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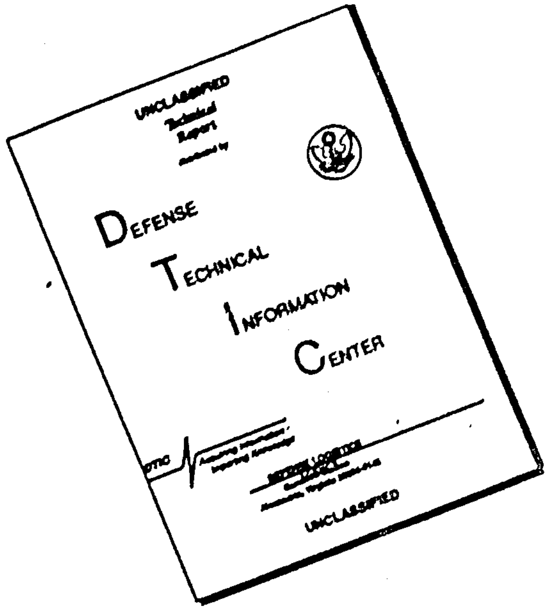

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ANALYSIS AND EVALUATION OF GERMAN ATTAINMENTS AND RESEARCH IN THE LIQUID ROCKET ENGINE FIELD

VOLUME IV

PROPELLANT INJECTORS

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ABSTRACT

This report on Propellant Injectors shows the interrelation of injector development to the design and performance characteristics of rocket engines. Various injector types are studied, design parameters established, and details of many leading foreign injectors summarized. For a complete coverage of these subjects, it is recommended that all volumes of this series be consulted. Utilization was made of the applicable portions of the 55,000 captured foreign documents relating to rocket engines, supplemented by interrogations of German technical personnel located in the United States.

ANALYSIS AND EVALUATION OF GERMAN ATTAINMENTS AND RESEARCH IN THE LIQUID ROCKET ENGINE FIELD

PREFACE

Volume IV, entitled "Propellant Injectors," is one of a series of 14 volumes covering the compilation, resume, and analysis of German liquid rocket engines, procured from the American Power Jet Co., under Contracts No. W-33-038 ac-17485 and No. AF 33(038)-3636 with the Intelligence Department, AMC, Wright-Patterson Air Force Base, Dayton, Ohio.

The 14 volumes of this series are as follows:

Volume I	Combustion Chambers
Volume II	Combustion Chamber Cooling
Volume III	Analysis of Design and Performance of Foreign Rocket Combustion Chambers
Volume IV	Propellant Injectors
Volume V	Propellant Supply Systems
Volume VI	Rocket Engine Turbines and Pumps
Volume VII	Thrust Control
Volume VIII	Rocket Engine Control and Safety Circuits
Volume IX	Liquid Rocket Engine Installation and Flight Program Factors
Volume X	Ground Handling of Operational Liquid Rocket Engines
Volume XI	Ground Handling of Operational Liquid Rocket Engine Propellants
Volume XII	Liquid Rocket Engine Test Facilities and Testing Techniques - Peenemunde Rocket Group
Volume XIII	Liquid Rocket Engine Test Facilities and Testing Techniques - BMW Rocket Group
Volume XIV	Liquid Rocket Engine Production Experience

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LIST OF SYMBOLS

Q = Volume rate of flow (cu in./sec)
C = Coefficient of discharge
A = Total discharge area (sq in.)
ΔP = Pressure drop across injector (psi)

ρ = Density (lb/cu in.)
c = Jet velocity (ft/sec)
F = Rated thrust (lb)
ρ_o = Density of oxidizer (lb/cu in.)

ρ_f = Density of fuel (lb/cu in.)
P_c = Chamber pressure (psi)
r = Mixture ratio (oxidizer/fuel)
P_e = Pressure at nozzle exit (psi)
$\frac{P_c}{P_e}$ = Nozzle expansion ratio
$\dot{W}_{sp}$ = Specific propellant consumption (lb/1000 lb sec)
$\dot{w}$ = Weight flow of propellants (lb/sec)

Subscripts

f = fuel
o = oxidizer

VOLUME IV

PROPELLANT INJECTORS

INTRODUCTION

Function

The function of the propellant injector is to introduce the propellants in the combustion chamber so as to obtain a safe, high-efficiency combustion. Although causing the efficient reaction of two highly concentrated energy sources would appear to be a simple matter, the injector design, in fact, presents one of the most complicated and difficult problems in the development of the rocket engine. This problem is increased by the complexity of the mechanical design frequently required to secure the desired propellant distribution in the limited space available.

General Considerations

Analysis of foreign rocket-injector design experience discloses that the development of propellant injection must take into account not only quantitative but also qualitative factors. These relate to the kinetics of propellant injection as well as to the interaction of the propellant injector with other system components. It is desirable that these be briefly noted before proceeding to the discussion of their effects in specific cases.

The relationship of the propellant injector to other parts of the rocket engine is less marked than that of other system components. The pressure drop through the injector affects the selection of the propellant supply system; for example, high injector drops are rarely compatible with pressure feed systems but are frequently permissible with pumps.

The design of the propellant injector must, however, be closely correlated with combustion chamber and ignition characteristics. Thus, American research discloses a relationship between injector design and heat transfer to the walls. A poor choice of injection angle may locate the flame front and maximum temperature directly on the wall. These factors make the cooling problem more critical and may result in motor failure. The use of spark-plug ignition frequently carries with it a need for the accurate location of the propellant intersection at a given point; pyrotechnic igniters are less critical in this regard.

It is rather surprising to note that injectors of all basic types were successfully developed for both self-reacting and non-self-reacting propellants. However, it is evident that adjustments for the self-reacting, or hypergole type, were less critical than for the non-self-reacting type. 1/

The design of injectors for anergole propellants is complicated by the fact that the rapid generation of gases at the point of combustion tends to throw the remainder of the propellants away from each other. Accordingly, extremely accurate and thorough initial distribution appears desirable. This was confirmed by Peenemunde experience.

1/ The Germans designated self-reacting propellant combinations (such as nitric acid-Tonka) as "hypergoles." Non-self-reacting propellants (such as liquid oxygen-alcohol) were termed "anergoles." These definitions will be adhered to in the body of this report.

Injector design is also influenced by heat-transfer considerations. Thus, partial vaporization of liquid oxygen invalidates calculations based on flow in the liquid state and causes the mixture ratio to shift, with probable detriment to performance. Also, account must be taken of the corrosive characteristics of nitric acid, and injectors intended for repeat use must be capable of disassembly and servicing.

All propellant injectors, regardless of the propellant combination or detail design, must satisfy certain requirements with respect to safety, reproducibility, ease of fabrication, and service.

The importance of designing for safety is self-evident. The reaction zone must be confined to the combustion chamber and the possibility of "flashbacks" either during operation or between runs must be eliminated. Accordingly, reliable seals must be provided in the injector head to prevent the propellants from premixing before injection. Furthermore, refinements are necessary in the detail design to prevent one of the propellants from dribbling upstream to the injector and reacting there when the motor is restarted. The latter point was a source of considerable difficulty in combustion chambers designed for intermittent use in a horizontal position.

Reproducibility is an extremely important, practical consideration in multiorifice type injectors, since they require an accurate determination of the intersection point for the reacting sprays. Designs intended for mass production must be selected so as to permit the maintenance of practical tolerances. This factor is directly related to ease of fabrication in designs such as the Wasserfall, which require the drilling of many closely spaced holes. A single setup for the boring operation is rarely possible, since the holes are generally directed at various angles. The time-consuming nature of this kind of operation is augmented by the need for absolutely smooth, clean holes. Such requirements frequently result in excessive rejection rates during manufacture and are, consequently, impractical for mass production.

INJECTOR TYPES

Injectors may, in general, be divided into two major groups: the spray type, where the propellants are injected in conical or cylindrical sprays; and the orifice type, where the propellants are injected in solid streams. Each of these groups may be further differentiated.

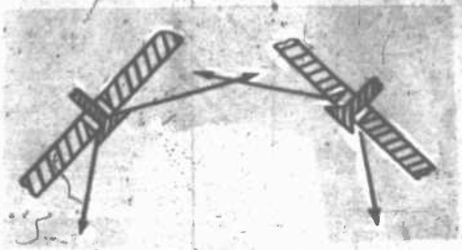
Spray Injectors

The four main types in the spray group are:

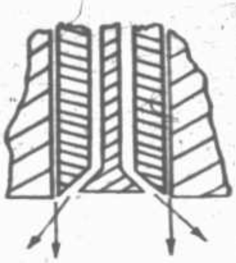
1. Individual intersecting sprays
2. Concentric intersecting sprays
3. Ring injectors
4. Centrifugal types

Description

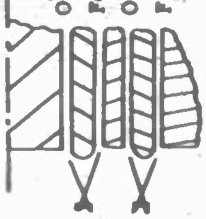
In the operation of the individual intersecting spray type, separate injectors are used for each propellant. The propellants emerge from the injectors through an annular slot in a hollow conical spray and are directed so that they impinge against each other. Injectors of this type were found in the P 3373, P 3374, and P 3390A.



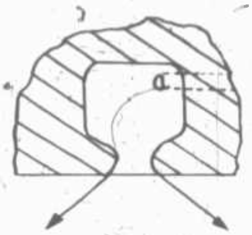
In the concentric type of injector the individual propellants are injected through concentric annular slots and emerge in hollow concentric sprays. The spray angles are so arranged that they impinge against each other. The Walter 109-509 is an example of this type.



The ring injector is a variation of the concentric spray type. In most cases, alternate rings inject the different propellants, the respective sprays intersecting with each other. This injector was developed by Dr. Beck (deceased). It was proposed for various Peenemunde applications and was applied in the Rheintochter III.



The operation of the centrifugal type of injector varies from the others in that the conical spray shape is attained by the centrifugal action of the propellants as they leave the injector. This motion is usually imparted to the propellants by tangential entry into the injector chamber from which they spread out into a conical spray as they leave through the orifices. An alternate method of attaining the centrifugal motion is by means of spiral inserts. These received their widest application in Peenemunde designs.



Centrifugal injectors were rarely used alone, except with a monopropellant. In bipropellant systems they were usually used for the inner spray in conjunction with a concentric spray type. It is also possible to use centrifugal injectors to achieve individual intersecting sprays.

Characteristics

The individual intersecting spray injector has the least favorable characteristics because of the difficulty of getting all of the oxidizer to intersect with all of the fuel, so that no unburned propellants leave the chamber. Another disadvantage is the fact that more than one injector has to be used, which raises additional manufacturing and service problems. To offset its poor distribution qualities, several such injectors were usually used together and the slots were made very thin as an aid to thorough atomization of the propellants. An advantage of this design is that if something goes wrong with one of the injectors the efficiency suffers but the system is likely to continue running. Moreover, there is no problem of sealing or leakage; hence the design can be very simple and the tolerances need not be exacting.

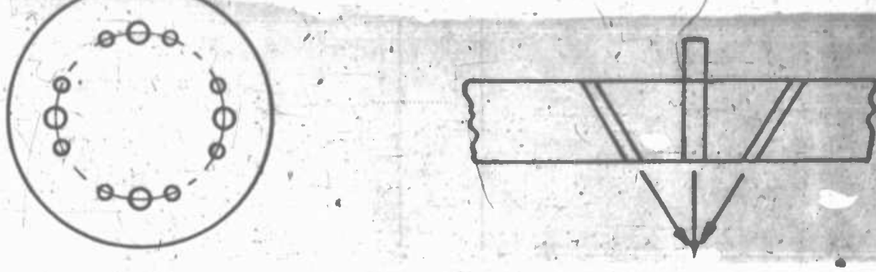
Concentric spray injectors achieve generally satisfactory distribution because mixture takes place around the whole periphery of the concentric spray. In general, this type of injector was of machined construction and did not require very much servicing. It was very safe as long as tight seals were maintained. On the other hand, concentric intersecting spray injectors appear to be less efficient in large units. Extreme care must be exercised in the manufacture of this type of injector, since the individual propellant passageways must be completely sealed from one another to avoid premixing and risk of explosion.

Propellant atomization is finer with ring injectors than with concentric spray injectors because the propellants are led through a larger number of thinner annular slots. However, ring injectors are extremely difficult to manufacture. The complexity of the design is aggravated by the requirement that the introduction of propellant should not be affected by conditions upstream from the injection point. Moreover, ring injectors must be built to very close tolerances.

One of the outstanding problems in the fabrication of the annular slots, which are characteristic of the spray-type injector, arises from the need for holding the annular slots absolutely uniform. Any deviation in slot width upsets the balance among the sheets of propellant injected and results in poor mixing, with consequent detriment to performance.

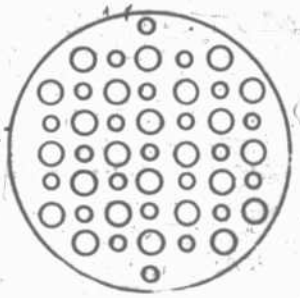
Orifice Type

Three varieties of orifice injectors have been found. The most widely used had holes for both propellants drilled to form a circular pattern around the face of the injector. The usual arrangement was two oxidizer orifices to one of fuel, set at angles which caused two oxidizer streams to impinge on a single stream of fuel. The resultant mixture ratio closely approximated that required for the most commonly used propellant combinations. It also provided a good balance for the required injector pressure drops.



This simple orifice injector was intended primarily for hypergole application, where the ignition lag period usually provided reasonably good mixing opportunity for the solid, high-density streams. It was found in the BMW 109-558, 109-548, and HWK RI 210b.

The second type is a version of the first, in which the whole face of the injector is covered with a multitude of holes. This is known as the spray-plate type and is characteristic of many Peenemunde injectors, including that of the Wasserfall.



Many different spray-plate arrangements were tested. Frequently, with hypergoles, a portion of the holes was allocated to maintaining combustion by providing intersecting oxidizer and fuel. Other groups of holes, intended to secure good atomization, impinged fuel streams against each other and oxidizer streams against each other, thereby effectively breaking up the propellants. The two zones were located close together so that the generated-propellant mists would react. Such arrangements were found in the Wasserfall and the RI-101b.

The third type employed random injection of the propellants with no attempt to secure intersection. It was hoped that the number of holes would be large enough to insure that all of the fuel and oxidizer would eventually react. This type was found in early Peenemunde designs, but it was gradually abandoned.

The element of randomization is frequently present even in highly developed injectors. For example, the A-4 injector apparently distributed a certain amount of its propellant unreacted into the combustion chamber proper.

Depending upon their complexity, varying degrees of manufacturing difficulty were encountered with orifice-type injectors. Analysis of Peenemunde test results discloses many rejections of injectors on the test stand, which had apparently passed inspection during manufacture.

<u>Composite Orifice-Spray Type</u>

In many cases the injector consists of composites of orifice and sprays. The A-4 injector was of this type. It represented the end point of a long and detailed series of experiments. It is notable that the Peenemunde organization began its development with a composite counterflow injector which was tried in the A-1 and A-2. It was thought that the counterflow features would improve the mixing, but these were found unnecessary, and the A-1, A-2 type gradually evolved into the "burner head" arrangement used in the A-4. This design sequence is of definite interest, and is discussed below in the sections of this report that deal with the Peenemunde counterflow injector, B series, and A-4.

INJECTOR DESIGN PARAMETERS

While the design of a specific injector must rely heavily on the results of past experience, a definite procedure may be set forth for determining fundamental dimensions. When the propellant mixture ratio, thrust, chamber pressure, and operating altitude have been selected, it is possible to solve the fundamental equation $F = c\,(\dot{w}/g)$ for the total weight rate flow of the propellants, since the value c may be calculated for each pressure ratio and for the mixture ratio for each propellant combination.

Theoretically calculated jet velocity values may then be corrected by various evaluation parameters, including X, (discussed in section 51-0-12A (Vol. I) of this report). The corrected value should be used in obtaining the required propellant flow. The total weight flow may then be broken down into its components according to the mixture ratio. The applicable formulas are as follows:

$$\dot{w}_f = \frac{1}{r+1}\,\dot{w}$$

$$\dot{w}_o = \frac{r}{r+1}\,\dot{w}$$

The volume rates of flow may then be determined:

$$Q_o = \frac{\dot{w}_o}{\rho_o}$$

$$Q_f = \frac{\dot{w}_f}{\rho_f}$$

The required discharge areas as a function of the pressure drop selected may then be determined from the conventional equation:

$$Q = C\,A\sqrt{2\,g\,\frac{\Delta P}{\rho}}$$

Theory alone is inadequate to determine the value of the discharge coefficient, C; hence, preliminary design assigns values based on past experience. Injectors employing a well-rounded orifice may assume a value of 0.9 - 0.95, and when slots are used, a value of 0.85 - 0.9 may be selected. As in other nozzle and orifice applications, it has been found that the specific conditions of manufacture and finish definitely affect the exact value of the injector-nozzle coefficient. Similarly, the all-important questions of distribution and "quality" of dispersion are not theoretically predictable, especially in the case of liquid oxygen. This factor may be illustrated by Peenemunde tests showing the importance of almost microscopic scratches and burrs in the orifice exit on the injector pattern.

The selection of the pressure drop is usually based on experience with the propellant combination and injector design. The chamber pressure drops for various foreign injectors are summarized in Table 1, "Summary of Foreign Injectors." Peenemunde usually preferred relatively low injector pressure drops, while other organizations tended to work at higher values. Two extreme cases were located. The first is the initial pressure drop of approximately 1200 psi in the 109-548. This system, however, is of the unregulated, "run down" type and the initial pressure drop is a type of transient that is speedily reduced. The second case is the radical proposal of Saenger, in which the 710 psi pressure drop is partly a consequence of the other design characteristics of the system. Inasmuch as it was not confirmed by experimental testing, this value should be regarded with caution.

The only limiting factor in assigning the pressure drop is to set it high enough to assure hydraulic stability. That is, to make certain that any small increase in chamber pressure will not cause pulsations to be set up. The mechanism of pulsing arises when a local increase in chamber pressure overcomes the injection pressure, so that the propellant supply temporarily ceases. When this occurs, the exhaustion of propellants continues until the chamber pressure drops enough to permit the flow to be resumed. In this way a series of oscillations may be set up, sometimes with disastrous results.

DETAILS OF LEADING FOREIGN INJECTORS

Individual Intersecting Sprays - P 3390A

The design of the injectors for the BMW P 3390A represented a logical and orderly development program based on previous experience with the P 3373 and P 3374. In the P 3390A design eight single-spray injectors were spaced in the chamber head. (See Figs. 1 and 2.) Four were for nitric acid injection and four for methyl alcohol. Figure 1 is a cutaway section showing the injectors in place, and Fig. 2 is a photograph showing a breakdown of the injector parts. The acid and alcohol injectors are identical except for the size of the slot width, which is determined by the dimensions of the outer housing.

At the start of this development program a number of points, regarded as fundamental to a good injection system, were enumerated as follows:

1. Low specific propellant consumption
2. Clear and even exhaust jet
3. Steady combustion
4. Good mixing of the propellants during the cruising thrust period, at low injection-pressure drops
5. Even temperature distribution on the inner jacket.

In order to attain these requirements the following points were measured:

1. Specific propellant consumption and efficiency of combustion as a function of injection-pressure drop
2. Influence of arrangement of the injectors in the head on the specific propellant consumption
3. Influence of the injector design on the specific propellant consumption.

In order to investigate the effect of injector distribution on specific propellant consumption, five series of tests were carried out with three different injector arrangements. Figures 3, 4, and 5 show the arrangements of the injectors and their characteristics. The tests are tabulated and discussed below and plotted in Figs. 6 to 9.

Series 1

Injector with twist insert (Dwg. No. T-255-01.017/018)[2]
Distribution No. 2 (Fig. 4)
Dural inner jacket with 2.24-in. diameter exhaust nozzle (Dwg. No. T-255-02.100)[2]

[2] Drawing numbers given refer to presently unavailable German drawings. It is known, however, that these closely resemble the injectors shown in Fig. 1.

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Series 1 Test Results					
Thrust (lb)	990	1100	1320	2240	3080
Chamber Pressure (psi)	199	213	256	405	540
Specific Propellant Consumption (lb/1000 lb sec)	7.14	7.0	6.4	5.8	5.25
Mixture Ratio (lb acid/lb alc)	2.36	2	2	2.1	2

Attempts were made to hold the mixture ratio constant, but it was found that injectors having twist inserts did not have the same mixture ratio at all injection pressures. The injector distribution used in this test series produced an exhaust that was very streaky and definitely divided into zones. The nonuniform propellant distribution caused various degrees of corrosion in the inner walls of the test motor, which became very rough at the throat and burned through in a short time.

Combustion at all thrusts was very unsteady and noisy, and at low thrusts strong surges with flashes of light were noted in the exhaust. The light flashes, due to the sudden addition of large amounts of nitric acid, gave the impression of afterburning outside the combustion chamber.

Series 2

Injector T-255-01.017/018 with twist insert
Injector Distribution No. 2 (Fig. 4)
Steel Inner Jacket T-255 Sk 357 2.36-in. diameter throat

Series 2 Test Results						
Thrust (lb)	880	1320	1980	2200	3150	3300
Chamber Pressure (psi)	171	227	327	355	497	525
Injection Pressure (psi)	192	256	374	398	569	604
Specific Propellant Consumption (lb/1000 lb sec)	7.6	6.6	6.4	5.75	5.3	5.3
Mixture Ratio (lb acid/lb alc)	2	2	2	2	2.2	2

These tests were very similar to those of Series 1 except that the inner jacket was made of steel. Again, the poor distribution caused high temperatures in the chamber and left black markings on the inner jacket, plainly showing that the combustion gases are divided into four zones. (Note discolored areas in Fig. 10.) The injector head also shows the effects of nonuniform combustion. (See Fig. 11.) The oscillations in injection pressure and the unsteady combustion were exactly the same as in the previous series of tests.

Series 3

Injector R III 12-1017a without insert
Injector Distribution No. 1 (Fig. 3)
Steel Inner Jacket T-265 Sk 357 2.36-in. diameter throat

Series 3 Test Results

Thrust (lb)	792	826	925	1100	2640	27[illegible]0	2860	3300
Chamber Pressure (psi)	149	156	177.5	184.5	426	440	455	525
Injection Pressure (psi)	163.5	170.5	191.7	199	490	511	532.5	625
Specific Propellant Consumption (lb/1000 lb sec)	10	8	10.2	8.8	5.43	5.4	5.37	5.3
Mixture Ratio (lb acid/lb alc)	1.8	1.8	1.8	1.5	2.07	2.08	2.08	2.08

Several changes were introduced for the Series 3 tests. Thrust was regulated by throttling valves in the propellant line. The twist inserts were eliminated from the injectors in the hope of preventing vibrations and oscillations. In addition, the injector distribution was altered. Because several conditions were changed in the same series of tests, it was difficult to ascribe the results to a particular change. Nevertheless, the following conclusions were arrived at after many tests:

1. The use of Injector Distribution No. 1 largely eliminated the streaky exhaust pattern, which became uniform and much clearer. Stress on the inner jacket was more even, but it still showed the formation of dark areas caused by high temperatures, and the throat was still rough and had a tendency to distort and dent.

2. It was found that specific propellant consumption is affected by injection pressure drop. Removal of the twist sprays, which would take some pressure drop, caused poorer atomization of the droplets and, consequently, higher specific propellant consumptions. (See Figs. 7 and 8.) 3/ Indeed, atomization was so bad in the lower thrust regions that there was danger of explosion, combustion being characterized by violent oscillations and flashes of flame.

Series 4

Injector R III 12-1017b without insert
Injector Distribution No. 1 (Fig. 3)
Steel Inner Jacket T-255 Sk 357 2.36-in. diameter throat

3/ It is interesting to note that the figure of merit of Fig. 8 reduces to the parameter X, discussed in the combustion chamber section (51-0-12A, Vol. I) of this report.

$$\frac{\dot{W}_{sp}\text{ (theoretical)}}{\dot{W}_{sp}\text{ (actual)}} = \frac{I_{sp}\text{ (act.)}}{I_{sp}\text{ (theo.)}} = \frac{c\text{ (act.)}}{c\text{ (theo.)}} = X$$

Series 4 Test Results							
Thrust (lb)	705	946	1065	1385	2750	3190	3300
Chamber Pressure (psi)	134.9	177.5	213	241.5	440	511	525
Injection Pressure (psi)	142	191.5	241.5	277	567	675	696
Specific Propellant Consumption (lb/1000 lb sec)	7.9	6.9	6.5	6.2	5.18	4.96	4.9
Mixture Ratio (lb acid/lb alc)	2	2	2	2	2	2	2

Since it was necessary to eliminate the twist inserts while yet improving the atomization over that in Series 3, the injector cross sections were made smaller and the sealing cones were given a double angle for better distribution of the propellants. The double angle caused the resulting spray to come out in a thick-walled, rather than a very thin-walled cone. With these changes, the quality of combustion improved, the combustion chamber temperature increased, and the specific propellant consumption went down.

However, dark spots and stripes continued to form along the entire length of the jacket (Fig. 12), following the course of the cooling spiral. These showed that the mixing of the propellants still had not attained the desired value. In this series the temperature was found to be so high that if the coolant flow were reduced by even a small amount the throat would burn through. (See Fig. 13.)

The exhaust in this series was clear and uniform, and on a clear day it was completely invisible at full thrust. This combustion system and chamber were accepted, but another test was run to see if any further improvements could be made.

Series 5

Injector R III 12-1017b without insert
Injector Distribution No. 3 (Fig. 5)
Steel Inner Jacket T-255 Sk 353 2.36-in. diameter throat

Series 5 Test Results								
Thrust (lb)	1100	1320	1760	2200	2350	2750	3235	3300
Chamber Pressure (psi)	198.6	234.1	298	362	383	440	518	525
Injection Pressure (psi)	220	265.8	355	447	478	561	681	696
Specific Propellant Consumption (lb/1000 lb sec)	6.5	6.15	5.65	5.45	5.3	5.1	4.9	4.83
Mixture Ratio (lb acid/lb alc)	2	2	2	2	2	2	2	2

The difference between this and the preceding series of tests was in the injector distribution clearly demonstrating the cause of the improved results. In this case the exhaust was clear and clean, and free from propellant zones. The Mach nodes were very distinct and the combustion in the lower thrust regions was better than in Series 4. Also, the chamber and injector head were found to have a more even temperature distribution, as can be seen by the uniform blackening in Figs. 14 and 15. Further improvements in this system were deemed impossible without a basic change in the head or injectors.

Conclusions

The following conclusions may be drawn:

1. The efficiency of combustion depends in the region of lower pressures on such aids to atomization as the twist inserts and the double-angle poppets.

2. The injector distribution showed only a slight influence on the specific propellant consumption. However, it is necessary that the best possible distribution be used for uniformity of the exhaust and for good temperature distribution in the combustion chamber. These tests showed that Injector Distribution No. 1 was acceptable, but that No. 3 had the best distribution and very uniform exhaust, as well as a somewhat better specific propellant consumption.

3. The quality of combustion and the steadiness of the exhaust are mainly dependent on injector design. It was determined that the injectors with twist inserts showed strong oscillations in injection pressure, while injectors without twist gave quiet combustion and uniform combustion pressures.

4. Combustion with clean exhaust appears to depend upon two major factors:

Mixture ratio The combustions were calibrated for a 2:1 mixture ratio, which was theoretically optimum. Hydraulic regulation maintained the ratio and kept the methyl-alcohol and nitric-acid pressures constant.

Injector Distribution The best distribution was obtained when there was a 1:1 opposition of an acid and alcohol spray assembly. Furthermore, the distribution study showed that injectors of the same propellant should not be adjacent to each other, nor should they inject in the same direction. It is rather surprising that experimentation was required to reach this apparently obvious conclusion. These tests also confirm the general experience that it is possible for unburned zones of each of the propellants to be exhausted if the distribution is poor.

5. Best results were obtained with injector R III 12-1017b, having the following characteristics:

Diameter of nitric acid annulus	= 0.292 in.
Diameter of methyl alcohol annulus	= 0.252 in.
Poppet angle	= 70°

The design sequence described above casts light on the injector design techniques and procedures used by BMW. An interesting note is that, although the same injector was used in both the P 3373 and P 3374, these basic tests were not carried out until the development of the P 3390A. The fact that this was BMW's first attempt to build a prime mover for a piloted aircraft probably stimulated the more extended effort. This work represents a leading reference for the design of anergole injectors (specifically nitric acid-alcohol), and presents many points of interest for future development.

Concentric Intersecting Spray (Self-Capping) - HWK 109-509

The 109-509 injection system was developed by Walter as the result of a long testing program beginning with the RI-203b. The individual injection units were of the concentric-slot type, with hydrogen peroxide on the inside and C-stoff on the outside. The over-all injection system (Figs. 17 and 18) was designed to permit groups of injectors to be shut off during the throttling process.

Three stages were used: the first two consisted of three injector units each, and the third stage consisted of six. Their somewhat asymmetric distribution is clearly shown in Fig. 18a. The T-stoff connections run directly into the injector, while for any given stage a single C-stoff inlet supplies the entire group of injectors through a plenum chamber. Accordingly, care should be taken in analyzing this figure to avoid the impression that the unit marked "c" is anything else but a fill connection.

The operation of the 109-509 injector is similar in principle to that of the P 3390A. Its major interest lies in its mechanical design. (See Fig. 16.) A spring-loaded, self-capping poppet was used to prevent any C-stoff leakage from working its way up into the T-stoff injector and causing explosions. Spiral guides, equivalent in action to the "twist inserts" of the P 3390A, were satisfactorily used in the 109-509.

A final point of detail design interest is the use of an insert piece to form the C-stoff injection annulus. This simplified the tolerance problem and made possible an individual matching of the injector dimensions with the desired slit widths. Although such an arrangement made interchangeability difficult, it certainly acted to reduce the manufacturing rejection rate.

An important advantage of the use of stages was the reasonably high degree of throttling that could be achieved without detriment to performance. The analysis of the throttling characteristics of the 109-509 is covered in detail in section 51-0-12D (Vol. VII) of this report.

A further benefit arose from the simplification of the starting problem. Walter apparently found that smooth starts were difficult if large quantities of hydrogen peroxide (T-stoff) were suddenly introduced into the chamber. On the other hand, optimum ignition requires the injectors to be operating at full flow at design pressure. These conflicting requirements were reconciled by recourse to staging, which permitted the gradual introduction of T-stoff.

Concentric Intersecting Sprays (Non-Self-Capping) - Peenemunde Ring Injector

Attempts to apply the principle of concentric rings to units of large thrust resulted in the ring injector developed by Professor Beck 4/ at Peenemunde. The large flow of propellants dictated an arrangement of more than one set of concentric rings, and much of the work on this injector was directed toward finding a mechanically acceptable design.

The rings were arranged so that the respective fuel and oxidizer spray cones intersected. Although the direction of the slots was always parallel to the axis of the motor, surface tension forces acting on the curved surface of the rings were expected to produce a bending of the sheets of liquid into a cone. This is schematically illustrated in Fig. 19. No direct experimental evidence of the operation of these surface tension forces was obtained. While it is probable that they were observed at a given pressure drop in "cold" testing with water or unreacted propellants, heat-transfer considerations and the location of the flame front would all play a part in the final result during actual runs. The operation of the ring injector, therefore, may be expected to be different for anergoles and hypergoles.

4/ Professor Beck was killed in the Allied air raid on Peenemunde in 1943.

Various methods of construction were proposed. The design shown in Fig. 20 is the original Beck injector. A casting (1) forms the basic piece for the injector. A series of grooves (2) are then machined into it. The individual insert rings (3) are machined and assembled by a shrink fit which produced a tight and reliable construction. The differential temperature for shrinking was approximately 320°F. However, warpage may be expected to cause difficulties with concentricity.

The second design, Fig. 21, differs from the original by the use of insert rings with orifices. The rings are held in place not only by a shrink fit but by a sawing and spinning operation performed on the rings to hold the inserts in place. This construction supplies the propellants by holes drilled from the top of the injector down into the individual grooves. It then passes through orifices in the ring inserts and through the metering annulus formed between the ring and the walls. On the whole, the proposed construction appears less desirable than in Fig. 20, since the additional machining produces no compensating advantage. Furthermore, the characteristics of the annulus depend in large measure on the accuracy and precision of the spinning process.

The arrangement proposed in Fig. 22 eliminates the use of a built-up construction and may be fabricated from a die casting according to the process shown in Fig. 19. The die casting is machined and sawed, the long rings are spun into place, and the ring slots are finish machined. This construction appears to be a considerable improvement over its predecessors.

The ring construction was suggested on a number of occasions as a substitute for the A-4 injector, not on performance grounds but, rather, because of the comparative ease of fabrication. It will be recalled that the A-4 required the assembly of 18 individual burner heads, each consisting of a number of individual parts. The possibility of substituting a single unit construction for this arrangement was attractive even if performance was somewhat diminished. In point of fact, however, Peenemunde never succeeded in developing a ring injector of performance equal to that of the A-4 burner head.

Tests with the ring injector in both large and small chambers disclose a pronounced tendency toward vibration and noisiness, so that oscillations appear to be a result of the basic kinetics of the spray intersection. Oscillations are not only a symptom of inefficient performance but also represent a safety hazard.

