been the inaccurate analytical representation of the structure. However, the techniques for stress analysis of complex shells have developed to the point where today even the most complex structures can be analyzed with a high degree of accuracy.

When some of the known failure modes have been ignored, some form of structural failure often has occurred. The most common modes of structural failure in regenerative chambers involve crippling of the heated wall (by thermal stresses), which has led to eventual fatigue failure, and low-cycle fatigue at stress concentrations in thin walls. Another major cause of chamber redesign has been the inability to produce a required structural fit or configuration by the use of reasonable fabrication procedures. When a brazed joint has been required at a blind contact or over a very long length, the successful fabrication of this joint has not

TABLE V. – Chamber Structural Considerations

Potential Failure Mode	Critical Location
Chamber hoop burst	Combustion chamber
Chamber inward collapse	Divergent section
Chamber elastic buckling	Throat; forward end
Chamber plastic buckling	Throat
Gas-side burst	Hot coolant-passage walls
Gas-side low-cycle fatigue	Hot coolant-passage walls
Gas-side buckling (crippling)	Hot coolant-passage walls
Ambient-side wall fatigue	Tube-to-support joints
Wall bending at discontinuity	Walls at flanges/support bands
Wall low-cycle fatigue at discontinuity	Walls at flanges/support bands
Flange joint cracking	Gas-side welds
Manifold burst	Turnaround manifold
Manifold cracking	Component attachment joints

Load Sources

Chamber pressure (transient and steady-state)

Coolant pressure (transient and steady-state)

Ambient pressure

Thermal expansion (transient and steady-state)

Transient dynamic loads: pressure; thrust; thrust misalignment moments; asymmetric flow separation; shutdown blowback

Gimbaling/snubbing

Appendages (propellant lines, component mounts)

Test fixtures (ground test, proof test, quality control)

Random engine vibrations

Vehicle accelerations

Aerodynamic drag loads

always been possible. This difficulty and many similar problems have been minimized in frequency and significance through close coordination between the structural designer and manufacturing personnel.

Structural tests for regenerative chambers are designed to verify that the structural design requirements have been satisfied. These tests are conducted by increasing load levels stepwise to the point of failure; measured strains at critical locations are used to verify the analytical models. The important achievement has been to simulate all of the loads, including pressure loads, thermal loads, and loads introduced at the interface joints. The pressure loads are simulated by the careful positioning of pressurant seals, and the thermal loads are simulated by additional application of pressure loading. Interface loads are simulated by using mechanical interfaces with stiffnesses similar to the operational joint.

2.1.7 Brazing

All of the tubular thrust chambers except Delta are assembled by furnace brazing. Although Delta chambers are produced successfully by welding, if the chamber were designed today, undoubtedly it would be brazed. Furnace brazing has proven to be a very reliable means of assembling coolant tubes or attaching enclosures to coolant passages. The brazed joints are solid, ductile, durable, and can be designed to have no adverse effect on the coolant system performance. This is not to indicate, however, that brazing is a simple, well-defined procedure. Every program has expended much effort and many dollars to select the alloys and define the procedures to braze chambers successfully.

Successful brazing entails, in order, (1) the definition of the optimum braze alloy, (2) the proper preparation of the article to be brazed, and (3) the use of effective brazing procedures. These key factors are defined by the designer and are established as specific procedures in a fabrication specification.

2.1.7.1 BRAZE ALLOYS

There are many commercial braze alloys that have excellent capabilities for brazing the materials used for regenerative chambers. Properties of these alloys are obtained readily in vendor literature. Basic properties include fluidity, melting characteristics, chemistry, ductility, and cost; all these features are considered when selecting an alloy for use. Without exception, ductile alloys have been chosen so that there may be some deflection without local failure. For furnace-brazed systems, the gold- and silver/palladium-based alloys are the most popular because of their fluidity and ductility. Used with clean hardware and in close fitups, they tend to exhibit excellent capabilities, but they are very costly. Hand-brazing has been accomplished successfully using low-melting silver-based alloys (early Atlas, Thor, and Titan), but furnace brazing is now used almost exclusively.

2.1.7.2 PREBRAZE JOINT PREPARATION

The preparation of the article to be brazed is of major importance. All manufacturers have had difficulty in obtaining a clean, close-fitting system that can be successfully brazed without adversely affecting the geometry of the coolant or structural systems. Cleanliness once achieved must be maintained. The parts to be brazed are cleaned by eliminating oxides, grease, oil, and loose particles such as scale, grinding dust, and residuals from tooling operations; commercial cleaners are used. The cleanliness is maintained during various operations by covering the article while it is in transit or is waiting for subsequent machining operations. As noted in section 2.1.5, the thin walls in regenerative systems must not be degraded by corrosion, erosion, or metallurgical change; brazing unclean parts can degrade the material. Problems that have been experienced with unclean systems include the following:

- Boron residuals from some solvents have attacked the intergranular structure of Inconel X at brazing temperatures.
- Chloride derivatives from chlorinated cleaning solvents have attacked the grain boundaries of CRES 347 material, although the corrosion is not advanced by brazing temperatures.
- Free lead from hammers and tapping blocks have attacked the intergranular structure of Inconel X.
- The oxides of aluminum in Hastelloy X have inhibited braze flow and coverage when the aluminum content has exceeded 0.2 percent and brazing temperatures have been held for an hour.
- Particles from grinding operations that took place near the article in the shop (in adjacent weld booths, for example) have deposited on the specimen to be brazed. The particles are virtually impossible to remove and can have many corrosive and inhibitive effects on the brazed specimen.
- With some stainless steels, residuals from tape that was applied to a thin wall caused intergranular corrosion during brazing.

The fitup of parts to be brazed is different for each chamber design; however, the controlling factors are similar. Successful brazed joints are achieved (presuming the correct braze alloy is used, the parts are clean, and the correct furnace cycle is used) by reducing all tube-to-tube gaps to less than 0.004 in. (0.102 mm), by juxtaposing the alloy and the gap to be brazed, by minimizing the length of shear joints into which the braze must be drawn, by filling voids with l00-mesh nickel chips or equivalent prior to brazing, and by ensuring that material deflection during brazing is small and not detrimental.

2.1.7.3 BRAZE PROCEDURE

The actual brazing process involves the planned positioning of the article in a retort within a brazing furnace and the provision of a controlled atmosphere and temperature surrounding the article. The goal is to achieve uniform coverage of braze alloy at the intended joints without incurring excessive runoff, contaminated fillets, or excessive changes in physical geometry.

The ability to plan and control the brazing cycle and atmosphere is well demonstrated. Generally, hydrogen as a blanketing gas is preferred because it reduces oxides on the specimen; however, hydrogen is not compatible with aluminum or titanium-bearing materials. Hydrogen is used only at very low dewpoints (less than -65°F [219 K]) so that the quantity of water vapor in the retort is minimal. Argon often is used as a purge gas to cool the brazed hardware, but only after the hardware is cooler than 500° to 700°F (533 to 644 K) so that surface oxidation will not result from the moisture in the argon.

The proper brazing temperatures for all braze alloys are set forth in the vendor literature, but sometimes it is difficult to achieve these temperatures uniformly and maintain them for the proper duration. Laboratory tests to evaluate specific braze flow characteristics usually are conducted, and specific evaluation is necessary when parts that are to be brazed have large differences in mass (e.g., thin tubes and thick flanges). The flow characteristics are studied in terms of the intended brazed joint. When gaps are small (tubes inserted into flanges), a fluid braze is desirable, and slightly higher than normal temperatures are planned. When braze runoff must be minimized, temperatures slightly lower than normal and short times at these temperatures are useful. When both kinds of joints are found on one piece of hardware, acceptable joints have been achieved by carefully determining an optimum alloy/time/temperature relationship. Superior joints have been achieved with two alloys that have brazing temperatures within 50°F (28 K) of each other. The lower-melt alloy is placed where high braze fluidity is desired.

The actual means of holding the surfaces to be brazed in the proper relationship (close fit while maintaining the over-all geometric design) varies radically for each design. The variations stem from the differences in configuration and the means of structural support being attached. Adjustable rings and bands or contoured pressure bags have been used successfully as tooling aids. When the tube bundle is to be brazed to a form-fitting external shell, where considerable contact must be achieved between the shell and the crowns of the tubes, the tubes are pressed against the shell by well-distributed forces derived from an internally mounted pressure bag. This scheme is favored over previously employed, internally mounted expansion rings. The rings were positioned and secured by hand, and many variations in shell/tube contact were experienced, the amount depending on the hardware and the operator. When an external contoured shell is not used, the tube-to-tube brazing is accomplished using adjustable support rings, supplemented in some cases by tack welding the tubes to permanent external support bands and to the fore and aft flanges.

Chambers that subsequently are to be wrapped with wire for hoop support or reinforced with a mechanically attached corset are brazed as a tube bundle, with aft reinforcement bands and fore and aft flanges. External tooling, consisting of a band wrapped about the bundle and secured with a turnbuckle, retains the proper tube-to-tube clearances. If feasible, the tubes are tack welded to the fore and aft flanges.

When square wire is to be wrapped and brazed into an integral corset about the throat region (brazed wire jacket), the tube bundle is first brazed while precisely constrained to maintain the external configuration. This procedure is necessary to maintain uniform curvature of the external contour so that the square wire will contact the crowns of as many tubes as possible. After the tubes are stacked carefully on a mandrel to achieve uniformity, adjacent tubes are precision welded together at three locations circumferentially along the throat region. The supporting bands on the aft nozzle also are attached to the tubes by tack welding, and these bands, plus a mechanically attached external hoop at the forward end, maintain the external tube contour during initial brazing.

When a pressure bag is used to force the tubes against an external shell during brazing, it is used also to force the tubes against the structural hoop support rings in the expansion nozzle. The rings are merely constrained by the forces of external, thermally expanding tooling. When no bag is used, the structural bands are fit and either tack welded prior to furnace brazing or hand brazed afterwards. Generally, it has been found that when one surface should be forced against another, the use of tooling that has a different coefficient of thermal expansion is successful in providing the desired force.

When hardware is not constrained uniformly, thermal growth can cause gaps. A band that was tack welded to the coolant tubes alternately fore and aft (fig. 5) rotated about the welds; uneven tube heights resulted. The solution to the problem was to weld every tube to the band fore and aft.

Chambers with external corsets that enclose the open side of a coolant tube (U-tube) and reinforce the structure have grooves in the corset into which the tubes are inserted. The tubes are maintained in intimate contact with each other and the corset by forcing shims into the gaps in the grooves between the legs of the tubes.

2.1.8 Chamber Assembly

The assembly of regenerative chambers is unique for each specific chamber design; in short, no two chamber designs are assembled the same. One concept of tubular construction may demand that the coolant tubes be brazed while pressed against a support shell, whereas for others the shell is attached after brazing the tube bundle. However, common problems have arisen during the assembly of most of the combustion chambers. These problems have involved inadvertent tooling damage to thin-wall structures, weld distortion of coolant passages, weld cracking of thin walls, and improper fit of matched parts.

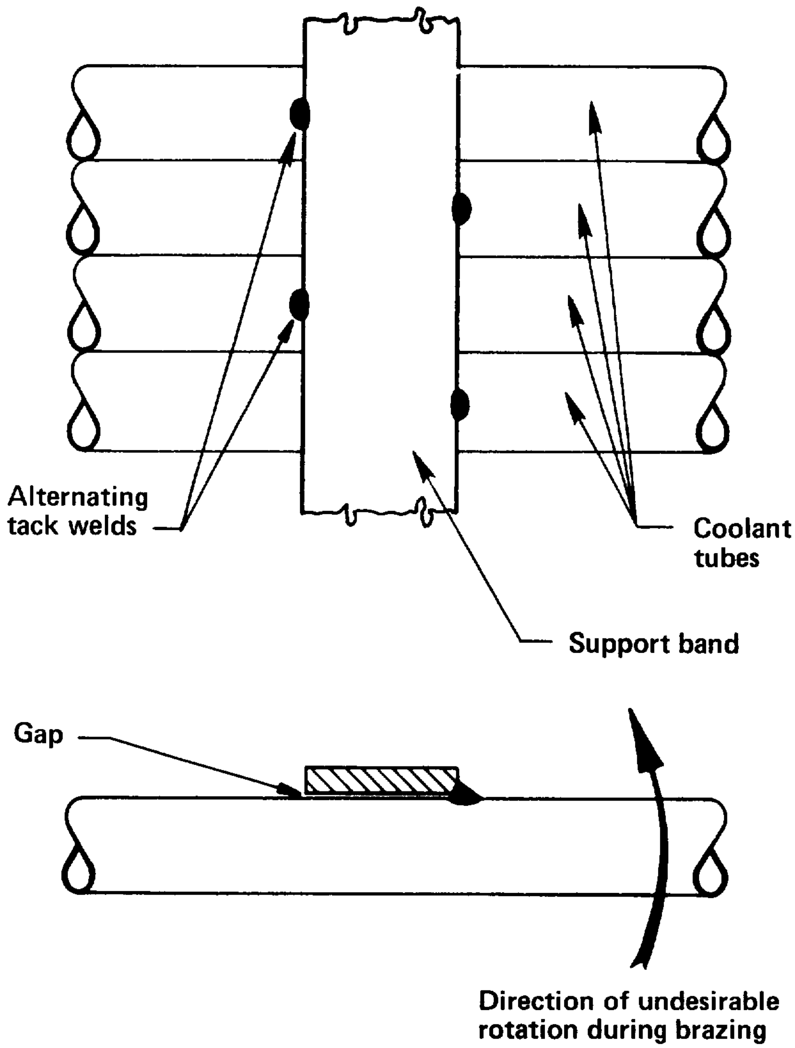


Figure 5. – Gap growth at support band with alternating tack welds

Although pieces are matched by design, they rarely fit as simply as the designer intends. Coolant tubes frequently are of poor quality in the first and final batches. Typical imperfections are waviness, cross-sectional variations, all-to-the-low or -high side of the tolerance range, tube twist, and inaccurate contour. First batches display these traits because the producer is in the midst of perfecting his process; final deliveries have been imperfect because marginal units, previously rejected, have been included in the critical final shipment of stock.

Assembly is complicated further by the fact that design tolerances do not always ensure that a proven means of fabrication can be used. When the designer has established a tolerance to prevent any chance of an interference fit, fabrication sometimes has been impossible. Usually, where necessary, the designer compromises and relies on a statistical basis of success, knowing that interference will occur only after an adverse stackup of many tolerances. Fitting problems have occurred where coolant tubes are inserted into flanges or are aligned with flanges; where coolant tubes are inserted into long, close-tolerance holes; where manifold tori are matched with mounting flanges; where expansion nozzle bands are attached uniformly to tube bundles; and where coolant tubes touch each other. These problems have been avoided to the greatest degree when the designer was sensitive to the problems of fabrication and assembly.

The assembly of coolant tubes involves some tack welding. The least number of welding problems has been encountered when laboratory studies preceded the full-scale assembly. Typical problems have been excessive weld dropthrough into the coolant passage, burnthrough or thinning of the coolant tube wall, degradation of the wall by voids or inclusions, and the production of stress concentrations. In the latter instance, braze, applied on and around the tack weld, has greatly reduced areas of high local stress.

Inadvertent tooling damage has occurred often. The problem emanates from an apparent lack of appreciation for the fragility of thin-wall surfaces. The tool designer has contributed to the solution of this problem by consulting the design engineer prior to proceeding on tool development. Still, damage has occurred, if not by oversight, then by malfunction of the tool. It has been important to recognize the problem and to establish damage limits for the hardware so that no time is lost in deriving repair procedures or conducting analytical exercises every time damage is encountered. All programs have accepted coolant-tube damage up to some pre-established limit. When repair was required, standard repair procedures were developed.

Weld distortion has caused many problems of assembly. Arc welds in particular subject parts to high heat loads, and the assembly of cooling manifolds and flanges by welding often has affected subsequent assembly or interface points. Welding by the electron-beam process is being used extensively to minimize weld distortion. When arc welding is used, close tolerance requirements are avoided, or a bias is provided for the pre-weld components so that the eventual distortion can be accommodated.

