Engineering Notes

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Completely Electroformed Lightweight Thrust Chamber

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Introduction

AT MBB, regeneratively cooled rocket engine thrust chambers, especially those for high heat flux loads as in high-pressure engines, have been developed for many years. During these development efforts, the milled copper chamber concept with electroformed closure evolved and was successfully used in different projects. One of these projects, a common MBB-Rocketdyne effort financed by the US-DOD and the German Ministry of Defense, first demonstrated the excellent capability of this concept for cooling of high-pressure engines.

The milled copper chamber concept with electroformed closure is best applicable to engines with extremely high heat flux and/or cyclic life requirements on the disadvantage of a relatively high weight compared with tubular thrust chambers which are not feasible for high-pressure engines. Therefore a concept was desired which offers lower weight at fairly high heat flux loads and which is cheaper in manufacturing than both the milled copper chamber with electroformed closure and the tubular chamber which needs complex brazing.

Systematic development efforts resulted in the completely electroformed nickel, copper, or copper/nickel thrust chamber, a fabrication model of which is shown by Fig. 1. In this concept, the cooling channels and the thrust chamber wall which takes the loads resulting from chamber pressure and thrust form one single integral piece of hardware. In all cases where the chamber wall material is nickel, the coolant inlet and outlet manifolds can be fitted to the chamber by welding.

Design

For demonstration fabrication and testing, a completely electroformed nickel chamber was designed. The size of the sea-level part of an 1,100 lb-LH_2/LO_2 engine was chosen; for nominal design conditions, see Table 1.

For proper dimensioning of the wall thicknesses and coolant channel cross sectional areas, numerous heat transfer and stress/strain calculations were performed. Because of limited funding the stress/strain calculations applying the TESTRAN-program of the IKO-Software GmbH, Stuttgart, Germany, could only be done under some simplified assumptions: a) plane cross sections remain plane under stress and thermal gradients; b) heat transfer coefficients are exactly known; c) stresses and strains are completely elastic; and d) thermal conductivity and thermal elongation of the materials are known over the total possible temperature range. The well-established TESTRAN-program is based on the method of finite elements. Two examples of the results of these calculations at the nozzle throat are shown in Figs. 2 and 3, giving the temperature distribution and stress distribution, respectively. The values of stress are given as v. Mises' combined stress.

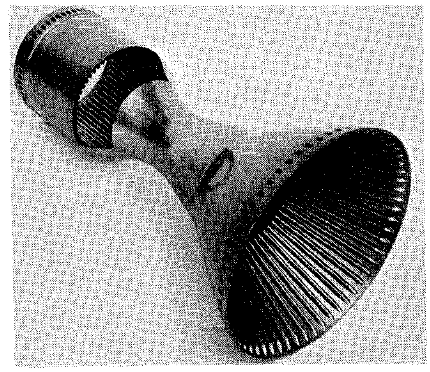

Fig. 1 Fabrication demonstration model, electroformed nickel. A window has been cut into this fabrication model to show the coolant channel cross sections and wall thickness.

Table 1 Design conditions of a 1,100 lb-LH_2-LO_2 engine

Propellants	LH_2/LO_2
Chamber pressure	425 psia (max)
Mixture ratio	5.5 (4-7)
Area ratio (sea level)	3.66

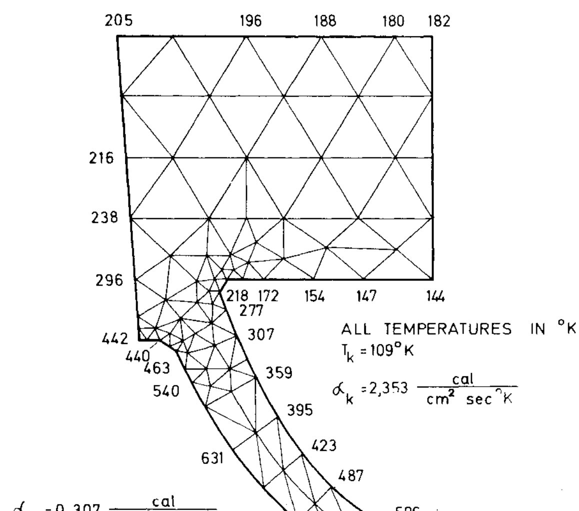

Fig. 2 Theoretical temperature distribution of one side of a cooling channel at nozzle throat.

The highest stress value in Fig. 3, being circa 610 N/mm^2 at the cooling channel tip, is a longitudinal compressive stress which is far beyond the materials' ultimate strength. Thus, results of calculations made under simplified assumptions indicated that the chamber would probably fail due to longitudinal buckling of the cooling channels. The wall thickness distribution for which the chamber was finally designed and fabricated is given in Fig. 4.

Fabrication

Fabrication is done by galvanizing the cooling channels onto a negative (or core) first. After the cooling channels are filled with an electrically conductive wax, the thrust chamber

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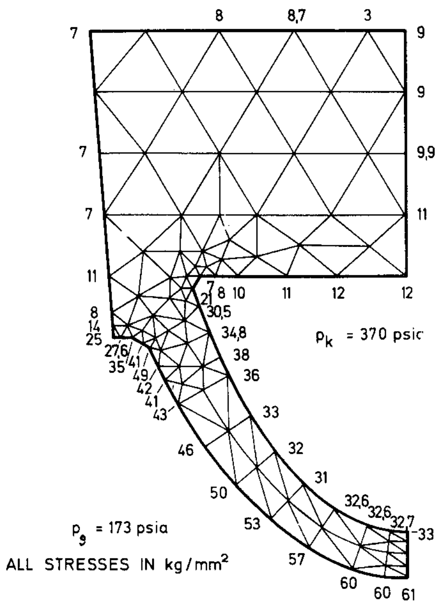
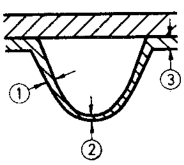


Fig. 3 Theoretical combined stress distribution of one side of a cooling channel at nozzle throat.