The ring injector construction appears best suited to applications of one-time operation in a vertical attitude, because the close proximity of the unsealed concentric rings renders probable a cross leakage of the propellant during the period of shutoff. This would almost certainly result in explosion on restart. At horizontal operation there is the possibility not only of cross leakage but also of asymmetric distribution if a low-pressure start should be undertaken. Depending on the propellant selection, this may offer an additional source of difficulty.

<u>Orifice-Deflector Plate Injector - HWK RI-210b</u>

The Walter injector for the RI-210b was intended for use in the Enzian power plant and was to operate with hypergole propellants. The injector assembly, shown in Fig. 23, is of welded mild-steel construction and is bolted to the combustion chamber by means of a flange. In contradistinction to the types previously discussed, the injector also formed the head of the combustion chamber.

Its operation was as follows: The oxidizer enters through a fitting at the head of the injector and fills the plenum chamber. A portion of the oxidizer then enters the combustion chamber through 20 orifices arranged around its circumference and inclined outward at an angle of 45°. The remainder of the oxidizer is led into an outer chamber where another series of 20 orifices, inclined toward the center of the combustion chamber at an angle of 40°, provides a further injection of the oxidizer into the chamber. The fuel enters through a fitting at the top of a circular half-tube welded to the top of the injector. From there it passes through 20 orifices and is injected parallel to the combustion chamber axis. The streams emerging from the inner and outer oxidizer orifices and the fuel orifices are designed to strike a target plate at their point of intersection and then enter the combustion chamber proper.

The deflector plate serves the purpose of further atomizing the propellant streams. It also compensates for any small misalignment of holes that may have occurred during manufacture. The propellant ignition lag was apparently sufficient to prevent combustion from taking place on the surface of the plate; hence, the plate was kept relatively cool. In order to reduce the heat transfer, the downstream section of the plate was coated with the same ceramic used to line the combustion chamber.

Figure 23 shows that the chamber pressure tap protrudes well down into the chamber. While no test data are available on this point, the flame front appears to be beyond the pipe entrance, since it would otherwise burn out. This injector is extremely simple and appears, in general, to be well designed. Its method of arrangement and mounting differs from BMW's, who used built-up, bolted injector assemblies, while Walter, as usual, tended to prefer welding.

Simple Orifice Type - BMW 109-548

The BMW 109-548 rocket engine was intended to be an expendable missile, and used nitric acid and Tonka as propellants. Its mission dictated the use of the simplest and cheapest construction possible; this was reflected in the injector design.

The 109-548 injector (Figs. 26-29) was to consist of three groups of orifices, each consisting of two oxidizer and one fuel orifice.

The development of this injector was begun with several simplified designs. In one of these the orifices were drilled parallel to the axis of the motor. This arrangement was unsatisfactory (Figs. 24 and 25), because the propellants did not impinge against one another except as mixed by turbulence in the chamber. At least part of the reason for the failure of this injector was that only six nitric acid and three Tonka orifices were used, and these were spaced too far apart.

Figure 24 presents a plot of injector pressure drop vs. efficiency factor (equivalent to the parameter X) for the P 3378, which was the prototype designation of the 109-548. Although the efficiency appears to increase with the pressure drop, this may well be accidental since the motor does not remain at any given chamber pressure but continually runs down. Test results are, therefore, rather unreliable.

Another experimental injector preceeding the final design provided parallel injection in conjunction with swirl inserts, designed to produce a spray effect. This was an improvement over pure parallel injection, but not as efficient as the final design, in which the swirlers were eliminated in favor of direct impingement. The angles of impingement apparently influenced the combustion efficiency. Orifice angles just less than 45° seem to have been most effective.

The construction of the injector was simplified to the maximum degree. The base piece was cast and machined, the orifices drilled by multiple drill presses, the entrance fittings were welded on, and the entire assembly was welded to the combustion chamber. Since this power plant was for one-time use only, disassembly and inspection were unnecessary, and the all-welded construction was satisfactory. The use of hypergole propellants made accurate drilling of the orifices desirable, though not absolutely necessary, since the hypergoles reacted even when small misalignments were present.

Leakage and corrosion were prevented by covering the holes with a special grease that was blown off when operation started. This precaution was taken to avoid explosion; the Tonka was injected approximately half a second before the nitric acid and there was the possibility that it could get into the nitric acid orifices.

The performance of this injector was not outstanding, but its extreme simplicity and ease of construction appear to have been well chosen. From the standpoint of future development, experiences with the alternate orifice arrangements tend to demonstrate the superiority of impinging over parallel injection.

Regulable Orifice Injector - BMW 109-558

The BMW 109-558 injector was of the typical hypergole type, using nitric acid and Tonka as propellants. Its unusual feature was the arrangement for throttling by shutting off groups of injector holes.

The design details of the 109-558 may be seen in Figs. 30-34. Figure 30 shows the injector assembly. Injection of the propellants was achieved through a circular arrangement of 12 groups of orifices, each containing one Tonka and two acid orifices. The upper end of the orifice holes could be successfully stoppered by the rotation of a spring-loaded shoe actuated by the Mach number regulator. In this way the unit could be throttled by varying the propellant supply.

Although most of the thrust was provided by the ring of orifices, a single, nonthrottlable stage consisting of two acid sprays intersecting with one fuel spray was located in the center. This was apparently intended to maintain the combustion by providing a constant thrust of 132 lb.

The regulable stage could be varied from 132 to 835 lb thrust. Regulation took place as follows. (See Fig. 30.) Through a series of gears from the Mach number regulator, part No. 12 activated gears Nos. 10 and 15. Gear No. 15 rotated the nitric acid control piece (18), and gear No. 10, acting through part No. 7, turned the Tonka regulating piece (21). Both throttling shoes were held flush to the surface by springs (19) and (20). They were arranged so that, as they revolved, they continually varied the number of orifices opened to the flow of propellants, thereby producing a corresponding variation in thrust.

The total number of orifices was 39. Twenty-six were for nitric acid and had a diameter of 0.0748 in.; the remaining 13 were Tonka orifices with a diameter of 0.0354 in. All were drilled so that the streams intersected at a common point. This arrangement had the usual two oxidizer streams intersecting with one fuel stream, but, contrary to the usual design practice, each group of two oxidizer streams and one fuel stream intersected with each of the other groups. This seems relatively inefficient since the combustion takes place at a single point rather than at a number of points around the chamber. However, the common intersection of all of the streams was probably desirable because of the regulator characteristics, which would otherwise make it possible for a fuel stream to intersect with only one or even no oxidizer stream, instead of the usual two, depending on the position of the throttle. The possibility of improper mixing and inefficient combustion was reduced by the method of intersection selected.

The mechanical construction of this injector was fairly difficult. The throttling piece must fit closely to prevent leakage, and all the propellant streams must intersect at a common point. A high degree of accuracy was, therefore, required.

The upper part of the injector was made of a casting and bolted to the lower section. The oxidizer and fuel spaces thereby created were sealed off from each other by seal (16). Seals (14) and (35) prevented the fuel and oxidizer from leaking around the throttle drive shafts.

A major disadvantage of this design is in the lack of cooling provisions for the orifices unused because of throttling. The orifice head was too thick for successful heat transfer from the propellant flowing behind it; hence, the orifice exits were not very well cooled. The importance of this factor was diminished by the fact that the unit was intended for single use only. If the orifices remained intact for the approximately 60-sec life of the missile, they were good enough.

Early versions of this injector were made entirely of cast iron, but the orifices became so corroded that the mixture ratio was completely altered. To remedy this condition while still using a cast-iron head, it would have been necessary to insert steel bushings into which the orifices would be drilled. Rather than go to all this trouble, a high-quality steel injector was used in the final version. Moreover, the deformation of the control parts and the large frictional forces between the control slide and the cast-iron head caused excessive torques and made regulation impossible.

The 109-558 represents an interesting experiment in throttlable injectors. It would appear to be satisfactory if the manufacturing difficulties could be overcome.

Tripropellant Injector - Winkler

The rocket experiments of Johannes Winkler were carried on during the years 1933 - 1939. While few details of his tripropellant injector are available, they are of interest in a general analysis of foreign liquid rocket research because this was the only example encountered of a tripropellant system using water as a coolant in the main chamber.

The Winkler injector was used on a test unit developing a thrust of 220 lb and an exhaust velocity of 6370 ft/sec. The schematic drawing (Fig. 35) shows the arrangement of three concentric rings of holes stepped downstream from each other. Each ring had 24 holes drilled parallel to the axis of the chamber. 5/ The inner ring supplied gasoline; the middle ring, liquid oxygen; and the outer ring, water. Provision was made for an igniter in the center of the injector.

The relatively high performance reported for this unit does not seem to be sustained by the injector details. Truly parallel injection downstream was demonstrated to have very poor mixture and combustion properties. Furthermore, the distribution of the water in 24 holes around the periphery of the chamber must be rather inefficient and requires a relatively large percentage of water.

This injector is of interest as analogous to the rocket work of the American, Dr. Robert H. Goddard, who also used a tripropellant combination. In Goddard's engine, however, the water was injected tangentially on the walls, thereby achieving a better distribution; and the alcohol and oxygen were injected in the form of concentric impinging sprays. Since the exhaust velocities reported by Winkler were of the order of magnitude of those reported by Goddard for a much superior injector, the conclusion is inevitable that Winkler's results were either exaggerated or obtained with another system.

Spray Plate - Peenemunde C-2 (Wasserfall)

The Wasserfall injector was begun in 1942, while the A-4 was reaching its final stage of development. The design of the Wasserfall injector began with A-4 type burner heads and gradually evolved into the spray plate. It, therefore, forms an interesting study of the practical changes that take place in the course of a design sequence and, because of the intensive effort expended by Peenemunde on this type of injector, offers considerable insight into spray-plate design.

Figure 36 shows one of the earliest C-2 designs using three injection heads of the A-4 type. It is not known whether such a unit was actually built and tested with visol and nitric acid, but the next design (Fig. 37) represented a departure in the direction of the spray plate. The three injector heads were combined into a single large unit that contained both oxidizer and fuel-spray nozzles.

5/ APJ reference, No. F 13-47 states that these holes were all approximately 0.04 in. in diameter, but this does not seem to conform with the mixture ratio requirements.

Although the nozzles were retained, they were all in one head and spaced alternately as in the spray plate types. The premixing zones of the injector heads were gone, and the flame front occurred immediately adjacent to the sprays. The welded construction of its predecessor was, however, retained.

In the next version (Fig. 38) the injector reached the first stage of its final form. Eight different hole sizes and arrangements were proposed with the intention of testing for the optimum mixture ratio and pressure drop. Eight circular rows of holes for oxidizer and fuel were drilled in a plate that comprised the head of the combustion chamber. The rows were spaced in four groups of two each. In the first, third, and fourth groups (counting from the inside), oxidizer streams from adjacent holes impinged against each other, as did the fuel from adjacent holes. In the second group the holes were arranged so that two oxidizer streams impinged against one of fuel. This group was to maintain ignition, whereas the other three were intended for atomization. This arrangement of ignition holes was maintained throughout the design sequence.

The reason for atomizing the propellants by spraying them against their own kind rather than against the opposite component was to avoid ignition at the point of impact, because the resulting gases could drive the remaining propellants apart before they were thoroughly atomized. The motion of the combustion gases from the ignition group caused a swirling of the atomized propellants from the other three groups so that they eventually contacted each other in a mist.

Experience with this version led to an attempt in the next (Fig. 39) to improve the ignition. Twenty-four centrifugal spray nozzles were inserted for ignition purposes, 12 for oxidizer, and 12 for fuel. The other propellants were injected as before.

The succeeding version reverted back to an injector similar to that in the first version. (See Fig. 40.) The number of holes was increased to 324 for fuel and 432 for oxidizer. The holes ranged around the combustion head in 12 circular rows, grouped by twos as in the first version. Four of the groups impinged against each other and two were used for ignition. These groups were arranged as follows:

Group No.	Purpose
1	Atomization
2	Ignition
3	Atomization
4	Ignition
5	Atomization
6	Atomization

The following version (Fig. 41) attempted to determine whether the distance between holes had any effect on the injection qualities. Therefore, the number, diameter, and arrangement of holes in this injector were identical with the preceding one except that the size was compressed to about three-quarters of the original.

In the next injector (Fig. 42) the number of double rows was again six but only one was used for ignition purposes. Also, improved material was used and the thickness of the plate could be decreased. This change proved to be advantageous since it saved not only weight but also considerable manufacturing time. It was also the first completely solid-plate injector, without any material taken out of its center. All the feed holes drilled in through the side were dead-ended.

The first production injector in the series (Fig. 43) differed from the previous one in that the holes were concentrated more in the center than in the outer rings. Again, two rows of holes were used for ignition. This version was assigned a production number and also a weight was calculated.

The final production of the Wasserfall injector sequence (Fig. 44) represented radical innovations from the standpoint of both design and manufacture. Ignition was no longer accomplished by impinging the propellants but, rather, by intersecting flat sprays of the fuel with streams of the oxidizer. Furthermore, while the use of holes was retained for the injection of oxidizer and some of the fuel, most of the fuel was injected in flat sprays. Flat sprays represented an innovation requiring extreme accuracy of manufacture, since the hydraulic characteristics of the spray slot vary with the dimensions. The extremely small sizes (0.031 in. by 0.0197 in. and 0.0354 in.) required highly accurate machining operations.

In the simplified manufacture of this injector the body was cast and grooved. The next step was to machine the openings for the fuel sprays and to drill the necessary fuel holes. The opening in the center was then threaded and the piece again finish-machined to fit the motor. The center plug was inserted into the body and the holed oxidizer insert pieces were fitted into the milled slots in the grooves.

Attention should be called to an ingenious method of reducing the rejection rate and simplifying manufacture. Figure 44 shows that the oxidizer holes were drilled separately on insert plates and slipped into place. This made it possible to obtain well-machined sets of inserts and, hence, a good hole arrangement . Although no manufacturing details are available, it appears probable that leakage around the slots was prevented by the use of a shrink or press fit.

This injector is pictured in Fig. 45 after a run. The face is seen to be scored, but the various fuel and oxidizer openings appear to be intact. Since this injector was intended for one-time use, the scoring should not appreciably affect its performance.

Although the injector described above was satisfactory, other proposals were advanced to improve the design. One of these (Fig. 46) was a cascade type, where the oxidizer was injected through orifices in a series of steps and impinged against the fuel coming in at right angles to it. The mixture then impinged against deflector plates so as to improve the atomization and mixing. This design offers an interesting arrangement, but the cooling problem would probably have been very serious.

Another proposal (Fig. 47) represents a simplification and development of the idea proposed above. Fuel and oxidizer were impinged against themselves for atomization. Ignition was initiated by spraying a small amount of oxidizer and fuel against a deflector plate in the center of the injector. The major part of the propellants was atomized by their being impinged against themselves and the resulting streams were directed against a deflector plate for further atomization and mixing. This proposal was never constructed because of the conclusion of the war.

The last proposal located for the development of the Wasserfall injector (Fig. 48) was made in January 1945. The novelty of this arrangement consisted in the use of an impact plate against which the ignition group was to impinge.

Although the drawing number indicates that this design represented the early stages of a proposal, it is of interest since it shows that the Peenemunde designers felt it possible to place a deflector plate and its supports some distance downstream from the injector. Two possibilities may be conjectured: first, the deflector plate would survive long enough to establish a smooth ignition and then burn away, or, second the flame front would be beyond the deflector plate surface and, hence, would not be exposed to destructive temperatures.

Certain details of this arrangement from the drawing are worth detailed comment. The ignition deflector plate is a ring held by a number of sheet-metal supports and is located 0.6 in. downstream from the injector face. A second deflector plate consists of a tapered ring arranged along the outside of the injector periphery and inclined inward at a 30 angle. Its outer edge is approximately 1.1 in. from the face plate. While it would appear that the ignition deflector is in danger of burnout, the outer one appears to have a better chance of enduring throughout the run. Unfortunately, this arrangement was never built and, hence, no test data are available.

The above design sequence permits the examination of a series of changes in foreign injector development. In this case it would appear that two leading factors were involved: the improvement of ignition and the improvement of atomization. Since no test data have been located, definite conclusions cannot be drawn, but the continuing modifications make it appear that the plate injector did not offer a satisfactory design.

In addition to manufacturing difficulties requiring accurate finish of a multiplicity of small orifices and passages, the spray plate also required extremely good distribution. It may well be that the arrangement in which approximately three-quarters of the propellant impinges on itself for atomization, while only approximately one-quarter of the propellant ignites directly on issuing from the spray plate, may be at fault. It will be noted that successful BMW injectors impinged all of the fuel on all of the oxidizer, thereby reporting a better velocity. This conclusion must, however, be confirmed by test results before being regarded as conclusive.

Cup Injector for "Cold" Reaction - HWK 109-507

The HWK 109-507 injector was intended for application in a "cold" motor. Inasmuch as hydrogen peroxide and liquid catalyst react quite completely if given time for thorough mixing, injector design may be considerably simplified.

The operation of the cup type injector for the 109-507 may be followed from Fig. 49. Catalyst was injected through line (B) and impinged upon impact plate (C), which atomized the catalyst to some extent. The hydrogen peroxide was injected through a series of holes in an atomizing cup (D). Both propellants then mixed in the mixing cup (E).

The method by which the catalyst was injected caused it to tend toward one side of the cup after bouncing back from the impact plate. Moreover, since the catalyst came through a relatively large opening and was dependent for atomization upon the force with which it hit the impact plate, atomization was usually far from complete. This was, therefore, not very satisfactory.

Consequently, swirl vanes had to be provided in the chamber as an additional aid to mixing and atomization. The presence of these vanes tended to keep the propellants in the chamber for a longer period, thereby allowing more time for mixing to take place. It will be noted that the use of swirl vanes was possible only because of the low chamber temperature produced by the hydrogen peroxide reaction. Other propellant combinations would have caused the vanes to burn out before the end of the run.

Despite the crude arrangement, the velocity efficiency factor X calculates to 0.825 (theoretical value: 3780 ft/sec; test value: 3175 ft/sec), confirming the impression that simple injectors are satisfactory for use in a cold reaction if the turbulence and stay time are adequate. Furthermore, the relatively low temperature of the reaction makes it possible to take liberties in design which are not permissible with other propellants.

The HWK 109-507 injector was the standard type developed by Walter for the hydrogen-peroxide, liquid-catalyst combination, and was also used on the HWK 109-500, 109-501, 109-502 as well as in steam generator applications such as the A-4. It appears to be quite satisfactory for this purpose.

Counterflow Injector - Peenemunde A Series

The counterflow injector represented an initial stage of the Peenemunde development, and variations of its basic form were used in all of the early A series as well as in the early B series JATO. Specifically designed for alcohol and liquid oxygen, it embodied a number of theories which had been developed in prototype research carried out by various private contractors and universities participating in the Peenemunde program.

The counterflow injectors were specialized cases of the individual intersecting orifice type combined with the orifice-spray type. They are in a category by themselves because either one or both of the propellants are injected in a direction that is opposed to the flow of the combustion gases. This was done in order to preheat the propellants and ensure efficient atomization.

In the first versions of the counterflow injector, used in the A-1 and A-2 (Fig. 50), the resultant direction of both propellants was toward the head of the chamber, with the fuel on the outside and the oxidizer on the inside. The fuel was injected at three points around the center of the chamber, through an orifice injector that consisted of a flat piece with straight holes drilled in it. The fuel flow was toward the center of the chamber in the direction of the head. The oxidizer, injected through a number of holes, impinged against a holed deflector that allowed part of it to pass through while the remainder was deflected toward the head of the chamber.

The ineffective atomization of the oxidizer, coupled with the location of the fuel injectors midway in the chamber, was probably responsible for the poor results of this method. As soon as combustion started, a large proportion of the fuel could be blasted out of the chamber before coming into contact with the oxidizer. In addition, the position of the fuel injectors made the combustion very susceptible to zoning, so that large amounts of oxygen could also remain unburned.

In later designs the oxygen was injected through orifice cups similar to those in Fig. 51. The cups were spaced around the head of the chamber and injected the oxygen in the direction of the nozzle. An attempt was also made to improve the atomization of the alcohol (Fig. 52) by injecting it through an inner and an outer tube, thus producing annular sprays. The two resulting sprays impinged against each other before coming into contact with the oxygen.

It is to be noted that in this new design the position of the fuel and oxidizer was reversed. The alcohol is now in the center and the liquid oxygen on the outside. This was done because the combustion heated the entire center pylon, so that if liquid oxygen were injected through it, the oxygen would become partly vaporized before being injected, and result in a varying mixture ratio. A disadvantage of putting the liquid oxygen on the outside was that it impinged against the heated walls of the chamber and could easily cause them to burn out if they were inadequately cooled.

This method of injection was retained in succeeding designs, but the following modifications were tried. The alcohol passed through a number of spirals and emerged in four spray cones. (See Fig. 53.) This improved the atomization but did not solve the distribution and mixing problems. As shown in Fig. 54, therefore, four conical sprays were arranged in the same plane, instead of in concentric circles as in the previous design. In this case there was one fuel spray for every oxidizer spray, but the mixing and distribution, although improved, was still poor.

In the next two designs (Figs. 55 and 56) self-capping injectors were attempted. In Fig. 55 the injector was so designed that parts (1) and (3) were fixed members and parts (2), (4), and (5) were movable. The injector is shown in a closed position. At the start of operation, parts (2) and (5) are moved down, thereby opening slot (A). Slot (B) remains closed by the action of spring (6), holding piece (4) flush with piece (3). It is believed that slot (B) opens by the force of the propellant when flow starts, and acts as a means of regulation.

In Fig. 56 parts (1) and (3) are the moving parts and part (2) is fixed. When parts (1) and (3) are moved in the direction of the nozzle, a slot is formed between parts (2) and (3), allowing a conical fuel spray to emerge and be injected toward the head. The slot is shut when cutoff if desired. Neither of the above designs offered any improvement over their predecessors.

One of the next designs tested was for a 44-lb thrust prototype (Fig. 57) of the A-3 injector. This arrangement brought the alcohol down the central pylon and injected it upstream against a deflector plate. The oxygen entered through a series of parallel holes drilled in the head plate. A portion of the oxygen struck the deflector plate and was intended to cool it, while the remainder passed directly downstream. The fuel holes were held small to insure a high injection velocity, permitting the alcohol to move against the stream of combustion gases and strike the impact plate.

This design had very poor mixing qualities and, consequently, poor performance. Furthermore, since unburned oxygen was constantly directed against the hot impact plate, the danger of burnout was always present.

The final design used in the A-3, A-5, and early B units was an improvement of the earlier counterflow injectors. The alcohol-injection pylon was retained, but the deflector plate was omitted. Atomization of the oxygen was improved by arranging six individually supplied oxygen sprays around the head of the chamber.

While the same mechanical design was retained in the A-5 as had been used in the A-3, the radical change was made of injecting the liquid oxygen through the pylon and entering the alcohol through the head sprays. This was probably done because it was easier to keep the pylon cool than the walls of the chamber. Hence, the danger of burnouts was somewhat reduced. Nevertheless, the problems of atomization and pylon cooling were not satisfactorily solved. The A-5 performance was somewhat better than that of the A-3 and the factor X was improved from 0.60 to 0.72.

Exhaustive tests disclosed that the counterflow injector did not improve performance and the pylon became progressively shorter in further test versions. The counterflow principle was completely abandoned with the later B series. However, the general arrangement of orifice sprays may be recognized in the burner head used in the A-4.

The use of counterflow injectors does not appear to be fruitful as a means of improving performance, since the predicted flow conditions in the chamber are rarely realized because of turbulence, heat transfer, and local gas velocity. Accordingly, it does not appear worthy of further development.

Burner Head Development - Peenemunde B Series

This series of injector design is of great interest as the forerunner of the A-4. Through many design changes that were based on experiments rather than theory, the exhaust velocity increased from 5250 ft/sec in the B-7, to 5850 ft/sec in the B-8, and up to 6000 ft/sec in the B-8a. The propellants used with these injectors were liquid oxygen and alcohol, and the thrust of the units was 2200 pounds.

Figures 59 and 60, respectively, show one of the first designs of this injector head and a photograph of a typical example of this sequence. The injector consisted of a holed cup that sprayed the liquid oxygen into the chamber, and four rows of fuel nozzles screwed into the walls of the chamber head, that sprayed alcohol. These fuel nozzles were of two varieties. One type (Fig. 61) was used for cooling and had tangential entries that imparted a centrifugal motion to the fuel, causing it to be injected in a hollow conical spray. This type was in the row nearest the oxygen cup in order to keep the cup and head cool, and in the row at the exit of the injector head in order to keep the chamber cool. The other type of fuel nozzle (Fig. 62) had three radial entrances and one vertical that caused the fuel to be injected in solid streams intended for combustion with the liquid oxygen. This type was in the two center rows of nozzles.

The liquid-oxygen injector cup contained a built-in cutoff valve as a safety feature. The valve was in the form of a poppet that was spring-loaded shut in order to prevent liquid oxygen from dribbling into the chamber after cutoff. The most important feature of this valve was not in its cutoff properties but in its regulating action. It was so designed that, when the propellant flow started, the pressure of the propellant would overcome the spring force and push the poppet open. This allowed the propellant to enter the chamber, where combustion took place and pressure built up. This pressure could enter a port in the bottom of the liquid-oxygen injector cup and act on the underside of the poppet so that it was held open by a force equal to that exerted by the liquid-oxygen pressure minus the spring force minus the force exerted by the chamber pressure. For this unit, this equaled a pressure difference of approximately 14-25 psi.

Therefore, if the chamber pressure increased 14-25 psi above its normal value, the force on the chamber side of the poppet would overbalance the force on the injector side and the poppet would close. This would cut the liquid-oxygen flow and the chamber pressure would drop, thereby allowing the poppet to reopen. It is entirely probable that this arrangement would produce poor combustion, since it could set up pulsations of supply which might build up. In addition, the poopet was guided only at the chamber end; therefore, it had an undesirable tendency to stick.

In the next design (Fig. 63) the valve construction was improved so that the poppet was guided at two points. The arrangement of the liquid-oxygen holes was also changed (Fig. 64) so that all the liquid oxygen was sprayed horizontally against the walls of the injector head. The theory was that the streams would hit the walls, further atomize, and then be deflected in the region of the alcohol streams. The alcohol nozzles remained the same except for slight changes in size. The arrangement of the rows was changed to provide additional cooling at the injector-head exit, accomplished by changing one of the rows of orifice nozzles to a row of spray nozzles.

The rest of the B-7 designs all remained basically the same as the previous one, except for slight modifications in the size and design of the fuel nozzles. During this period, work started on the B-8 model. The injector for this unit was almost identical to the B-7 versions, except that the fuel entrance was also provided with a cutoff valve. (See Fig. 65.) This valve consisted of a rubber diaphragm that was fitted all around the injector and covered the entries to the fuel nozzles. During normal flow the diaphragm was forced open by propellant pressure. When cutoff was desired a pressure greater than the fuel pressure was applied on the opposite side of the diaphragm, so that it was forced down on the fuel nozzles and cut off the fuel flow.

To use this valve, a new fuel nozzle had to be designed that would have its entrance flush or below the seating surface of the diaphragm. This was accomplished by using spiral inserts to rotate the flow and plain orifice nozzles for straight injection. (See Figs. 66, 67, and 68.)

The liquid oxygen valve was the subject of the next major design change. (See Fig. 69.) The poppet was replaced by a spring-loaded ball. However, it is open to the same fundamental objections as its predecessor. The general arrangement of spray holes, which is also characteristic of the A-4 burner head, is retained.

The design of the B-8a (Fig. 70) brought about further changes in the fuel nozzles and in the liquid-oxygen injector and valve, resulting in improved operation of the valve and of fuel injection. The unsatisfactory spiral inserts of the B-8 were replaced by going back to tangential entry for the cooling nozzles and radial entry for the other nozzles.

The next B-8a design (Fig. 71) was carried through to the final production version, Rl-1016. (See Fig. 72.) It represents an almost complete shift in design philosophy. The entire arrangement of injector control, an arrangement so laboriously worked out in the earlier version, was abandoned. The new design is of the spray-plate type, analogous in principle to those discussed for the Wasserfall. It is worth noting that Peenemunde actually contemplated using the same type of injectors for both anergole and hypergole combinations. In view of the considerable success of this design, some doubt is cast on the validity of theories which hold that there is a fundamental difference in requirements for anergole and hypergole injection systems. This conclusion is, however, qualified by the absence of exact details regarding the arrangement of the holes in the spray plate. The preceding discussion on the Wasserfall displays the importance of even small changes in orientation, alignment, and patterning in determining performance. Accordingly, the foregoing deduction must be subject to review in the light of further testing.

The fuel injection system of this B-8a design provides several points of interest. Figure 72 shows that the fuel is not permitted to enter directly into the chamber from the jacket, but first passes through a push-pull valve, which can be set up to either open or close the system. The extreme ruggedness of the seals is noteworthy, as well as the simple arrangement used to align the tolerances in the poppet-piston connection. An additional feature of this fuel injection system is the location of a ring of holes set around the periphery of the injector head to provide cooling. The oxygen injection is conventional for the Peenemunde spray plate.

The constructional details of this injector, with its complicated configuration of the main body and the complexity of machining and welding, should be noted. Apparently, the oxygen injector chamber (L) was turned on a lathe and then the lip (M) was spun over. An extensive degree of milling was required to form the receivers for the oxygen inlets, pressure tap, and fuel valve.

In summary, the B-series displays the genesis of two leading tendencies in Peenemunde injector design: the highly efficient burner head used in the A-4, and spray plate which was attempted in the Wasserfall.

Composite Orifice-Spray Injector - A-4

The A-4 injector was the end product of an extensive and lengthy development program. It evolved from research begun as early as 1936 and was carried out not only at Peenemunde but at various universities and research institutes. Although it was not entirely satisfactory from the viewpoint of fabrication, its performance was extremely good. Exhaust velocities were variously reported from 6320 ft/sec to 7120 ft/sec.

The A-4 injector assembly was composed of 18 burner heads, each consisting, in effect, of an individual injector. In part, this was the result of A-4 prototype development, which proceeded on a 3080-lb thrust unit. When the required thrust for the A-4 was set, it was a relatively simple matter to combine the requisite number of these 3080-lb thrust injector units.

The operation of the burner head was based on the principle that the various streams of propellant need not intersect with one another; rather, they were injected into the burner head area in quantities sufficient to permit thorough mixing to take place before entering the flame front. It was stated, without experimental proof, that the flame front lay within the combustion chamber, at the mouth of the burner head. Combinations of simple and centrifugal orifices were used to secure maximum mixing and atomization of the alcohol. The oxygen was, in all cases, injected into a many-holed atomizer cup, very much as in a shower head. (See Fig. 73.)

The experimental development described above, beginning with the counterflow injectors of the early A series and proceeding through the Peenemunde JATO development, was continued on a 3080-lb thrust prototype. (See Fig. 74.) To simplify experimentation, the injector head of this prototype was bolted to the rest of the chamber and provisions were made for a replaceable oxidizer cup and for individual alcohol orifices and spray nozzles.

With the successful completion of tests on the prototype unit, the feasibility of using a multiplicity of such heads for any desired thrust was tested on an experimental motor using three equally spaced burner heads. (See Fig. 75.) This proved successful, and so the third stage was to build a complete A-4 motor using 18 heads. (See Fig. 75.) In this series the Germans went successively from 3080-lb thrust to 10,240-lb and then to 55,000-lb thrust.

In the final design (Fig. 82) the burner heads were arranged in two concentric rings, the outer ring containing 12, and the inner ring 6 injector assemblies. A variety of other arrangements was tried. Figure 77 displays a case in which the injector heads were arranged around the periphery of the combustion chamber with their inner surfaces merged. The fuel nozzles are to be found throughout the whole chamber head, and were apparently intended for both cooling and combustion.

Although no test results are available, it does not appear to have been too happy a choice. Much of the fuel injected from the center of the head would probably have remained unburned on leaving the chamber. Furthermore, the location of the flame fronts would have been somewhat unsatisfactory from the standpoint of cooling.

In all early units the injection cups consisted of five rows of screwed-in nozzles (an arrangement very much like that shown in Fig. 86). The highest row was designed as a spray for cooling purposes and was of the type shown in Fig. 80a. It had two tangential entry points that caused the alcohol to emerge as a highly atomized spray. The next two rows of alcohol injection nozzles were intended solely for combustion and consisted of simple, drilled orifices, so that the fuel entered in solid streams. The fourth and fifth rows, of the type shown in Figs. 80b and 80c, were designed for both cooling and combustion. These differed from the upstream spray orifice in the use of a large exit opening, which caused the resultant spray to have a wide angle. Auxiliary holes were also drilled in rows 4 and 5 to inject fuel in solid streams. Furthermore, the tangential fuel entry into the spray insert was supplemented by a hole drilled coaxially with its exit. (See Figs. 86d and 86e.) This would tend to make the fuel spray more "solid."

The entire arrangement was determined by trial and error. Various positions and designs were tested before the final design was settled. A basic rule of thumb used was "Wherever the injector wall burns out, insert additional cooling nozzles."