2.1.9 Laboratory Proof Testing

To meet quality control requirements, fluid-cooled combustion chambers are tested as pressure vessels in the laboratory for structural integrity and leakage; the coolant passages are often flow tested with water or air to measure the flow resistance of the cooling circuit. "Proof" pressure is applied to a pressure vessel at room temperature to demonstrate satisfactory workmanship and material quality. Proof pressures normally are 20 percent greater than maximum operating pressures; they are applied while the hardware is inspected visually for adverse distortion. Some manufacturers inspect for leaks while holding at proof-pressure conditions; others conduct a leak test at 75 percent of proof pressure as a safety precaution. Current systems usually require that there be no allowable leakage. Occasionally, a leak is detected in a configuration where the source is not clearly identifiable. In this event, repairs are made by guessing the location of the leak and using substantial quantities of braze alloy for repair.

During proof and leak testing, tooling is used to support areas of the structure that must be overpressurized for the sake of the test. Examples of such areas are the hoop restraint required for a tube bundle prior to attaching the permanent external hoop support, and the walls that separate the coolant from the hot gas at the forward end of the chamber. In this latter case, a low pressure differential due to the pressure of the hot gas exists across this wall during operation. However, in the expansion nozzle, the pressure differential becomes substantial, and this pressure loading dictates the condition of the proof testing of the coolant passages. With the high pressure required for proof testing the coolant passages in the aft nozzle, tooling support is provided to walls in the combustion zone that need not be designed for these high pressure loads. Proof testing of these surfaces is effected at reduced pressure levels.

The calibration flow test is performed almost exclusively with water while flowing to back pressure to prevent flow cavitation. It has been found that the inlet lines must be simulated and the level of back pressure must be carefully defined in order to avoid a loss of flow similarity. For hydrogen-cooled chambers, satisfactory flow calibration techniques have not been determined. Rather, flow tests are conducted with air during assembly to ensure that none of the flow passages is obstructed by foreign matter.

2.1.10 Operational Problems

Two major factors influencing the ultimate design of every chamber are the operational environment (including field service) and the interactions between the combustion chamber and the other components of the engine. The major operational problems have involved (1) thermal damage, usually during the development phase; (2) transient and dynamic behavior during engine testing; (3) small hot-gas leaks detected in the field; (4) vibration effects; and (5) environmental factors.

Thermal damage has occurred during early development phases as a result of improper injector design; incompatibility with the injector has not been exclusively the fault of the chamber. Rather, these two components have had to be developed simultaneously, with design margins for the chamber as described in section 2.1.1.5. Compatibility of the injector and chamber has been influenced by injection density, distribution, and angle; film cooling; recirculation; and the forward-end design of the chamber.

Start and shutdown transients have caused damage to regenerative chambers through both pressure-surge and thermal effects. Satisfactory start transients have been defined ultimately using trial-and-error procedures based on past experience. Water-hammer effects have been avoided when transient-flow analyses preceded the test activity, but assumptions have been necessary to characterize the combustion portion of the model. Generally, transient problems are less severe for coolant systems with relatively small volumes that can be filled quickly; in some cases system pressure drop has been compromised slightly in order to decrease the volume. Hard starts due to large fill volumes have been softened by filling the coolant passages with a nonreactive liquid prior to the test (e.g., in F-1 and in the Titan engines.)

During shutdown, coolant tubes have been overheated when the coolant flow was brought to a stop in the presence of continued heating, particularly when an uncooled expansion nozzle was used (Stage II Titan). Overheating during development testing has been avoided by purging the fluid downstream of the propellant valve through the jacket.

Also at shutdown, heat-sensitive materials have been damaged by heat soakback from the hot segments of the chamber. When materials with limited heat resistance are used, they are displaced from the hot-gas surfaces by at least 0.1 in. (2.54 mm) to preclude damage due to heat soakback. Where possible, the heat transmission path is designed to inhibit the flow of heat to the heat-sensitive area (e.g., purge tubes are used to reduce heat transmitted to epoxy bed on backside; heat is conducted away from seal surfaces).

Liquid-hydrogen coolant systems have experienced difficulties resulting from ice formation (frozen water vapor) on the exterior of the cooled surfaces. During the development of the RL 10, ice formation in areas where water vapor would accumulate deformed the coolant tubes beneath the structural shell. The process of deformation was progressive with each test, involving cyclically the collection of water vapor during chill-down, freezing and attendant expansion that permanently deformed the coolant passages, and melting and evaporation after the test when the hardware warmed up. The J-2 suffered similar damage during development. For the RL 10, the problem of ice formation and damage was resolved by sealing the critical areas from the atmosphere; for the J-2, subsurface voids were designed so that water vapor that liquified on the surface would drain off rather than collect and later freeze.

Another operational problem with liquid-hydrogen cooling has involved the time period for priming the coolant system during the start transient, before ignition. It has been found that a slow (10-15 min) bleed-in of the hydrogen through the chamber prior to ignition prechills the components to the point of thermal equilibrium where gas-free primed coolant flow is achieved.

After operation and prior to shipment or disassembly, most regenerative chambers are drained and flushed to remove the coolant. Further, facility leak checks are conducted with water in the coolant passages, and the water also must be removed subsequently. Drain ports are provided at low points on the chambers; these ports are capped during firing. Occasionally, the ports have not been accessible, or they interfered with adjacent mating parts and have hindered the attachment of the chamber to carrying rigs. These problems were solved by relocating the ports to acceptable locations.

Tubular chambers generally are not instrumented easily. Measurements of static pressure normally are made in the mounting flanges, where a portion of manifolding is accessible. Often, pressure-mapping has been compromised because of the inadvisability of attaching pressure instrumentation directly to the coolant passages. Thermocouple data has been even more elusive because of the precision involved in imbedding microminiature thermocouples successfully in the hot-gas walls of the coolant passages. Braze-patch techniques have worked well to provide temperature data. In some cases, when a chamber had been constructed without proper provision for instrumentation, the instrumentation had to be compromised because the chamber could not easily be altered to satisfy the requirements.

Small leaks have occurred in the field, sometimes with the chamber mounted on a flight vehicle. These leaks have been repaired on site, usually by a team selected specifically for this purpose. In some cases, the leaks have been accepted, and the chambers operated successfully in flight. Similarly, handling damage is normal, and most of it is acceptable without repair. When repair has been required, it has been expedient to make the repair according to a pre-established set of directions.

2.2 Transpiration Cooling

Transpiration cooling utilizes a coolant, usually one of the propellants, flowing through a porous combustion chamber wall countercurrent to the heat conduction. Three heat-transfer phenomena are involved in the process: (1) the coolant flowing through the wall picks up the heat that is being conducted by the wall from the hot-gas surface; (2) the coolant as it leaves the wall reduces the temperature of the gas in the boundary layer; and (3) in some instances the boundary-layer temperature reduction may persist downstream from the point of injection and thereby provide downstream film cooling. Although this cooling technique has been studied extensively, transpiration cooling of rocket thrust chambers was not really successful until the period between 1966 and 1969 when prolonged cooling was achieved on the programs summarized in table VI. The work has progressed to the point that transpiration cooling is considered feasible but is not a fully developed technique.

TABLE VI. – Chief Features of Successful Transpiration-Cooled Thrust Chambers

Program	Wall Construction	Wall Material	Propellants	Coolant	Flowmetering	Fabrication and Test Experience	Reference
1	Sintered metal powder	Tungsten	N_2O_4/A-50	NH_3	None	Plugging occurred; cracks developed; difficult to fabricate	24
2	Sintered wires (Rigimesh)	CRES 347	FLOX/CH_4	CH_4	Plenum orificing; axial control	Hot-spot erosion	4 to 7
3	Spiral wound ribbon	CRES 321; Ni 200	N_2O_4/A-50	N_2O_4	None	Bonding difficult; bonds failed during test	25
4	Plates	Copper	LOX/LH_2	H_2	Entrance orificing; axial control	Erosion on occasion; fairly thick plates	26 to 28
5	Plates	CRES 347	N_2O_4/A-50	N_2O_4	Metering grooves; axial/tangential control	Streak erosion on occasion; thin plates	3
6	Plates	CRES 347 Ni 270	N_2O_4/A-50 CTF/MHF-3	N_2O_4 CTF	Metering grooves; axial/tangential control	Streaking injector; startup anomalies; boundary-layer tripping	29

Two types of porous walls have evolved: discrete-pore walls used in Programs 3, 4, 5 and 6 and the random-pore walls used in Programs 1 and 2 (table VI). Discrete-pore walls normally have been constructed by the stacking of plates, discrete passages being formed in the sandwiching process. Flow control has been accomplished by tailoring the passages. The random-pore walls are constructed by pressing metal powders or wires or felts together; the random alignment of voids forms the passages. Flow control has been accomplished by compartmenting and orificing. In both methods, the flow control is located away from the heated zones. Often, manifolding concepts include orificing to produce coarse control of the axial flow. Tables VII A and VII B, based on most of the development work done to date and not merely on the successful programs shown in table VI, provide a fairly extensive evaluation of both kinds of wall construction. While some of the actual problems that occurred are shown in tables VI and VII, the most significant design problem with porous walls has been the development of metering or orificing methods to control the coolant flow through the porous wall while simultaneously accommodating both severe pressure gradients and varying heat loads.

With sintered-wire random-pore construction, flow control has been achieved along the length of the chamber by forming compartments or plenums that feed discrete zones. Each zone is individually orificed in the unheated entrance area. This technique provides flow control along the length of the chamber, but tangential control around the chamber is not achieved, and hot-spot erosion has been observed. The erosion is caused by increased localized pressure losses around the overheated areas that tend to divert coolant away from these hotter zones; this escalating diversion process has been termed "hot-spot instability". The coolant diversion also tends to exaggerate local effects caused by injector streaking.

With the plate discrete-pore construction, both axial and tangential flow control have been achieved by careful design of metering grooves etched into the plates so that the flow is not influenced by variations in the heating rate. Precise designs have been developed, and the flow distribution on each plate is controlled to the point that chambers have been fired successfully even with severely streaking injectors.

The analytical methods that are available for the design of transpiration-cooled chambers have not been subjected to the "test of time"; at present, it appears possible to design a "safe" cooling system but not an optimum one. Extensive work has been done to describe the heat-exchange phenomena near the heated surface. Here a good understanding of local thermal conditions is required; and, in rocket engines, confidence in this area (as noted before) is somewhat marginal. Thus, the more sophisticated approaches do not seem warranted at this time. Design of hydraulic systems within the walls generally involves relatively straightforward network approaches unless random-pore concepts are used; then the prediction of the pressure-drop/flow relationships when heating occurs is not accurate. In addition, "short-circuiting" of the flow by local pressure gradients or local heating often has been overlooked. Studies involving structural considerations have been limited because no flight-type hardware has ever been built.

TABLE VIIA. – Evaluation of Random-Pore Walls

Consideration	Sintered Powders	Sintered Wires (Rigimesh)
Flow control method	Thickness variation	Manifold orificing
Fabrication	Limited demonstration	Demonstrated
Materials used	Most metals	CRES 347
Possible materials	Most metals	Most metals
Porosity control	Fair	Good
Cleaning/Passivating	Poor	Poor
Weight	Low	Medium
Potential cost	Low	Moderate
Axial flow control	Poor	Fair
Tangential flow control	Poor	Poor
Heat-Exchange effectiveness	Excellent	Excellent
Film-Cooling effectiveness	Excellent	Excellent
Repairability	Poor	Poor
Advantages	Cooling effectiveness close to theoretical Relatively easy to fabricate to shape Low cost and low weight	Cooling effectiveness close to theoretical Relatively broad test experience
Disadvantages	Plugging Poor flow control Cracking Porosity variability	Plugging Difficult to repair Local overheating Porosity variability

TABLE VIIB. – Evaluation of Discrete-Pore Walls

Consideration	Plates[1]	Plates[2]	Ribbons
Flow control method	Internal metering	Integral orificing	Manifold orificing
Fabrication	Demonstrated	Demonstrated	Limited demonstration
Materials used	Cu, Ni, CRES, graphite	Cu	CRES, Ni, Inconel
Possible materials	Both metals and non-metals	Both metals and non-metals	Ductile metals
Porosity control	Excellent	Excellent	Good
Cleaning/Passivating	Good	Good	Good
Weight	Medium to high	Medium to high	Medium
Potential cost	High to moderate	Moderate	Moderate
Axial flow control	Excellent	Excellent	Fair
Tangential flow control	Excellent	Fair	Fair
Heat-exchange effectiveness	Good	Good	Fair
Film-cooling effectiveness	Good	Fair	Poor
Repairability	Good	Fair	Poor
Advantages	Positive flow control Wide choice of materials Precise porosity control Repairable Relatively broad test experience	Positive flow control Precise porosity control Moderately repairable Relatively broad test experience	High production potential
Disadvantages	Complex structure High cost High weight Physical size limited	High weight Physical size limited	Poor flow control Poor structural integrity Difficult to fabricate Materials limited

[1] References 3 and 29
[2] References 26, 27, and 28

Support shells, flanges, and associated structures have not been evaluated seriously, because only workhorse-type experimental hardware has been built to date. The design of the contour is recognized as an important consideration. Experience to date has shown that a minimum surface area is desirable and that steep pressure gradients should be avoided.

Because experience has been limited to construction of experimental hardware, not a great deal is known about fabrication problems. However, certain observations unique to transpiration-cooled systems have been made, as follows:

- Tolerance control of flowmetering orifices must be of a high order because small variations can lead to flow rates significantly different from the design rate.

- Small discontinuities on the gas-side surface can cause chamber failures. Apparently the resulting turbulence not only increases the local heat transfer but also promotes reaction between combustion gases and propellant coolant. This combination of effects produces a very severe thermal environment.

- Porous walls contoured by machine methods can be plugged by "dirt" in the machining oils and by material resulting from chemical breakdown of heated oil.

- Longitudinal surface welds and aligned lands on the porous surface can overheat if they are not adequately covered by coolant.

- Porous materials brazed to support structures can be plugged as a result of the strong capillary tendencies of porous media. Welding of porous media may result in brittle areas around the weld.

Enough information now exists to show that operation of transpiration-cooled chambers is feasible and that consistent and reproducible results may be obtained. Actually a fair amount of data of good quality exists, because most of the workhorse chambers were well-instrumented and provided both thermal and fluid-flow data. The observations below, therefore, have good substantiation and reflect a reasonable understanding of operational problems:

- Injector streaking is magnified by combustion at the cooled wall.

- Filtering of the coolant before it enters the porous media is absolutely necessary to prevent plugging.

- Failure to insure that coolant flow is established in all parts of the chamber during startups can lead to chamber failures in uncooled regions.

- Choking of coolant flow under vacuum conditions can influence the starting sequence, although this phenomenon has not been thoroughly examined.

- ▹ The depth of heat penetration into the porous wall increases under throttled conditions unless special flow adjustments are made.

- ▹ Hot spots can develop in seemingly well-cooled zones, indicating that the properties of random-pore media may change with time.

- ▹ Wall temperatures can be accurately measured by small thermocouples imbedded in the porous wall (especially the plate walls).

These representative problems show that many design, fabrication, and operational areas must be resolved before transpiration cooling can be considered operational.

2.3 Film Cooling

Nearly all fluid-cooled chambers have experienced some form of overheating from injector maldistribution and streaking. The overheating almost always has been eliminated by revising the injector pattern or by film cooling; in rare instances, the chamber tubes have been redesigned for higher velocities or thicker walls.

As shown in table VIII, in all of the major regeneratively cooled chambers supplemental cooling is derived from film cooling (which is normally provided from the injector). Film cooling is used to (1) reduce the severity of the thermal conditions near the wall,(2) produce a more acceptable chemical environment, or (3) achieve a combination of (1) and (2). On occasion, film cooling is used to overcome very localized overheating simply by directing coolant at the affected area. As noted above, injector maldistribution and streaking impact the cooling requirements; therefore, successful chamber design dictates that both the injector designer and the chamber designer must understand the principles of film cooling in order to interface effectively. Their common goal is to achieve the combination of film cooling and regenerative cooling that produces the required margins of chamber safety while maintaining high combustion efficiency. The principal design problems have resulted from the inability to (1) provide an *a priori* prediction of film-coolant quantities, and (2) size and arrange the flow streams so that the required quantity of coolant can be used efficiently.