	1	2	3
CYLINDRIC PART OF THRUST CHAMBER	0,5	0,4	0,5
CHAMBER THROAT	0,4	0,3	0,5
NOZZLE	0,5	0,4	0,5

Fig. 4 Wall thickness distribution of fabricated nickel thrust chamber.

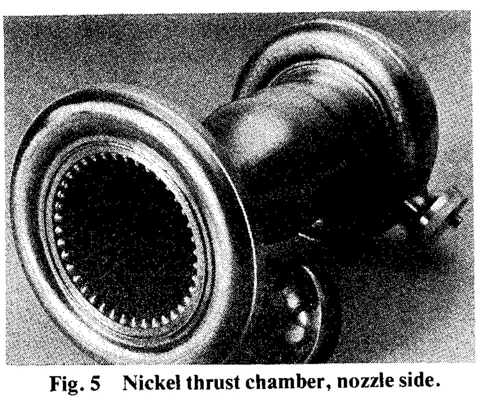


Fig. 5 Nickel thrust chamber, nozzle side.

wall is galvanically deposited and boned to the cooling channels. When enough material has been deposited, the coolant inlet and outlet holes of each cooling channel are bored or electro-discharge machined and the wax is melted out. After a careful cleaning process, the coolant inlet and outlet manifolds are welded to the chamber. To finish the outer chamber wall, a turning process may be applied. No special finishing is required for the inner cooling channel surfaces. One of the complete thrust chambers which was tested is shown by Fig. 5 from the nozzle side.

The complete thrust chamber equipped with battleship inlet and outlet manifolds has a total weight of 5.34 kg, whereas a milled copper chamber with electroformed nickel closure of the same size and also with battleship manifolds, which was designed for multiple cycling conditions (attitude control application) has a total weight of 8.28 kg.

Table 2 Chamber test conditions

$p_c = 150$ psia	$r = 3$-6	$T_{H_2} = 85$ K	LOX
	$r = 4$-6	$T_{H_2} = 150$ K	LOX
	$r = 4$-6	$T_{H_2} = 290$ K	LOX
$p_c = 215$ psia	$r = 4$-6	$T_{H_2} = 290$ K	LOX
$p_c = 140$-215 psia	$r = 4$-6	$T_{H_2} = 290$ K	LOX
$p_c = 300$ psia	$r = 4$-6	$T_{H_2} = T_{O_2} = 290$ K	

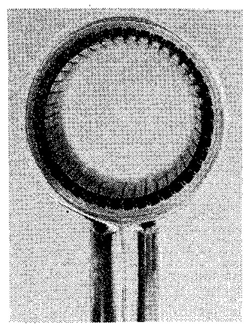


Fig. 6 Fabrication model for near cylindrical wall, rectangular cooling channels.

Testing and Test Results

Testing of the electroformed nickel thrust chambers was done on one of MBB's cryogenic test stands in Ottobrunn near Munich. The chambers were run with a previously developed and tested coaxial jet injector giving a c*-efficiency of 98%. Although the thrust chambers were designed for LH_2/LO_2 conditions, testing was done only with GH_2/LO_2 and GH_2/GO_2 due to cost considerations.

Yet cold hydrogen gas, cooled down in a LN_2-heat exchanger to a minimum temperature of 85 K, was used, too. The thermal loads for the thrust chambers were increased systematically by increasing the hydrogen inlet temperature from test series to test series. During a series at constant hydrogen inlet temperature, the mixture ratio was increased up to a value of 6. At ambient temperature, different series with increasing chamber pressures and mixture ratios were run.

Table 2 gives the complete set of test conditions under which the chambers were tested without any failure.

At the highest possible chamber pressure with GH_2/GO_2, where also combustion temperature is a maximum, the mixture ratio was further increased until failure of one chamber which occurred at a mixture ratio of 7.

Since the chambers were designed for LH_2-conditions, the wall temperatures during tests with GH_2 were approximately 200 K higher than under nominal design conditions. Under these circumstances the test results showed in fact an excellent operational flexibility of these electroformed nickel chambers. Test results showed that measured and predicted overall heat transfer at normal running conditions were within a band of not more than + 12%.

Additional Technology Work

Further technological efforts were undertaken in order to decrease the surface area being in direct contact with undisturbed combustion gases of such chambers. Figure 6 shows a fabrication model having a resulting hot-gas surface in direct combustion gas contact being very close to a cylindrical surface. Because of financial restrictions, it was not yet possible to demonstrate the feasibility of this concept by testing, too.

Conclusions

The test results achieved with the electroformed nickel thrust chambers as described showed the excellent operational flexibility of that chamber concept at fairly high heat flux loads occurring in H_2/O_2 chambers run with gaseous propellants at high mixture ratio. By these tests it was also successfully shown that the results of the theoretical calculations with regard to stresses were too pessimistic.