The foregoing description is fundamental for the A-4 burner head. However, several details were changed during the development process. For example, it was realized that economies could be achieved if the simple orifices were drilled directly through the walls instead of being first placed in inserts which were then threaded in place. In another design (Fig. 81, area M) the number of alcohol rows was cut down to three by combining rows (B) and (C) of Fig. 86 into one. This changed the injector characteristics unfavorably and in the next version (Fig. 82, area N) the old arrangement of five alcohol injection rows was used. Since orifice nozzle inserts were not required for rows (B) and (C), it was possible to reduce the wall thickness, as shown in area (O) of Fig. 83.

The brass oxygen atomizer cups were screwed into the top of the burner head and fed by individual supply lines fastened to external nipples. Figure 73 presents the detail arrangement and dimensions of the holes. A series of flat faces was machined on the oxygen spray so that the injection holes could be drilled perpendicular to the face, thus maintaining a true circular exit cross section for the orifices and, hence, reliable flow coefficients. Manufacturing considerations also played a part in this decision, since it would be extremely difficult to locate holes accurately on the curved surface. The general arrangement of the oxygen head and its orientation to the alcohol may be seen in Fig. 84 with special reference to points (4), (5), (6), and (7).

The details of the final assembly may also be noted from Figs. 84 and 85. Structurally, the head consisted of a series of three successive welded shells which, respectively, formed the inner wall of the combustion chamber, the jacket for regenerative cooling, and the plenum chamber for the alcohol. The excellent performance of the A-4 injector assembly was partly due to the fact that unburned particles passing downstream from the flame front of an individual burner head had a high probability of reacting with other unburned particles from the other heads, thereby obtaining a more complete combustion. This accounts for the superior performance of the A-4 injector as compared with the B series, which used only a single-burner head.

Variations due to manufacture were frequently considerable, and each A-4 combustion chamber was proof-tested before shipment, although the sheet metal structures were susceptible to subsequent corrosion. The manufacturing difficulties encountered with the large amount of welding led Peenemunde to search for improved arrangements. Suggestions were made to use spray plates similar to those in the Wasserfall, and one of these is shown in Fig. 87. However, nothing came of them.

Military application was influenced by the susceptibility of the injector to clogging when particles of rust would break off from the welds on the sheet metal walls. This resulted in a requirement that the A-4 be fired, if possible, within two weeks of manufacture. Interrogation of German personnel regarding the most probable cause of A-4 failures elicited the opinion that the rust hazard was predominant.

The A-4 injector is not readily susceptible to disassembly. However, this requirement is not important in the case of a missile, if adequate preflight test procedures are carried out. In part, this was achieved by providing for field testing of the injectors with special equipment, and by providing a shutoff control during the launching period in case of unsatisfactory combustion (Vorstufe).

In summary, the A-4 injector may be regarded as an outstanding example of a high-performance injection system. Much was learned in its development that would appear capable of further application.

SUMMARY AND CONCLUSIONS

The foregoing analysis of foreign injector development confirms the importance of step-by-step development as the outstanding practical means of improving injector performance. It also discloses the considerable problems which must be overcome in the practical fabrication of injectors. The over-all importance of high combustion efficiencies and low specific propellant consumption has long been recognized. Actually, the importance varies with the impulse of the system, systems of low impulse resulting in a lower penalty from inefficient combustion than those of high impulse.

Table 1 presents a summary of foreign liquid-rocket injectors. The exhaust velocity values quoted as "actual" are the maximum reported. Accordingly, a degree of exaggeration is possible depending on the instrumentation and optimism of the test engineer. The values for Peenemunde, BMW, and Walter may be expected to be fairly reliable while those for experimental injectors should be regarded with greater caution. 6/

The relative success of the different injectors with reference to performance may be judged by the use of the parameter X (covered in detail in APJ Report No. 51-0-12A, Vol. I), corresponding to the ratio of the actual to the theoretical exhaust velocity. The range of X runs from a low of 0.555 for the RII-203b to 0.95 for the A-4. These values must be considered in the light of evidence that widely varying exhaust velocities were reported for the same engine, depending on the chamber pressure, mixture ratio, accuracy of instrumentation, and accidental factors.

An interesting feature of this table is the disclosure of the progressive improvement which may be achieved with the same basic type of injector. For example, BMW improved the efficiency of their hypergole, orifice-type injectors from X = 0.782 in the 109-548 to X = 0.85 in the 109-558. Similarly, Peenemunde was able to improve their anergole burner head systems from relatively poor beginnings to X - 0.95.

Unit	X
B-7	0.75
B-8	0.835
B-8a	0.855
A-4	0.95

6 For example, the high exhaust-velocity values quoted by Saenger were questioned by various German engineers who claimed that they had been exaggerated.

These improvements may be taken as roughly indicating the possibilities of intensive research. It will be seen that BMW improved their performance by approximately 10%, while the corresponding betterment for Peenemunde was 25%.

Of the 30 injectors covered by Table I, 20 were predominatly orifice and 10 were spray. Neither type is associated with a single propellant combination or range of thrusts. For example, liquid oxygen-alcohol was successfully burned in both orifice plates and spray burner heads, although orifices appeared to be less efficient. On the other hand, hypergole injectors were developed for both sprays and orifices. The alternative types are found through the entire range of thrusts, with recourse being had to a multiplicity of either sprays or orifices as the thrust increases.

Table I also calls attention to an additional parameter of interest in injector design, i.e., the injector pressure drop. Peenemunde worked with lower injector drops than either Walter or BMW. Apparently, 20-50 psi was regarded as entirely reasonable by Peenemunde, while BMW and Walter preferred drops up to 200 psi.

Several unusual values were located. The Saenger injector represents an extreme case with a drop of 710 psi. However, the entire Saenger system is atypical in its basic design parameters. Similarly, the 1200-psi pressure drop reported for the 109-548 is merely the initial pressure drop and arises from the thrust/time program of the system rather thanfrom any considerations of efficiency.

Manufacturing considerations played a considerable part in determining injector selection and design. Inasmuch as most of the designs were ultimately planned for mass production, the factors of reproducibility and relative cost naturally played an important role. All of the leading foreign rocket organizations made efforts to simplify their injector construction. The spray plate was advantageous in this regard since the production operations could be highly mechanized. On the other hand, spray injectors usually required individual attention and finishing of subassemblies. This accounts for the efforts made by Peenemunde to redesign the highly efficient A-4 burner head and substitute, instead, rings and spray plates. In some cases even performance was sacrificed to make simplified fabrication possible.

The detail mechanical design of injectors was also influenced by manufacturing considerations. The design histories of the 109-548 and the B series are cases in point. In the final analysis the injector, in common with other parts of the rocket engine, must show the influence of mission as a primary or a secondary factor in determining the design characteristics, although the injector is subject to fewer compromises and, hence, is less influenced by this factor than are other engine components.

The analysis discloses that it is relatively easy to achieve a moderate performance with almost any type of injector, but efficiencies beyond 90% are obtained only through a close study of test results and a full utilization of all design possibilities.

TABLE I
SUMMARY OF FOREIGN INJECTORS

Model Number	Type of Injector	Fuel	Oxidizer	Propellant Type 1/	Thrust (lb)	Chamber Pressure (psi) 2/	Pressure Drop (psi)	Velocity (ft/sec) Actual	Velocity (ft/sec) Theo.	X $\frac{Vel_{act}}{Vel_{th}}$
109-507B	Orifice	T-Z	-	H	1320	270	-	3420	4070	.84
109-509A-2	Spray	C	T	H	330-3740	300	-	5830	6480	.90
RII-203B	Spray	T-Z	-	H	330-1650	270	-	3670	6620	.555
RI-210B	Orifice	E	SM	H	2200-4400	-	192	6210	-	-
109-501	Orifice	B Br Z	T	H	2200	300	-	5380	-	-
P 3370	Spray	C	T	H	2200	370	-	3960	-	-
P 3373	Spray	M	S	A	3300	284	199	5900	-	-
P 3374	Spray	M	S	A	1320	426	-	5900	6750	.875
109-548	Orifice	R	S	H	66-308	496	-1200	5670	7250	.782
109-558	Orifice	R	S	H	132-835	426	85	6120	7200	.85
109-718	Orifice	R	S	H	2750	425	50-70	6280	7020	.895
P 3390A	Spray	M	S	A	660-3300	570	100-170	6540	6890	.95
P 3390C 3/	Orifice	R	S	H	330-1100	-	-	-	-	-
P 3390C 4/	Orifice	R	S	H	2970-4400	-	-	-	-	-
E-4	Orifice	V	S_v	H	2200-4400	470	85	5830	-	-
Rheintochter	Spray	V	S_v	H	3740-5060	270	43	5860	-	-
B-7	Orifice	M	Lox	A	2200	142	42	5250	7000	.75
B-8	Orifice	M	Lox	A	2200	142	42	5860	7000	.835
B-8a	Orifice	M	Lox	A	2200	142	42	5990	7000	.855
C-2	Orifice	V	S_v	H	12,100-17,600	280	28-42	5900	-	-
A-2	Orifice	Alc	Lox	A	660	-	-	4540	7500	.605
A-5	Orifice	Alc	Lox	A	3300	-	-	5380	7500	.72
A-4	Orifice-Spray	Alc	Lox	A	16,000-59,600	206	20-40	7120	7500	.95
A-5II	Orifice	Alc	Lox	A	3300	-	-	5700	7500	.76
Beck	Spray	Alc	Lox	A	2200	206	21.0-42.5	6150	7500	.825
Beck	Spray	Alc	Lox	A	55,200	206	71	6090	7500	.81
Taifun	Orifice	V	S	H	1320-2200	440	-	5040	-	-
109-513	Orifice	Alc	Lox	A	1340	213	-	5900	7510	.785
Winkler 5/	Orifice	Br	Lox	A	220	292	-	6375	7780	.82
Saenger	Orifice	B Oil	Lox	A	2200	515	710	7850	8350	.94

1/ A Anergole; H Hypergole
2/ All values are maximum quoted
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4/ Climb Chamber
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[32]	Cole, R. A.	See Ref # 12	
[33]		A Summary of German Rocket Power Plants U.S. Naval Technical Mission in Europe Tech. Rpt. No. 194-45 1945 APJ No. 13-41	
		Available from CADO	ATI-4005
		WINKLER	
[34]		Interview of Johannes Winkler Regarding Liquid Propellant Rocket Units Luftfahrtforschungsanstalt CIOS Target No. 4/167 1945	
		Available from CADO	ATI-53881
		WASSERFALL	
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[37] Wolf	The German Guided Missile Hs-293 AMC Summary Report No. F-SU-1129-ND 1947	
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A-4

[38] Kindermann Poewer	A-4 Geraetebeschreibung (Baureihe B) (A-4 Manual (Model B)) Heeres Versuchsanstalt Peenemunde 1945 FE 661 APJ No. A-9-43	
	Not available from CADO	
[39]	Report on Operation "Backfire" Volume II 1946	
	Available from CADO	ATI-87

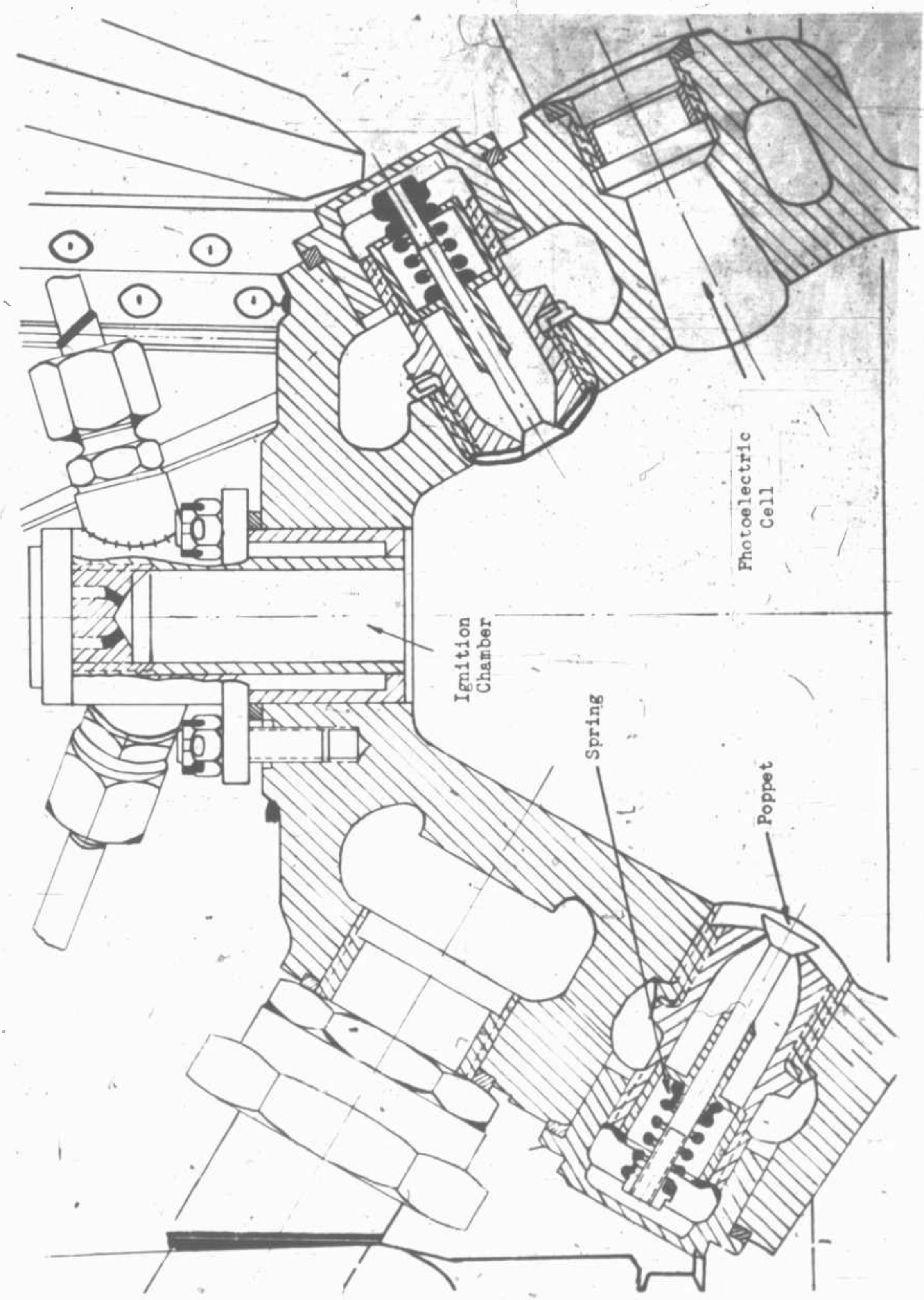


Fig 1 - Head of Combustion Chamber P 3390A Showing Injector

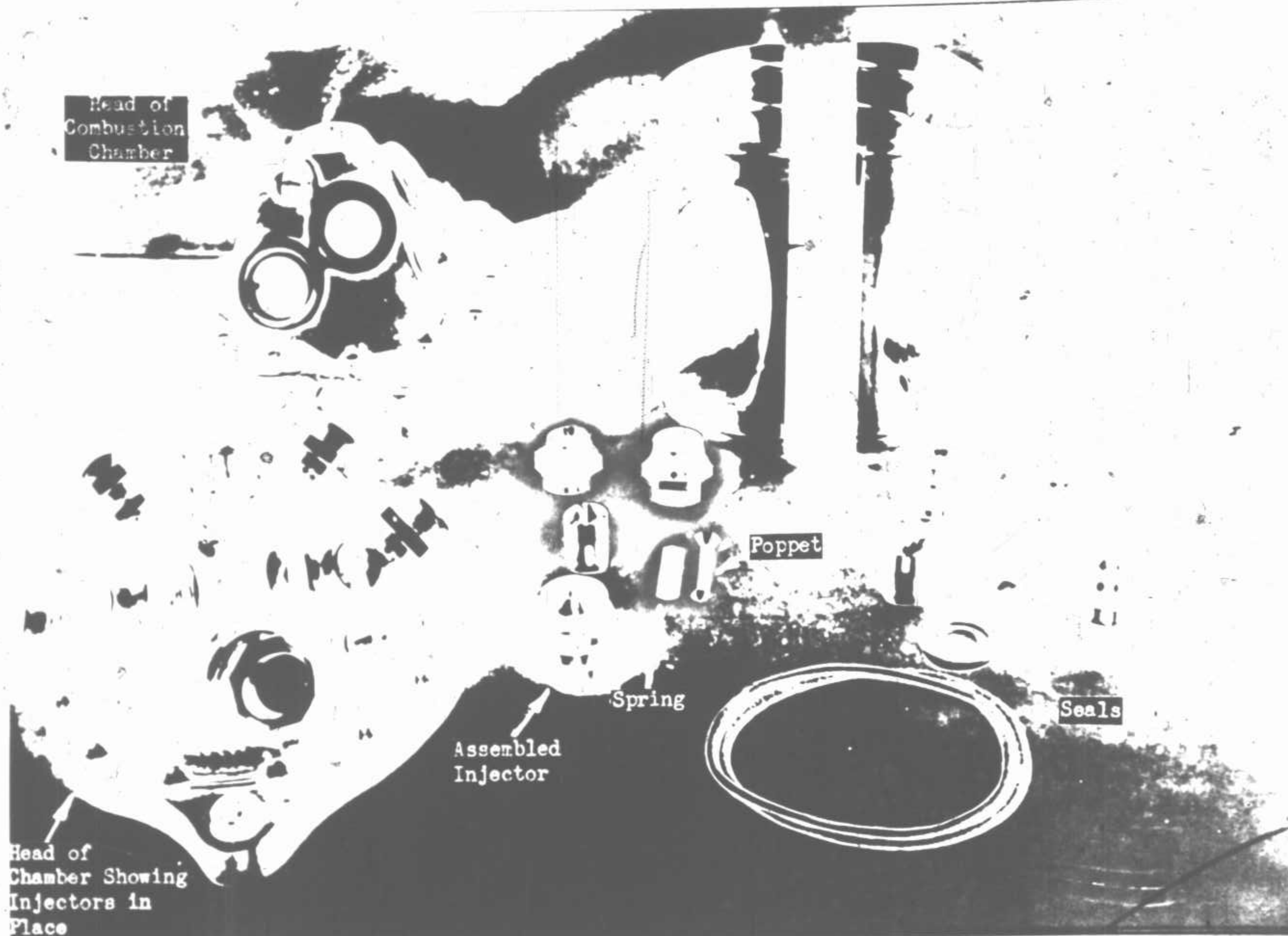
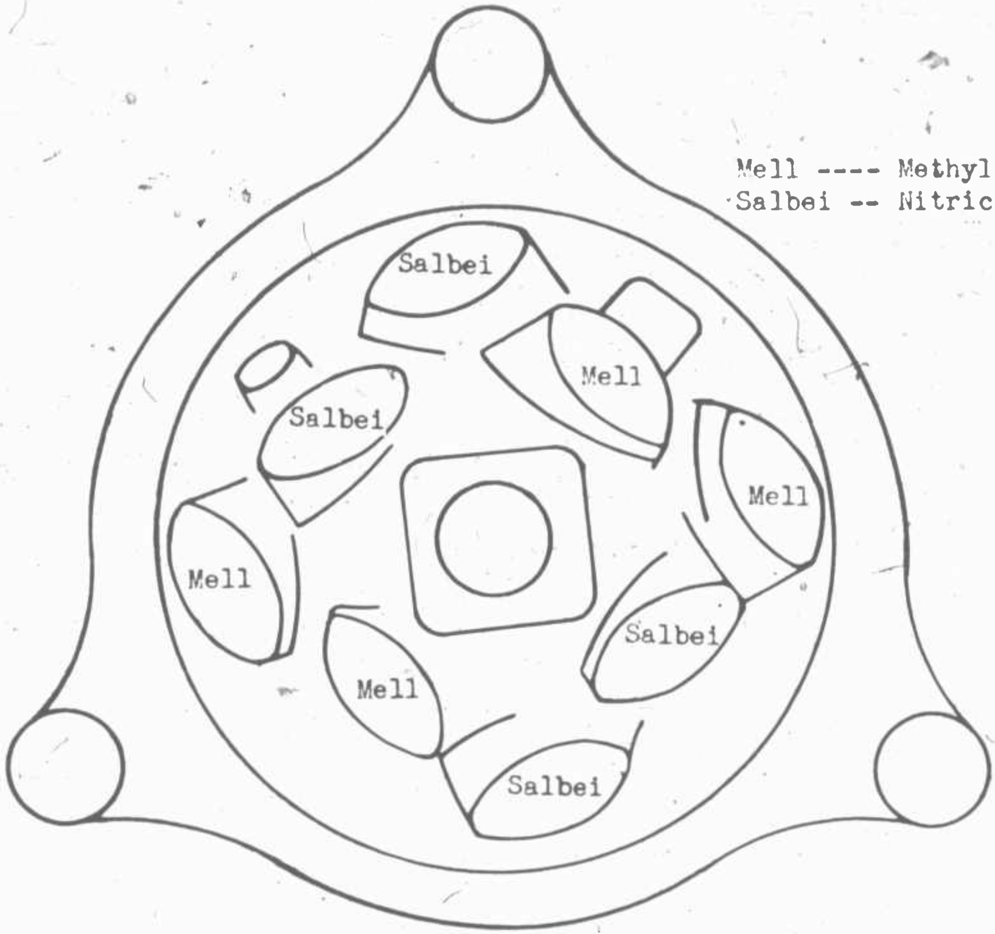


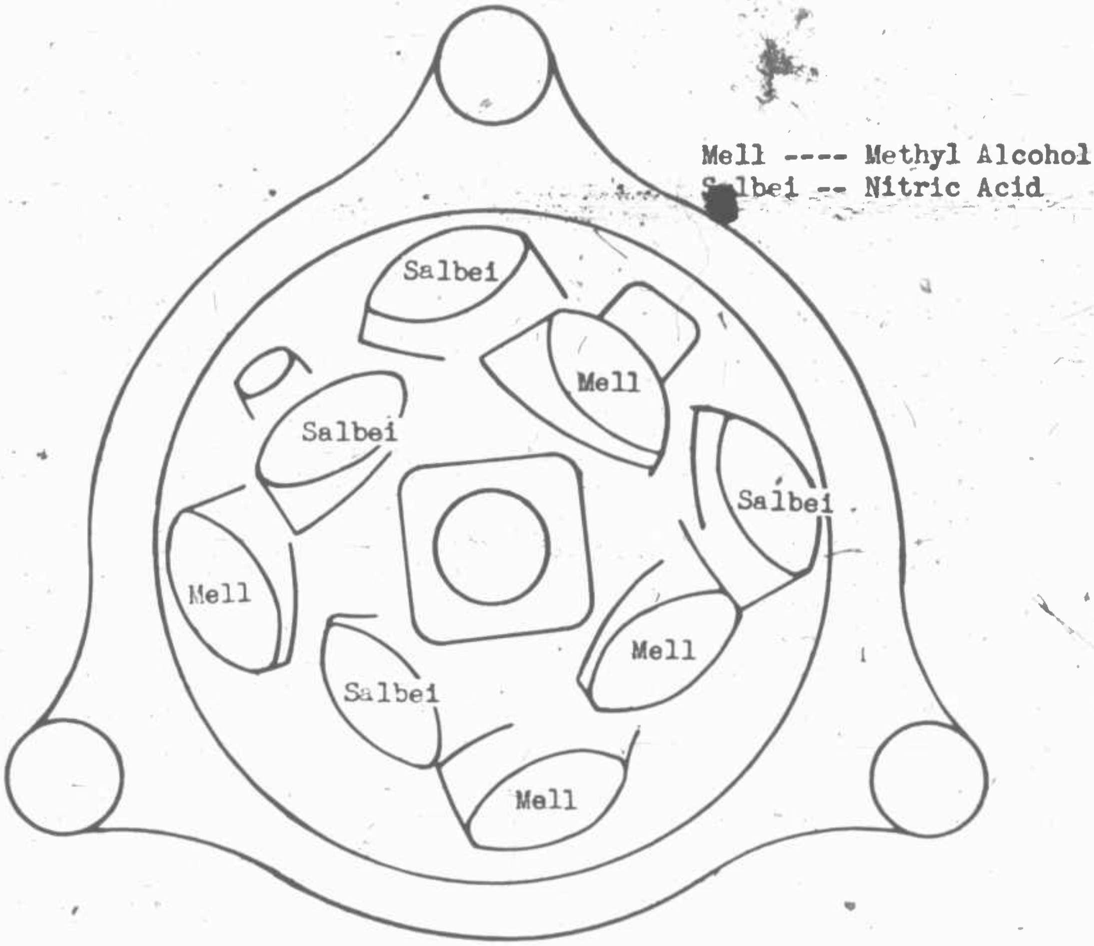
Fig. 2 - Parts of P 3390A Combustion Chamber and Injectors



Mell ---- Methyl Alcohol
Salbei -- Nitric Acid

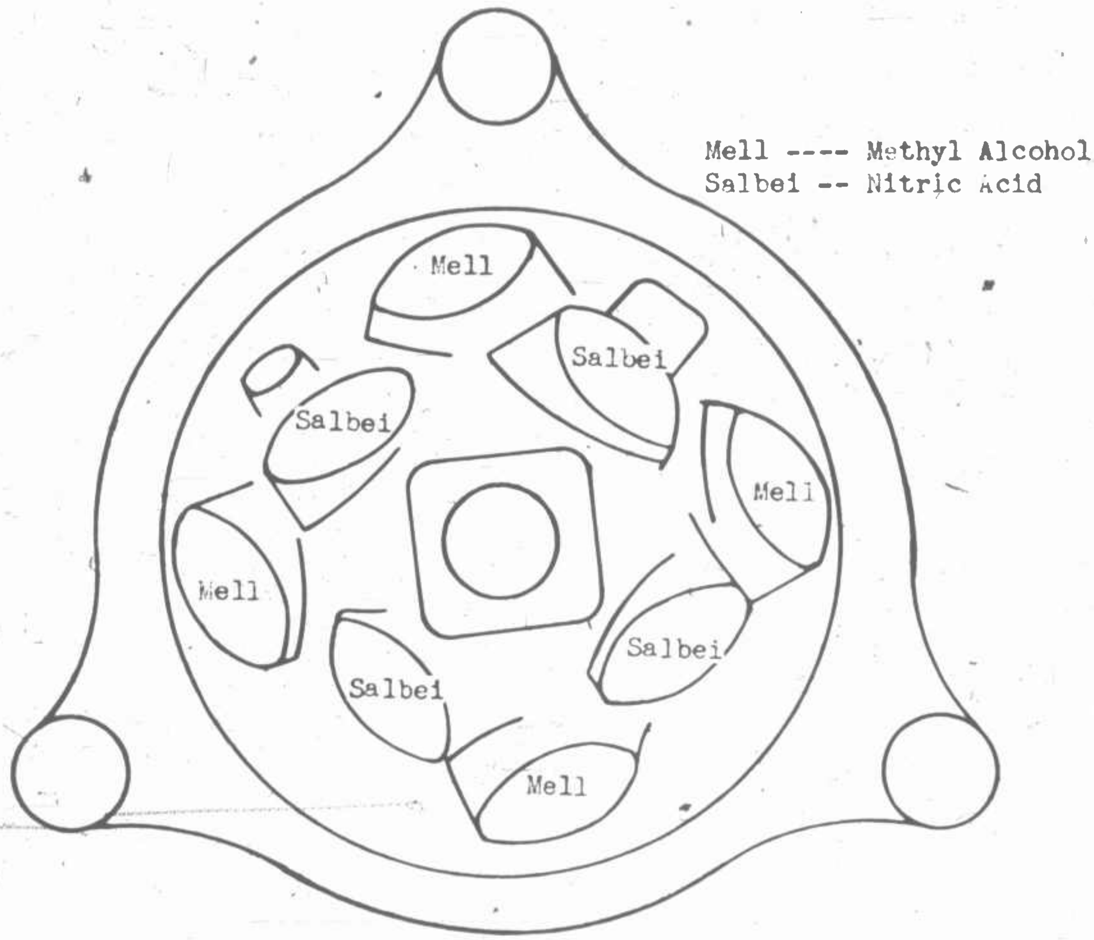
Each injector in the outer row has an injector of the other propellant component assigned to it in the inner row. The injection head is designed so that when the inner injectors are placed in it they face in a counterclockwise direction, whereas injectors in the outer row are faced in a clockwise direction. This arrangement causes the injector pairs to operate against each other. It is unavoidable that despite this, two injectors of a single propellant are next to each other.

Fig. 3 - Injector Distribution No. 1 for P 3390A



As in distribution No. 1 each injector in the outer row has an injector of the other propellant assigned to it in the inner row. As a result of the different directions that the injectors face when placed in the injection head, the injectors in one row operate against the injectors in the other row. In contrast to distribution No. 1, there are two pairs of injectors of the same propellant next to each other.

Fig. 4 - Injector Distribution No. 2 for P 3390A



The arrangement of the injectors for this distribution corresponds to that of distributions 1 and 2. Since each row contains injectors of different propellants, the distribution of propellants in the chamber is uniform. There is no piling up of propellant in certain regions and there are no streaks formed in the exhaust. As in the other distributions, the direction of injection is determined by the shape of the head so that an injector in the outer row always operates against an injector in the inner row.