In spite of many studies of film cooling carried out over the past several years, accurate prediction methods still are not available. The major unknown is the interaction of the film coolant with the combustion gases; this interaction is known to depend on such things as the velocity, location, and direction of injecting the film and on the energy-release potential at the wall compared to that in the prime combustion zone, but there are additional factors not yet identified. Also, part of the prediction uncertainty stems from the inaccuracies in modeling the local thermal conditions that exist without film cooling; these conditions are an essential input to the composite calculation. In a real situation, therefore, the predictions represent more of a rough estimate than an absolute requirement. Consequently, when possible, the design provides flexibility to accommodate the inevitable changes that will have to be made.

TABLE VIII. – Major Regeneratively Cooled Chambers With Supplemental Film Cooling

Chamber	Propellants	Regenerative Coolant	Film Coolant	Source of Film Coolant
F-1	LOX/RP-1	RP-1	RP-1	Injector orifices
J-2	LOX/LH_2	GH_2	GH_2	Injector orifices
RL 10	LOX/LH_2	GH_2	GH_2	Injector orifices
Agena	IRFNA/UDMH	IRFNA	UDMH	Injector orifices
Titan I family	LOX/RP-1	RP-1	RP-1	Injector orifices
Titan II family	N_2O_4/A-50	A-50	A-50	Injector orifices; secondary tubes[1]
Titan III family	N_2O_4/A-50	A-50	A-50	Injector orifices
X-15	LOX/NH_3	NH_3	NH_3	Injector orifices

[1] Tubes adjacent to injector baffles

A somewhat qualitative understanding exists on how the coolant streams should be canted relative to the wall and to each other in order to (1) minimize mixing with the reactants; (2) maximize coverage of the surfaces to be protected; and (3) develop penetration to protect these surfaces over maximum length. The film coolant, normally injected through a ring of orifices around the periphery of the injector, can be directed parallel to or against the chamber wall. In most cases, a constant orifice diameter and peripheral spacing is maintained to provide uniform injection. It is believed that when the coolant is injected as a non-impinging stream into an unreactive environment, it traverses the chamber length more effectively and is presumed to provide protection for the convergent section and the throat zone of the chamber. When protection of a forward flange surface or the forward cooling zone is critical, greater stream spreading and sheet formation is provided by impinging the propellant directly on the wall. Combinations of both wall-impinging and non-impinging film-coolant streams are used for efficient protection of the entire combustion zone.

Selective orifice sizing has been used to achieve minimum film-coolant flowrates. The larger orifices are used at hot streaks; between the hot streaks, less film coolant is provided. This method of tailoring film coolant tends to result in circumferentially uniform wall temperatures. Local protection has also been achieved by the addition or enlargement of discrete orifices or the installation of flow tubes to place film coolant directly at heated areas.

An alternative or supplement to film cooling is barrier cooling, in which sets of bipropellant injection elements adjacent to the chamber wall are operated at low O/F ratio. This procedure produces a milder thermal and chemical environment and involves more propellant in the combustion process.

Film-coolant injection in the convergent section, via short tubes located between coolant tubes, has been attempted during development programs; only limited success has been achieved. Currently, this method is not an accepted technique for supplemental cooling, because problems of manifolding, structural integrity, and assembly procedures have not been resolved.

2.4 Coatings

Coatings have been used on a few chambers to provide chemical and thermal protection for cooled walls (table IX). On paper, there are many reasons for coating regeneratively-cooled chambers (e.g., to achieve local chemical protection, lower coolant bulk temperatures, lower heat fluxes, lower coolant pressure drop, higher chamber pressure potential, or increased throttling range). An additional factor is the simple desire to improve performance by replacing film cooling with coatings. Despite all these reasons, coatings remain a very controversial subject because of their tendency to spall, delaminate, and crack. The Agena and the X-15 chambers achieved extended lifetime by using a coating as a chemical or erosion barrier; the X-15 chamber, however, must be recoated after a set number of firings

TABLE IX. – Coated Thrust Chambers

Designation	Propellants	Coating[1]	Thickness in.	Thickness mm	Purpose	Remarks
Able/Vanguard (ref. 30)	IRFNA*/UDMH	Tungsten carbide	0.005	0.127	Erosion barrier	Aluminum tube chamber; improved duration.
X-15 (XLR-99)	LOX/NH_3*[f]	Nichrome/ZrO_2 Mo/ZrO_2	0.016	0.406	Thermal barrier	First used Rokide Z, which spalled; spalling still a problem in production even with coating shown.
Agena B (ref. 31)	IRFNA*/UDMH[f]	Ni/ZrO_2 (grad)[2]	0.040	1.020	Thermal barrier	First used Al_2O_3, which spalled and had limited success; coating shown is in production use.
Agena B (3096) (ref. 31)	IRFNA*/UDMH[f]	Al_2O_3	0.005	0.127	Erosion barrier	Just below injector, improved duration; coating is in production use.
Titan II/Stage II (ref. 32)	N_2O_4/A-50*[f]	W/ZrO_2/Si	0.040	1.020	Thermal barrier	3 restarts/533 seconds; some success; local spalling.
J-2	LOX/LH_2*	Inconel/ZrO_2 (grad)	Not Available		Thermal barrier	Some success in tests up to 6000+ seconds; not used in production.
Titan IIA (ref. 2)	N_2O_4*/Alumizine[f]	HfO_2-W/Hf/HfO_2 (grad)	0.030	0.762	Thermal barrier	Extensive laboratory studies on coatings preceded development; failure of barrier consistently resulted in chamber failure.
ARES (ref. 3)	N_2O_4*[f]/A-50	W/ZrO_2/Si	0.025	0.635	Thermal barrier	
AGC Advanced	LF_2/LH_2*	W-W/ZrO_2	0.030 to 0.080	0.762 to 2.030	Thermal barrier	Vapor deposit W; flame spray W/ZrO_2.

* Coolant
[f] Film Coolant
[1] Applied in successive layers.
[2] Gradated coatings were applied so that the percentage of constituents changed in successive layers.

because of spalling. As an actual thermal barrier, success of coatings to date is restricted to (1) the considerable progress achieved during laboratory plasma-arc testing; (2) a few demonstration firings on actual chambers; and (3) progress toward a more fundamental understanding about the real problem -- HOW TO KEEP THE COATING ON.

The coating continues to be considered as an afterthought to or "fix" for an existing marginal design. Thin monolayers of plasma-sprayed material have been used to provide a degree of chemical protection. Coatings applied in successive layers now are generally recommended because they provide better thermal shock resistance. At one point, very thick coatings were considered during development programs (ref. 2), but cracking, especially on shutdown, was severe, and the rejection of residual heat presented a problem. Chemical compatibility of the coating material with the propellants and the combustion products at operating temperature has been studied, but coatings that proved tough and erosion resistant in the laboratory often were found susceptible to erosion in an actual combustion chamber. Methods for reinforcing and for attaching coatings (e.g., screens, wires, brazing) also have been examined without notable success.

The most successful coatings have been those produced during the combustion process. The kerosene propellants (as well as other carbon-bearing propellants) actually deposit a carbonaceous layer on the surfaces that are exposed to fuel-rich combustion products. These deposits provide a tenacious coating, which is self-healing and effective enough so that it must be accounted for in the thermal analysis, since the total heat rejected to the coolant is reduced. But, periodically, random flaking of the deposits occurs; hence, local areas are subjected to full heat loads intermittently during operation as well as during the short period when the coating first forms. Fuel additives containing silicon (e.g., ethyl silicate or silicone oil) have been shown to form self-renewing thermal barriers on combustion chamber walls.

3. DESIGN CRITERIA and Recommended Practices

3.1 Regenerative Cooling

3.1.1 Coolant Passages

3.1.1.1 BASIC REQUIREMENTS

The coolant-passage configuration shall (1) provide adequate cooling with minimum pressure drop, (2) be low in cost to fabricate, and (3) be light in weight when constructed.

The practices recommended for selecting a coolant-passage configuration are summarized as follows:

(1) For maximum heat flux below 12 BTU/in.^{2}-sec (1.96 kJ/cm^2-sec), a simple channel-wall design is recommended.

(2) For maximum heat flux in the range from 10 to 25 BTU/in.^{2}-sec (1.64 to 4.09 kJ/cm^2-sec), tubular construction is recommended; however, advanced techniques of channel-wall construction (refs. 5 through 8) may be used.

(3) For maximum heat flux above 25 BTU/in.^{2}-sec (4.09 kJ/cm^2-sec) advanced techniques of channel-wall construction should be used.

(4) For small units, at thrust levels below 20,000 lbf (89.0 kN), simple channel-wall construction is preferred.

(5) For minimum weight, tubular construction is recommended.

(6) For arguments of fabricability and cost, and in cases where selection is not clearly ordained, refer to past experience; select the configuration that makes maximum use of available data and fabrication experience.

3.1.1.2 NUMBER OF PASSES

The number of coolant passes shall be sufficient to produce effective cooling within the constraints of available feed pressure, simple manifolding, low gimbaled-mass moment of inertia, and low system weight.

For storable coolants at subcritical pressures, two passes normally are recommended, because higher coolant velocities are achievable with larger tubes than with one pass. A recognizable system advantage is derived from two-pass construction because the heavy manifolding is located at the forward end of the chamber. The gimbaled-mass moment of inertia is thus reduced, and the natural resonant frequency of the engine is increased.

For coolants operated over a temperature range where large differences in transport properties and density exist, 1 or 1½ passes are recommended. This practice generates the density change in the low-heat-flux zones, and high coolant velocities then can be achieved at the throat and in the combustion zone with nominal tube diameters. It is recommended that liquid hydrogen be introduced in the expansion nozzle, since hydrogen as a coolant exhibits poor qualities and rapidly changing properties near the critical point. Thus, the cooling phase that has the poorest capabilities is isolated within the regime of lowest heat flux.

One-pass coolant systems should be considered for relatively low thrust levels when the feed pressure is limited and two-pass cooling is not suitable.

3.1.1.3 TUBES

3.1.1.3.1 Geometry

Tube geometry shall not result in high costs or potential fabrication irregularities.

Use the simplest tube geometry possible, considering first a tube with no taper, then one that is tapered in one direction only, and lastly one that is tapered in both directions with the smallest diameter in the center. Each additional step of tube forming earns, of course, a greater cooling capability, but each step also increases the cost and difficulty of tube fabrication.

For tapered tubing, it is recommended that the total taper achieved by a reduction process (spinning or swaging) be limited to a maximum of 3:1 (diameter ratio). If a total taper greater than 3:1 is required, use an expansion process at the large end to achieve a maximum recommended total taper of 6:1. Beyond this ratio, excessive costs can be incurred by both the development of the process and the increased time usually required for additional precision working. An alternative to excessive tube working for large diameter ratios is to employ a bifurcation joint, where two smaller tubes are joined to the large end of a single tube (sec. 3.1.1.3.3).

It is recommended that the wall thickness of a coolant tube be altered along the length only if the alteration might benefit the cooling in critical areas, control overall heat rejection, or increase the strength of the tube; a maximum one or two thickness tapers is recommended. All tapers should be linear, with at least two inches provided as a transition section between two zones of constant wall thickness. Guidelines for tapering wall thicknesses are as follows:

(1) Increase the wall thickness where a greater margin of safety is required for coolants operated at subcritical pressures; the resultant reduction in heat flux reduces the susceptibility to film boiling.

(2) For heat-flux-limited coolants, where the total heat rejected to the coolant must be kept at a minimum, taper the wall thickness throughout the expansion nozzle (starting several inches aft of the throat plane).

(3) Use thin walls where the heat loads are highest and the temperature of the gas-side walls must be controlled below the allowable limit.

3.1.1.3.2 Wall Thickness

Tube wall thickness shall preclude unacceptable effects of physical and chemical degradation.

Tube walls should exceed 0.010 in. (0.254 mm) in thickness. Thinner walls have proved susceptible to critical damage or failure through the presence of normal flaws, granular effects in the material, erosion or corrosion due to the combustion environment, and denting due to handling. Even though thermal and structural considerations may indicate that tube wall thickness of 0.010 in. (0.254 mm) or less would be adequate, the troubled history and expense of thin-wall tubes indicates that they are a poor risk.

3.1.1.3.3 Bifurcation Joints

Bifurcation joints shall provide for ease of assembly without adversely affecting the coolant flow.

Use either of two methods for achieving bifurcation joints (fig. 6): (1) full welding, with the tubes fitted against each other; or (2) brazing, with the secondary tubes inserted into the primary tube. Use the welded configuration if heating is critical and the effective wall thickness must be held at a minimum. To achieve the welded joint, form the ends of the two smaller tubes into "D" shapes, one being the mirror image of the other. Placed back-to-back, the D-shaped ends of the two tubes are first welded together with an edge weld along the flat line of contact. Match the circumference of the joint to the shape of the single large tube, and join the two tubes to the primary using a butt weld (fig. 6). Use precision welding techniques to avoid excessive dropthrough of the weld material at the joint. Do not force the fit of the butted joint, because deformation of the center wall of the two-tube section (flat side of the "D") may occur during assembly. The fit should be within 0.003 in. (0.076 mm).

To achieve the brazed joint, prepare the ends of the secondary tubes as described above for the welded joint, and weld the joint between the secondary tubes, top-to-bottom at the end. Match the circumference of the secondary assembly to the inside dimensions of the primary tube. Insert the secondary tubes into the primary, avoiding forcing, and braze the units together using powdered alloy and induction-brazing techniques.

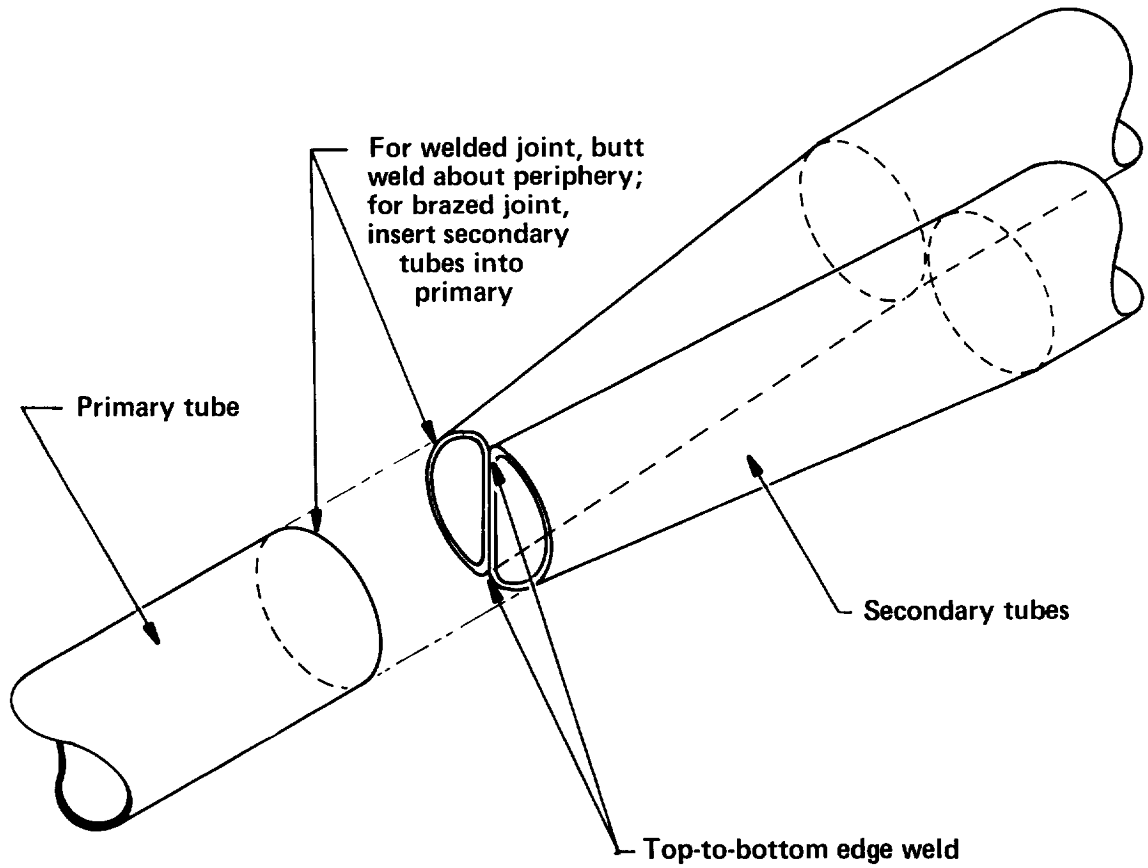


Figure 6. — Bifurcation joint construction

3.1.1.3.4 Tolerances

Design tolerances shall result in (1) flow control within acceptable levels and (2) tube-to-tube and tube-to-flange fitup within limits necessary for brazing.

It is recommended that tube circumferences be held within 0.010 in. (0.254 mm) at all stations and that tube wall thicknesses be within plus or minus 10 percent of the nominal thickness. Control the fit of the sides of the tubes by describing at each station an included angle equal to 360° divided by the total number of tubes, and by requiring that each side of the tube be within 0.003 in. (0.076 mm) of the surfaces described by the angle. Gaps as great as 0.006 in. (0.152 mm) will result, but work these gaps to less than 0.003 in. (0.076 mm) by careful peening and swaging techniques applied to the outer crowns of the tubes.

3.1.1.4 CHANNEL WALLS

The channel-wall configuration shall provide adequate cooling with minimum pressure drop and shall be low in cost to fabricate.

Two alternative simple designs are recommended: (1) dual concentric shells that form a coolant passage between the shells, and (2) a monolithic construction that contains drilled coolant passages within a single shell. For the concentric shells, use axial flow whenever practical and helical flow when necessary. Form the coolant channeling by attaching a helical wrapping of wire in the gap between the two shells. Adjust the angle of the helix to achieve the required dimensions for controlling the coolant velocity. For the drilled passages, drill separate ringed segments of the chamber to achieve the required coolant velocities within each segment. When assembled with manifolding at the interfaces, these segments form a monolithic chamber construction.

Several other fabrication techniques (refs. 8, 9, and 10) merit consideration when more complicated cooling passages are required, either to handle high heat loads or to provide greater flexibility in the development program. These techniques include spin liners with milled channels, cast liners with integral coolant channels, electroformed or powder-metallurgy structures, and electroformed or brazed closures.

3.1.1.4.1 Passage Shape

The shape of coolant passages shall preclude flow stagnation and excessive pressure drop.

In channel-wall construction, the flow passages almost invariably are rectangular in cross section; therefore, the ratio of width to height is the shape parameter of chief concern. It is recommended that, in regions of high heat flux, rectangular flow passages have width/height ratios of less than two so that velocity effects at the corners of the flow channels are avoided. Width/height ratios of eight may be acceptable provided that the channel height is greater than 0.10 in. (2.54 mm). All chamber designs that specify rectangular channels having aspect ratios greater than about four should be examined for flow separations and resulting eddy formation; use visual studies with full-scale plastic models.

For machined passages, surfaces finishes should be evaluated for each method of machining – mechanical, photo-etch, electron-discharge milling, and electrochemical milling; assess carefully the surface finish (root mean square) produced by a given method and the effect of that finish on pressure drop.

3.1.1.4.2 Double-Wall Construction

When the flow guide is not attached to both walls, double-wall construction shall minimize interpassage leaks.

Dimension the outer shell for a fit ranging from a slight interference to a slight clearance (±0.010 in. [±0.254 mm]). It is recommended that, where possible, an interference fit be planned. When this kind of fit is not possible, and the outer shell fits to the inner shell in two halves, weld joints should be designed to pull the two shells into sufficient contact. If no flow bypass is tolerable, braze or weld both shells to the guide. If brazing is used, gaps less than 0.004 in. (0.102 mm) should be obtained through tight tolerances, hand fitting, use of dissimilar metals (greater expansion for internal shell), or rolling the external surface.

3.1.1.4.3 Interchannel Areas

Regions between cooling channels shall not cause local overheating at the gas-side surface.

When cooling is reduced by the physical presence of a wire or flow guide or by material between drilled channels, examine the two-dimensional thermal effects. This examination will indicate how wide the land can be and, for dual-shell construction, whether the flow guide needs to be in intimate contact with the inner wall. To enhance two-dimensional cooling (fin cooling), use highly conductive materials and maintain intimate contact between flow guides and the heated wall.

3.1.1.5 SPECIAL THERMAL AND HYDRAULIC CONSIDERATIONS

3.1.1.5.1 Gas-Side Heating

Initial design shall be based on conservative estimates of the gas-side thermal conditions, especially near the injector.

The procedure shown in table X is recommended for calculating gas-side heating as a first approximation. In this procedure, the only major parameter that is influenced directly by the injector is recovery temperature T_r which is calculated using a c* adjustment term; use a conservative approach for determining T_r by basing the c* adjustment on the maximum c*

TABLE X. – Procedures For Estimating Gas-Side Thermal Conditions

(1) Estimate heat flux from $\phi = h_g (T_r - T_{wg})$

(2) Obtain h_g from $(St)(Pr)^{0.6} = C_g (Re)^{-0.2}$

(3) $T_r = \left(\frac{c^*_{act}}{c^*_{th}}\right)^2 \left[T_{FS} + Pr^{1/3} (T_o - T_{FS})\right]$

(4) Calculate properties at T_{FS}.
(5) Use figure below for C_g factors.
(6) In the expansion section,use two-dimensional mass flux (ρu) near the wall in calculating St and Re.
(7) Use enthalpies if significant dissociation exists.
(8) Thermal radiation effects not included (usually negligible).
(9) Caution: Predictions may be very conservative (1) if laminarization of the boundary layer occurs, and (2) near the injector where combustion is incomplete.

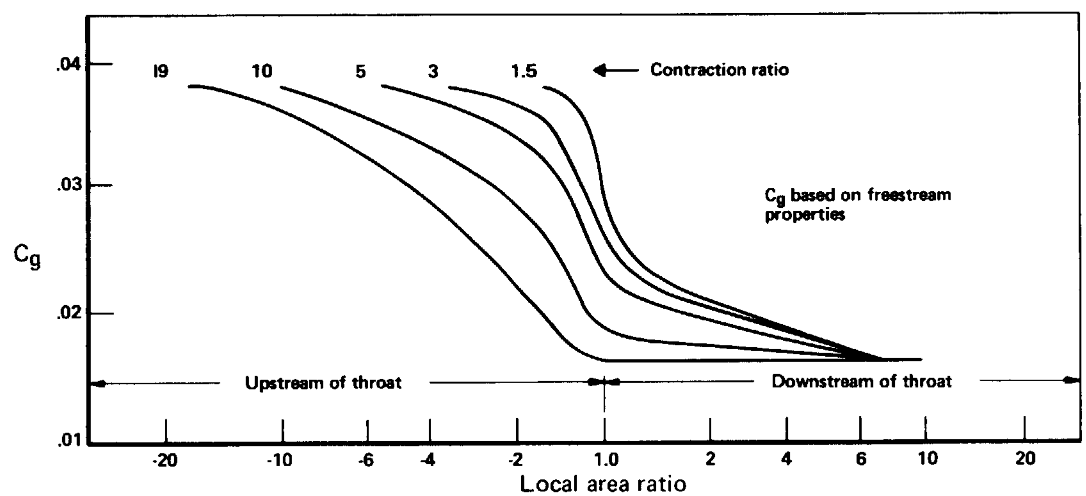


Figure 7. – Heat-transfer correlation factor C_g as a function of local area ratio and contraction ratio

value achievable. Further, injector streaking can cause localized operation at off-design mixture ratio; hence, for the boundary, use transport properties that are based on the worst possible conditions. These conservative procedures are particularly recommended for the first 3 in. (7 to 8 cm) of the chamber length, since this region is especially susceptible to local streaking and erosive effects.

During the initial test phase, it is a recommended practice to measure wall temperature or heat flux, so that the thermal model can be verified or appropriately altered. One of the most successful and economical methods of measuring wall surface temperatures is the braze patch. With this method, spots of various braze alloys, 0.25-in. (6.35 mm) diameter and 0.002-in. (0.051 mm) thick, are applied at specific locations. The patches are scratched on the surface; when the scratch disappears, the solidus temperature of the alloy has been reached.

3.1.1.5.2 Thermal Margin of Safety

The coolant-passage configuration shall provide adequate thermal margin of safety based on wall temperatures and coolant capability; the configuration shall be alterable to increase the margin of safety.

A conservative practice when significant data exist is to operate heat-flux-limited systems at less than 80 percent of the mean burnout heat flux. (Limits for burnout heat fluxes are reported in ref. 34). When data on heat-flux-limited coolants are unavailable, no serious chamber design effort should be pursued without first acquiring the missing data experimentally. When the coolant is not limited in the sense of film boiling, determine the cooling requirements on the basis of the allowable stress at the highest working temperature (sec. 3.1.6).

If the margins of cooling are less than 15 percent, width/height ratios of rectangular cooling passages should be less than 2.0 or the passage height should be at least 0.2 in. (5.08 mm) to avoid locally depressed velocities. Account for the two-dimensional heat conduction in channel-wall configurations.

For curved flow passages, such as the nozzle throat area of tubular chambers and the helical passages of double-wall chambers, consider the two-dimensional flow effects. If curvature forces the coolant flow against the heated wall, an experimental enhancement factor for gases may be applied, but use of a factor is not recommended for liquids. If the coolant bulk is forced away from the heated wall (e.g., in helical passes, or in transition from cylindrical chamber to convergent section in a tubular chamber), it is recommended that a reduction in film coefficient be assumed.

To minimize the chances for streaking, gouging, or erosion at the forward end of the chamber, keep forward flanges as short as possible, do not operate coolant channels near both heat flux and temperature limits, and plan to use supplemental film cooling as described in section 3.3. If possible, avoid irreversible design features such as a forward flange that cannot be shortened, or a wall thickness or cooling channel that cannot be altered, or film cooling that cannot be modified either in quantity or pattern.

3.1.1.5.3 Coolant Velocity

Coolant passageways shall not cause excessive coolant velocities that result in unanticipated, intolerable pressure drops.

Keep liquid coolants at velocities below 200 ft/sec (61 m/sec). At velocities above this, excessive pressure drops can occur because of minor variations in flow area and surface roughnesses. It is recommended that gases be used below Mach number 0.3, with an absolute maximum velocity of Mach 0.5. If this velocity is exceeded, sonic choking is probable at bends, contractions, or exit/entrance regions.

3.1.1.5.4 Wall Temperatures

Wall temperatures shall remain below values at which chemical reactions that degrade cooling occur.

To avoid coking deposits on the cooled surfaces, do not operate with liquid-wall temperatures above 850°F (728 K) for RP-l, or above 600°F (589 K) for furfuryl alcohol. Aerozine-50 should be used at wall temperatures below 600°F (589 K) to avoid detonation. Generally, maintain wall temperatures below the saturation or critical temperature of detonable propellants when experimental data do not exist.

In the analysis of liquid-wall temperatures, do not overlook transient periods when (1) cooling might not be completely developed to the eventual full-pressure conditions, or (2) combustion has been terminated and heat soakback occurs.

3.1.2 Manifolds

3.1.2.1 FLOW DISTRIBUTION

Manifolds shall effectively distribute the coolant flow within the allowable pressure drop.

An annular inlet manifold is recommended; the configuration should lie between the constant-area and the constant-velocity shapes. Dynamic head effects at the inlet to the torus can be suppressed by using a flow splitter, which divides the flow to each side and passes a small portion to feed the passages in the region of the splitter. Flow separation should be prevented by shaping the vanes in conjunction with a inlet turn. For double-wall helical passages, the inlet manifold must direct the coolant into the helix smoothly with no stagnant areas at the edges of the passage.

For multi-pass coolant systems, an open annulus is recommended for the turnaround manifold, providing that the flow through the first pass is satisfactorily uniform. Such a common manifold will eliminate flow variations in the subsequent pass that could be caused by the inlet manifolding to the first pass. Minimum flow velocity within thermal limits should be planned for this manifold.

An alternative to the open annulus is a manifold that maintains separate circuits for the channels. This configuration is recommended as a means to be considered for improving the flow distribution to the first pass by providing high-resistance, parallel-flow circuitry downstream from the inlet manifold. However, it must be recognized that the common annulus offers a simple way to achieve uniform flow in the passes subsequent to the first, whereas a manifold that maintains separated flow will propagate flow variations throughout the system. Therefore, in considering configurations for the turnaround manifold, compare the flow variations for each pass against the local coolant capabilities.

The forward flange contains outlet manifolding that feeds the chamber coolant to the injector. In this manifolding and in the inlet systems, it is recommended that normal methods of reducing pressure drops be used even though they may present manufacturing difficulties. These methods include round turns, smooth transitions, contoured passages, and the use of low velocities at areas of discontinuities where no transition may be possible.

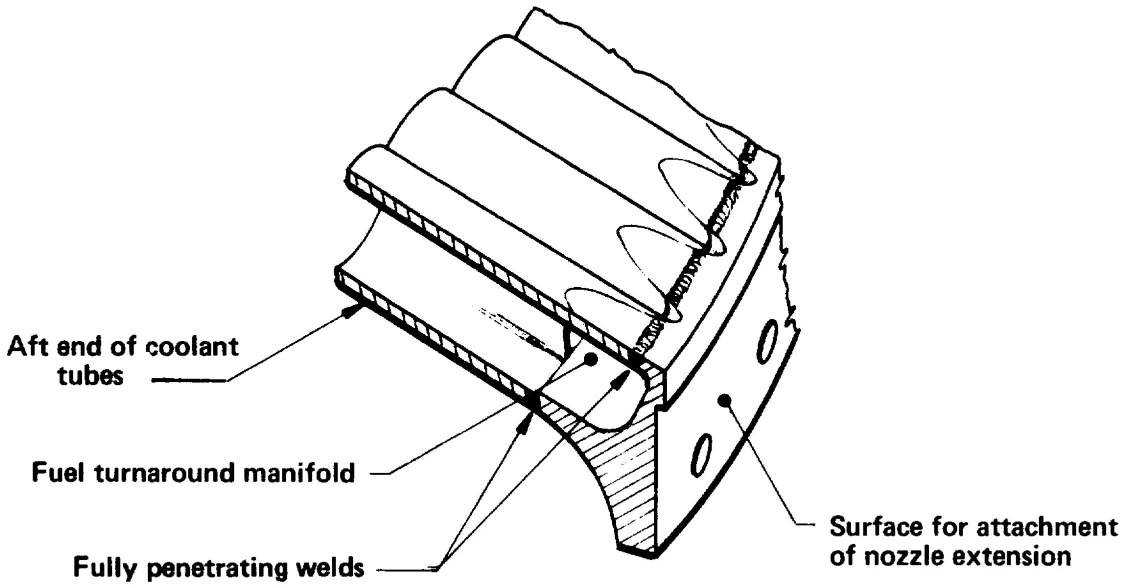
Actual flow variations should be measured in a cold-flow facility where each pass of a coolant system should be flowed with fluids that simulate the coolant. Actual inlet conditions (lines and valves) are mandatory for these tests, and back pressure should be used to preclude cavitation within the coolant passages.