Fig. 5 - Injector Distribution No. 3 for P 3390A

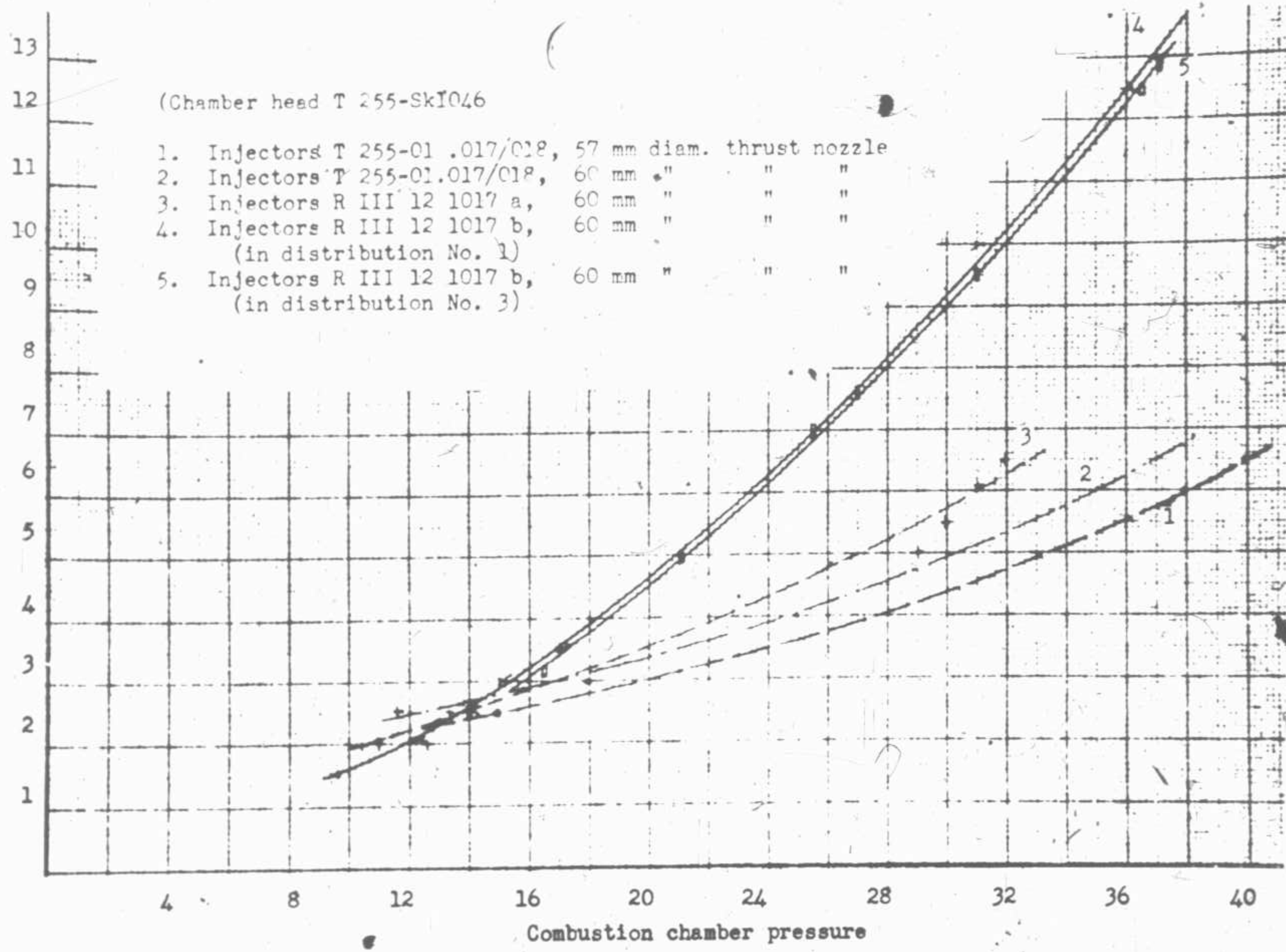


Fig. 6 - Injection Gage Pressures vs. Combustion Chamber Pressure for P3390A

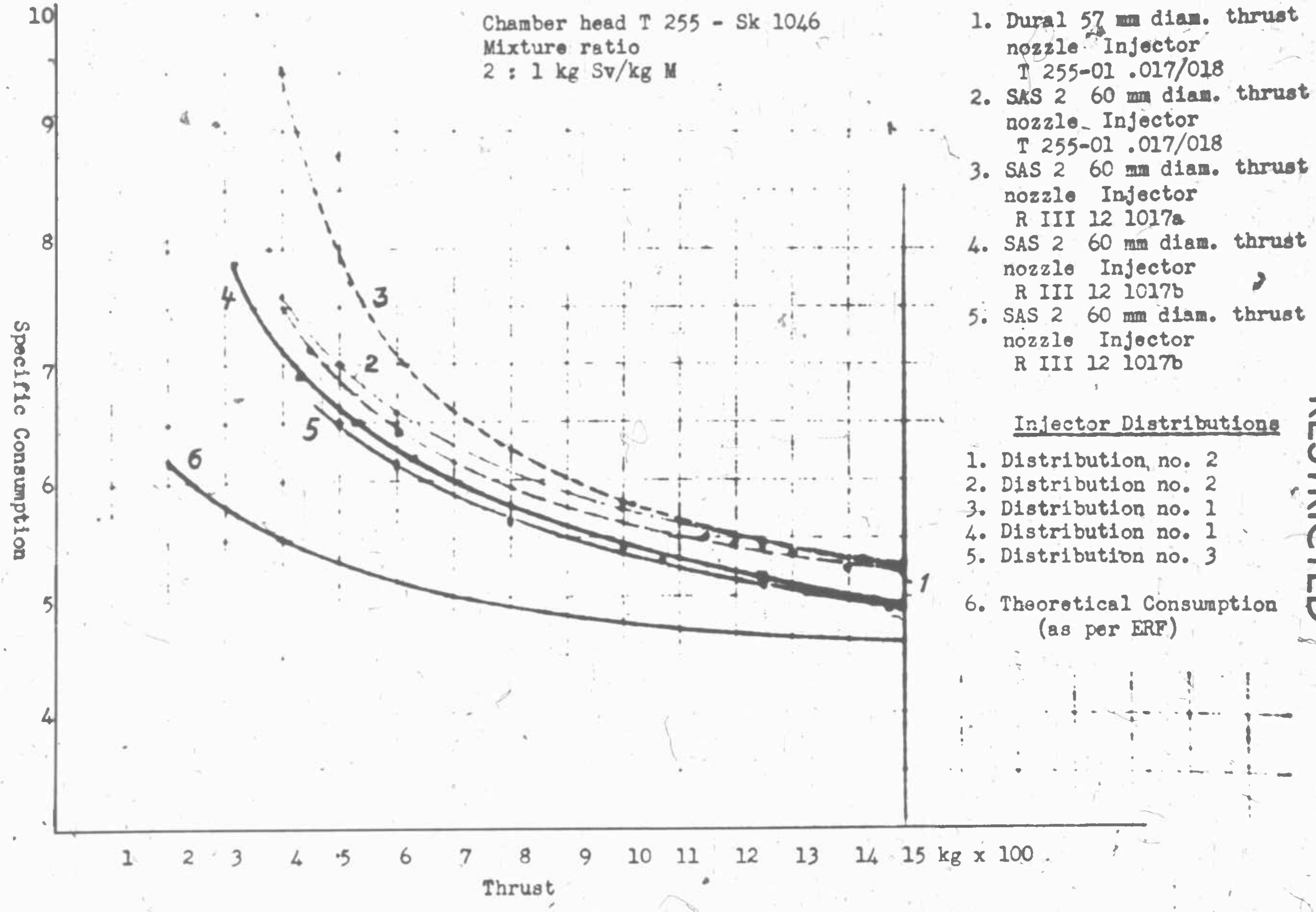


Fig. 7 - Thrust vs. Specific Consumption for P3390A

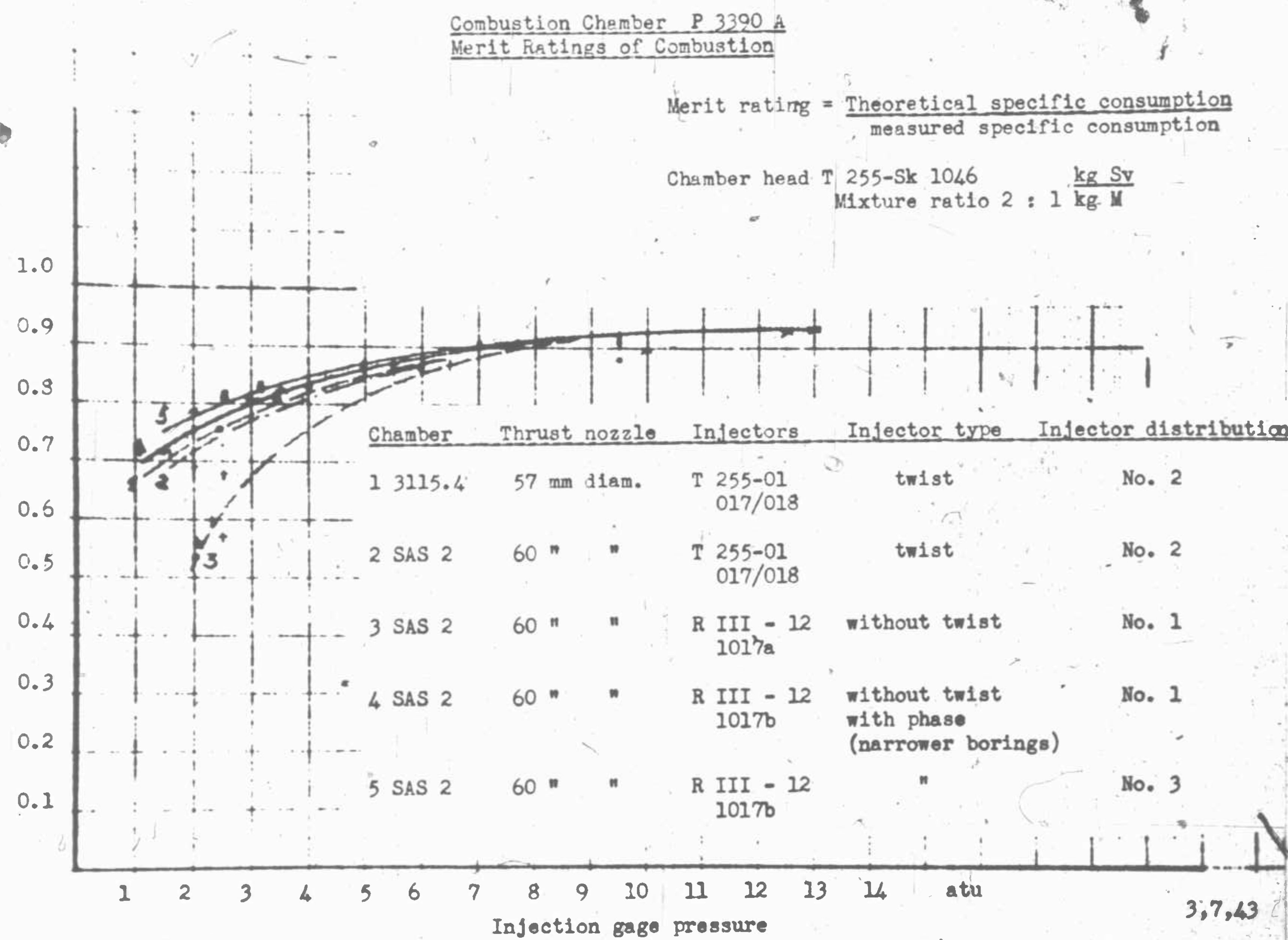


Fig. 8 - Injection Pressure vs. Merit Combustion Rating for P 3390A

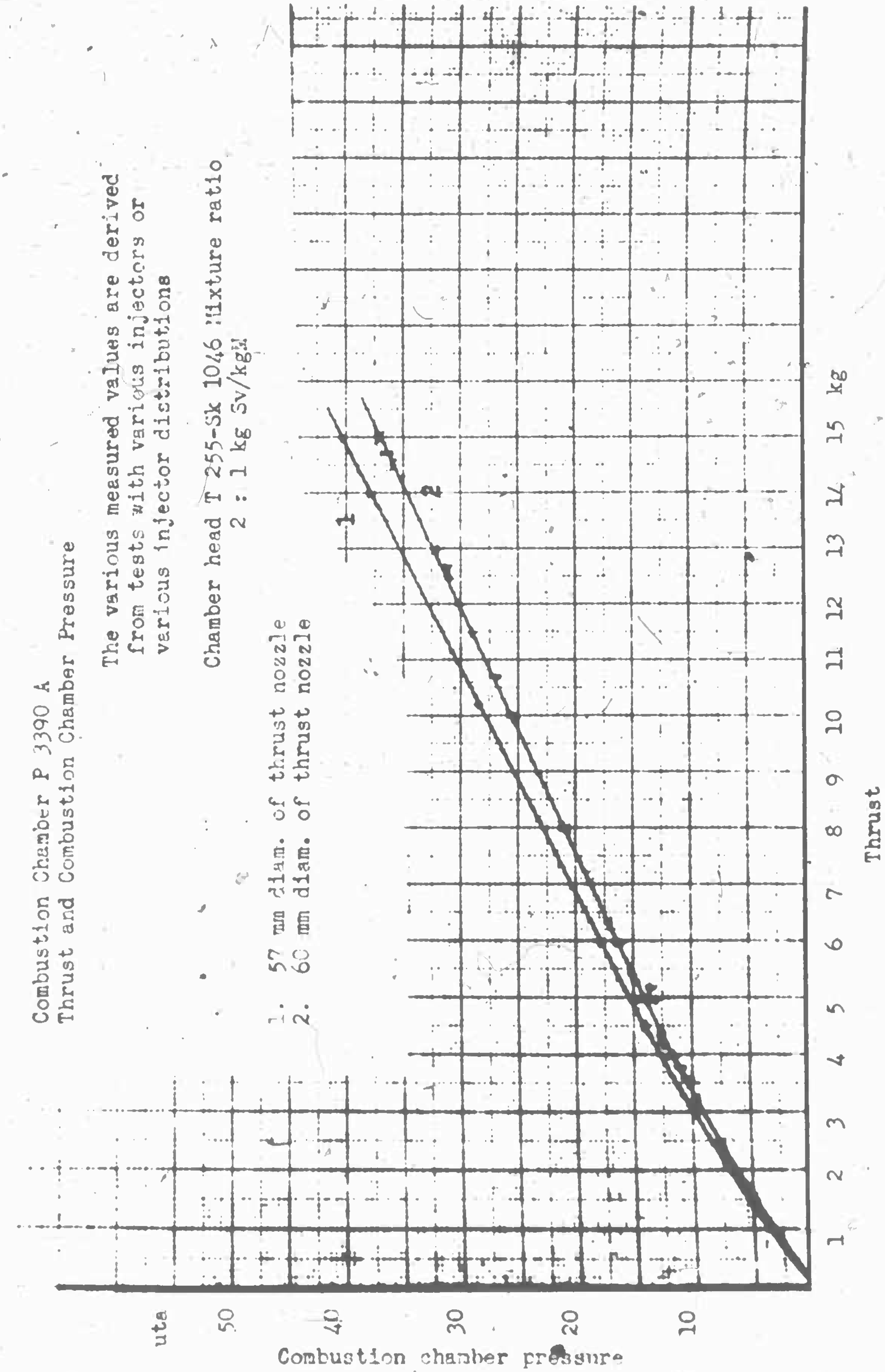


Fig. 9 - Thrust vs. Chamber Pressure for P 3390A

Combustion Chamber Inner Jacket T 255-Sk 357

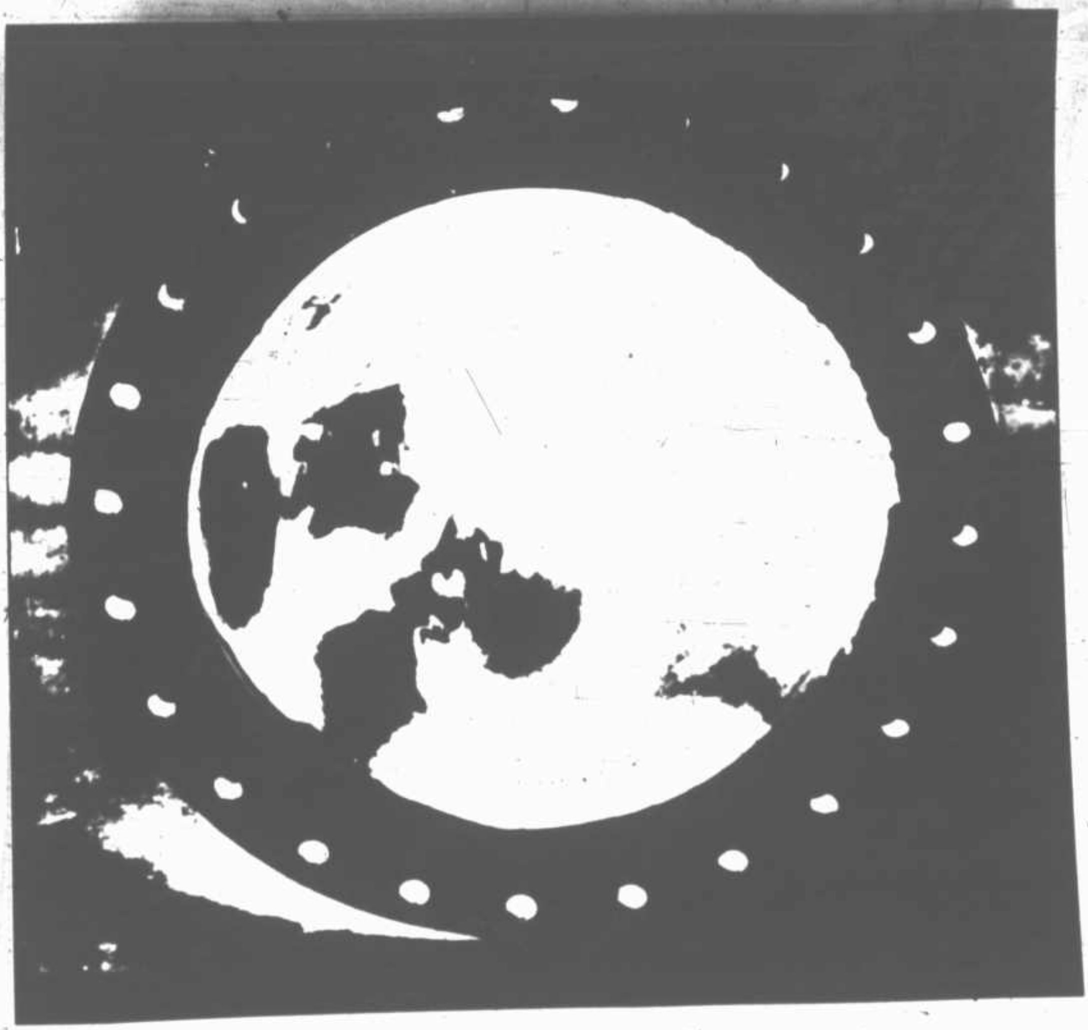


Fig. 10 - Appearance of the Thrust Nozzle After Three Hour Run With Injector Distribution No. 2

Combustion Chamber Head T 255 - Sk 1046

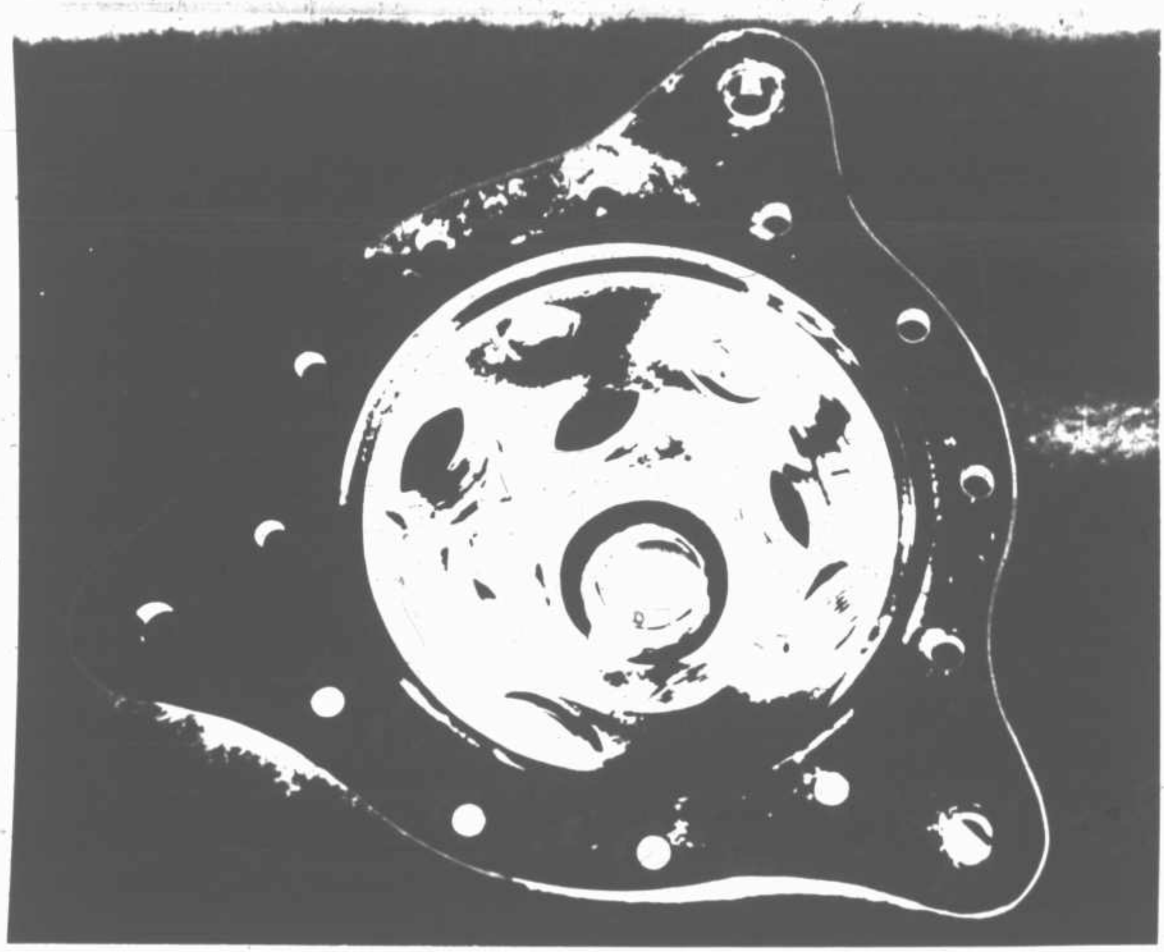


Fig. 11 - Appearance of Head After Three Hour Run With Injector Distribution No. 2

Combustion Chamber Inner Jacket T 255 - Sk 357

Fig. 12 - Formation of Dark Spots After Half-Hour Run With Injector Distribution No. 1

Combustion Chamber Inner Jacket T 255-Sk 357

Fig. 13a - Thrust Nozzle Burned Through at Neck After 13-Minute Run With Partial Cooling and Injectors R-III 12-10175 (cut apart)

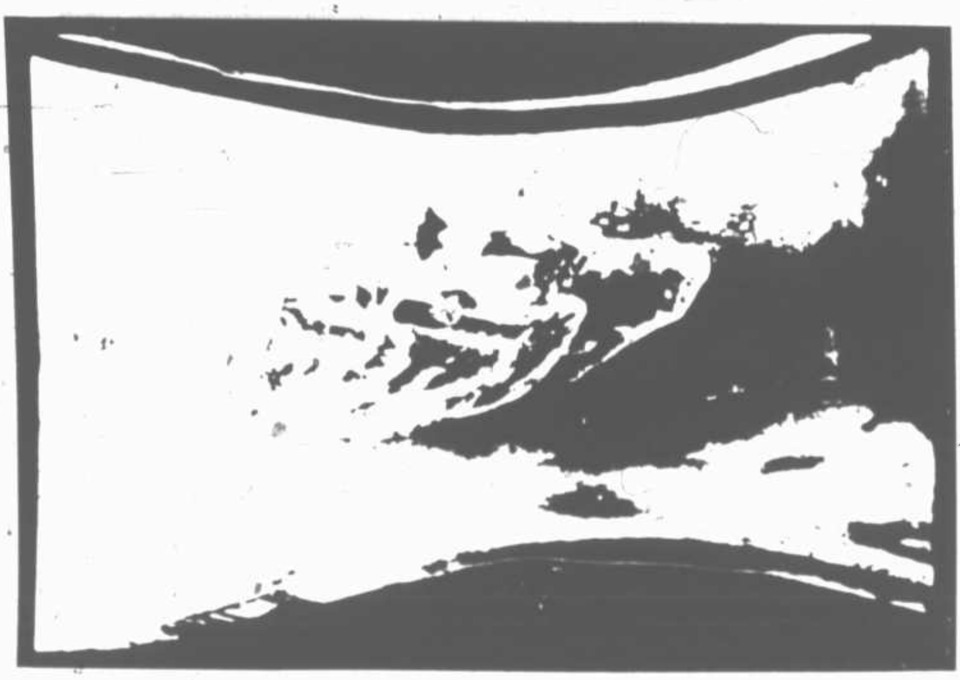


Fig. 13b - Thrust Nozzle Burned Through After 10-Second Start With Injectors R-III 12-1017b and Partial Cooling

Combustion Chamber Inner Jacket T 255-Sk 357

Fig. 14 - Formation of the Dark Spots After 1-Hour Run With Injector Distribution No. 3

Combustion Chamber Head T 255-Sk 1046

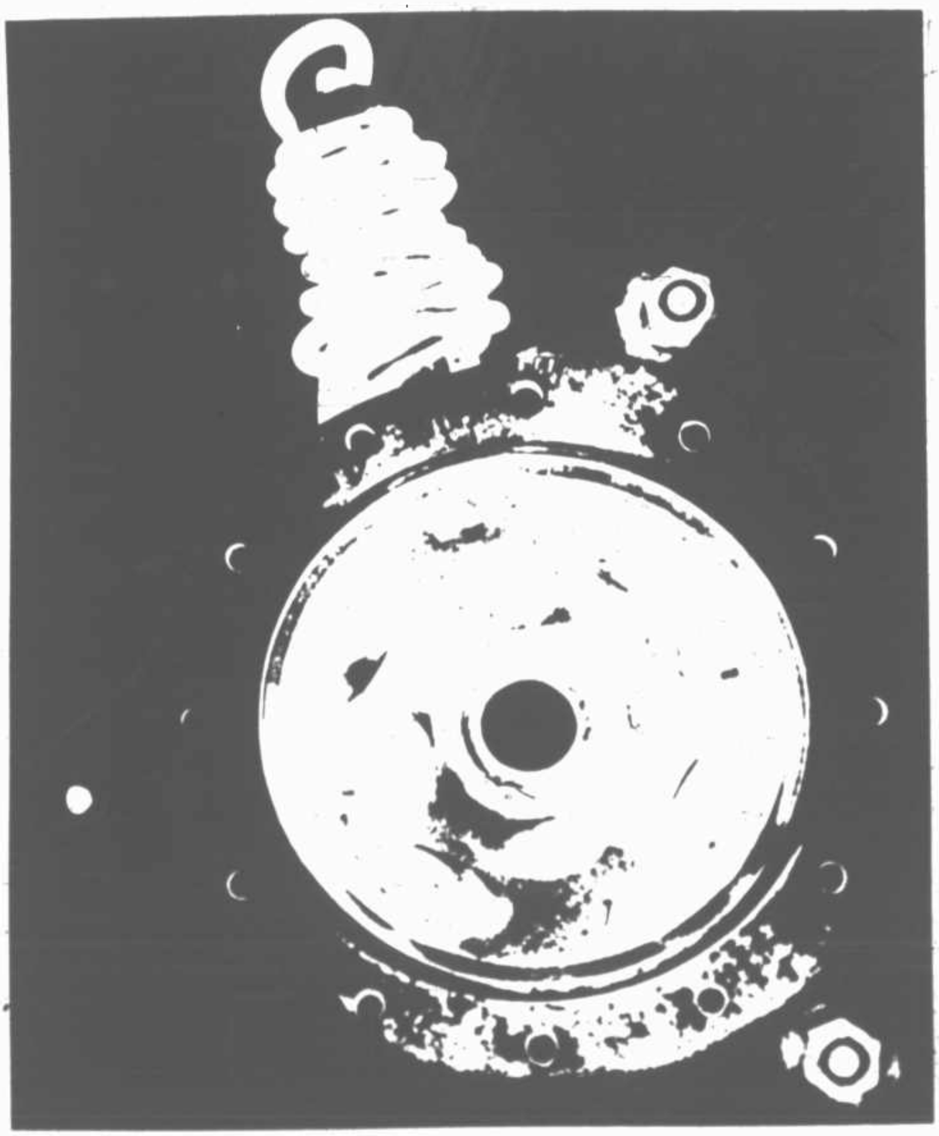


Fig. 15 - Appearance After 1-Hour Use With Injector Distribution No. 3

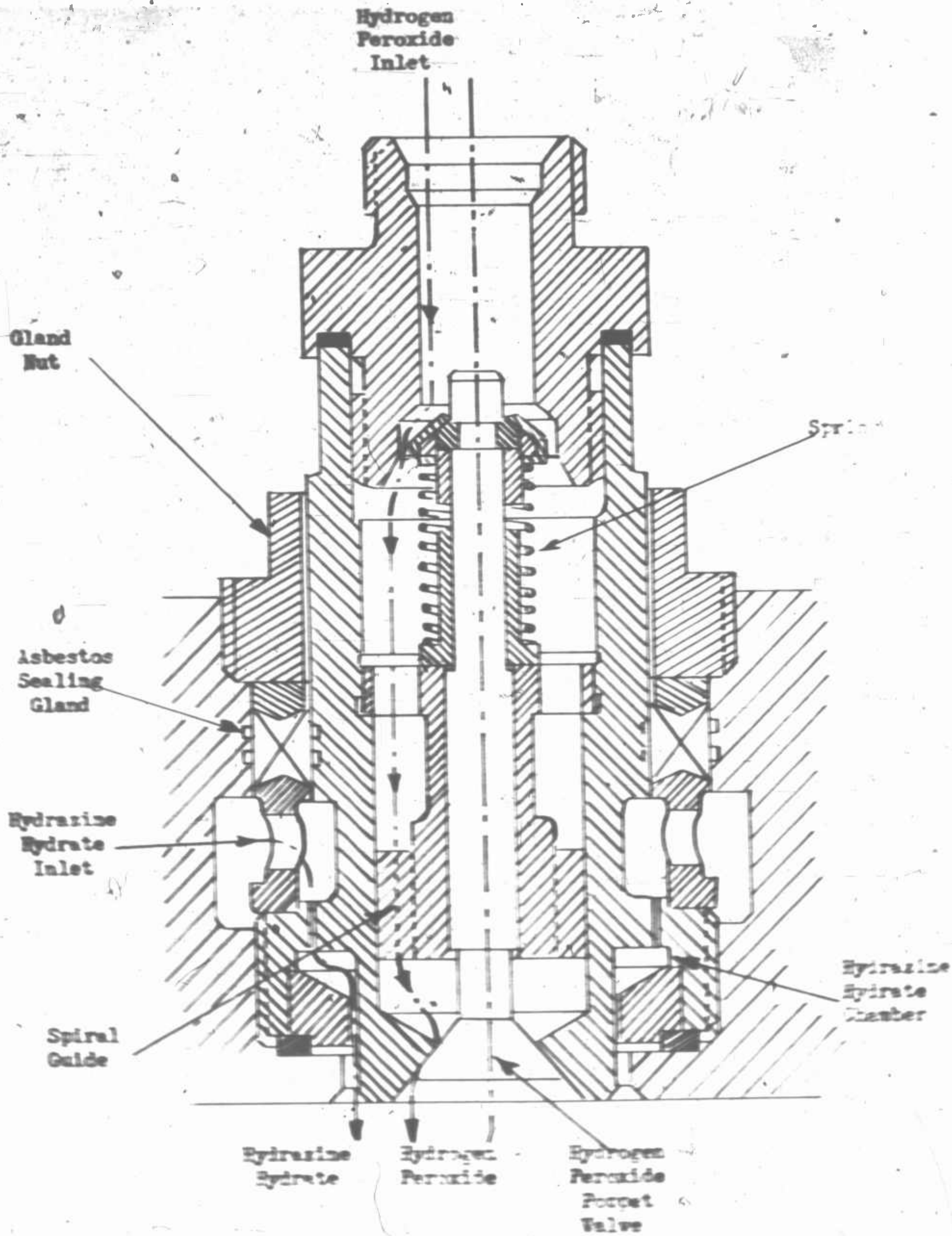


Fig. 1b - Final Design of BMI 100-500 Injector

Fig. 17 - Head of HWK 109-509 Showing Injectors in Place

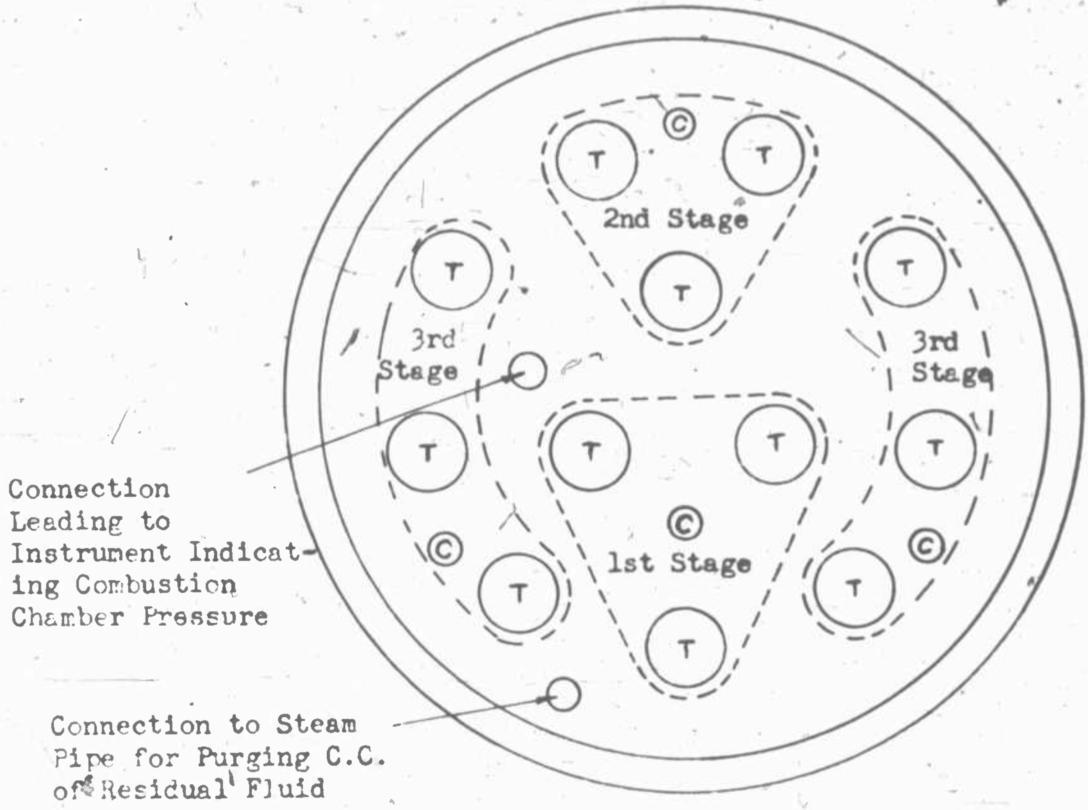


Fig. 18a - Combustion Chamber Burner Plate Showing Method of Zoning Burners into Three Separate Stages

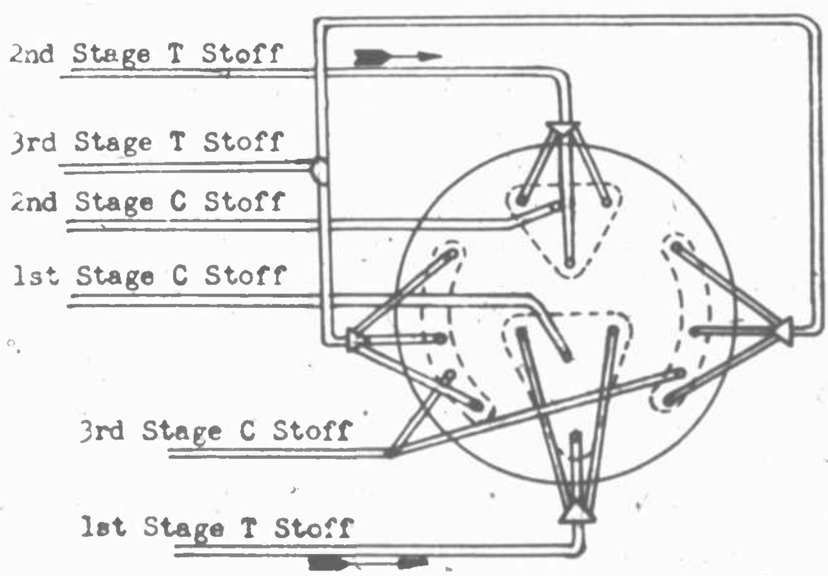


Fig. 18b - Method of Dividing the Delivery Pipes to Serve Each Stage Walter 109-509 Motor