3.1.2.2 STRUCTURE

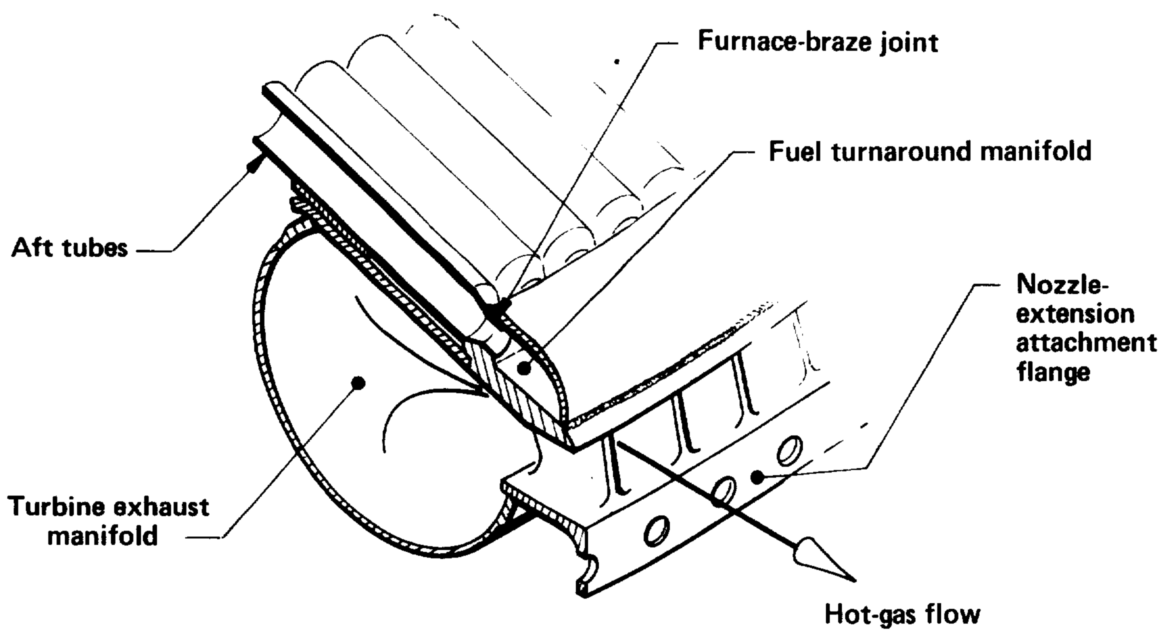
Manifolds shall not cause chamber distortion, form stress concentrations in thin members, or hinder subsequent assembly operations.

Minimize distortion from arc welding by (1) using more than one pass to accomplish a fillet or groove weld, (2) minor peening (CAUTION: If peening is desirable, the designer should be consulted to evaluate the consequences of local permanent yield.), (3) step welding, and (4) designing for minimum amounts of weld material. When gross distortion (e.g., out-of-roundness) is inevitable, mechanical pressing to return the parts to their required shape should be considered. Distortion from welding can be minimized by using electron-beam welding in lieu of arc welding wherever possible.

Avoid large bending discontinuities by providing a transition section at the joints between thin cooled sections and heavy manifolds. The transition is accomplished by a short (1/2 to 1 in. [1.27 to 2.54 cm]) taper of the manifold wall (fig. 8), or by supporting a thin section (coolant tube) over one side more than the other (fig. 4). In addition, large stresses developed within the manifold by the pressure or appendage loads should be transmitted to



(a) Welded flange/manifold



(b) Brazed flange/manifold with secondary cooling manifold

Figure 8. – Interface flange construction

the cooled chamber (and its structural support) through smooth lines of stress transfer. This transfer is accomplished by geometric design that avoids discontinuities and by use of fully penetrating weld joints.

When critical brazing operations must follow the installation of manifolds, install the manifolds without degrading the article to be brazed. Carefully weld or fit the turnaround manifold to each tube so that the gaps are maintained within prescribed limits.

3.1.3 Chamber Reinforcement

3.1.3.1 THROAT REINFORCEMENT

3.1.3.1.1 Form-Fitting Shell

A form-fitting shell shall provide sufficient st uctural restraint without allowing the reinforced section of the chamber to fail independent of the shell.

Form-fitting brazed shells are recommended for the strongest, lightest-weight reinforcement. Although specific analyses must be performed (sec. 3.1.6), a distributed contact area of approximately 70 percent or greater usually is required for the tube-to-shell contact joint. To effect this degree of contact, either stack the chamber tubes inside the contoured shell and force them against the shell while brazing, or use square wire wrapped about tubes that are already brazed. Braze the square wire into a rigid shell with a braze alloy lower melting than that used for the tube-to-tube joints. This latter method is recommended in the case of a short shell that is needed to resist buckling in the nozzle throat area only. Forward of this shell, the tube bundle alone must be able to carry the meridional loads. The square wires are brazed together after being wrapped under 100 to 300 lbf (445 to 1334 N) of decreasing tension. Brazing of adjacent strands is enhanced by knurling 0.001-in. (0.0254 mm) deep grooves across the sides of the wire; the grooves provide lines of flow for externally applied braze powder. The wire will contact those tube crowns that protrude above the level of the two adjacent tubes. Areas where the wire does not contact the tubes should have shims fitted into the gaps at the critical ends of the shell. As a result, full contact with wide brazed joints can be achieved at the ends of the shell, where the loading is the most severe.

When it is desired to extend the shell all the way to the forward flange, it is recommended that the tubes be brazed to a machined shell, an internally mounted, stainless-steel pressure bag being used to hold the tubes against the shell during brazing. The bag should be quilted for uniform pressure distribution, with walls about 0.010 in. (0.254 mm) thick. Use low pressure (about 1/3 psi [2.3 kN/m^2]) and use the blanketing gas for the pressurant. The contour of the bag should be the same as the internal contour of the chamber. During brazing, place high-silica-glass cloth between the tubes and the bag to prevent braze runoff from joining the two.

Use either X-ray or ultrasonic techniques to measure the percentage of tube-to-shell braze contact. X-rays offer the additional advantage of a positive visual evaluation of the contact area.

For maximum strength, fabricate the one-piece shell from an ageable steel, and age harden after all brazing is completed. If the shell material is different from the tube material to take advantage of age hardening, there must be a distinct payoff that is warranted. In general, because of welding and brazing problems, avoid use of different materials (sec. 3.1.7.2.3).

3.1.3.1.2 Integral Support Structure

A support structure integral with the coolant passages shall not distort the passages.

The outer wall of double-wall construction and the body of a drilled-passageway configuration provide primary structural support. Loads in these sections together with the loads at the hot-gas walls must be absorbed or transmitted without deforming the coolant passages. Use the analytical procedures described in section 3.1.6 to calculate the structural requirements, but be certain to use realistic (or conservative) thermal profiles of the walls.

3.1.3.1.3 Cylindrical Shell Support Structure

A cylindrical shell attached to the coolant structure shall not cause excessive stress concentrations at the two planes of attachment.

The cylindrical shell (fig. 2(a)) is recommended for large systems where the nozzle throat can withstand the local meridional loads, but some of the nozzle thrust loads must be transmitted around the throat. Normally the shell is rigid enough to contain lightening holes for reduced weight and visual access to the tube bundle. Of course, hoop reinforcement to carry the pressure loads must be included.

At the forward end, attach the cylindrical shell to the forward flange by welding. Attach the shell at the aft end to a heavy ring, brazed to at least 80 percent of the tubes for a length of at least 1 in. (2.54 cm). For weldable tube materials with wall thicknesses in excess of 0.015 in. (0.381 mm), tack weld the ring to the crown of every tube; this procedure pulls the tube against the ring prior to brazing. If welding is inadvisable, special tooling must be developed to press the ring physically against the tubes during brazing. Use shims to fill gaps in excess of 0.004 in. (0.102 mm).

3.1.3.1.4 Mechanically Attached Shell

A simple bolt-on or weld-on shell shall provide sufficient hoop restraint to the coolant structure to preclude gross deformation of the chamber contour.

Form the internal contour of the shell to match the theoretical external contour of the coolant structure. For bolt-on assembly, split the shell in half, provide bolting flanges, and heavily coat the inner surface of the shell with fresh epoxy to fill voids during assembly. Do not use epoxy resins where cryogenic coolants are involved unless considerable cracking and breakdown of the epoxy filler can be tolerated.

In cryogenic applications, segment the shell into approximately six pieces and clamp them tightly in place while effecting the longitudinal weld joints. Weld shrinkage automatically pulls the shell snugly about the coolant structure.

To remove the shells, cut the welded joints, remove the bolts, and, where epoxy is used, pry the shell off physically unless it is possible to decompose the epoxy by heat or by chemical means.

3.1.3.2 HOOP REINFORCEMENT

Hoop restraint shall prevent distortion of the chamber contour and the coolant passages.

When hoop support of the coolant structure is required, the best procedure is to use either the high strength properties of an integral shell or high-strength wire wrapped about the chamber; either method makes maximum use of high-tensile-strength materials. The wire overwrap should be applied under 100 to 200 lbf (445 to 890 N) tension and secured at the ends by a friction band. When cryogenic coolants are not involved, embed round wire in epoxy to keep adjacent strands from rolling or creeping over each other in the convergent and divergent sections of the nozzle. Recommended alternatives to epoxy bedding are to overwrap the wire with a light layer of glass-filament roving or equivalent, or use square wire.

3.1.3.3 NOZZLE REINFORCEMENT

The expansion nozzle shall withstand inward hoop loads during transient and sea level operation; unsupported spans shall not fail in bending between ring supports.

Use bands about the expansion nozzle to absorb inward hoop loads; "I", "Vee", or "hat" sections are recommended for the bands to increase the bending stiffness. Braze the bands to the coolant structure; use special tooling to hold the bands in place during brazing, or tack weld the bands to the coolant structure. Tack welds are not recommended where coolant wall thicknesses are less than 0.016 in. (0.406 mm). The bands should be spaced closely enough to preclude bending of the cooled walls between the bands.

If the bands are welded to the tubes, subsequently braze each weld joint to distribute the contact over a wider area. If welding is not feasible, brazing should be accomplished by holding the rings against the nozzle with strips of a metal that has a low coefficient of thermal expansion.

A turnaround manifold or an attachment flange is an excellent nozzle support ring and, where used, should be designed to help in the structural frame; either a flange or manifold is inherently stiffer than the normal support band.

3.1.4 Interface Flange

3.1.4.1 STRUCTURAL EFFECTS

Interface flanges shall not cause distortion, form stress concentrations in thin members, or hinder subsequent assembly operations.

In the design of interface flanges, as in the design of manifolds, avoid large bending discontinuities at the joints between thin, cooled sections and heavy flanges; transmit large stresses developed within flanges that contain manifolds or absorb appendage loads to the cooled chamber (and its structural support) through smooth lines of stress transfer. Recommended practices are given in the second paragraph of section 3.1.2.2

When arc welding is used to effect a juncture, minimize distortion by the methods given in the first paragraph of section 3.1.2.2.

When critical brazing operations must follow the installation of flanges, install the flange without degrading the fit of the article to be brazed. Carefully weld or fit the aft flange (integral to the turnaround manifold) to each tube so that the gaps are maintained within prescribed limits.

3.1.4.2 THERMAL EFFECTS

Heavy interface flanges shall not overheat and distort as a result of exposure to the combustion gases.

For heavy flanges, limit the length of flange exposed to the hot combustion gases to approximately 2 in. (5.1 cm). If supplemental cooling is necessary, use film cooling (sec. 3.3) impinging directly on the flange surface. For structural analysis (sec. 3.1.6), ensure that correct thermal profiles are used for the flange sections. Where heat flux is high, form the tubes to place the flange out of the hot-gas stream.

3.1.5 Materials

3.1.5.1 COMPATIBILITY

Wall material shall be compatible with the coolant and the products of combustion and shall not degrade unacceptably during use.

The thin, cooled walls of fluid-cooled chambers must not be excessively degraded in ductility, strength, or thermal conductivity through exposure to either the combustion products or the coolant. Some degree of degradation is inevitable, the amount depending upon the environment and the operational demands, but minimize the extent of change by choosing materials of excellent, known compatibility for the application and by operating them at the stress margins prescribed in section 3.1.6.

It is recommended that the design incorporate materials with well-known and proven properties; avoid use of unknown exotic materials. On occasion, a new material may appear beneficial. In such a case, commercial literature should be consulted for compatibility data, and acceptability of the material for a given application should be verified by a thorough test program.

For chambers that are subjected to corrosive environments in the field, stainless steels or nickel are recommended for cooled walls. These materials must, of course, be protected from highly oxidizing environments either by film or barrier cooling or by coatings (secs. 3.3 and 3.4), or simply by operating them at safe temperatures. Carbon steels that can be sensitized should not be used for walls whose temperatures are expected to be in the 800 to 1500°F (700 to 1089 K) range. Use nickel-base alloys (e.g., Hastelloy X) in applications where wall temperatures must exceed 1600°F (1144 K) and carburization of the base metal must be prevented. In applications where 0.001 to 0.005 in. (0.0254 to 0.127 mm) of carburization can be tolerated (sec. 3.1.6), materials susceptible to carburization may be used if temperatures do not exceed 1700°F (1200 K). Since the nickel-base alloys are expensive to handle and machine, their use is not warranted unless wall temperatures above 1600°F (1144 K) are planned, or increased strength is needed. Any contact between nickel-base alloys and sulfur-bearing materials should be avoided.

3.1.5.2 PHYSICAL PROPERTIES

Wall material physical properties shall be equal to or better than the minimum values reported in standard literature sources or values derived by laboratory testing.

Use MIL-HDBK-5 (ref. 23) or an equivalent reference source to identify material strengths and other physical properties. However, some materials experience considerable changes in properties during machining and cold working; generally, these operations tend to strengthen a material that is annealed. Though this effect may be beneficial, corrosion resistance and ductility can be decreased. When fabrication processes have altered material properties, these properties should be evaluated metallurgically to confirm grain orientation, intergranular structure, grain size, and distribution of constituents. For the steels, grain sizes in the range of ASTM 4 to 8[1] are recommended, and carbide precipitation is undesirable, particularly when carbide chains are formed.

[1]Anon: ASTM Standards. Pt. 31, Sec. E-7, Am. Soc. For Testing and Materials (Philadelphia, PA), revised annually.

Generally, ductile materials are recommended; their properties are particularly beneficial at stress concentrations. Use material with 6 percent or more elongation at the operating temperature or material having a Charpy test value of at least 15 lb-ft (20.3 N-m) at the operating temperature. This value should be verified by test, because precipitation hardening and cold working can decrease the ductility during fabrication.

When strengths higher than those indicated by reference sources are required, and the material is believed to be in a state of increased strength due to cold working, run standard tensile tests for applicable data. This practice can result in considerable increases in allowable working stresses with no weight increase or redesign.

3.1.6 Structural Analysis

3.1.6.1 GENERAL REQUIREMENTS

3.1.6.1.1 Model Adequacy

The structural model of the regenerative chamber shall include all significant load sources.

Table V presents the loads to be considered. Identify each as a function of time, and analyze the structure for the worst load combinations. Where possible, use load levels that have been measured on similar hardware as a basis for deriving new loads, rather than relying on purely theoretical estimates.

3.1.6.1.2 Failure Prediction

The structural design shall present a reasonable probability that structural failure will not occur during performance of the specified mission.

If load levels and safety factors are not specified for the system, it is recommended that the following factors be adopted:

<u>Pressure Factors</u>

Proof: 1.2 x MEOP at design service temperature.
Burst: 1.5 x MEOP at design service temperature.

Since tests at proof pressures at elevated temperatures for heated components generally are not feasible, use an equivalent proof pressure at room temperature. Equivalent pressure is derived by multiplying proof pressure by a proof-pressure factor. The proof-pressure factor is defined as the ratio of the burst pressure at proof-test temperature to burst pressure at the design service temperature.

Inertia and Thrust Load Factors

Design yield: 1.2 x limit load
Design ultimate: 1.5 x limit load

Shock and Dynamic Load Factors

Use equivalent static loads derived from dynamic analyses and subject these loads to the inertia and thrust load factors given above.

Temperature Factors

Design a component for the critical operating conditions created by the worst combination of pressure and temperature occurring during engine transient and steady-state operation. Consider in the analysis experimental thermal data obtained from test programs for similar hardware whenever such data are available. Add a temperature increment of 50°F (28 K) to the temperatures predicted by the thermal analysis to arrive at maximum temperatures or thermal gradients. Apply no other factors of safety to thermal loading.

3.1.6.1.3 Crippling and Bursting Failure

The combustion chamber shall be resistant to failure resulting from crippling or bursting of the heated walls.

In the design of regeneratively cooled chambers, the evaluation of the failure modes of coolant-passage burst and crippling of the heated wall (items 5 and 7 on table V) is critical in precluding later costly redesign. The other modes shown on table V either are not unique to regenerative chambers or do not represent areas of major redesign if the initial part has insufficient strength. For these other modes, use approximate and quick methods of analysis for the initial design of the related components. Use rigorous analyses, however, for the initial design of the coolant passages, the heated walls, and the internal structural support of the coolant-passage configuration. During the design phase, coordinate the design with manufacturing personnel to avoid a configuration that in fact cannot be manufactured or assembled.

3.1.6.1.4 Failure In Any Mode

The combustion chamber shall be resistant to failure in any mode.

Design for positive margins of safety (MS>0) for all modes of failure.

Define the allowable material strengths with careful consideration given to the effects of load, temperature, and time associated with the design environment. For single-load-path structures, use the minimum values (A values) guaranteed in reference 23 for the allowable yield and ultimate properties; for multiple-load-path structures, use the 90 percent probability values (B values).

Categorize the stresses to ensure that proper evaluation of their importance can be made. It is recommended that the following three categories be used to aid in describing stresses:

Primary stress: Stress developed in response to an imposed load to satisfy the laws of equilibrium between external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. If a primary stress exceeds the yield strength of the material through the entire thickness, the occurrence of failure depends entirely on the strain-hardening properties of the material.

Secondary stress: Stress developed by the self-constraint of a structure to satisfy an imposed strain rather than to be in equilibrium with an external load. The basic characteristic of a secondary stress is that it is self-limiting, since minor distortions can satisfy the discontinuity conditions or thermal expansions that cause the stress.

Peak stress: Maximum level of stress in the region under consideration. The basic characteristic of a peak stress is that it causes no significant distortion; it is objectionable mostly as a possible source of fatigue failure.

Primary stresses in ductile materials. – For margins of safety based upon material yield in non-welded areas, use an allowable stress that is the lower of the two values: (1) 0.2% offset tensile yield strength at the operating temperature, or (2) 0.2% total plastic creep strength at the operating temperature and required life. For welded areas, use 85 percent of the above values unless test data justify otherwise. The calculated effective stress is the stress derived from the critical yield loading conditions.

For margins of safety based upon ultimate stresses in non-welded areas, use an allowable stress that is the lower of the two values: (1) the ultimate tensile strength at the operating temperature, or (2) creep rupture strength at the operating temperature and required operating life. For welded areas, use 85 percent of the above values unless test data justify otherwise. The calculated effective stress is that derived from the critical ultimate loading conditions.

Calculate the effective stresses on the basis of the distortion energy theory (ref. 35):

$$\sigma_{eff} = \frac{\sqrt{2}}{2}\left(\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\tau_{xy}^2 + 6\tau_{yz}^2 + 6\tau_{zx}^2}\right)$$

where

σ_{eff} = effective stress
τ = shear stress
σ = direct stress
x,y,z = the three mutually perpendicular planes

Primary plus secondary and peak stresses in brittle material. – For the margins of safety for the yield and ultimate conditions, use the same allowable stresses as defined above. However, determine the effective stresses by the Mohr theory (ref. 36) for a biaxial stress field:

$$\sigma_{eff} = \frac{1-r}{2} (\sigma_x + \sigma_y) + \frac{1+r}{2} \left(\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2} \right)$$

where

$$r = \frac{\text{allowable tensile strength}}{\text{allowable compressive strength}}$$

Primary plus secondary and peak stresses in ductile material. – Large cyclic strains at high temperatures and few strain cycles can result in fatigue failures. It is recommended that the margin of safety for fatigue be defined as

$$MS_{fatigue} = \frac{\epsilon_t}{\epsilon_{eff}}$$

where

ϵ_t = allowable cyclic strain for an average life 4 times the required number of engine firings or induced strain cycles

ϵ_{eff} = calculated effective cyclic strain

For an approximate evaluation of the allowable cyclic strain, it is recommended that the following formula be used (refs. 37 through 41):

$$\epsilon_t = \frac{2F_{ty}}{E} + \frac{e\,N^{-1/2}}{2}$$

where

F_{ty} = 0.2% offset yield strength at the maximum temperature of the cycle

E = Young's modulus at the maximum temperature of the cycle

e = fracture elongation

N = average cyclic life in cycles, taken as 4 times the number of engine firings

For more accurate and detailed predictions, the methods and test data of references 42 through 46 are recommended; reference 46 is especially recommended.

For a fully constrained uniaxial thermal expansion, the effective cyclic strain equals $\alpha \Delta T$, where α is the coefficient of thermal expansion, and for a fully constrained biaxial thermal expansion, it is $2 \alpha \Delta T$. In general, it is recommended that the effective cyclic strain for a biaxial state of strain be calculated from the following equation, as described in reference 43:

$$\epsilon_{eff} = \frac{2}{\sqrt{3}} \sqrt{\epsilon_x^2 + \epsilon_x \epsilon_y + \epsilon_y^2}$$

where ϵ_x and ϵ_y are range values for mutually perpendicular principal strains.

3.1.6.2 DESIGN ANALYSIS

3.1.6.2.1 Buckling Strength

The composite chamber structure shall have adequate strength to preclude elastic or plastic buckling under ultimate load conditions.

The analyses shall demonstrate that positive margins of safety exist under the ultimate load condition. Use the computer program described in references 47 and 48 to calculate the general capacity of the combustion chamber for resisting lateral and axial buckling loads. The cards and listing of this computer program are available from COSMIC, University of Georgia, Athens, Georgia 30601.

It is recommended that a computer program similar to that described in reference 49 be used to evaluate composite shell bending stresses; such a program accommodates anisotropic shell properties. If the theoretical elastic lateral buckling load gives associated stresses that are greater than the material proportional limit, estimate the plastic buckling capacity, so that the potential buckling prior to attaining unacceptable plastic bending conditions may be evaluated. Methods for estimating the plastic buckling capacity are given in reference 36.

3.1.6.2.2 Composite Load Resistance

A chamber that uses a shell integral with the coolant passages to resist both hoop and meridional loads shall not fail as a result of composite loading effects.

Compute the stresses by use of appropriate shell theory (refs. 50, 51, and 52). Computer programs as described in references 49, 53, 54, and 55 are recommended. It should be noted that the presence of a compressive meridional stress will reduce the magnitude of hoop tensile stress at which general yielding starts.

3.1.6.2.3 Tube Compressive Strength

Coolant tubes shall not buckle under ultimate compressive loading.

The longitudinal compressive strains due to mechanical and thermal loading must not exceed the buckling capacity of the wall. It is recommended that buckling or crippling of coolant tubes be analyzed by the use of the techniques and findings set forth in references 42, 45, 56, and 57.

3.1.6.2.4 Tube Fatigue Strength

The heated walls shall resist fatigue failure during the required life of the engine.

Design the heated walls so the average theoretical low-cycle fatigue life of the wall exceeds the required number of operational cycles by a factor of four. The method described in reference 44 using the thermal plus the mechanical stresses is recommended for predicting low-cycle fatigue life. To calculate stress levels due to the thermal gradient, the methods set forth in references 42 and 43 are recommended. However, other methods as outlined in references 38 through 43 and in reference 45 are also acceptable.

3.1.7 Brazing

3.1.7.1 BRAZE ALLOYS

Braze alloys shall be (1) compatible with materials and configurations to be joined; (2) ductile, durable, and capable of providing a uniform joint with no internal cracks or voids; (3) strong enough to satisfy structural requirements; and (4) as economical as possible.

It is recommended that laboratory brazing studies be performed to supplement data found in the literature, particularly when new material/alloy combinations are planned. Simulated joints heated over a range of furnace temperatures readily display the brazed joint characteristics. The joints should be cross-sectioned, then microphotographically examined to evaluate minimum and maximum temperatures and times, peculiarities due to the configuration, grain structure and voids or cracks internal to the braze, and anomalous erosion or corrosion of the base metal.

It is recommended that ductile alloys be used to preclude fractures in brittle joints. Generally, regenerative thrust chambers experience considerable material deflection with some local yielding.

Eutectic compositions and precious-metal (gold, silver, palladium) alloys are recommended for close-tolerance joints because these materials have high fluidity and ductility. Some of the multiphase alloys are useful if they can be heated rapidly above the melting point of the high-melting phase. However, if the process is not rapid (i.e., if it takes more than 10 min.), the low-melting phase separates, flows into the joint, and can form a brittle or porous braze constituency. Some large physical gaps, however, require multiphase alloys; their sluggish flow qualities are useful in filling large gaps [0.003 to 0.010 in.(0.0762 to 0.254 mm)].

Although the precious-metal alloys are expensive, they are generally recommended because of their fluidity, ductility, and utility. Joints that do not require tight tolerances and are not highly stressed (e.g., heavy tube-to-tube fillets [0.040 in. (1.02 mm) or greater contact], loose tube-to-flange joints, and external band-to-tube joints) should be brazed with less costly alloys.

It is recommended that when light, exposed joints (e.g., tube-to-tube) and heavy, shielded joints (e.g., tube-to-flange) are brazed simultaneously, two different but compatible alloys be considered for use. The alloy at the flange should melt 25° to 50°F (14 to 28 K) lower than the alloy at the tube joints. This layup results in uniform braze flow at both joints, such as might be obtained by brazing the different zones during separate cycles.

3.1.7.2 PREBRAZE JOINT PREPARATION

3.1.7.2.1 Cleanliness

The chamber shall be capable of being thoroughly cleaned at the areas to be brazed; the cleaning materials and procedures shall be compatible with the material to preclude the formation of residues that inhibit the braze flow; and cleanliness shall be maintained through the braze cycles.

Thoroughly clean the parts prior to assembly by use of appropriate commercial cleaners and the processes and controls prescribed for their use. Nonchlorinated solvents are recommended; do not clean Inconel X with solvents that contain boron. Where titanium- and aluminum-bearing iron alloys are to be brazed, plate the stock with nickel if the quantity of these elements is sufficient to form excessive surface oxides. For Hastelloy X, preclude detrimental oxide formation by keeping the aluminum content below 0.15% for normal brazing and below 0.02% for parts that are heated for periods in excess of 40 minutes to reach brazing temperatures.

It is recommended that bright annealing be considered as a process to precede a braze cycle to remove surface oxides formed during handling and storage. Some physical movement is experienced during such annealing, similar to what would occur if the parts were being brazed. Hence, final fitting and adjustments can be done after annealing to eliminate large gaps that might not fill with braze.

Once the individual parts that comprise a chamber are free of grease, dust, scale, and dirt to the acceptable particulate level, the basic cleanliness should be maintained. Use special shrouding to cover the exposed parts while they are idle or in transit, and take special precautions (e.g., clean-room environments) to avoid contamination while the parts are being assembled. Though tapping blocks are commonly used to hammer surfaces and parts to assemble and achieve close fits, do not use blocks that could leave damaging residues on the hammered surfaces (e.g., do not use lead hammers for working Inconel X). Nylon, Teflon, or hard rubber are the recommended materials for the tapping blocks.

3.1.7.2.2 Joint Gap Size

Gap size at a joint shall not exceed the largest size that is known to be acceptable for successful brazing.

It is recommended that no brazed joints be planned for gaps that exceed 0.004 in. (0.102 mm). For gaps below this size, surface tension can draw and contain the melted braze; for larger gaps, the fluid will neither be drawn nor retained even if it is preplaced in the gap. However, larger gaps can be successfully brazed if the gap is in a basin and the part is oriented so that gravity retains the molten alloy within the basin. Such a configuration exists within tubular chambers at the forward end. Here, the alloy collects at the point where the tubes enter the flange if the brazing is accomplished with the forward end down. Braze collects in a similar manner at the aft end when the chamber is brazed with the aft end down.

When larger gaps inadvertently occur or must exist by design, often they can be filled with 100-mesh chips, usually nickel, which are sintered in place. If an annealing cycle is scheduled prior to brazing, the sintering and annealing can be accomplished simultaneously. The resultant porous structure will draw braze alloy into it effectively. This procedure is recommended where internal voids or loose fits exist around a coolant tube that is inserted into a flange, or where braze fillets are desirable at a tube-to-tube joint adjacent to a flange.

Gaps no greater than 0.004 in. (0.102 mm) wide are guaranteed by fitting and inspecting to 0.002 in. (0.051 mm). Further, after bright annealing as recommended in section 3.1.7.2.1, critical joints can be reinspected, and excessive gaps can be eliminated.

When tubes are stacked for a tubular chamber, inherent gaps are minimized if the tubes are inserted into a precision-drilled forward flange; additional control is achieved if the aft flange is also a drilled configuration. It is recommended that 0.002-in. (0.051 mm) shims be placed between the tubes near the throat plane. Minor shimming adjustments will take up slack or allow for tight fits. This procedure distributes the slack about the tube bundle while it is being rigidly clamped.

3.1.7.2.3 Motion Restraint

During brazing of the chamber, there shall be no relative physical motion that causes excessive increase in gaps at the brazed joints.

It is recommended that materials with similar coefficients of thermal expansion be used for the elements of brazed chambers. Also, positive tooling to press joints together lightly (e.g., pressure bag inside tube bundle to be brazed to shell, or clamping band around a tube bundle) should be planned. When circumferential bands are tack welded to the tube crowns to rigidify the bundle for brazing and to serve as eventual hoop-load-carrying members, they should be welded on both sides of the band to prevent rotation about one weld tack. If a bright-anneal cycle is not used prior to brazing (such a cycle would form and display gaps that would normally occur during brazing), it is recommended that a preliminary exploratory furnace cycle be conducted without the braze alloy to evaluate relative motion of the chamber components. Procedures can then be implemented to eliminate the adverse motion.

3.1.7.3 BRAZE PROCEDURE

3.1.7.3.1 Alloy Placement

Braze alloy shall be placed at specific locations and in a manner that guarantees the successful achievement of braze coverage at the required joints.

The best practice is to apply the alloy immediately at the point where a brazed joint is desired. For tube-to-tube joints, the braze alloy should be applied in powder form mixed with an acrylic resin binder to hold the powder in place. Any of several commercial binders are available, but one that is recommended is Nicrobraz Cement. The binder must leave no residue at brazing temperatures.

For tube-to-shell joints, alloy in foil form is recommended. It is placed within the shell prior to stacking the tubes in place.

For brazed wire shells, foil is placed on the crowns of the tubes prior to wrapping the square wire. For band-to-band joints, either foil or powder is recommended. If the foil is used, it should be placed under the band; the powder should be applied against the edge of the band on the upper side with respect to the orientation within the brazing furnace. Generally, foil is recommended for blind joints whenever it can be preplaced.

For tube-to-flange joints, powder should be applied around the tube at the joint. Generally, an excess of powder is beneficial. Refer to section 3.1.7.1 to review the desirability of using a slightly-lower-melting alloy at these tube-to-flange joints than at the tube-to-tube joints, when the two types of joints are brazed simultaneously.

Wherever tack welds on coolant tubes exist (e.g., band-to-tube fitting, or tube-to-tube rigidity for brazed-wire shell reinforcement), alloy in powder form should be applied over and around the weld.

3.1.7.3.2 Braze Retort Configuration

The retort in the brazing furnace shall be configured to radiate heat uniformly to hardware in an atmosphere that will not inhibit the braze flow or attack the base metal.

The furnace heats a retort that envelops the hardware and radiates heat to it. The heating coils or source should be configured so that the retort is heated uniformly to minimize thermal gradients (top-to-bottom) in the hardware.

The recommended atmospheres are hydrogen, argon, vacuum, and dissociated ammonia. Generally, very dry hydrogen (dewpoint less than -65°F [219 K]) or pure argon should be used. For compatible materials (300- and 400-series stainless steel, some nickel-base alloys, and oxygen-free hard copper), hydrogen is recommended; its use will retain bright surfaces. For materials not compatible with hydrogen, argon is recommended. A vacuum is suitable for alloys that have low vapor pressures. Dissociated ammonia should not be used with metals that are susceptible to nitriding.

3.1.7.3.3 Retort/Chamber Mounting

The chamber shall be mounted within the retort in an orientation that enhances braze coverage at critical joints.

Use the force of gravity to help draw or collect braze material at critical joints. Orient the chamber so that long shear joints will be vertical during brazing and the source of the braze alloy will be at the top of the joint. If large fillets or collections of braze material are desirable at certain joints, orient the chamber in the retort so that braze will tend to flow naturally into or toward these locations.