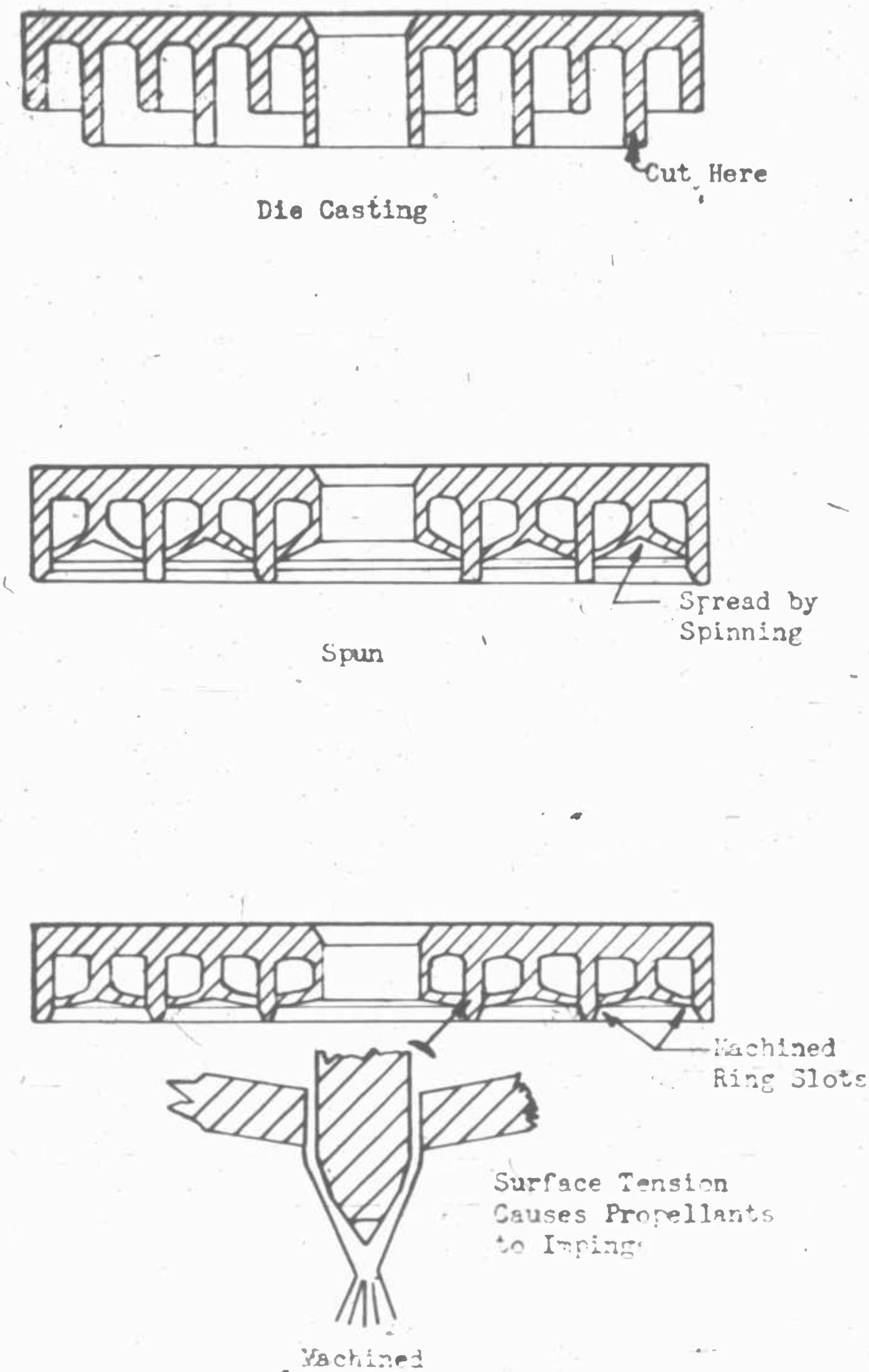
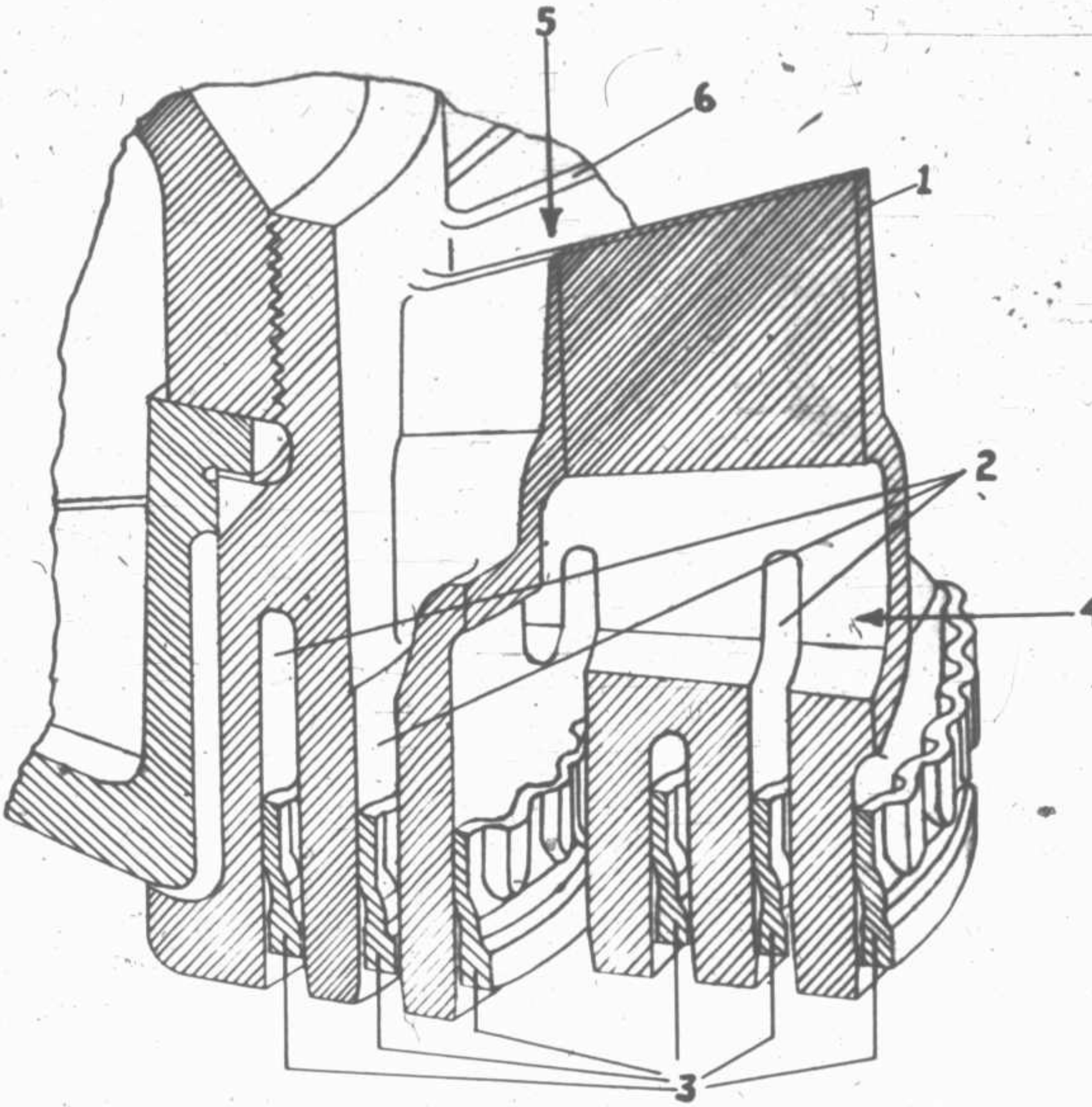


Fig. 101- Manufacture of Ring Injector



1. Basic piece
2. Grooves
3. Rings
4. Hollowed-out passageways
5. Top of injector
6. Fins
⟶ Direction of flow indicated by arrow

Fig. 20 - Partial Section of a 25-ton Ring Injector

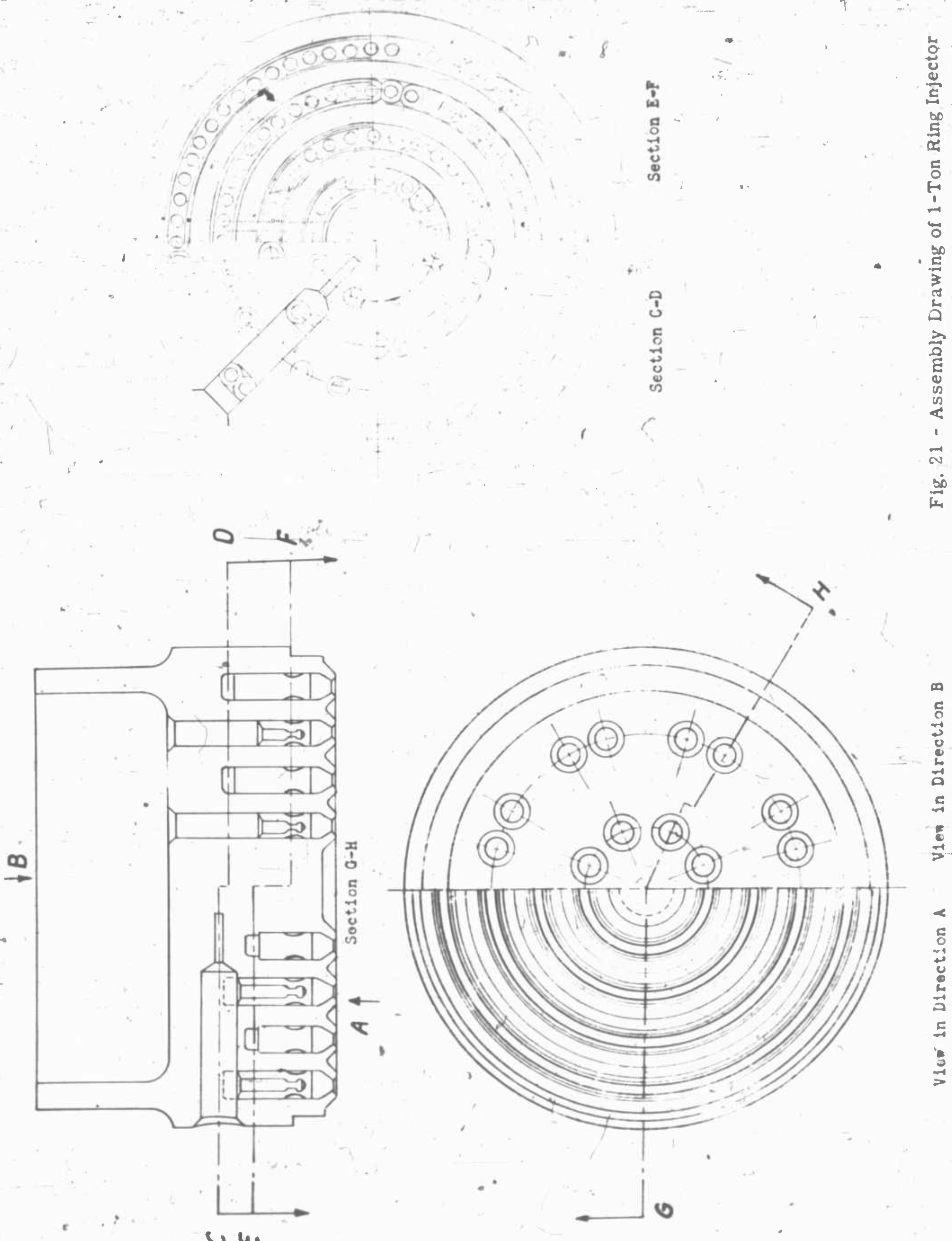


Fig. 21 - Assembly Drawing of 1-Ton Ring Injector

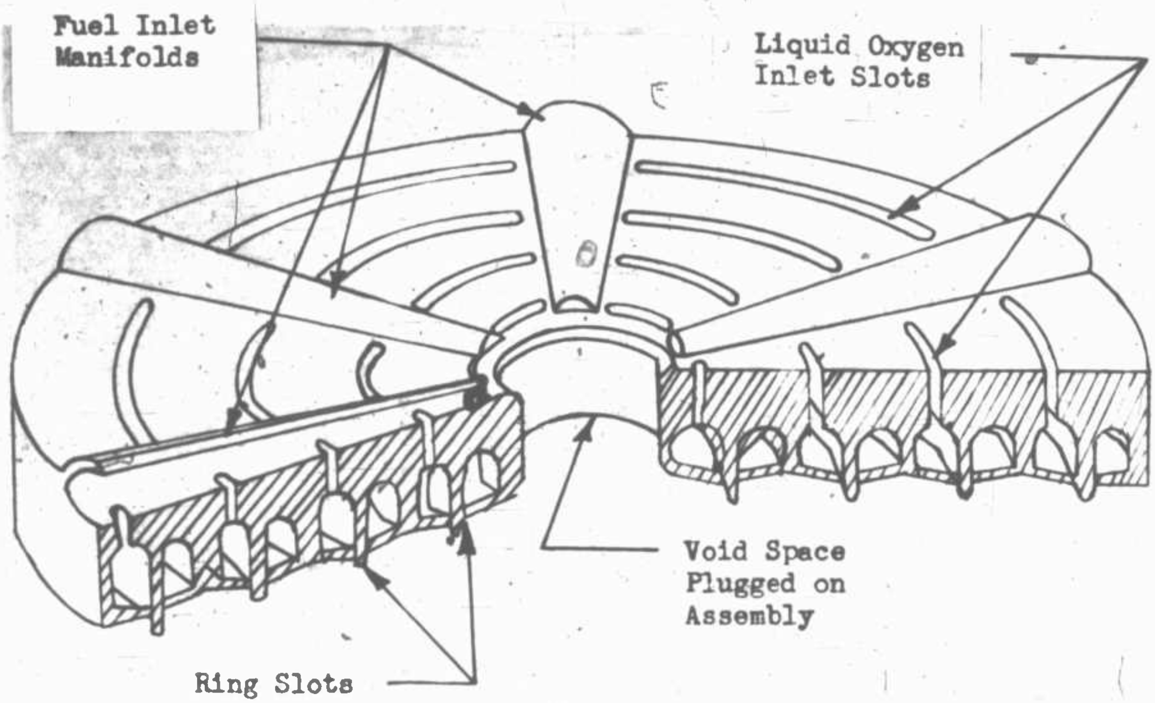


Fig. 22 - Ring Injector

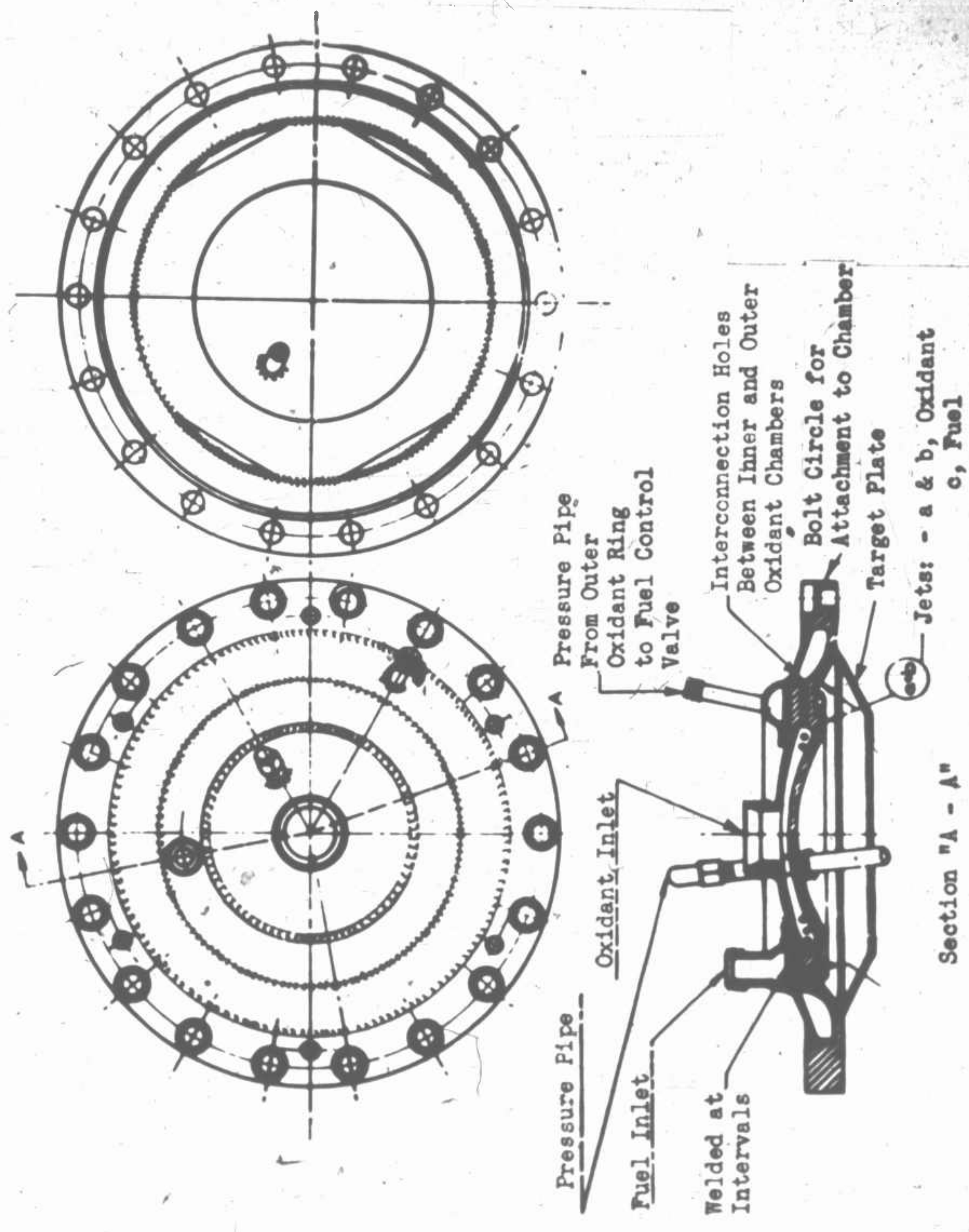


Fig. 23 - HWK RI 210B Injector Assembly

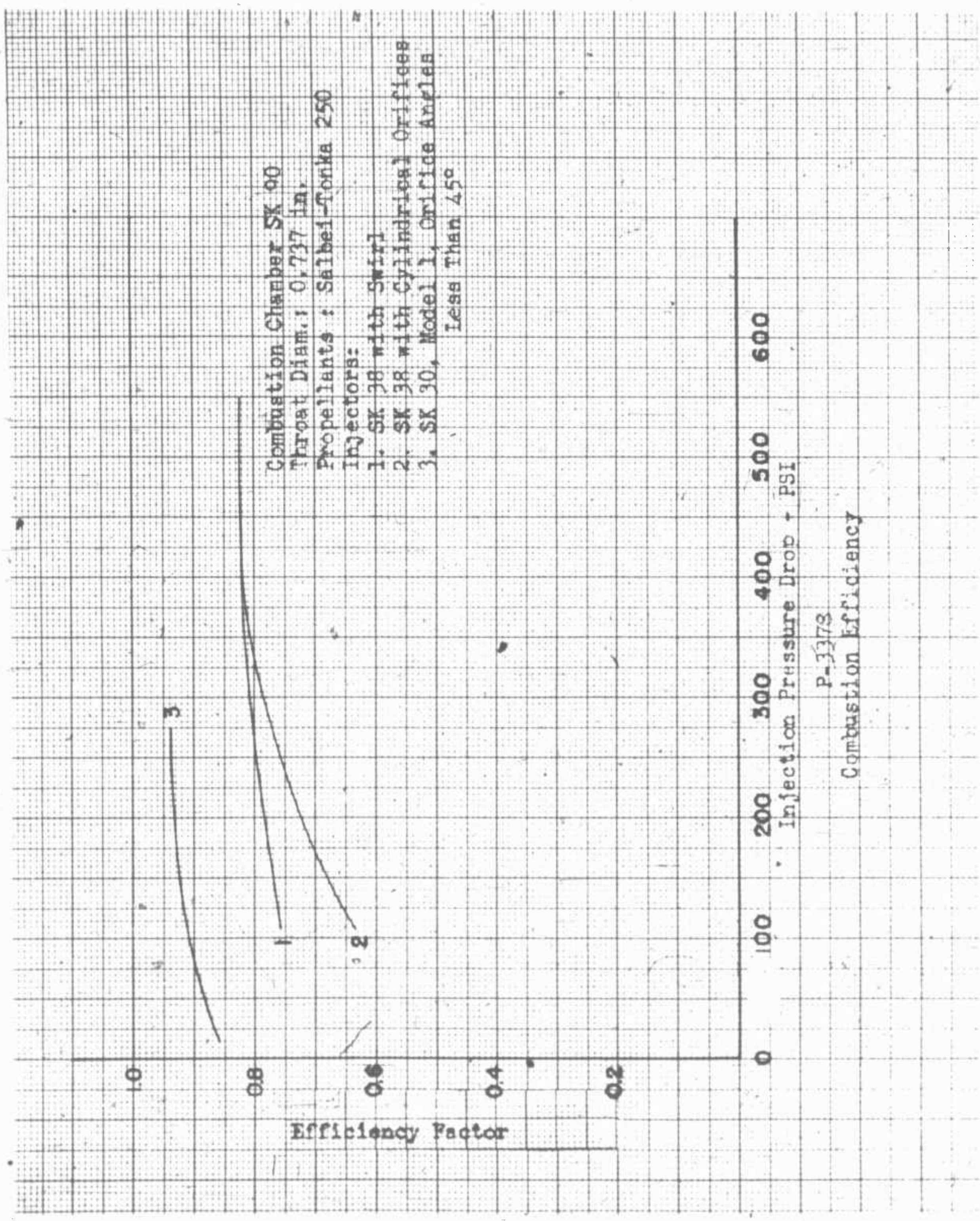


Fig. 24 - Injector Pressure Drop vs Efficiency Factor for BMW 109-548

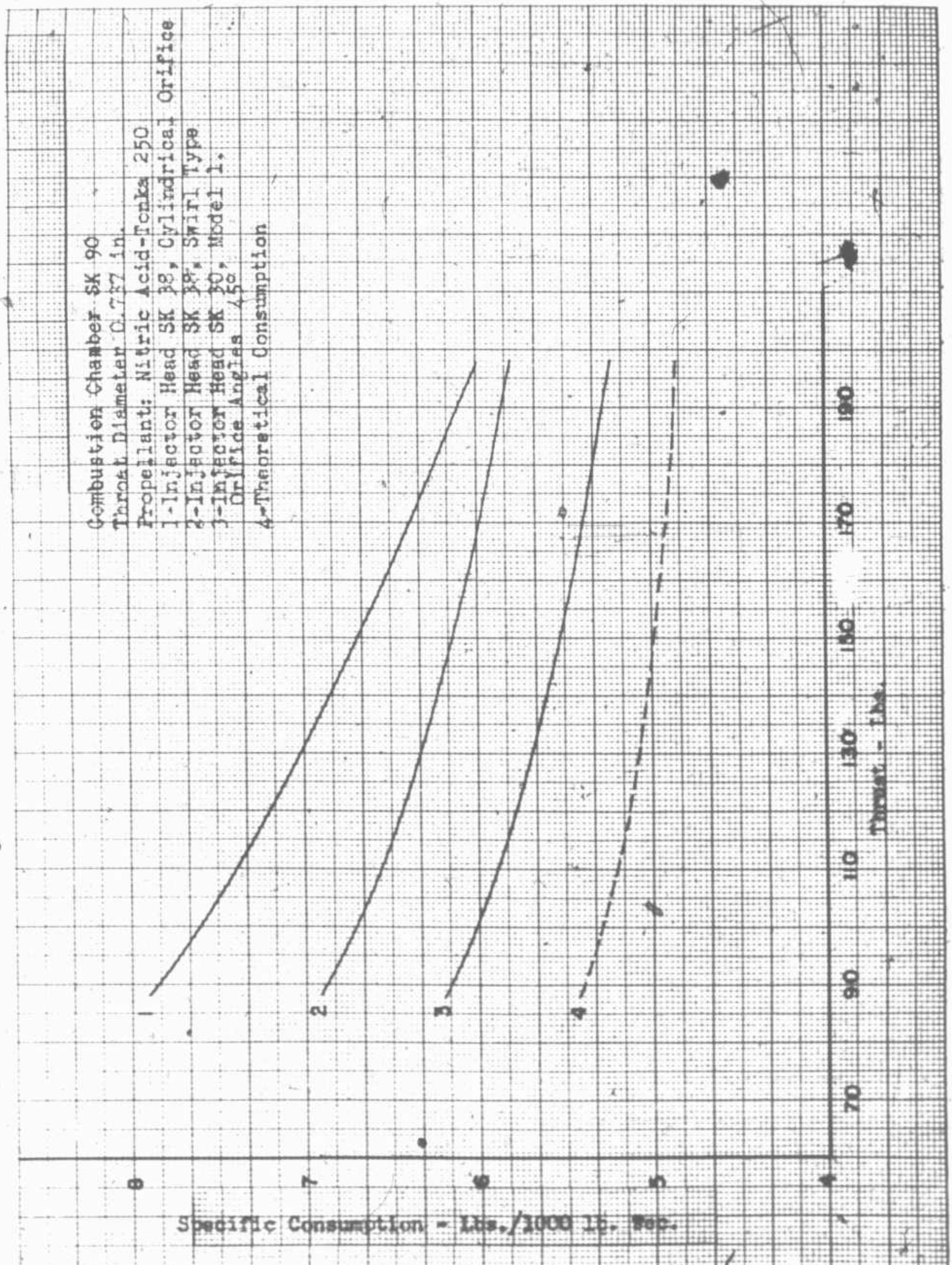


Fig. 25 - Variation of Specific Propellant Consumption With Thrust - BMW 109-548

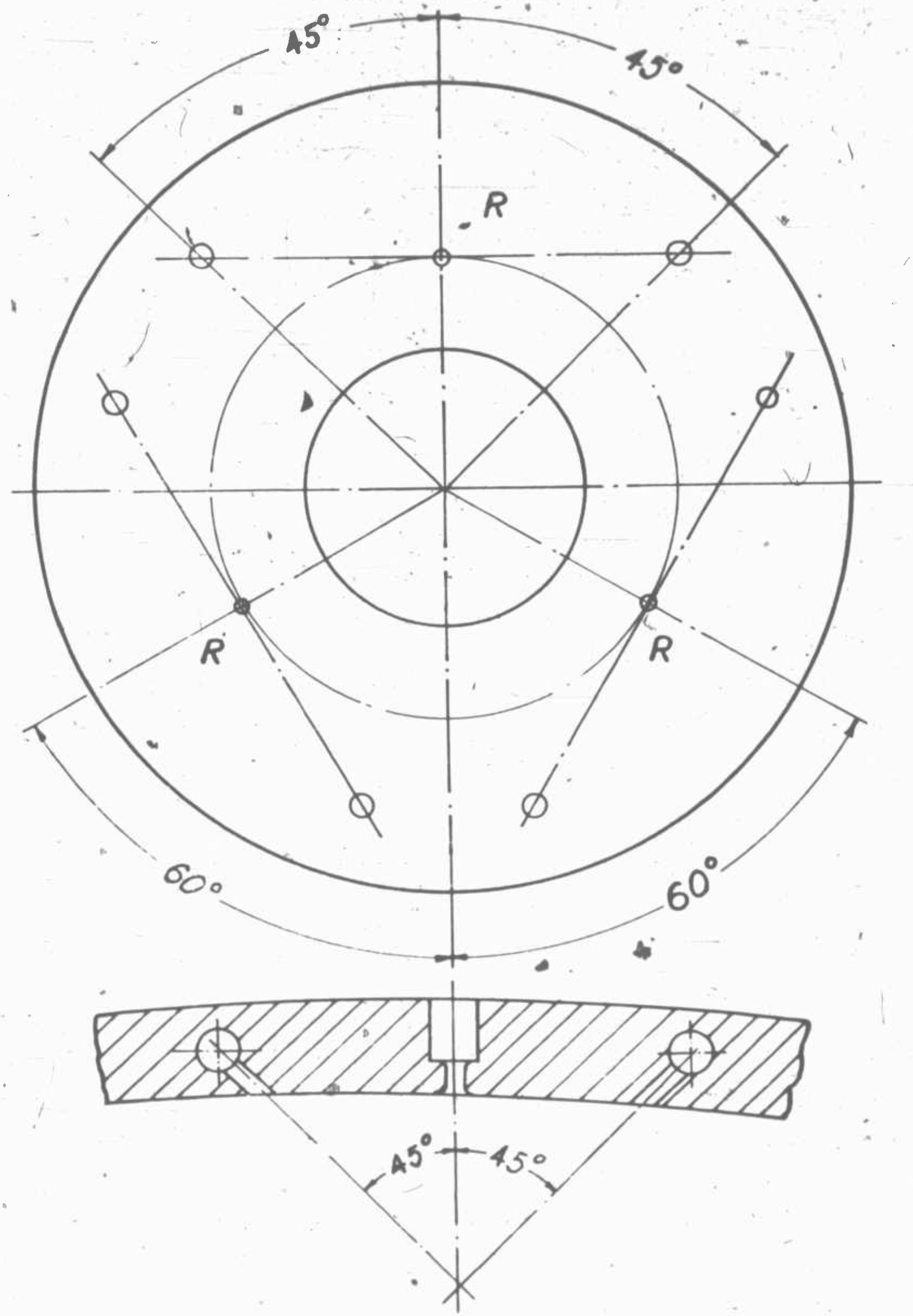
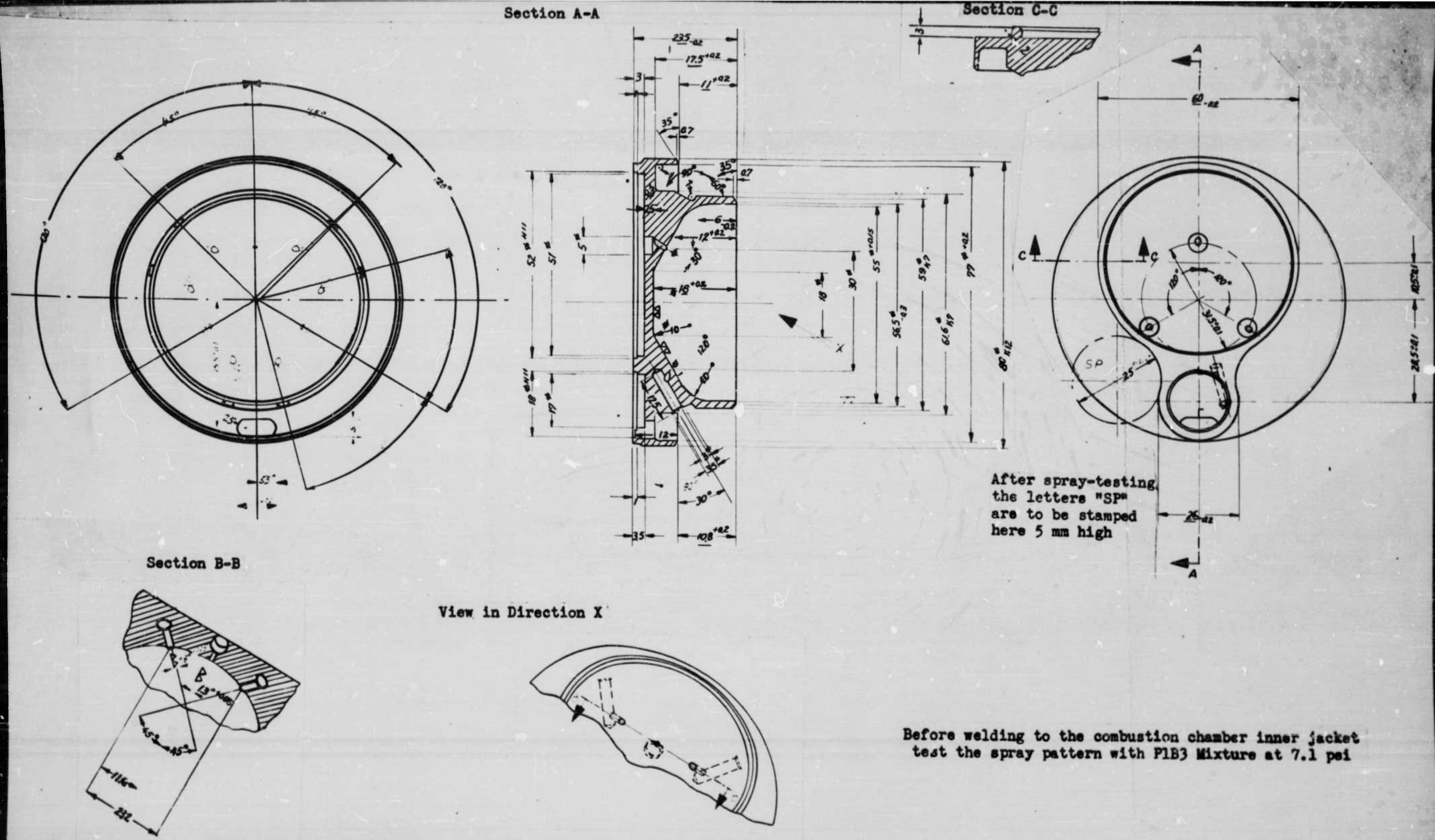