3.1.7.3.4 Braze Joint Temperature

> *Instrumentation shall monitor accurately the temperatures at the joints during brazing.*

Thermocouples mounted in close proximity (within 4 in. [10.2 cm]) to the general area that is to be brazed are recommended. The couples should be accurate within 10°F (5.6 K), and they should be mounted at a point similar in mass to the structure to be brazed. At least two couples should be located so that they may be compared with each other.

3.1.7.3.5 Braze Cycle

> *The braze cycle shall produce conditions at the brazed joints necessary for successful brazing.*

The recommended practice is to subject the hardware for minimum durations (2 to 3 min.) to the temperature range at which the braze is fluid; this practice minimizes excessive runoff. When a eutectic-type alloy with multiphase melting is used, the practice is to achieve the temperature of the higher-melting phase rapidly, then cool down rapidly to minimize the runoff of the lower-melting phase.

When large masses are brazed (e.g., heavy forward flanges), it is good practice to conduct a soak period at a temperature about 50°F (28 K) below the solidus point of the alloy (sec. 3.1.7.1). The duration of this soak period should be 20 to 30 min.

The environment (sec. 3.1.7.3.2) should be maintained as required without disturbing the part to be brazed. The dewpoint must be maintained continuously by injecting dry blanketing gas into the retort while the wetter gas is withdrawn at a low point. Though the inlet gas is dry, it is also cold, and it should not be directed at the hardware.

Conduct the cooling period by removing the furnace and dropping a water tower about the retort. Heat, therefore, is radiated and convected to the cooling tower. At 500 to 700°F (533 to 644 K), cooling is hastened by purging the atmosphere within the retort with large volumes of argon. Above these temperatures, the moisture in the argon causes oxidation on the surfaces of the hardware. Minor oxidation is not damaging unless subsequent braze cycles are planned. Therefore, if subsequent brazing is contemplated, it is recommended that the parts be cooled to 500°F (533 K) before purging with argon. Otherwise, cool to 700°F (644 K) before purging, so that major oxidation is avoided.

3.1.7.3.6 Cycle Repeatability

The design shall allow for repeated braze cycles.

It is recommended that all brazed joints be designed so that, if necessary to attain an acceptable braze, a cycle could be repeated with additional alloy. Provide for accessibility that will permit shimming gaps that may exist at the ends of brazed-wire jackets or under support bands in the expansion nozzle. Plan for as many as five recycles to achieve a completely satisfactory brazed unit, even though the basic plan may call for only one or two cycles. Recycle as many times as necessary, but do not accumulate a time-temperature exposure that causes excessive grain growth, degrading grain-boundary precipitation, or corrosive attack of the base metal by the braze alloy.

Two cycles at different temperatures should not be conducted before the acceptability of the first braze cycle is confirmed. This practice precludes a situation where the higher temperature cycle must be repeated and thereby jeopardize the condition of a lower-melting alloy at other locations. Similarly, cycles in which the orientation is important must be protected during subsequent repair cycles in other areas. Physical shielding with up to 12 layers of high-silica-glass cloth is recommended to prevent remelting in critical areas during repair cycles.

Where small areas are void of braze, hand repair with lower-melting alloys is recommended.

3.1.8 Chamber Assembly

3.1.8.1 PASSAGE DEGRADATION

The coolant passages shall not be obstructed by weld dropthrough, nor shall the thin walls within cooled chambers be degraded by tack welds or stress concentrations.

Minimize the degree of weld dropthrough at tack welds and weld joints on thin-wall coolant passages by evaluating samples and establishing controllable procedures. When the dropthrough is significant and could cause up to a 5-percent restriction, it is recommended that uniform tacks be effected for all of the tubes. Do not allow restrictions above 5 percent. Where the welds exist, evaluate the metallurgy of the base metal microphotographically for acceptability, and establish procedures to avoid weak joints. As noted previously, braze around the tack welds on the walls of the coolant passages to strengthen the local area and to provide a greater distribution of the local stresses.

3.1.8.2 CHAMBER DEGRADATION

Combustion chamber fabrication procedures and test fixtures shall not damage critical surfaces of the hardware.

Review the following test fixtures and procedures to identify configurations or situations that could damage or degrade the chamber: throat plugs used for pressure checking; mandrel or tube support methods, which may overstress tube crowns during braze cycles; contamination of tubes, which may occur during heat treating or which may be caused by compounds used during cleaning and forming; and protective covers for the ends of the chamber.

3.1.8.3 CHAMBER DENTS

The combustion chamber shall be capable of incurring minor dents that do not jeopardize its structural integrity or serviceability.

It is standard practice to accept chambers that contain some dents if no failure will result from the dent. Each dent requires individual attention. Mild dents in the divergent section are routinely accepted. Dents between the throat and injector are not. These dents must be evaluated to determine if they will (1) reduce coolant flow, (2) perturb the gas-side boundary layer, (3) interfere with liquid-side cooling capabilities, or (4) fail under fatigue loading. For the evaluation of low-cycle fatigue, it is recommended that a comprehensive test program, similar to those described in references 42 and 45, be accomplished to determine the acceptability of dents.

Monitor all dents during the development program to aid in setting realistic damage limits. Establish the limits in terms of numbers, size, and shape of the dents.

3.1.9 Laboratory Proof Testing

3.1.9.1 TEST OBJECTIVES

Proof and leak testing of the pressure-containing structure shall verify structural integrity without degrading other parts of the structure in any way.

Proof testing according to the definitions of section 3.1.6.1.2 is required for pressure vessels. Proof test all pressure-bearing structures and sub-structures relative to the maximum pressure for each; i.e., the chamber should be tested relative to the maximum chamber pressure, and the coolant passage should be tested relative to the maximum passage pressure. While each part is being tested, it is important that other lower-pressure elements are not overloaded. Support these areas on the hot-gas side while the passages are tested to proof pressure conditions; test the lower-pressure areas to proof conditions during another test.

3.1.9.2 LEAK DETECTION

The coolant system shall be capable of being checked for leaks so that leakage and source may be identified.

Ensure that all areas of the pressure vessel are amenable to leak testing by visual observation or pressure-decay methods. Provide visual accessibility in some manner so that the location of the leak can be discerned. If such accessibility is not obvious, consider a leak test where the pressurant is applied in the opposite direction to the normal pressure.

3.1.9.3 FLOW CALIBRATION

Flow calibrations shall provide flow-resistance data sufficiently accurate to be used effectively in subsequent engine balance calculations.

The recommended practice is to employ a test facility that uses water at rated flow and at the rated flow ± 10 percent ; average these data. Use the engine lines between the valves and the chamber, and preferably include the valves. Maintain a back pressure of at least 100 psi (689.5 kN/m^2) to prevent flow cavitation within the flow passages.

For hydrogen-cooled systems, it is recommended that both air and water be used for the calibration fluid. Correlate the calibration data with hot-fire data, and continue the calibration procedures until either a lack of correlation is found or a positive, useful correlation develops. If no correlation exists, discontinue the flow calibrations.

3.1.10 Operational Problems

3.1.10.1 TRANSIENT OPERATION

The chamber shall not incur thermal damage from transient operation during start or shutdown.

Configure the coolant system so the coolant flow will be distributed uniformly about the chamber before injection into the combustion zone commences. To achieve this condition, consistent with recommended practices for designing manifolds (sec. 3.1.2), use common manifolds (annuli) wherever possible, particularly at the inlet, at the turnaround point, and within the outlet manifold.

For areas that rely heavily (or completely) on film cooling for protection during steady state, provide thicknesses that will diffuse local heating by conduction during start-transient conditions. This precaution is particularly recommended when an oxidizer-rich start is used and initial high heat loads must be dissipated into heavy walls rather than allowed to raise the temperature of thin ones above the failure point.

With cryogenic coolants, anticipate that lengthy (as much as several hours) prefire chilldown may be required for engine system purposes.

3.1.10.2 POSTFIRE HEATSOAK

Chamber components that are susceptible to thermal damage shall not be overheated and damaged by postfire heatsoak,

This problem usually can be countered by standard system procedures such as water flushes and purging, but be cognizant of the locations of heat-sensitive materials and evaluate the potential for damage. Non-metallic seal surfaces and epoxy closures can be degraded by heat; displace these elements sufficiently far from exposure to hot areas or protect them with postfire purges or water flushes. Seals that are overheated during heatsoak periods can be replaced, of course, but this is expensive. Rather, separate heat-sensitive seals from hot gases by at least 0.1 in. (2.54 mm).

3.1.10.3 WATER-VAPOR TRAP

A combustion chamber cooled by cryogenic fluids shall not contain structural voids that trap water vapor.

It is recommended that the design preclude exposed voids (e.g., shell-to-tube gaps) or that exposed voids possess ample drainage when the chamber is mounted in conventional firing attitudes. Provide ample drainage by maintaining the drain path at the same dimension as the void, without flow restriction.

3.1.10.4 DRAIN PORTS

The combustion chamber shall contain accessible drain ports for removing residual coolant from the coolant system.

Consider all firing and transporting positions to identify the low points in the manifolding. Locate the ports at these low points and ensure accessibility while the chamber is on the test stand or in holding fixtures; ensure that the ports do not interfere with mating parts (e.g., covers, lines, and other adjacent hardware) or hinder the attachment of the chamber to carrying rigs.

3.1.10.5 INSTRUMENTATION

Initial designs shall provide for sufficient instrumentation to describe gross characteristics of the coolant system; eventual production designs shall provide for temperature and pressure probes adequate to produce satisfactory operational data.

For evaluation of distributed effects during development tests, it is suggested that coolant inlet, turnaround, and exit conditions be measured at a minimum of three different circumferential orientations. Measurements of hot-gas wall temperatures at a minimum of three axial locations in the combustion zone and two aft of the throat are advised, the recommended method being the braze-patch technique (sec. 3.1.1.5.1). Use this aggregate of data to evaluate streaking, discontinuities, and the accuracy of the thermal model.

For production, limit the instrumentation to single measurements at the inlet and exit points only. Select the locations to be representative of a mean value, and ensure that they do not interfere with mating parts or hinder the attachment of the chamber to carrying rigs.

3.1.10.6 HANDLING AND TRANSPORTING DAMAGE

The coolant system shall be capable of withstanding normal impact and handling damage; if required, repair of such damage shall be feasible.

As described in section 3.1.8.3, most normal handling damage will be acceptable without repair. However, some need for repair should be anticipated, and procedures should be evaluated and established beforehand. Generally, damage to single tubes of tubular chambers may be repaired by one of two methods. One is "windowing" and patching, a process wherein a piece of the wall that contains the damage is removed, and a form-fitting patch is welded in place; an X-ray evaluation is advised. The other is "zipper welding," wherein the tube is sliced open and spread apart, the damage is repaired, and the tube is reformed to its original shape with the slit welded shut. This method is also recommended for non-tubular chambers. It is recommended that for large areas of damage in tubular chambers, sections of several tubes be replaced. Remove unacceptable dents by the most appropriate of several methods: (1) hammering through an access provided by splitting the wall of the passage on the back side, (2) "windowing," (3) internal swaging through an access path peculiar to the chamber, or (4) applying heat to the dent while the coolant passage is pressurized to low pressure.

3.2 Transpiration Cooling

3.2.1 Mechanical Design

3.2.1.1 CHAMBER CONTOUR

The chamber contour shall minimize (1) the amount of surface area that must be cooled and (2) the magnitude of local pressure gradients.

A tradeoff study should be made of performance, amount of coolant, and the contour; the extent of tradeoff depends to a large degree on the quality of the injector and the L* required to produce good performance. The following recommendations should be used as guidelines in selecting the contour: (1) use conical shapes where possible; (2) avoid high contraction ratios; (3) avoid large contraction angles; and (4) minimize the distance between the injector and the throat.

3.2.1.2 WALL MATERIAL

Porous wall materials shall have a proven history of reproducibility.

Only two porous walls can be recommended at this time: the discrete-pore walls formed by stacking thin-grooved plates, and the random-pore walls formed by compartmented sintered wire screens.

3.2.1.3 FLOW QUANTITY

The (initial) coolant flow shall provide sufficient overcooling to allow for the uncertainties in the thermal and hydraulic prediction models,

Ideally, the coolant flow distribution should be based on experimental heat-transfer data obtained from the actual injector that will be used. If these data are not available, the following procedures are recommended: (1) for discrete-pore systems, use the analytical methods outlined in reference 58 to predict flow rates; (2) for random-pore systems, use the simple method of Rannie (ref. 59); (3) calculate the heat-transfer coefficients by the method outlined in table X; (4) do not anticipate laminar boundary layers; and (5) use at least twice the calculated coolant flow rates in initial testing, if possible, and plan to back off gradually.

3.2.1.4 PRESSURE DROP

The allowable pressure drop shall provide for an extensive flowmetering network.

A significant amount of pressure drop must be available for flowmetering. Furthermore, the available drop must also be adequate to develop a "hardened system" that will not be prone to flow chugging. It is recommended that the driving pressures be at least 15% greater than the maximum anticipated local pressures.

3.2.1.5 HEAT LOAD VARIATION

The coolant flow shall accommodate both axial and tangential heat load variations.

The need for axial flow control to produce optimum (minimum) coolant requirements is generally recognized. It may well be, however, that tailoring the flow to accommodate tangential variations due to streaking injectors is the limiting problem. Without tangential control, one must set the flow rate to cool the hottest zones around the chamber, and since these may represent only a small percentage of the total surface, the major portion of the chamber is significantly overcooled. It is recommended, therefore, that (1) streaking be minimized and (2) provisions for tangential as well as axial metering be provided, especially in the combustion zone.

3.2.1.6 FLOW-CONTROL SIMPLICITY

The coolant flow control shall require a minimum of hardware manipulation.

Since the need for flow adjustments has been emphasized, it is necessary that the design incorporate methods that will facilitate these adjustments; the types of methods depend, of course, on the basic chamber design. The following are recommended considerations: (1) flowmetering external to the chamber permits varying the flow to individual axial sections; (2) removable housings can provide access to internal orifices that should be resizable; and (3) sets of orifices that can be short-circuited by a machining process can provide a simple means to reduce flow.

3.2.1.7 FLOW-CONTROL THERMAL PROTECTION

Flow metering shall not be affected by the heat load to the wall.

A heat-conduction analysis is required to ensure that the flowmetering devices are not overheated. Recommended methods available to isolate them include use of a material with lower thermal conductivity, longer conduction distances, minimum conduction areas, maximum wall-to-coolant contact area, and higher coolant flow rates.

3.2.1.8 FLOW-CONTROL CHARACTERISTICS

The hydraulic characteristics of individual circuits within the flowmetering network shall be known accurately.

Schedules should be established so that (1) the hydraulic characteristics of various components (e.g., the wall material and the orifices) can be measured, (2) the characteristics of individual circuits can be measured, and (3) the total component can be tested. A comparison of measured data with predicted behavior is the only check that is available to ensure that the components will work as expected.

3.2.1.9 FLOW-CIRCUIT STRUCTURE

The porous wall and components within the hydraulic circuit shall not buckle as a result of pressure loading.

The porous wall normally will not be used for pressure containment; this is supplied by some type of reinforcing housing. However, pressure differentials across orifices and across the porous wall may be very significant, especially during startups and shutdown. Thus, the entire hydraulic circuit should be evaluated to ensure that localized distortion cannot occur.

3.2.1.10 HOT-SPOT INSTABILITY

Local wall failures shall not result from hot-spot instability.

Hot-spot instability occurs when the heat-exchange portion of the flow network has enough hydraulic resistance to affect the flow. Thus, local overheating generates an increase in flow resistance, diverting coolant flow from the place that actually needs more flow. The following steps are recommended: (1) eliminate localized hot zones due to the injector; (2) avoid nonuniform porosity that may initiate the hot spot; (3) compartmentalize the surface to isolate damage and to help restrict flow to preferred directions; and (4) make the hydraulic resistance of the heated zone a negligible portion of the overall resistance.

3.2.1.11 NOZZLE-EXTENSION LOSSES

The location of the nozzle-extension attachment shall minimize coolant losses.

Thermal conditions below the throat require continuation of transpiration cooling into the divergent section. It is recommended that a nozzle extension be attached as close as possible to the throat; this location will minimize cooling losses, reduce fabrication problems, and avoid possible very low pressure zones. Extension attachment may be facilitated by using the lower transpiration sections to film cool upper sections of the extension.