Fig. 26 - Sketch of BMW 109-548 Injector Showing Distribution of Holes and Injection Angles



Before welding to the combustion chamber inner jacket test the spray pattern with P1B3 Mixture at 7.1 psi

FIG. 28 - BMW 109-548 I[illegible]

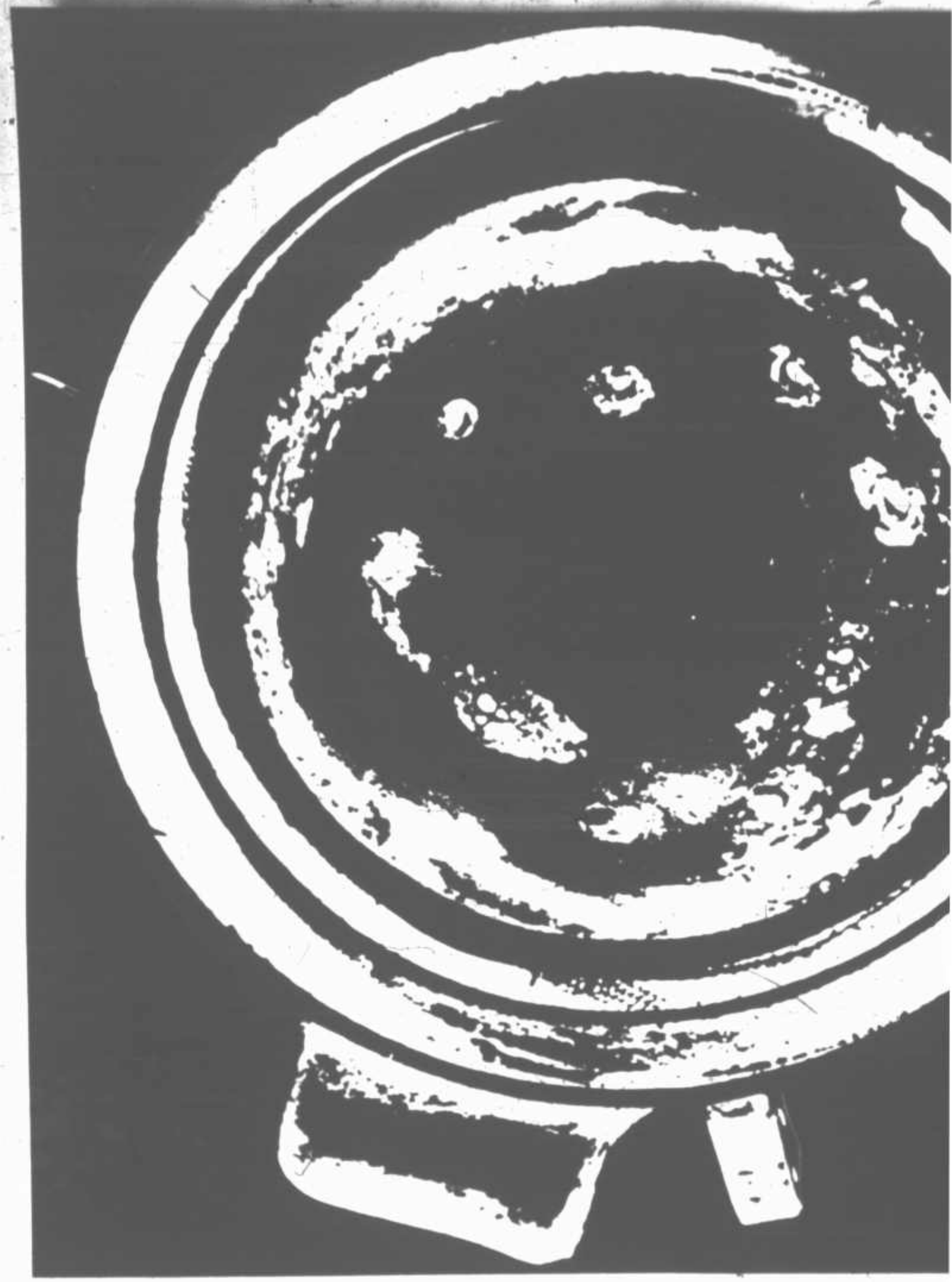
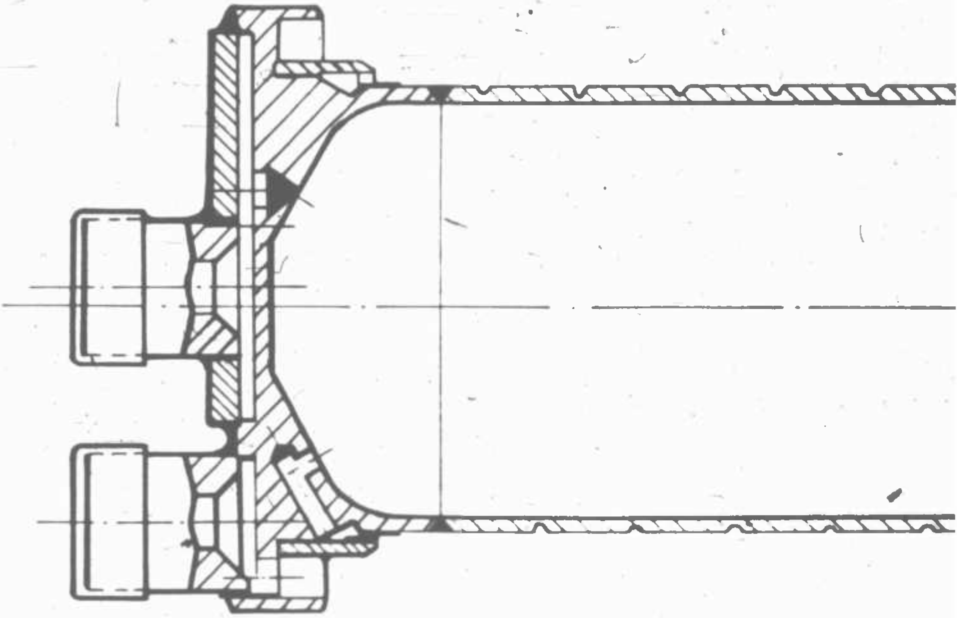
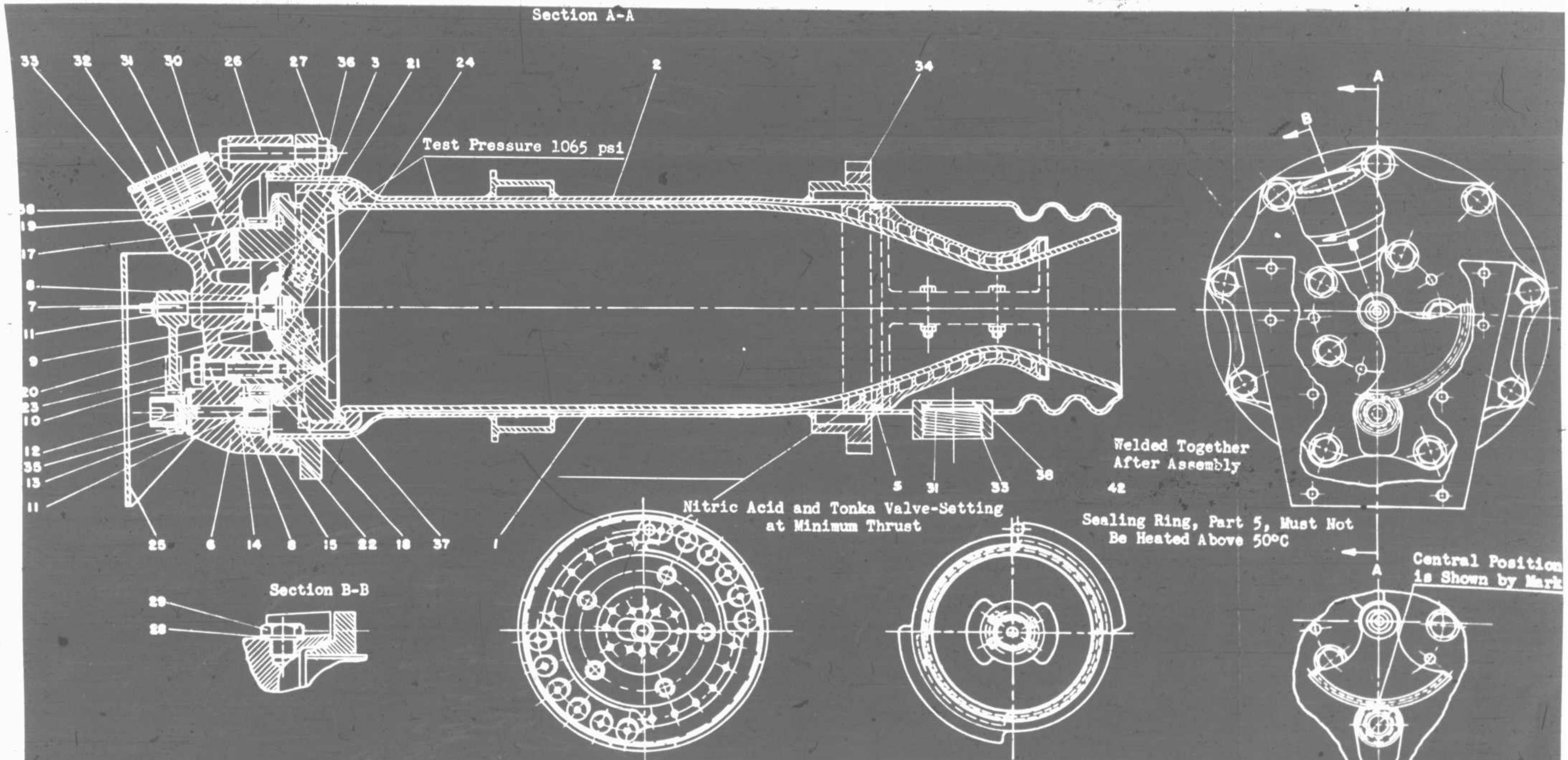


Fig. 28 - BMW 109-548 Injector



Filter Ring Shrunk on at 752-788±°F

Fig. 29 - Inner Jacket of Chamber for BMW 109-5
Showing Injector Head With
Fittings Welded in Place



42		36	109-558-200-028-74	30	109-558-200-037-15	24	M8x32 LgN 14179	18	109-558-200-071-13	12	109-558-200-060-14	6	109-558-200-004-12
41		35	109-558-200-062-15	29	BM12x15DIN7604L1	23	8 LgN 141 32	17	109-558-200-056-14	11	Idealscheibe AV Ve W (140)	5	109-558-200-090-15
40	Schweissdraht	34	109-558-200-034-14	28	D12x16DIN7603	22	109-558-200-059-15	16		10	109-558-200-092-14	4	
39		33	B32x15 LgN 14490	27	M8 LgN 144 83.1	21	109-558-200-093-14	15	109-558-200-066-14	9	109-558-200-069-15	3	109-558-200-711-13
38	D22x29 DIN 7603	32	109-558-200-073/083-14	26	M8x52 LgN 141 79	20	109-558-200-056-14	14	109-558-200-070-15	8	109-558-200-065-15	2	109-558-200-710-12
37	109-558-200-029-15	31	109-558-100-011-14	25	109-558-200-027-12	19	109-558-200-057-14	13	109-558-200-054-14	7	109-558-200-091-15	1	109-558-200-713-13

Fig. [illegible] Showing Injector Details

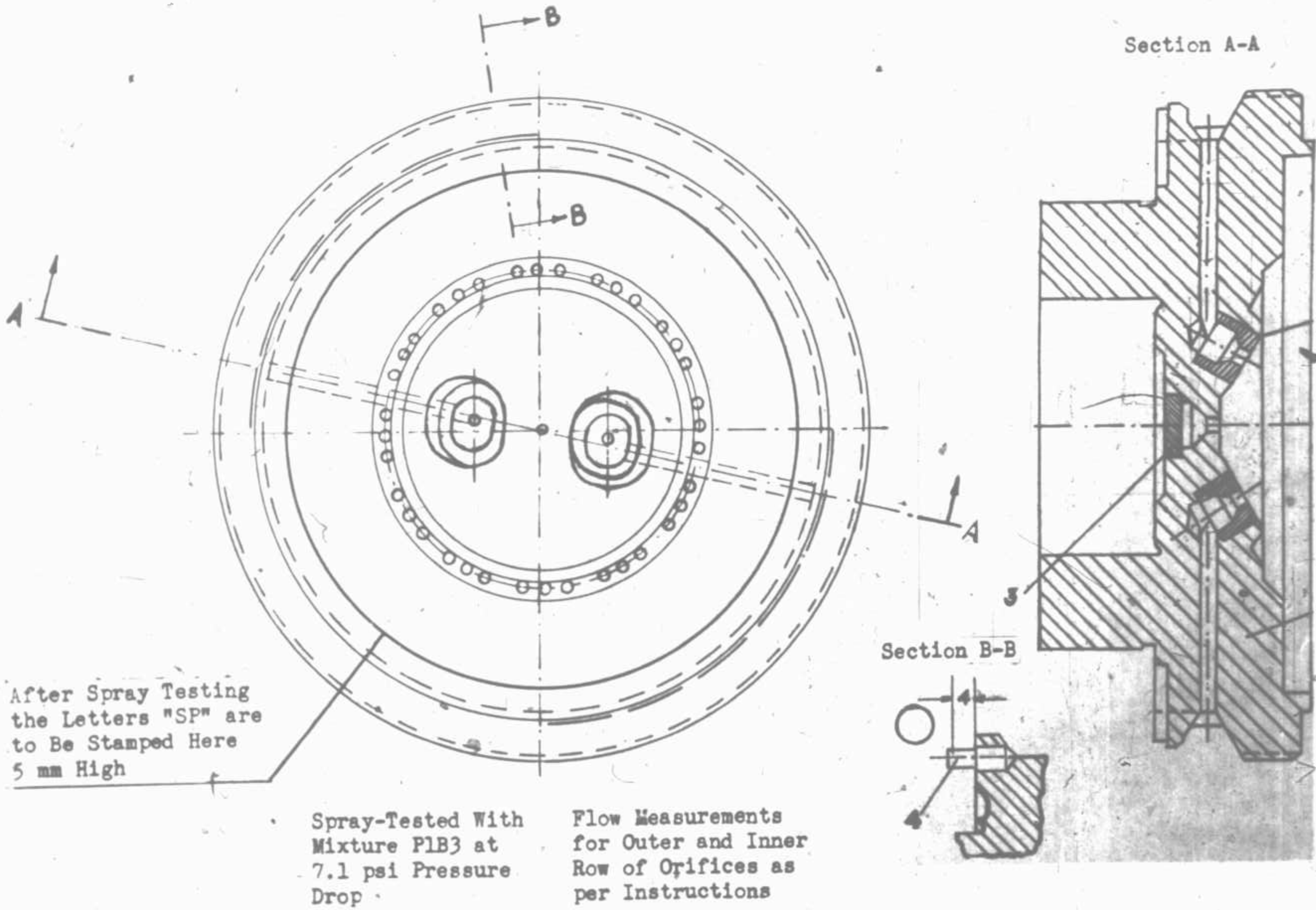


Fig. 31 - BMW 109-558 Injector Head Ready for Installation Showing Details of First-Stage Injection

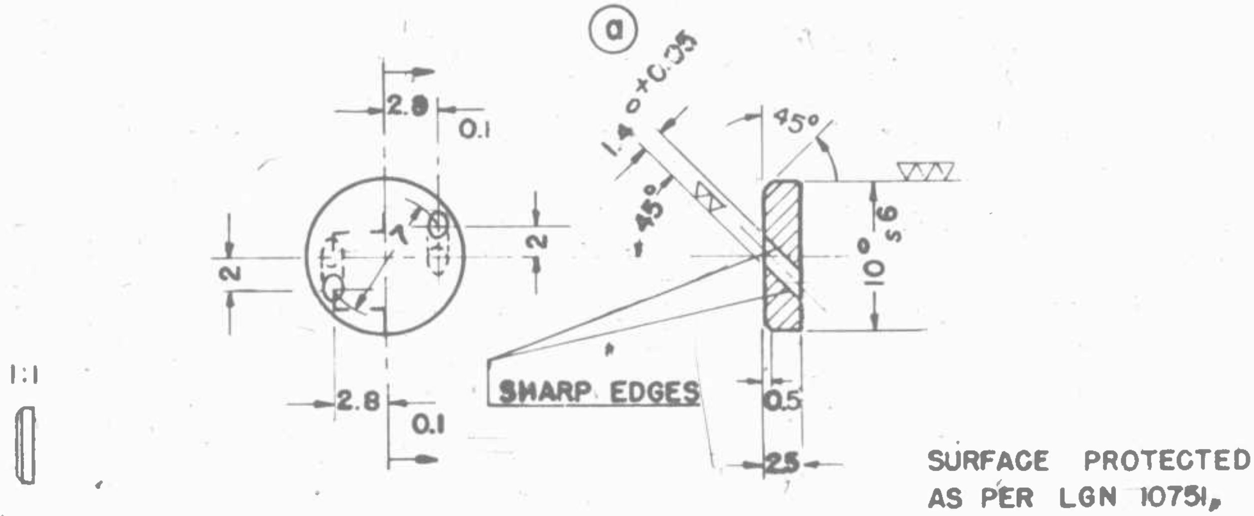


Fig. 32 - BMW 109-558 Injector Subassembly Showing Detail of Inserts

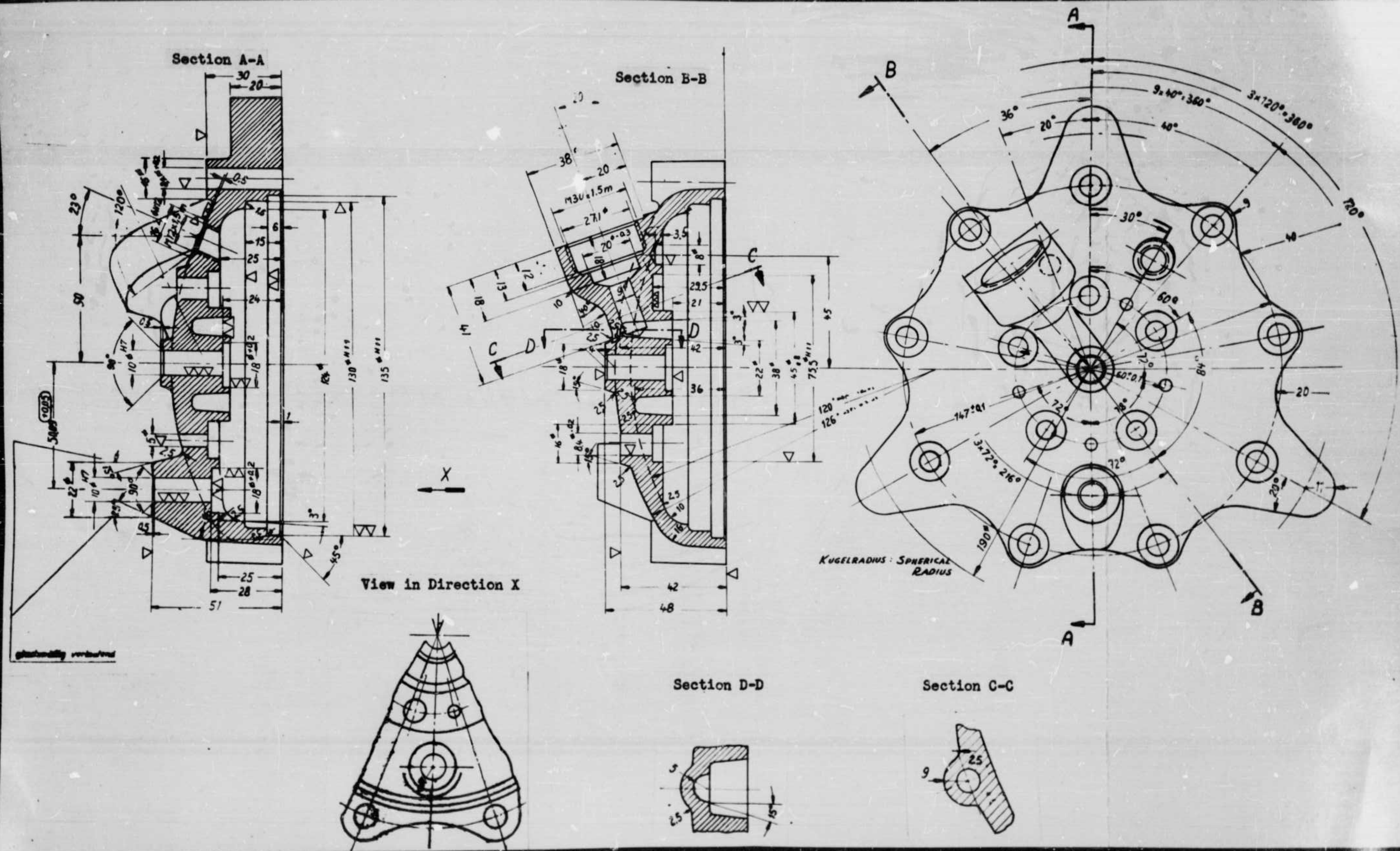
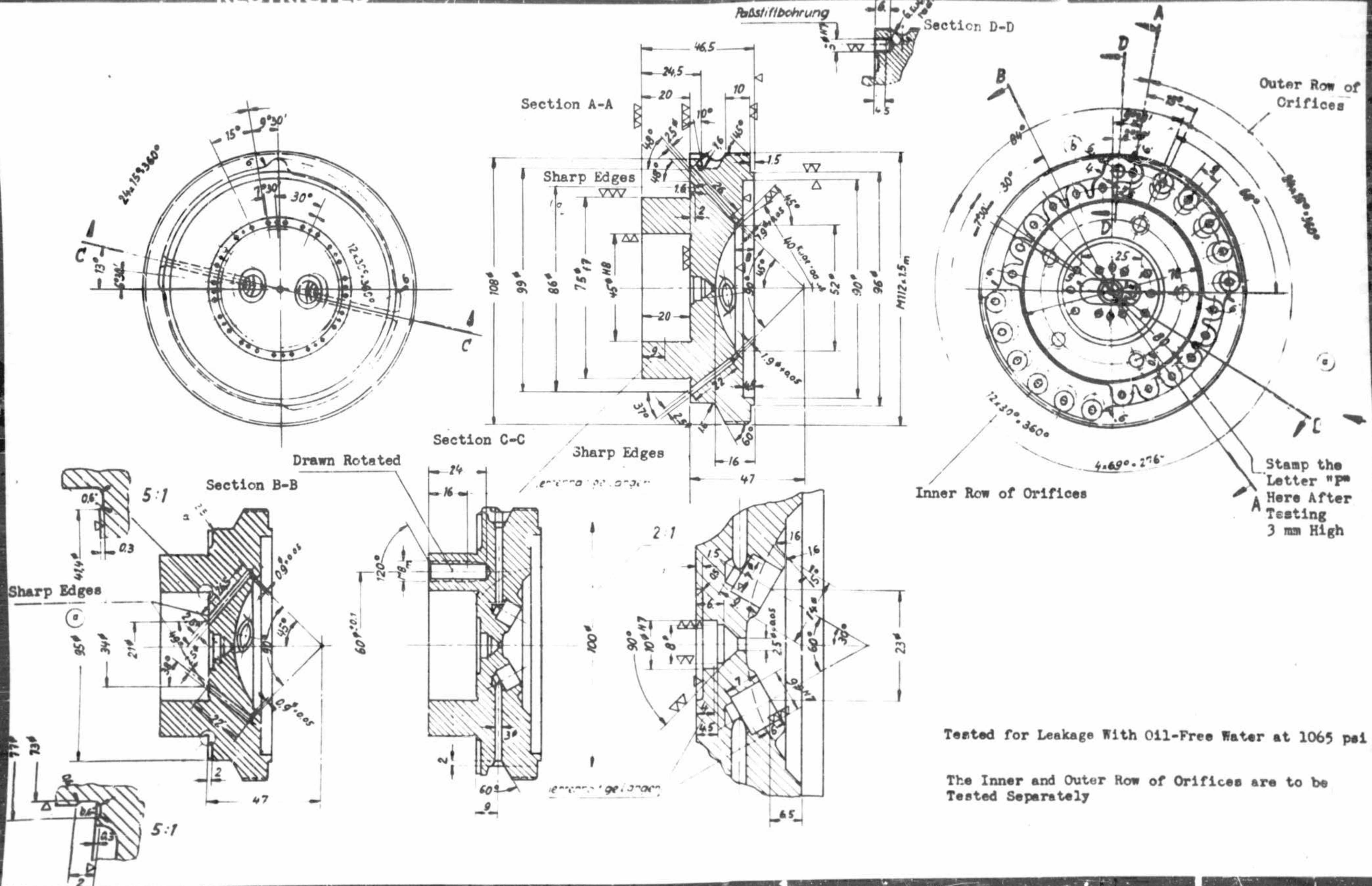


Fig. 33 - Upper Portion of BMW 109-558 Injector Giving Dimensions



Tested for Leakage With Oil-Free Water at 1065 psi

The Inner and Outer Row of Orifices are to be Tested Separately

Fig. 34 - Lower Portion of BMW 109-558 Injector Giving Dimensions

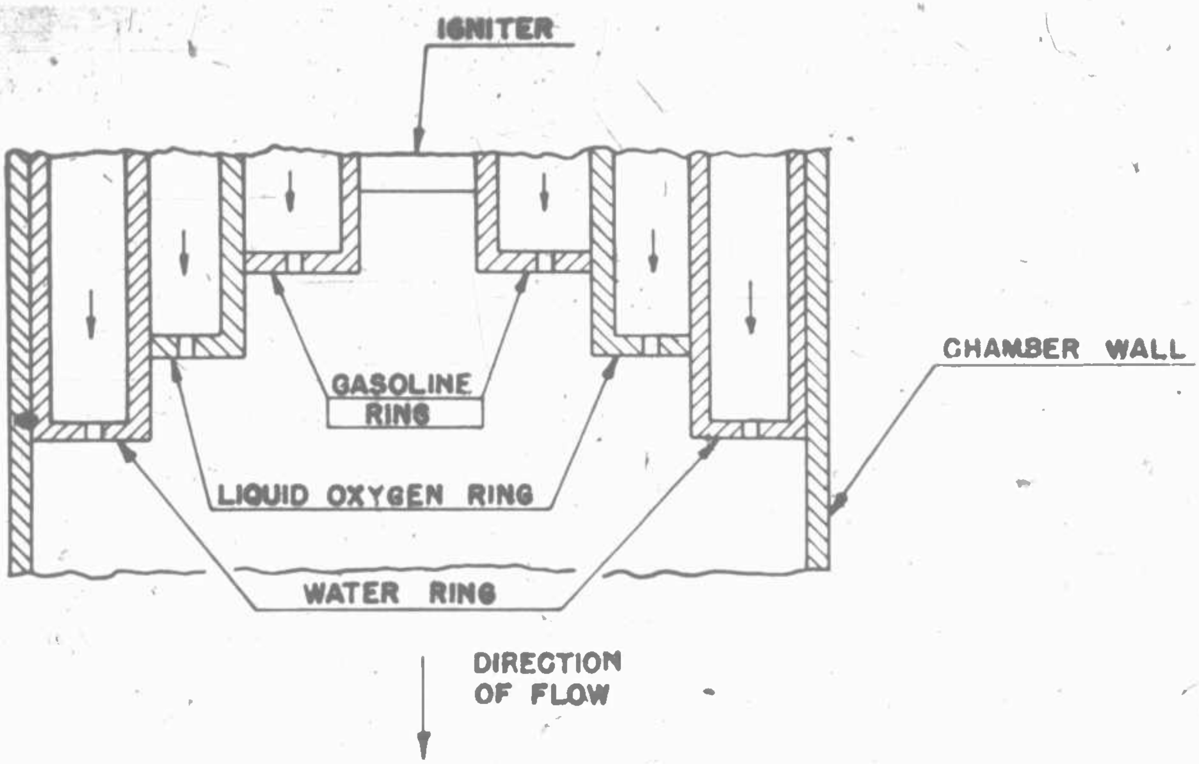


Fig. 35 - Schematic Arrangement Winkler Experimental Injector

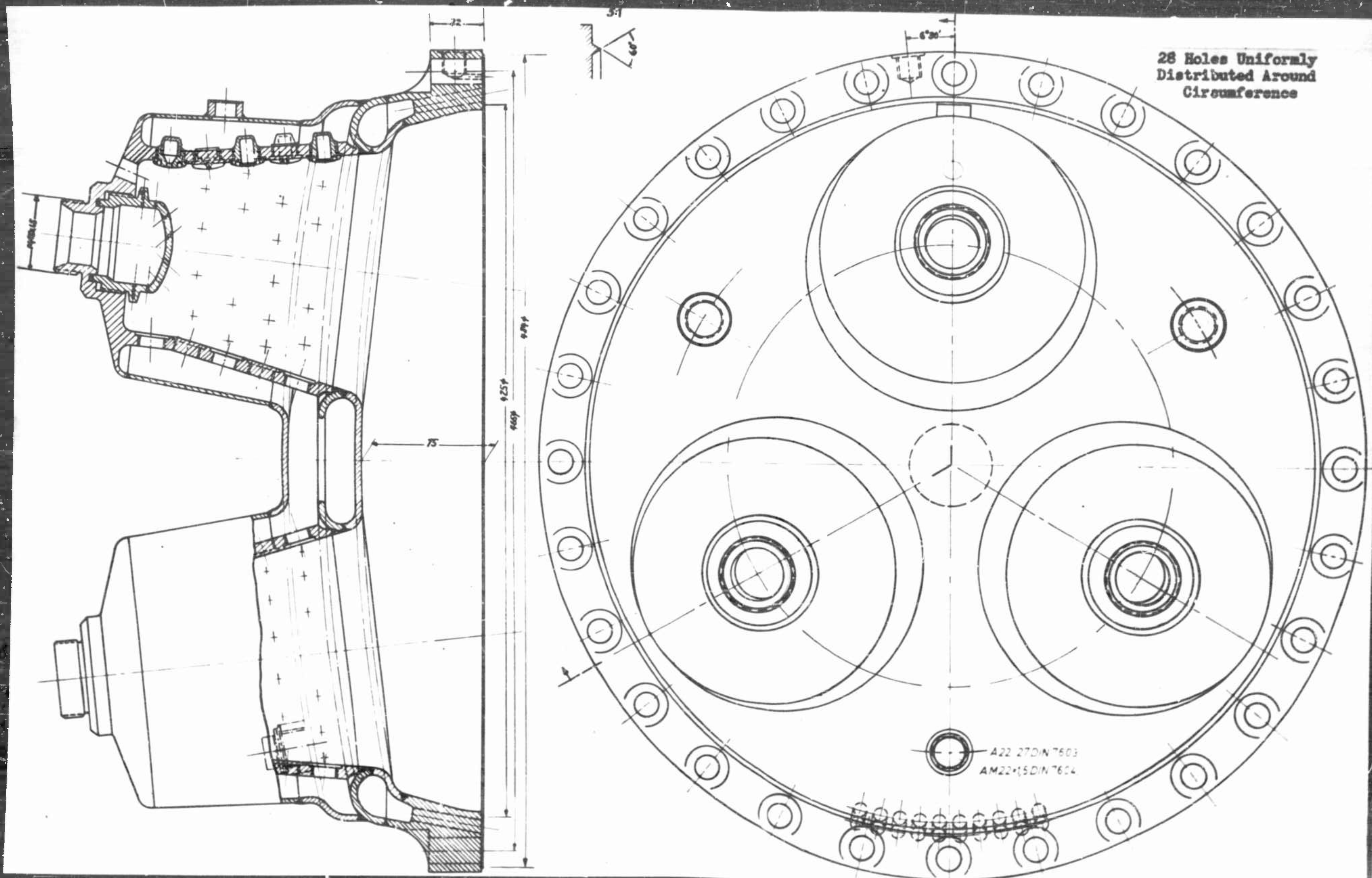


Fig. 36 – Head of [illegible] Combustion Chamber Showing [illegible] Injector Heads

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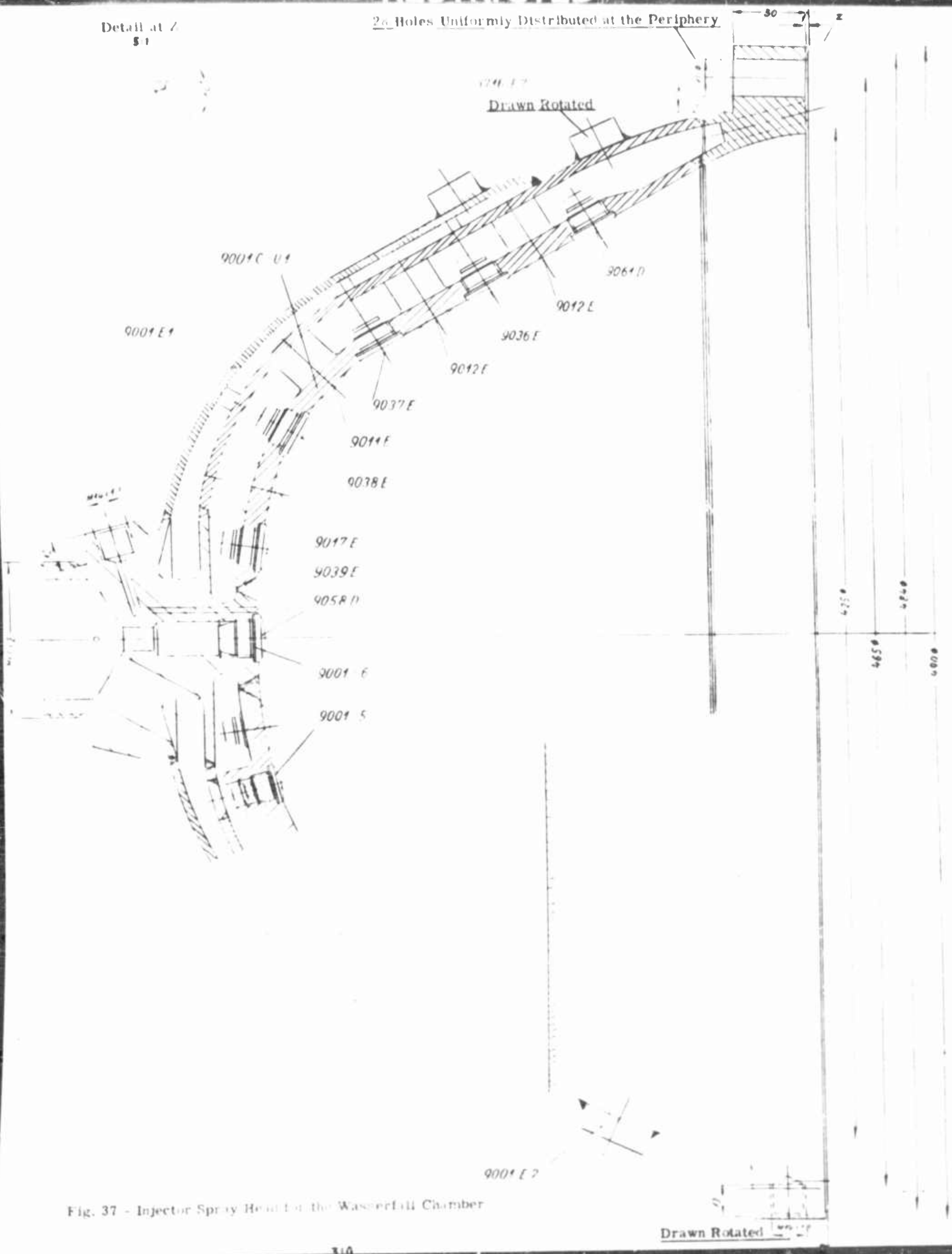

Fig. 37 - Injector Spray Head for the Wasserfall Chamber

Parts List for Figure 38

Zeichn.-Nr.: 9090 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	m
D_1	196	36	1.3	36	1.8	0.34
D_2	186	36	1.3	36	1.8	0.34
D_3	162	36	1.3	36	1.8	0.34
D_4	152	36	1.3	36	1.8	0.34
D_5	126	18	1.3	36	1.8	0.34
D_6	112	18	1.3	36	1.8	0.34
D_7	88	18	1.3	18	1.8	0.34
D_8	78	18	1.3	18	1.8	0.34
	Σ =	216		252		
	F =	286	mm^2	642	mm^2	

Zeichn.-Nr.: 9091 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	m
D_1	196	36	1.2	36	1.9	0.3
D_2	186	36	1.2	36	1.9	0.3
D_3	162	36	1.2	36	1.9	0.3
D_4	152	36	1.2	36	1.9	0.3
D_5	126	18	1.2	36	1.9	0.3
D_6	112	18	1.2	36	1.9	0.3
D_7	88	18	1.2	18	1.9	0.3
D_8	78	18	1.2	18	1.9	0.3
	Σ =	216		252		
	F =	244	mm^2	715	mm^2	

Zeichn.-Nr.: 9092 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	m
D_1	196	36	1.1	36	2.0	0.27
D_2	186	36	1.1	36	2.0	0.27
D_3	162	36	1.1	36	2.0	0.27
D_4	152	36	1.1	36	2.0	0.27
D_5	126	18	1.1	36	2.0	0.27
D_6	112	18	1.1	36	2.0	0.27
D_7	88	18	1.1	18	2.0	0.27
D_8	78	18	1.1	18	2.0	0.27
	Σ =	216		252		
	F =	205	mm^2	792	mm^2	

Zeichn.-Nr.: 9093 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	m
D_1	196	36	1.0	36	2.1	0.2
D_2	186	36	1.0	36	2.1	0.2
D_3	162	36	1.0	36	2.1	0.2
D_4	152	36	1.0	36	2.1	0.2
D_5	126	18	1.0	36	2.1	0.2
D_6	112	18	1.0	36	2.1	0.2
D_7	88	18	1.0	18	2.1	0.2
D_8	78	18	1.0	18	2.1	0.2
	Σ =	216		252		
	F =	169	mm^2	873	mm^2	

Zeichn.-Nr. : drawing number
Teilkr. : diameter of arc of circle
Brennstoff : fuel
Salbei : nitric acid
Lochanzahl : number of holes
⌀ : diameter

Zeichn.-Nr.: 9094 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	⌀P
D_1	196	36	1.2	36	1.9	6
D_2	186	36	1.2	36	1.9	6
D_3	162	36	1.2	36	1.9	6
D_4	152	36	1.2	36	1.9	6
D_5	126	18	1.2	36	1.9	6
D_6	112	18	1.2	36	1.9	6
D_7	88	18	1.2	18	1.9	6
D_8	78	18	1.2	18	1.9	6
	Σ =	216		252		
	F =	244	mm^2	715	mm^2	

Zeichn.-Nr.: 9095 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	⌀P
D_1	196	36	1.3	36	2.0	5
D_2	186	36	1.3	36	2.0	5
D_3	162	36	1.3	36	2.0	5
D_4	152	36	1.3	36	2.0	5
D_5	126	18	1.3	36	2.0	5
D_6	112	18	1.3	36	2.0	5
D_7	88	18	1.3	18	2.0	5
D_8	78	18	1.3	18	2.0	5
	Σ =	216		252		
	F =	286	mm^2	792	mm^2	

Zeichn.-Nr.: 9096 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	⌀P
D_1	196	36	1.4	36	2.1	4
D_2	186	36	1.4	36	2.1	4
D_3	162	36	1.4	36	2.1	4
D_4	152	36	1.4	36	2.1	4
D_5	126	18	1.4	36	2.1	4
D_6	112	18	1.4	36	2.1	4
D_7	88	18	1.4	18	2.1	4
D_8	78	18	1.4	18	2.1	4
	Σ =	216		252		
	F =	332	mm^2	873	mm^2	

Zeichn.-Nr.: 9097 C1						
Teilkr. ⌀		Brennstoff		Salbei		
		Loch-anzahl	y ⌀	Loch-anzahl	x ⌀	⌀P
D_1	196	36	1.5	36	2.3	3
D_2	186	36	1.5	36	2.3	3
D_3	162	36	1.5	36	2.3	3
D_4	152	36	1.5	36	2.3	3
D_5	126	18	1.5	36	2.3	3
D_6	112	18	1.5	36	2.3	3
D_7	88	18	1.5	18	2.3	3
D_8	78	18	1.5	18	2.3	3
	Σ =	216		252		
	F =	382	mm^2	1047	mm^2	

Fig. 38 - Experimental Spray Plate Injector I for Wasserfall
(Sheet 1 of 2 Sheets)

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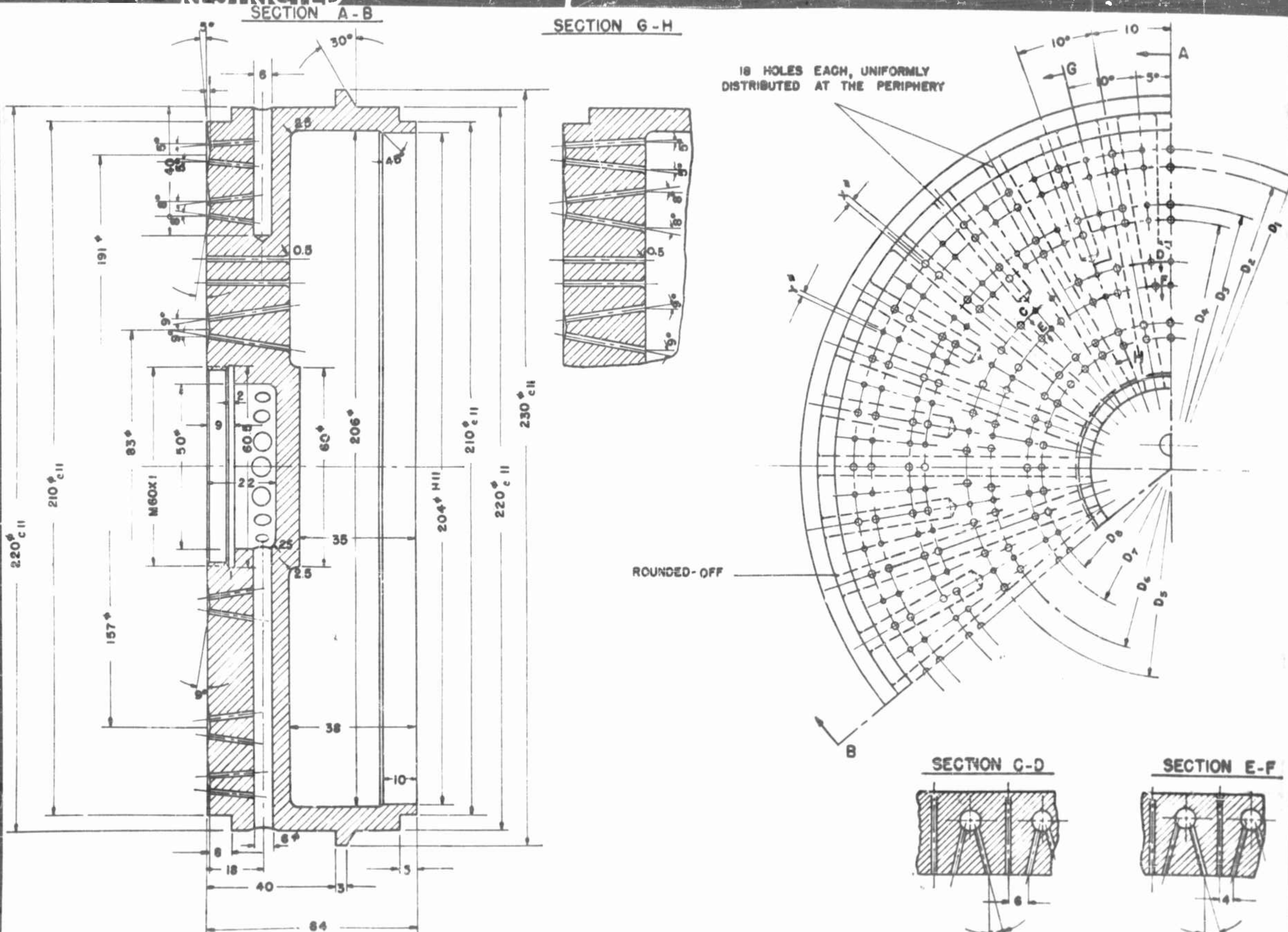
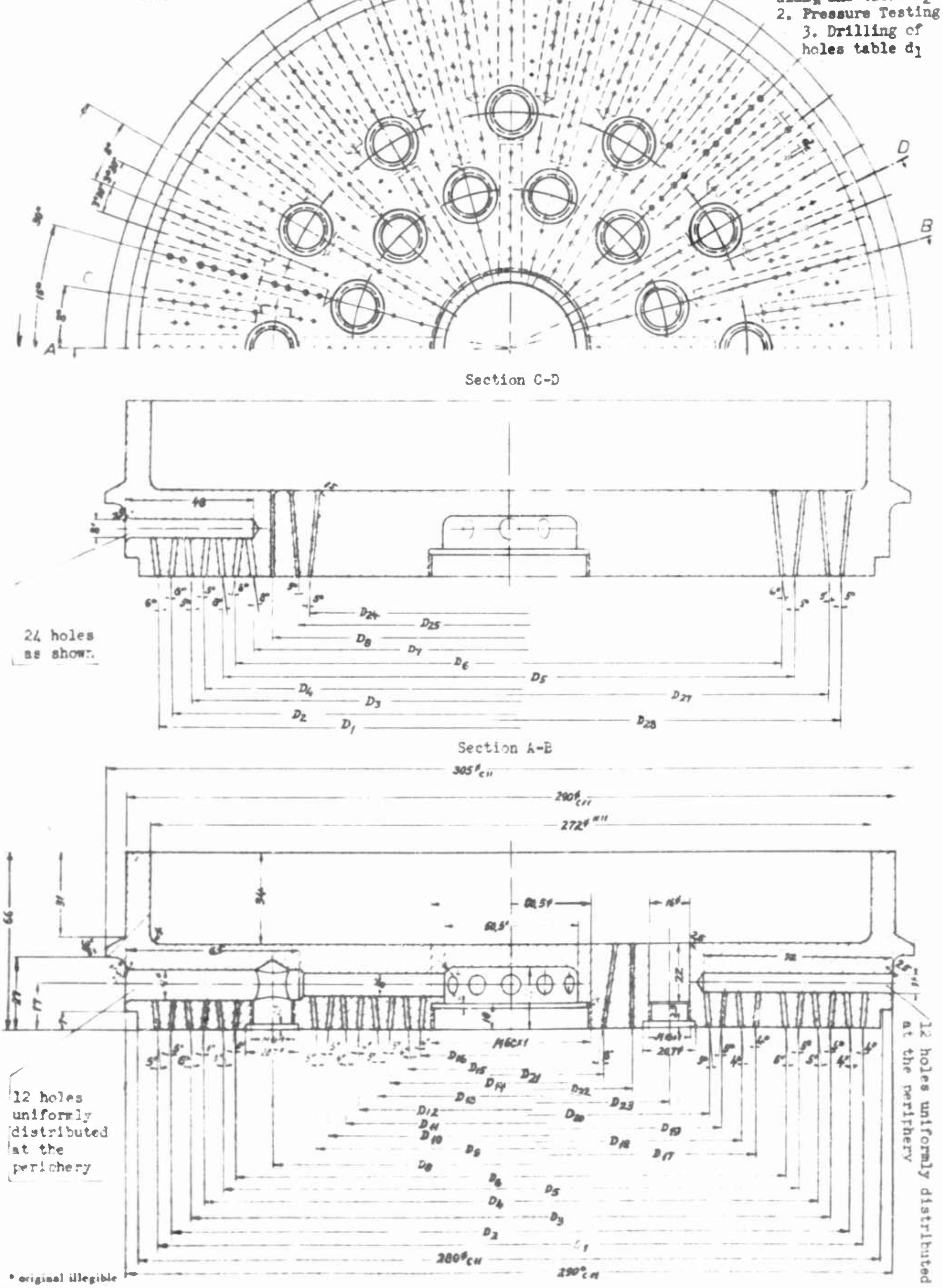


Fig. 38 - Experimental Spray Plate Injector [illegible] for Wasserfall
(Sheet 2 of [illegible] Sheets)

Teilkreis ⌀ : diameter of arc
Anzahl Bohrg. : number of holes
Loch ⌀ : hole diameter

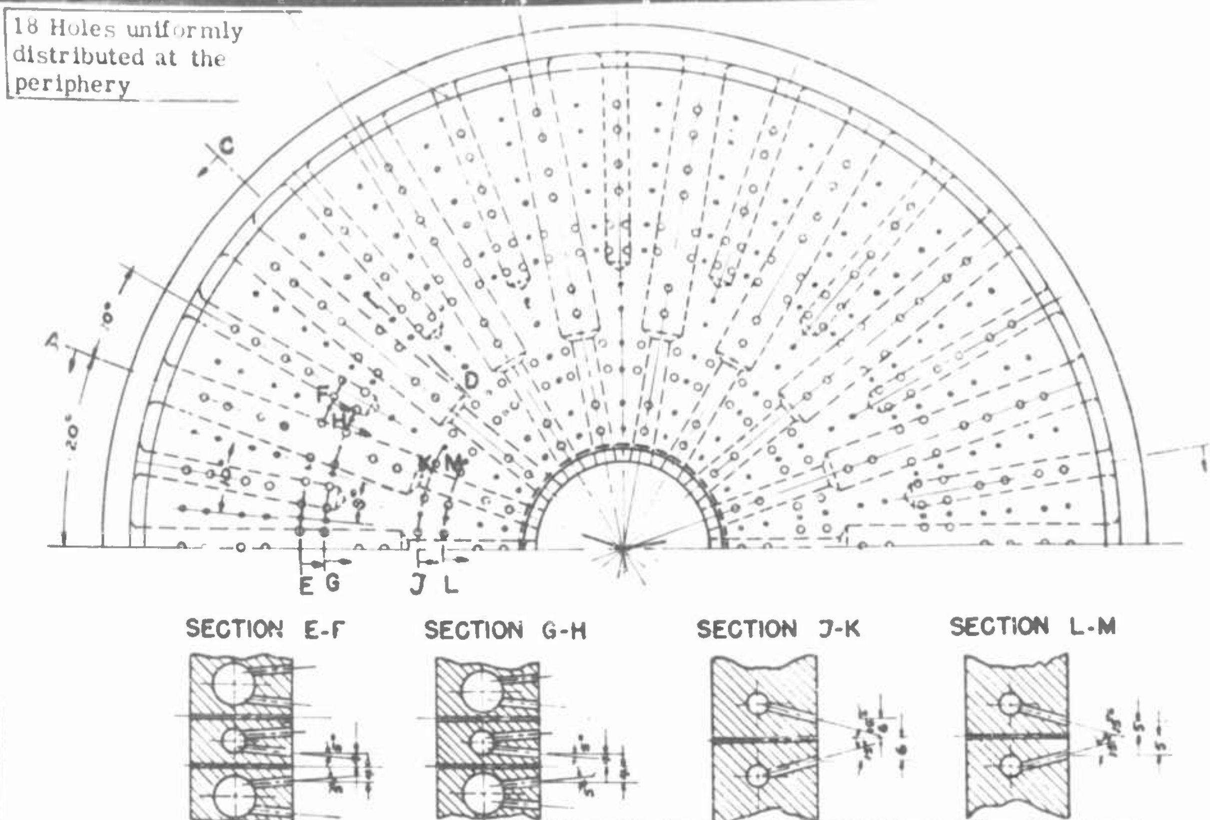
Fabrication Procedure
1. Drilling of holes 12 mm diam, 8 mm diam, and table d_2
2. Pressure Testing
3. Drilling of holes table d_1

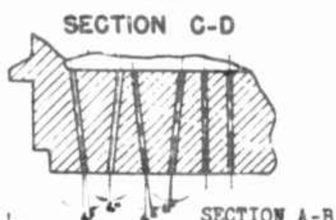


• original illegible

o	Teilkreis ⌀ mm		Anzahl Bohrg.	Loch⌀ mm	Continued				Continued			
d_1	D_1	266	48	2.0	D_7	•	24	2.0	D_{14}	92	12	2.0
	D_2	•	48	2.0	D_8	•	12	•	D_{15}	78	12	2.0
	D_3	•	48	2.0	D_9	•	12	2.0	D_{16}	68	12	2.0
	D_4	•	48	2.0	D_{10}	•	•	2.0	D_{17}	185	12	2.0
	D_5	•	48	2.0	D_{11}	125	12	2.0	D_{18}	175	12	2.0
	D_6	•	48	2.0	D_{12}	115	12	2.0	D_{19}	160	12	2.0
					D_{13}	102	12	2.0	D_{20}	150	12	2.0

•	Teilkreis ⌀ mm		Anzahl Bohrg.	Loch⌀ mm	Continued			
d_2	D_{21}	70	12	1.5	D_{27}	243	48	1.5
	D_{22}	92	12	1.5	D_{28}	253	48	1.5
	D_{23}	120	12	M16x1	D_5	218	48	1.5
	D_{24}	152	24	1.5	D_6	208	48	1.5
	D_{25}	162	24	1.5	D_8	180	24	1.5





D	ø	Anzahl der Bohrg. o	Anzahl der Bohrg. *
D_1	260	36	36
D_2	245	36	36
D_3	225	36	36
D_4	210	36	36
D_5	190	72	36
D_6	175	72	36
D_7	155	18	18
D_8	140	18	18
D_9	120	36	18
D_{10}	105	36	18
D_{11}	85	18	18
D_{12}	70	18	18
Σ		432	324

Anzahl der Bohrg. : number of holes

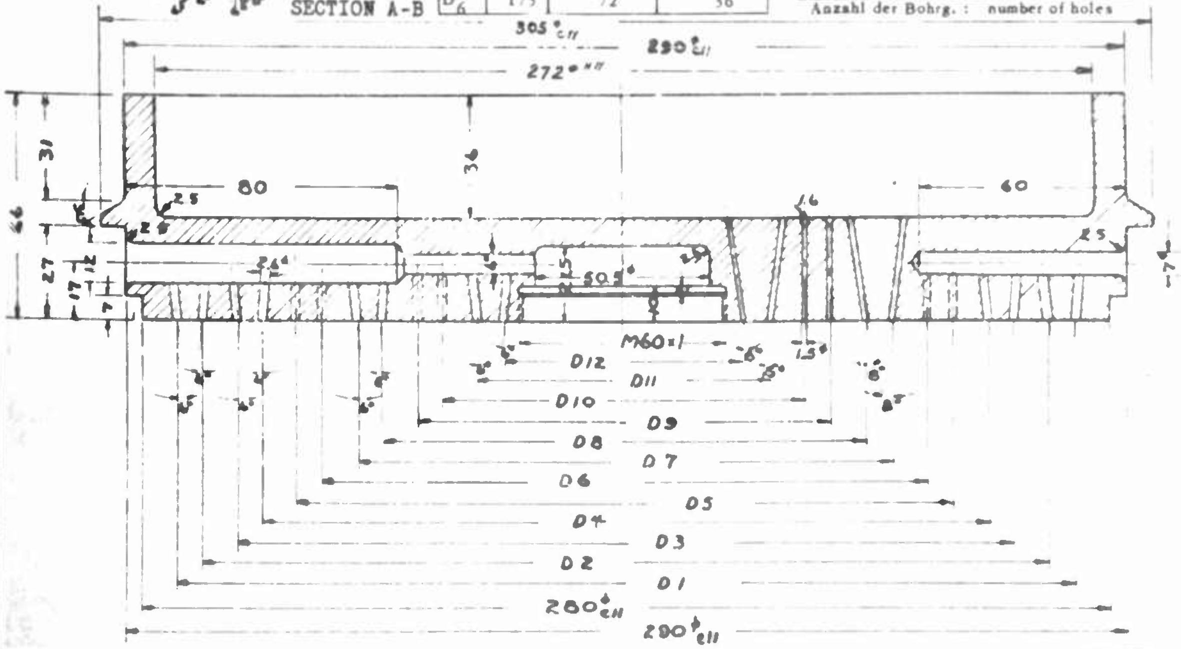
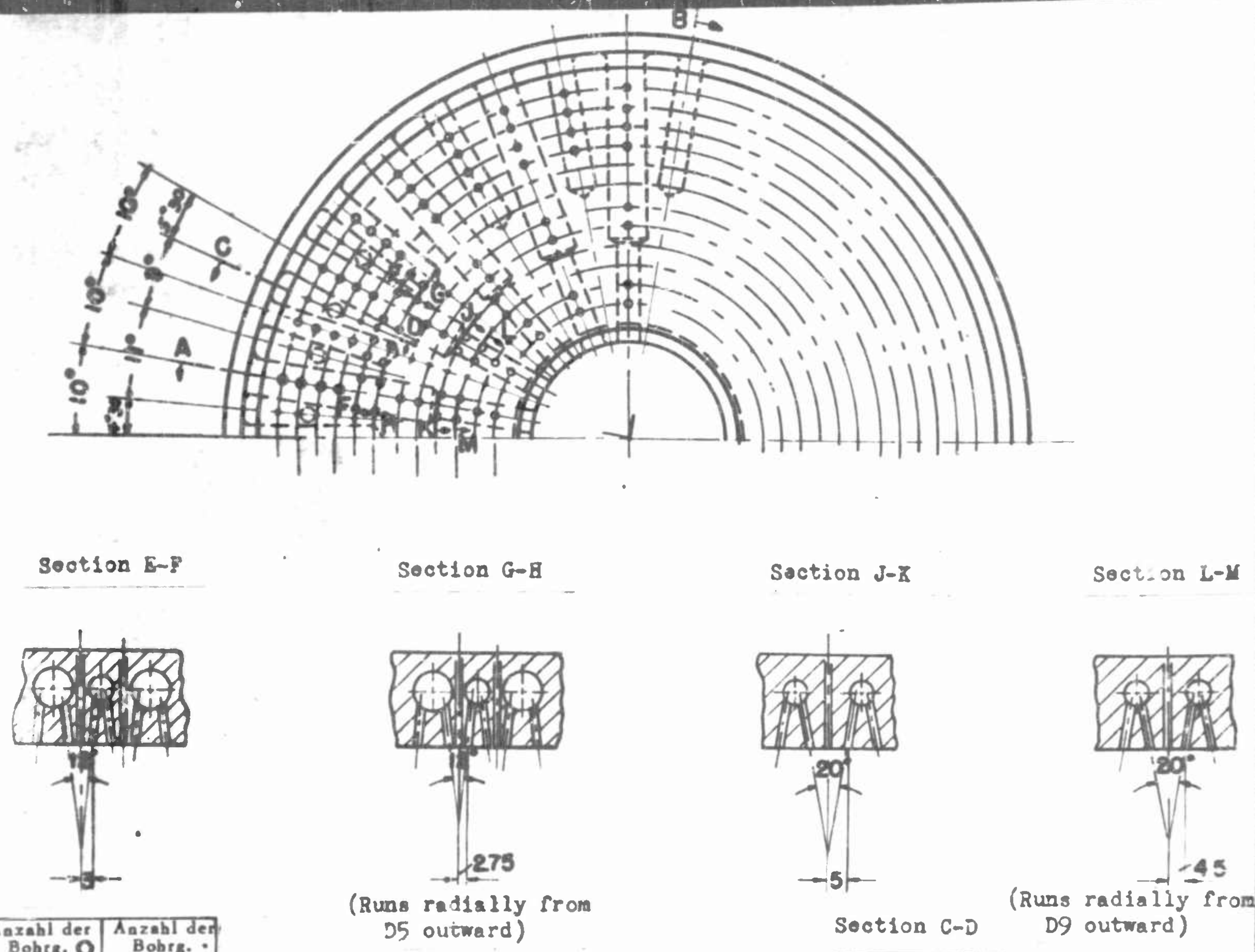
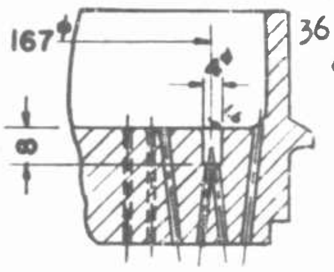
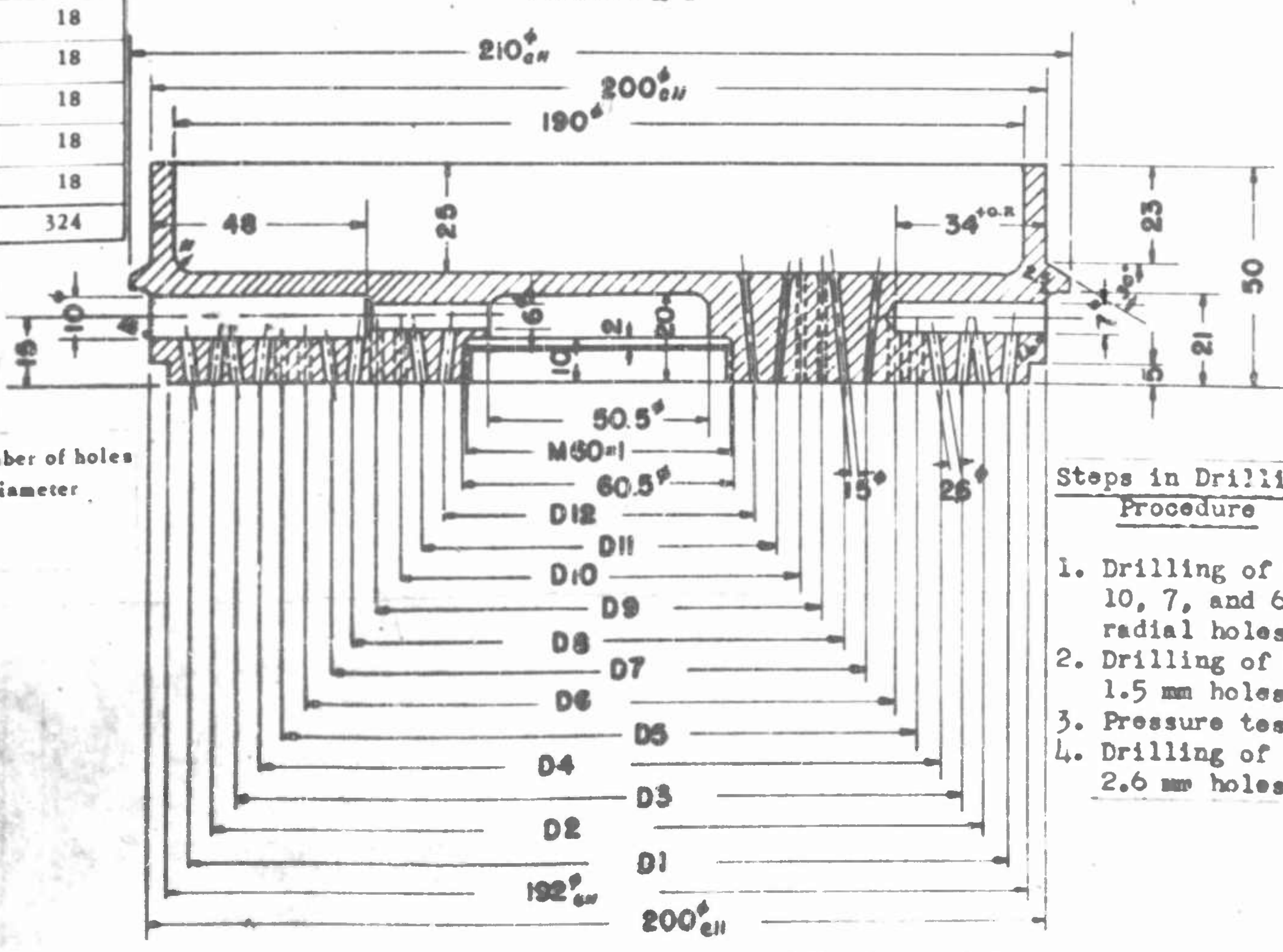


Fig. 40 - Experimental Spray Plate Injector III for Wasserfall



D ϕ	Anzahl der Bohrg. O	Anzahl der Bohrg. •
D_1 - 182	36	36
D_2 - 172	36	36
D_3 - 162	36	36
D_4 - 152	36	36
D_5 - 142	72	36
D_6 - 132	72	36
D_7 - 120	18	18
D_8 - 110	18	18
D_9 - 100	36	18
D_{10} - 90	36	18
D_{11} - 80	18	18
D_{12} - 70	18	18
Σ	432	324





Anzahl der Bohrg. : number of holes
D ϕ : D diameter

Steps in Drilling Procedure

1. Drilling of the 10, 7, and 6 mm radial holes.
2. Drilling of the 1.5 mm holes.
3. Pressure test.
4. Drilling of the 2.6 mm holes.