3.2.2 Fabrication

3.2.2.1 PREVENTION OF PLUGGING

The porous wall shall not be subject to plugging.

Filtering during operation is fairly obvious – but anything flowed through the wall at any time must be filtered, no matter whether the flow is through the normal entrances or back through the chamber side. The filter size should be adjusted to catch particles smaller than the smallest coolant passage in the porous media. If this size is unknown, a series of experiments should be carried out to determine the filtering requirement.

Porous walls are especially vulnerable to braze plugging. All brazing specifications should note the capillary nature of porous walls and special precautions should be taken to avoid contamination. During any brazing it is recommended that (1) minimum amounts of braze material be used, (2) drain paths and collection points be identified, (3) dewetting agents be used judiciously, (4) chamber movement be avoided, and (5) braze-furnace gases be filtered.

All machining procedures should be reviewed to ensure that contamination of the porous wall cannot occur. Machining porous parts is in an innovative stage and no standardized methods are established. It is recommended that the following precautions be taken during machining: (1) flow filtered oil through the wall during electrical discharge machining – this action minimizes but does not eliminate carbon contamination; (2) flow filtered nitrogen through the wall during any dry machining process; (3) consider wax impregnation to protect pores during machining; and (4) avoid overheating the wall anytime it contains a decomposable material that leaves a residue.

3.2.2.2 WALL BENDING LIMITS

Physical bending of the porous wall shall not result in serious distortion of the porous matrix.

The random-pore materials normally must be bent to form the chamber contour. The radius of curvature cannot be so small as to alter significantly the hydraulic characteristics of the porous wall or produce residual stresses. Since little is really known about these fabrication limits, it is recommended that the limits be determined experimentally.

3.2.2.3 LOCALIZED OVERHEATING

The design shall contain no uncooled welds or aligned bands that can produce localized overheating.

Lands and welds should be located in the chamber so that cooling is provided by carryover from passages above these uncooled zones.

3.2.2.4 SURFACE ROUGHNESS

The chamber surface shall be smooth enough to avoid creating flow disturbances.

The rough-surface effect is related basically to boundary-layer tripping. While the minimum size for a flow-disturbing protrusion into the stream is not known, significant overheating has been observed with protrusions approximately 0.005 in. (0.127 mm) in height above the chamber surface; therefore, it is recommended that the surface finish be at least smooth enough to preclude protrusions of this size.

3.2.3 Operation

3.2.3.1 START SEQUENCE

The startup sequence shall establish proper coolant flow before ignition occurs.

Startups of transpiration-cooled chambers have proved to be of particular concern. It is recommended that the following be given special consideration to ensure that a safe startup will occur: (1) ignition should not occur until coolant flow is established in the longest flow path; (2) precooling may be necessary to avoid choking with non-cryogenic coolants; (4) all the circuits must be full, with no gas pockets, or backflow of combustion gases may occur; (5) overcooling in the steady state may be necessary to overcome a transient problem; and (6) manifold sizes should minimize transient times.

To minimize potential chamber damage, temperatures at the gas-side surface should be monitored during the initial flow-adjustment testing. The most successful programs to date have had small thermocouples (0.010 to 0.020 in. [0.254 to 0.508 mm]) imbedded in the porous materials to monitor surface temperatures; these fast-response measurements actually have been used to terminate the firing if temperatures become excessive. This procedure is recommended when practical.

3.2.3.2 COMPONENT GROWTH

Component growth during firing shall not produce detrimental surface discontinuities.

The chamber may often be built up from a series of segments that can distort, grow, or shift during the firing, thereby producing boundary-layer trips . An analysis of this growth potential should be made. If a strong tendency exists, it is recommended that additional coolant be introduced above the potential trip location.

3.2.3.3 WALL REPAIR

For a test chamber, the porous wall shall be repairable.

Every chamber run to date has eventually suffered some damage; often the damage was a local zone of erosion. The possibility of local damage should be anticipated and repair means established. Recommendations are as follows: (1) build the chamber in segments that can be replaced; (2) build in sufficient depth of porous material so that minor grinding can be carried out; and (3) leave the damage and readjust the local cooling (sec. 3.2.1.3).

3.2.3.4 INJECTOR CHARACTERISTICS

The injector characteristics shall not degrade the operation of a transpiration-cooled chamber.

The combustion pattern produced by the injector is of fundamental importance to the operation of a transpiration-cooled chamber. This is a recognized fact that is often ignored because of the difficulties in characterizing the pattern. It is recommended that the chamber designer work with the injector designer to produce an injector that provides minimum chemical and thermal streaking and also produces a peripheral atmosphere that is compatible with the coolant.

3.2.3.5 THROTTLED OPERATION

During throttled operation, heat penetration into the wall shall not jeopardize flow control, and coolant driving pressure shall be adequate for all needs.

Throttling appears to be a natural operational mode for transpiration-cooled thrust chambers because performance is not seriously degraded. It is recommended that the flowmetering devices be re-evaluated to ensure that they are not affected by the added heat penetration, and to establish that the available pressure drop is sufficient to provide flowmetering and the "hard system" requirements.

3.3 Film Cooling

Film-cooling flow shall be capable of providing twice the estimated required quantity.

Until more sophisticated techniques are established, use the method described in table XI for estimating the quantity of film cooling that is required for a specific case. When information is available for systems that are similar to a new design, the quantity of film cooling should be based on these results within the framework of the approach in table XI.

The method of injecting the film coolant should be flexible enough to provide for additions of up to 100 percent more than the original estimate, both locally and grossly. When very

TABLE XI. – Procedure For Estimating Film-Cooling Requirements

(1) Estimate flow and liquid length from

$$\int_{\text{inj. pt.}}^{L_{\ell}} h_g (T_r - T_{sat})\, dA = \left(\frac{\eta_m}{\eta_g}\right) w_{FC}\, (C_p\, \Delta T_{sub} + \Delta H_v)$$

For cylindrical chambers, the result of integration is

$$h_g\, (T_r - T_{sat})\, \pi D_c L$$

(2) Calculate h_g and T_r from table X.

(3) Find (η_m/η_g) in ref. 60 or use 0.4 as a conservative approximation.

(4) Set T_{wg} equal to T_{sat} in liquid region.

(1) Estimate film temperature T_F as a function of length by numerically integrating the following expression (adapted from ref. 21):

$$\frac{dT_F}{dx} = 1.628 \left[\frac{\pi D_c h_g}{C_p}\right] \left[\frac{v_g}{v_f} \left(\frac{1}{\pi D_c}\right)\left(\frac{C_p}{k}\right)\right]^{0.125} (w_{FC})^{-0.875} (T_r - T_F)$$

where x is the distance along the contour from the injection point.

Use film coolant properties.

Start at the end of the liquid region if appropriate.

(2) Calculate local h_g and T_r with techniques given in table X.

(3) For estimates of local heat flux, use local h_g from (2) and set $T_r = T_F$.

OTHER SITUATIONS

Exothermic decomposition. – Assume decomposition at the end of the liquid length; set initial T_F equal to the decomposition temperature.

Endothermic decomposition. – Account for dissociation with an effective specific heat.

Secondary or multiplane film cooling. – "Mix" residual film coolant plus new coolant and use mixed mean temperature to begin new analysis, or assume stratification of coolants and readjust T_r in the expressions above to the appropriate T_F. Downstream injection will promote turbulence [see item 9, table X].

small quantities of film coolant are required, it is recommended that no less flow be used than that controlled by 0.015-in. (0.381 mm) diameter orifices spaced 0.3 in. (7.62 mm) apart.

It is recommended that optimum film cooling be considered in cases of well-defined heating patterns and demands for maximum performance. Tailor the circumferential distribution of film cooling to concentrate the coolant at hot streaks where it is needed, and minimize coolant in the cool streaks. This tailoring can be accomplished only after an experimental evaluation has been made of the injector heating pattern.

3.4 Coatings

3.4.1 Spalling Without Failure

Localized spalling of the insulation coating in a chamber shall not result in chamber failure.

When calculating bulk temperature rises, include in the thermal model any coatings that are applied intentionally for insulation or that develop inherently as deposits from the reactants; references 61 and 62 provide information on carbon formation. However, local cooling at all stations within the coated area must be sufficient even in the absence of the coating.

Use a base metal that is compatible with the combustion products so that, if the coating spalls, the base metal will not be chemically attacked.

3.4.2 Coating Strength

Protective coatings shall withstand transient conditions, states of residual heat, injector streaking, and repair operations.

Coatings that will withstand thermal shock without fracture can be obtained by using very thin gradated coatings 0.004 to 0.010 in. (0.102 to 0.254 mm) thick, preferably composed of materials containing a metal additive. In addition, the nature of the environment must be evaluated during transient operation, when oxidizer-rich mixtures and streaking can exist; the coating must be compatible with these transient conditions. The result may involve the use of a surface coating that represents a compromise from that desired for steady-state operation.

The residual heat within the coating at shutdown must be dissipated without damage to the coating or the chamber. Residual heat appears to be a particular problem in thick coatings.

The extent of this problem is not known, although some analyses indicate that potential hazards exist. The following procedures are recommended: (1) determine if melting of the base metal from the residual heat at shutdown is a possibility without postfire cooling; if melting is possible, consider supplemental cooling operations; (2) if a detonable coolant is used, estimate the bulk temperatures to see if detonation can occur; and (3) if oxidizer is used as a coolant, consider the problem of compatibility between the hot coating and an oxidizing atmosphere in the combustion chamber after shutdown.

Anticipate local spalling of protective coatings and establish repair criteria and procedures. Use fairly heavy and rigid surfaces to minimize motion of the coated surfaces during operation to reduce spalling. Heavy flanges and rings are more adaptable to protection by coatings than are flexible coolant tubes or thin cooled walls. Further, heavy surfaces are amenable to grit blasting to provide roughened surfaces for stronger bonding. Unfortunately, repair is an ill-defined area. Some suggestions, however, are to (1) permit small amounts of spalling, (2) recoat by local application of the top-coat if it is gradated, (3) avoid putting on too thick a repair coating, and (4) if feasible, remove all the old coating and recoat.

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GLOSSARY[1]

Term or symbol	Definition
A	area, in.^{2} or ft^2 (m^2)[1]
bifurcation joint	junction of two tubes or passages with one larger tube or passage
boundary-layer trip	discontinuity or local turbulence in the boundary layer generated by a protrusion from the surface in contact with the boundary layer; tripping usually increases the severity of the thermal environment
c^*	characteristic exhaust velocity, ft/sec (m/sec)
C_g	heat-transfer correlation constant
C_p	specific heat at constant pressure, BTU/lbm-°R (J/kg-K)
Charpy test	a test for impact strength in which a notched bar (of specified dimensions) is struck by a swinging pendulum, and the energy absorbed in the fracture is measured. A striking velocity of 17.5 ft/sec (5.33 m/sec) is employed; test values are given in lb-ft (N-m).
coking	developing a residue when burned or distilled
contraction ratio	ratio of the area of the chamber at its maximum diameter to the area of the throat
D	diameter, in. or ft (m)
e	fracture elongation, in./in. (m/m)
E	Young's modulus, psi (N/m^2)
F	thrust, lbf (N)
F_{ty}	0.2% offset yield strength, psi (N/m^2)
ΔH_v	heat of vaporization, BTU/lbm (J/kg)
h	convective heat transfer coefficient, BTU/in^2-sec-°F (J/m^2-sec-K)
hat	descriptive term for a flanged, square-bottom "U" cross section
k	thermal conductivity, BTU/hr-ft-°F (J/hr-m-K)

[1]Parenthetical units here and in the text are in the International System of Units (SI units). See Mechtly, E.A.: The International System of Units. Physical Constants and Conversion Factors, Revised. NASA SP-7012, 1969.

Term or symbol	Definition
L	length, in. or ft (m)
L*	characteristic chamber length, $L^* = V_c/A_t$
$L\ell$	chamber length to be film cooled, in. or ft (m)
MEOP	maximum expected operating pressure, psi (N/m^2)
MS	margin of safety
N	average cyclic life, cycles
P	pressure, psia (N/m^2)
Pr	Prandtl number, $\mu C_p/k$
R	ratio of the design load (or stress) to the allowable load (or stress)
r	ratio of allowable tensile to compressive strengths
Re	Reynolds number, $\rho u D_c/\mu$
solidus temperature	temperature at which melting starts
St	Stanton number, $h_g/\rho u C_p$
T	temperature, °R or °F (K)
tripping	see "boundary layer trip"
u	velocity at edge of boundary layer, ft/sec (m/sec)
V	volume, ft^3 or $in.^3$ (m^3)
v	velocity, ft/sec (m/sec)
w	flowrate, lbm/sec (kg/sec)
α	coefficient of thermal expansion, in./in.-°F (m/m-K)
Δ	difference or change in a quantity
ϵ_{eff}	calculated effective cyclic strain, in./in. (m/m)
ϵ_t	allowable cyclic strain, in./in. (m/m)
η_g	h_g enhancement factor
η_m	mixing loss factor

Term or symbol	Definition
μ	viscosity, lbm/ft-sec (N-sec/m^2)
ϕ	heat flux, BTU/in.^{2}-sec (J/m^2-sec)
ρ	density, lbm/ft^3 (kg/m^3)
σ	direct stress, psi (N/m^2)
τ	shear stress, psi (N/m^2)
Subscripts	
act	actual
B	bulk
c	chamber
crit	critical
eff	effective
F	film
FC	film coolant
FS	freestream
g	gas-side
ℓ	liquid
o	stagnation
r	recovery
sat	saturation
sub	subcooling
th	theoretical
t	nozzle throat
wg	gas-side wall
wℓ	liquid-side wall
x,y,z	rectangular Cartesian coordinates

Material (designation in monograph)	Identification
A-50, Aerozine-50	50/50 blend of hydrazine and UDMH
Alumizine	proprietary blend of hydrazine, aluminum powder, and gelling agent
CRES	corrosion resistant steel
CTF	chlorine trifluoride
DECH	diethylcyclohexane
DETA	diethylenetriamine
EDA	ethylenediamine
FLOX	mixture of LF_2 and LOX
Freon	E. I. Dupont Co. trademark for a family of fluorinated hydrocarbons
GH_2	gaseous hydrogen
Hastelloy X,N	Haynes-Stellite Corp. designations for nickel-base high-temperature alloys
Inconel X, 718	International Nickel Co. designations for nickel-chromium alloys
IRFNA	inhibited red fuming nitric acid
LF_2	liquid fluorine
LH_2	liquid hydrogen
LOX	liquid oxygen
LPG	liquefied petroleum gas
MHF-3, 5	mixed hydrazine fuels
MMH	monomethylhydrazine
Nickel A; Nickel 200	International Nickel Co. designation for commercially pure nickel

Material	Identification
Nickel 270	International Nickel Co. designation for high-purity nickel
Nicobraz cement	a proprietary acrylic resin binder for braze alloy powders; product of Wall Colmony Corp. (Detroit, MI)
Rigimesh	trademark of Aircraft Porous Media, Inc. (Glen Cove, NY) for porous plate formed by compressed, sintered stacks of wire screen
Rokide	trademark of The Carborundum Co. (Niagara Falls, NY) for flame-sprayed coating, usually zirconia or alumina
R 235	General Motors Corp. designation for an agehardenable nickel-base casting alloy
Teflon	E. I. Dupont Co. designation for tetrafluoroethyene fluorocarbon resins
TD nickel	E. I. Dupont Co. designation for a nickel strengthened by dispersions of thoria
UDMH	unsymmetrical dimethylhydrazine
Waspaloy	Pratt & Whitney Aircraft designation for a nickel-base, high-temperature super alloy
WFNA	white fuming nitric acid
6061-T6	Aluminum Association designation for a heat-treated, wrought aluminum alloy
304	AISI designation for a low-carbon, austenitic stainless steel
316	AISI designation for a high-temperature, nonstabilized stainless steel
321	AISI designation for a titanium-stabilized, austenitic stainless steel
347	AISI designation for a columbium-stabilized, austenitic stainless steel
29-20 SS	Carpenter Steel Co. designation for a stabilized, austenitic stainless steel
4130	SAE designation for low-alloy carbon steel
5052	non-heat-treatable aluminum alloy

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