Fig. 41 - Experimental Spray Plate Injector IV for Wasserfall

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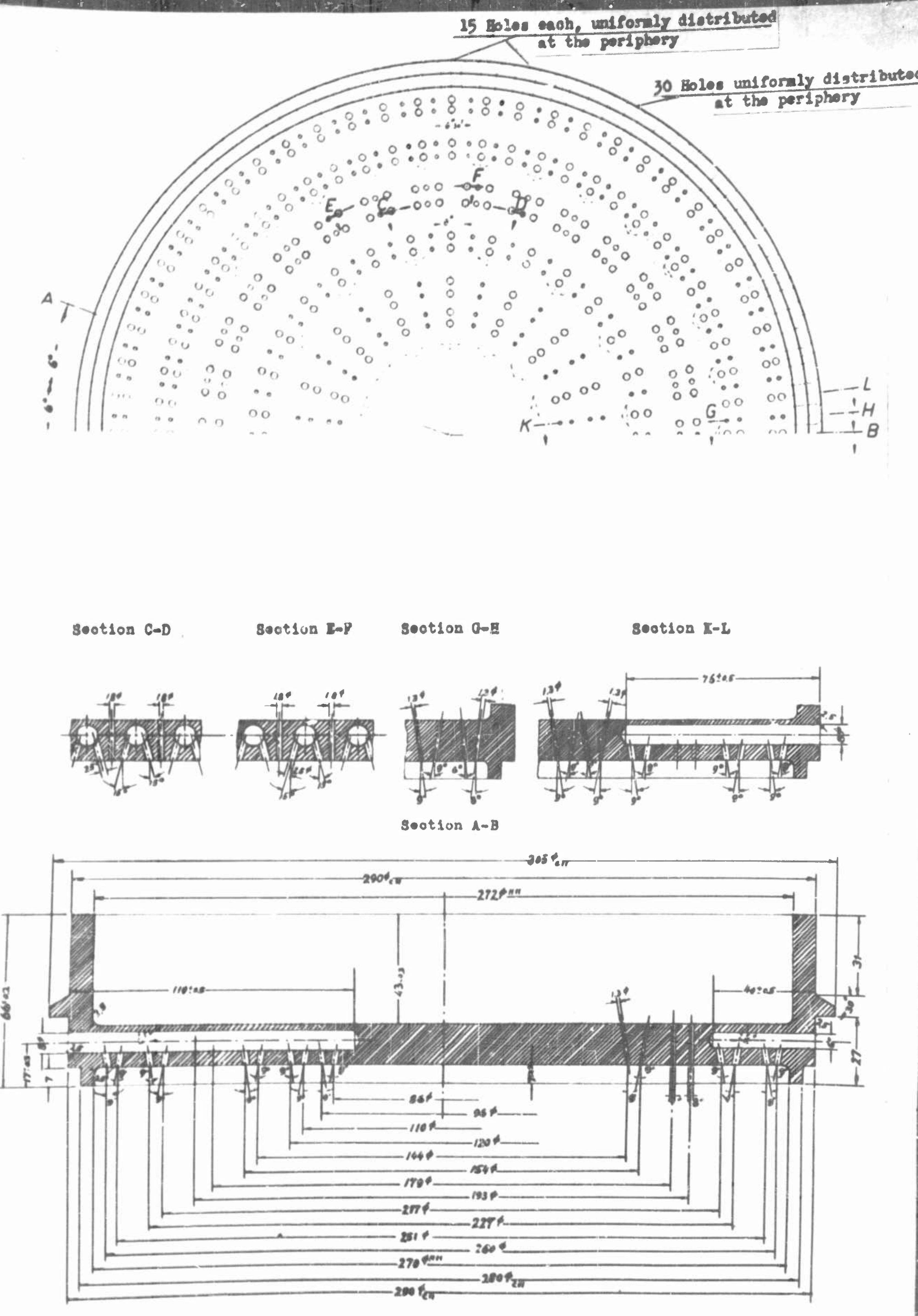
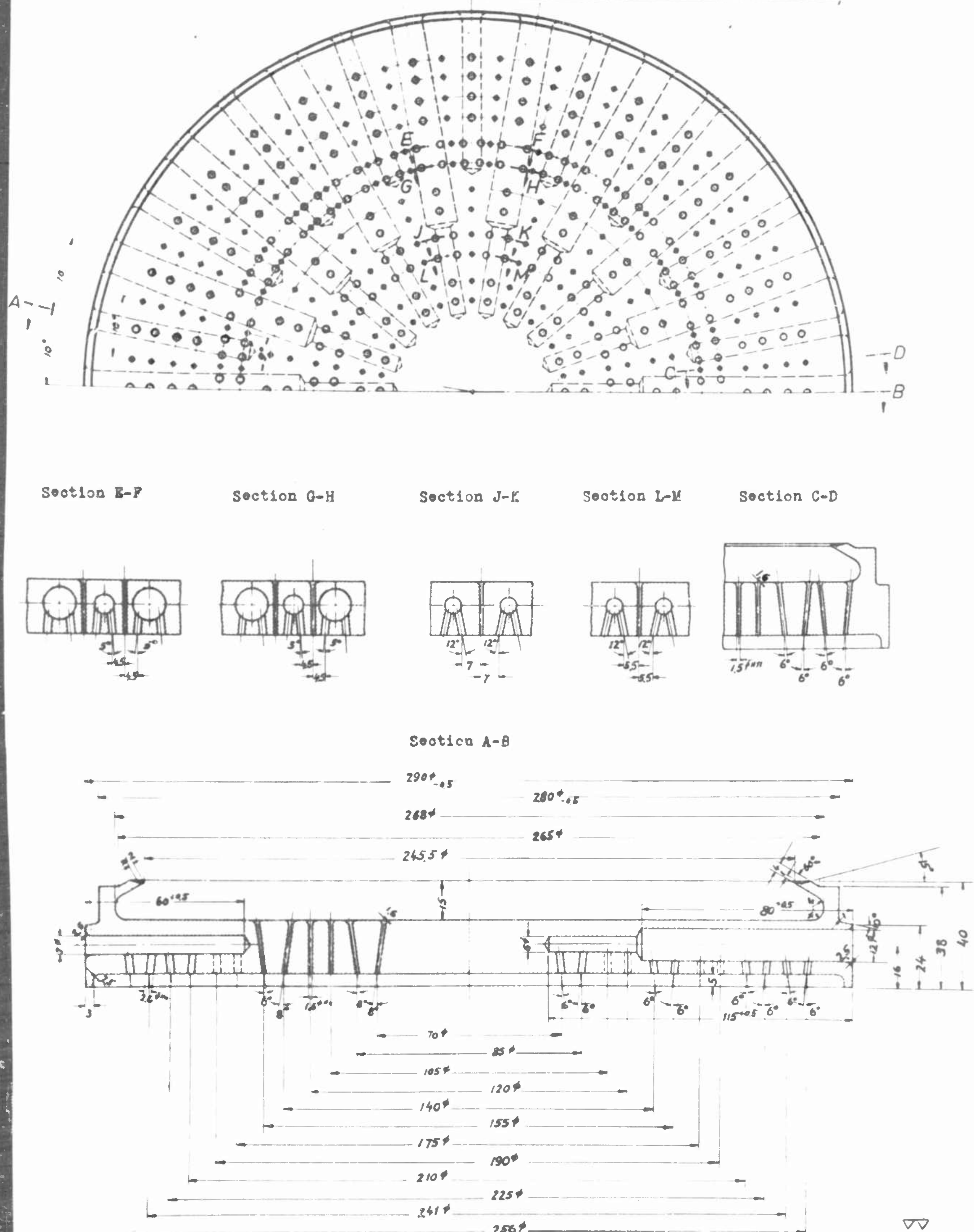


Fig. 42 - Experimental Spray Plate Injector V for Wasserfall



The 12, 7, and 6 mm diameter holes must not be touched by the 1.5 mm holes.

After drilling these holes a 142 psi pressure test is to be made as a check.

Fig. 43 - Early Production Version of Wasserfall Spray Plate Injector

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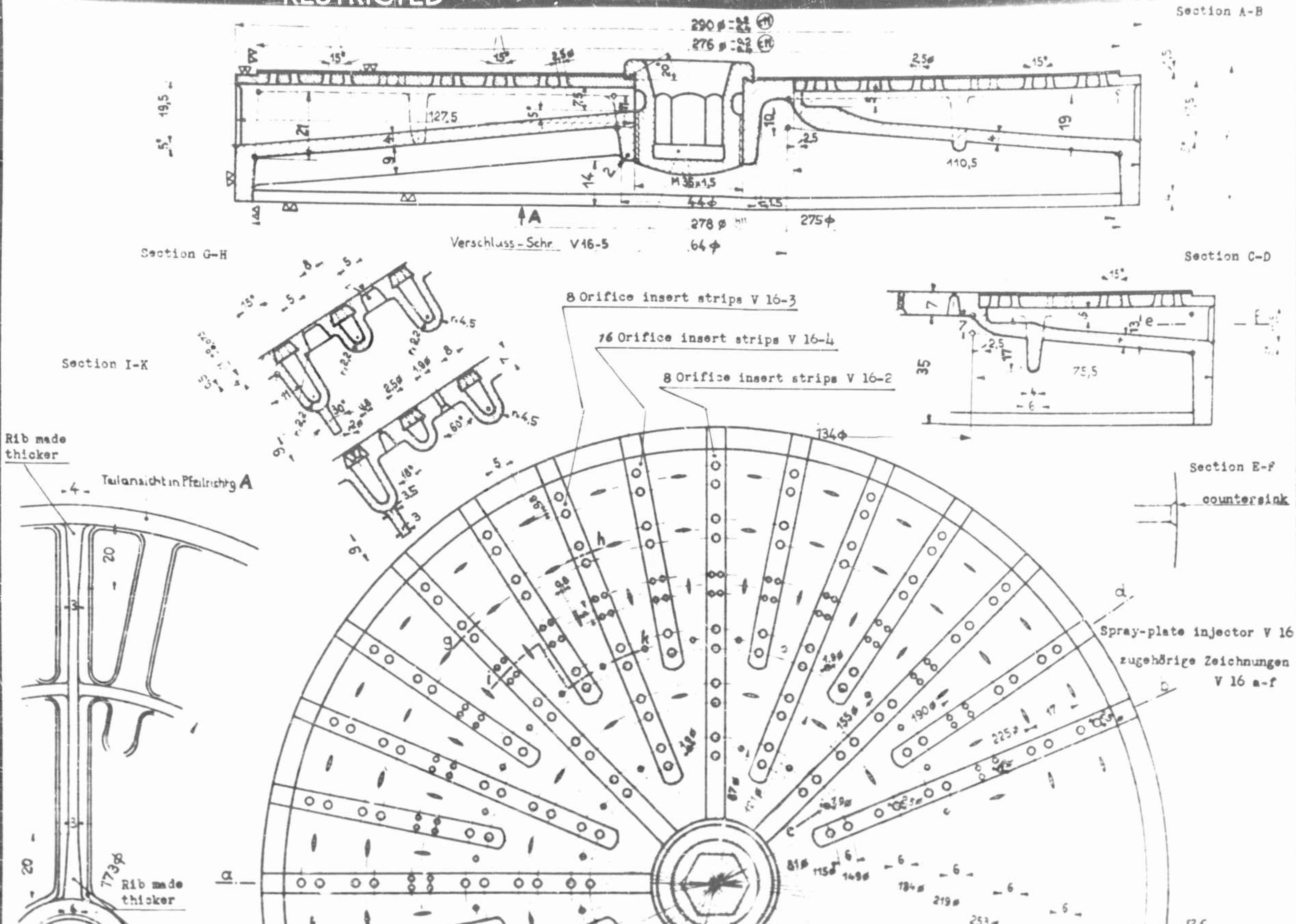

Fig. 44 - Final Production Version of Wasserfall Spray Plate Injector

Fig. 45

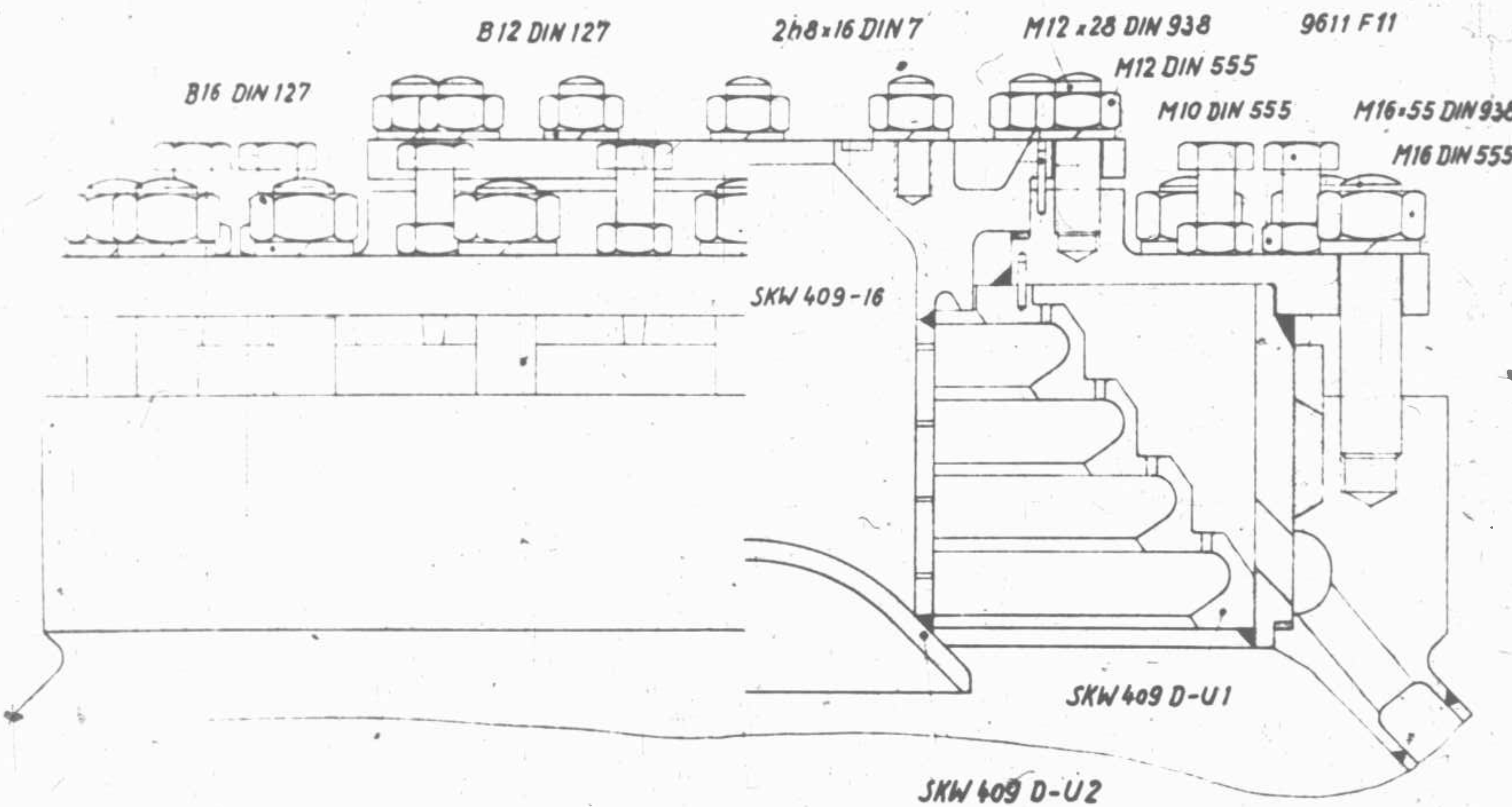

Fig. 46 - Proposed Wasserfall Cascade Injector

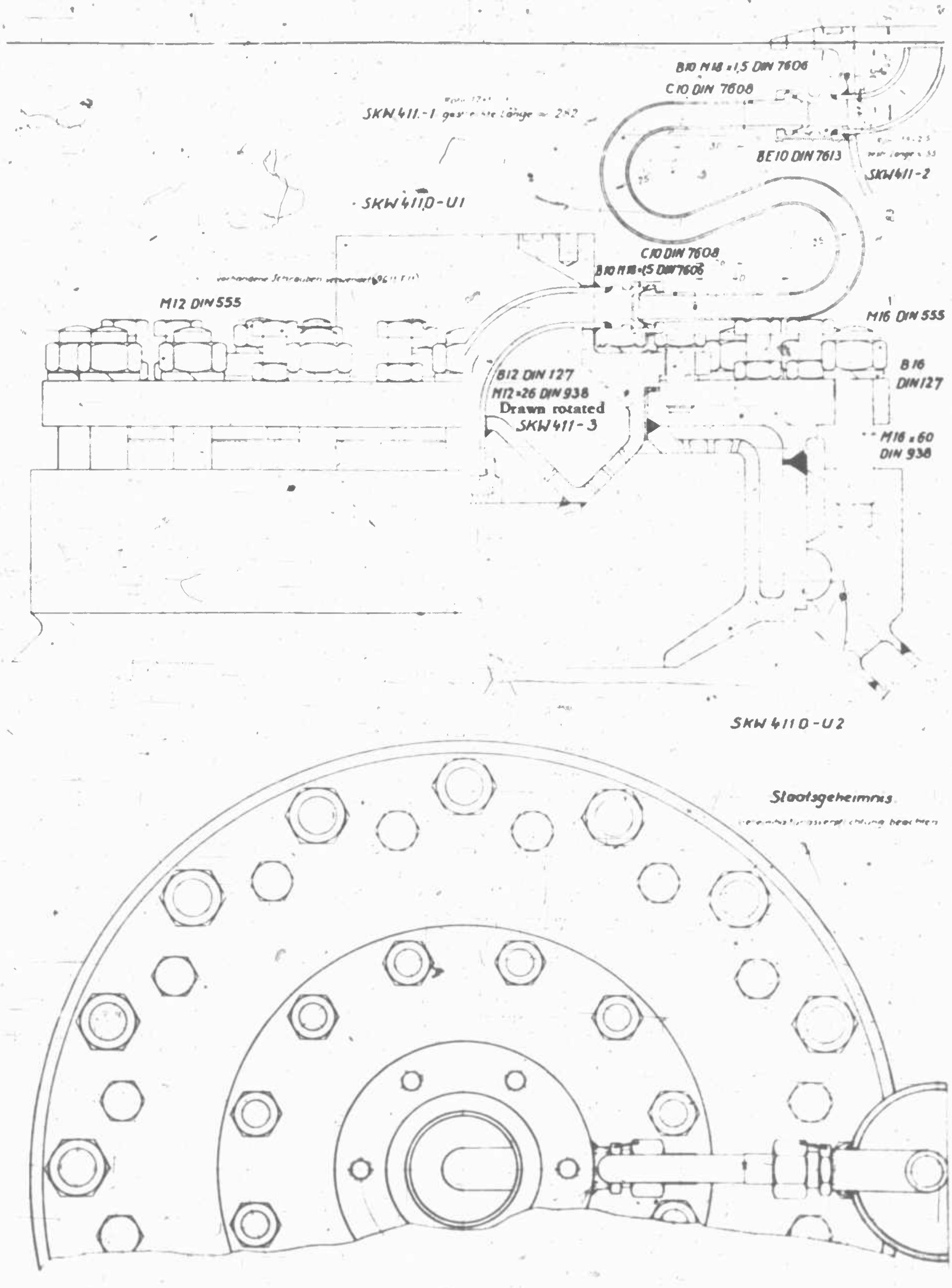

Fig. 47 - Proposed Wasserfall Deflector Plate Injector

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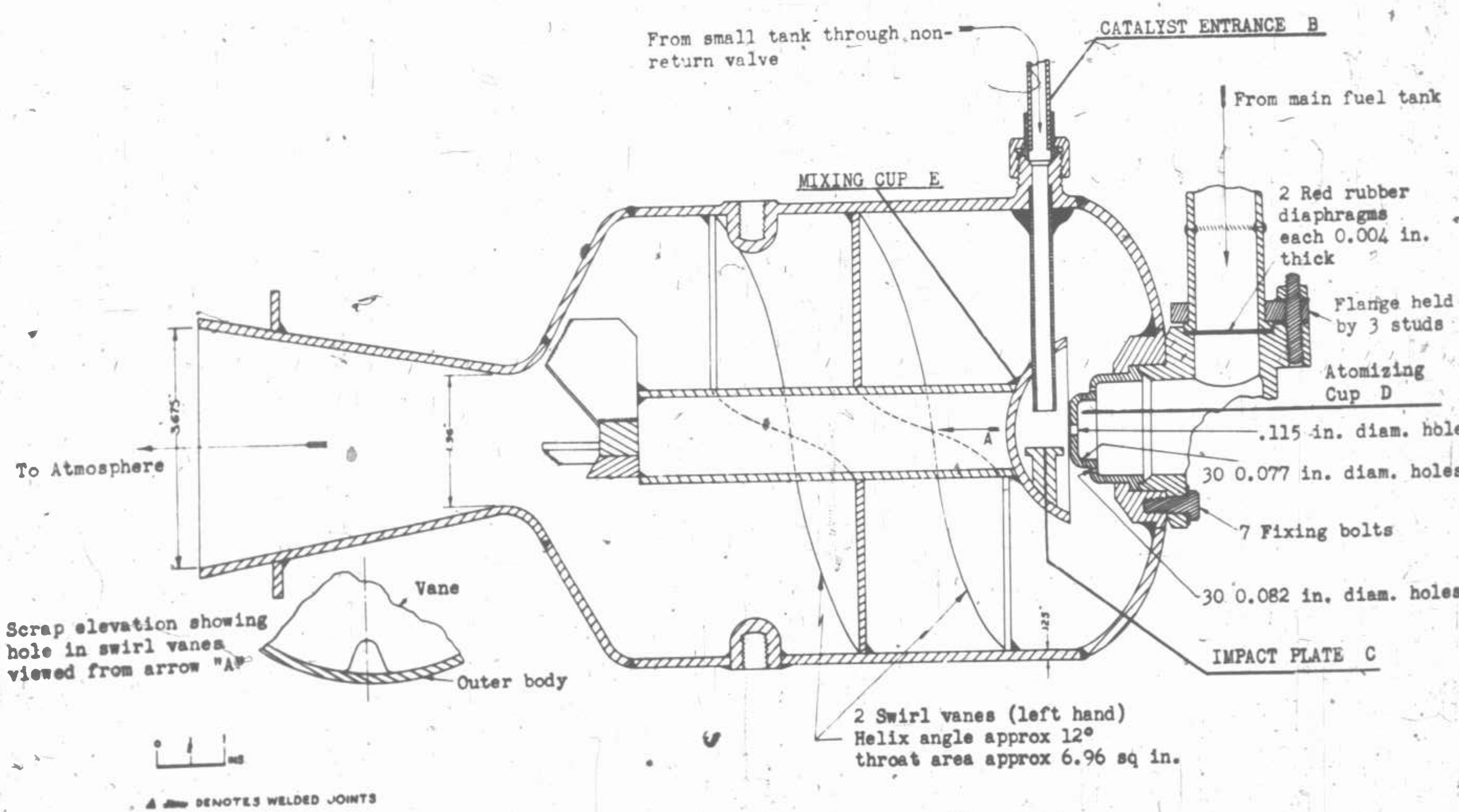


Fig. 49 - Detail of HWK 109-507 Combustion Chamber With Injector

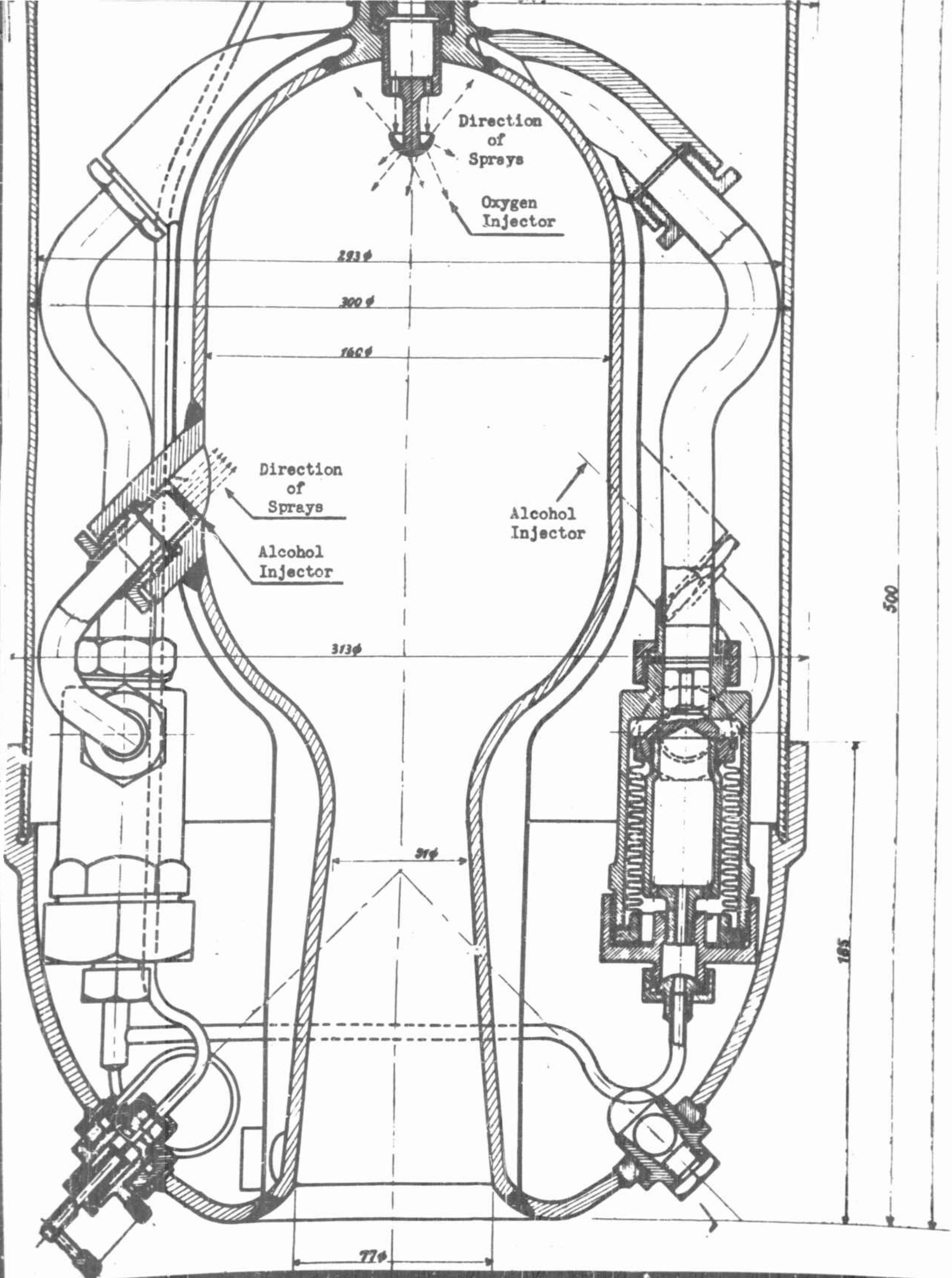
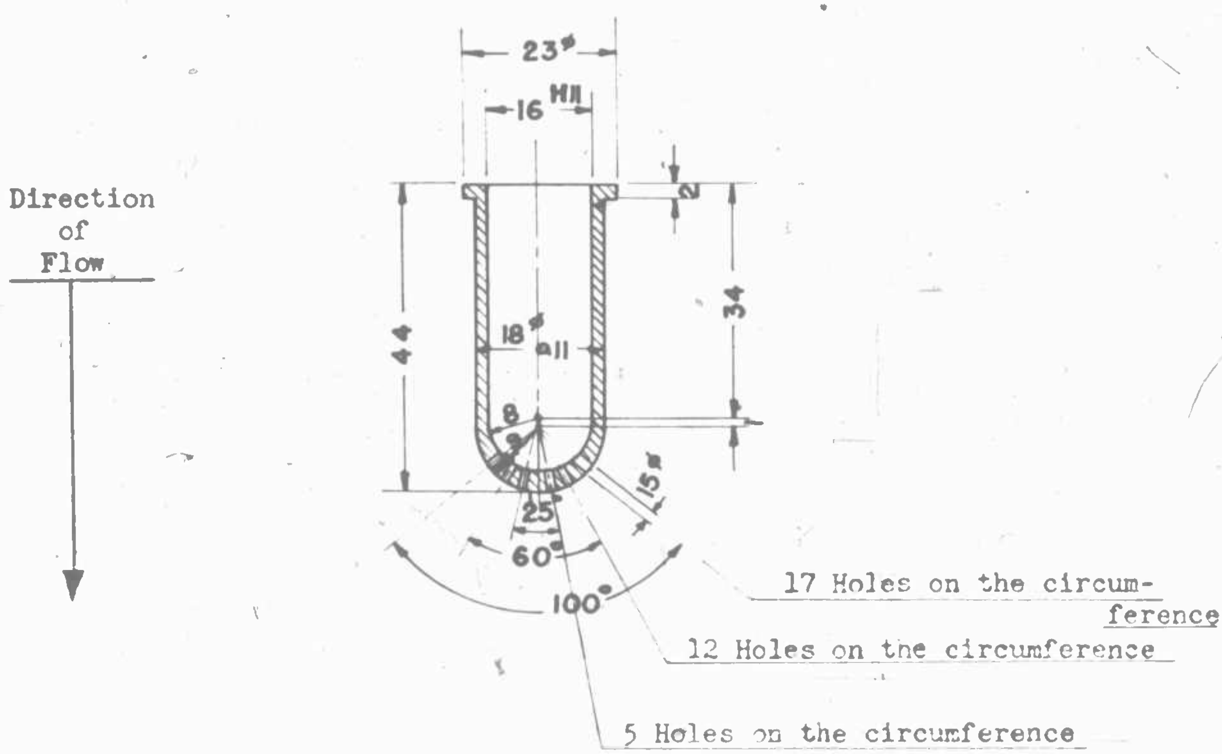


Fig. 50 - A-2 Section Showing Motor and Injection System



Total number of holes: 34

Total number of holes cross section : 60 mm^2

Fig. 51 - Oxygen Injector Detail

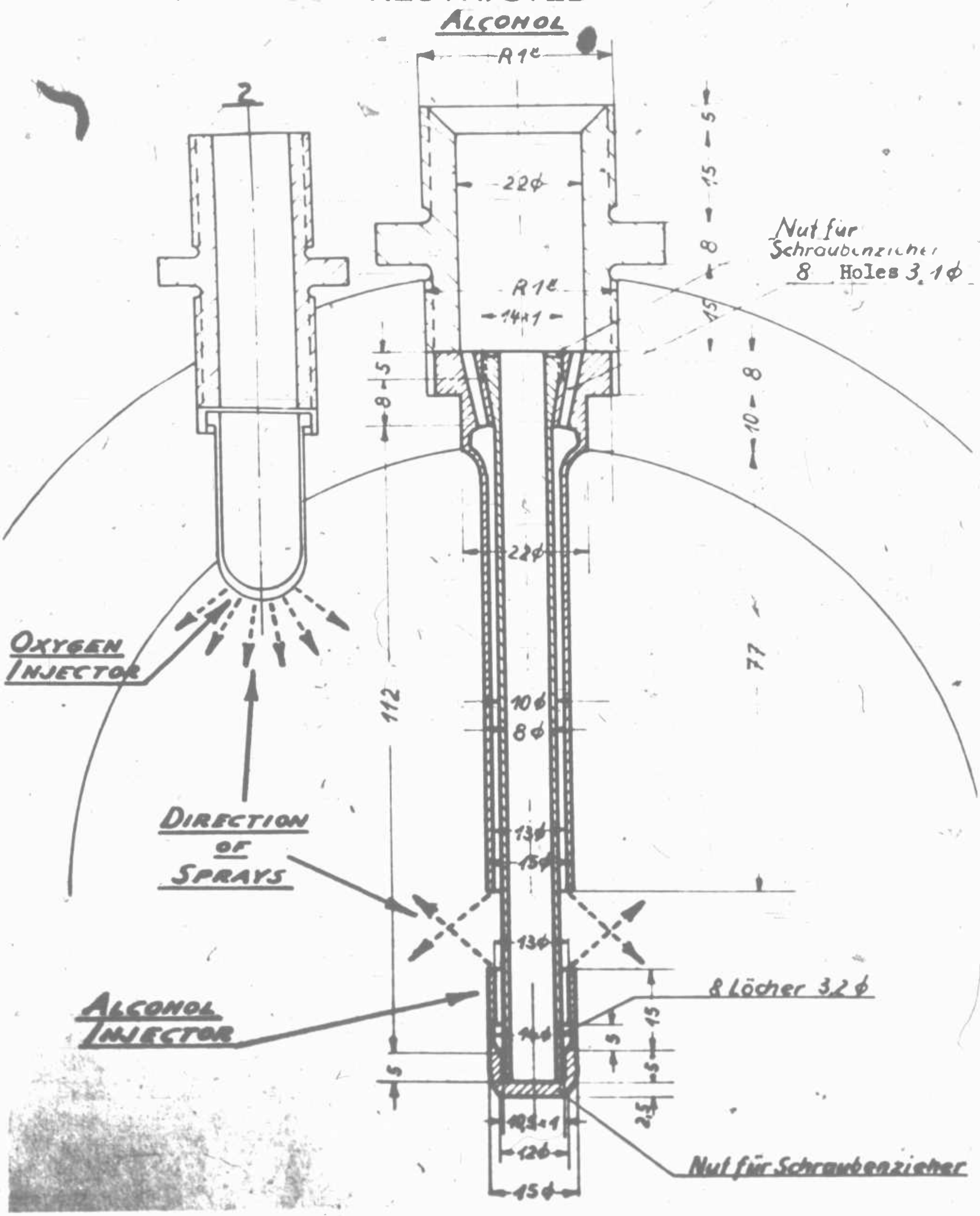


Fig 52 - Counterflow Injector

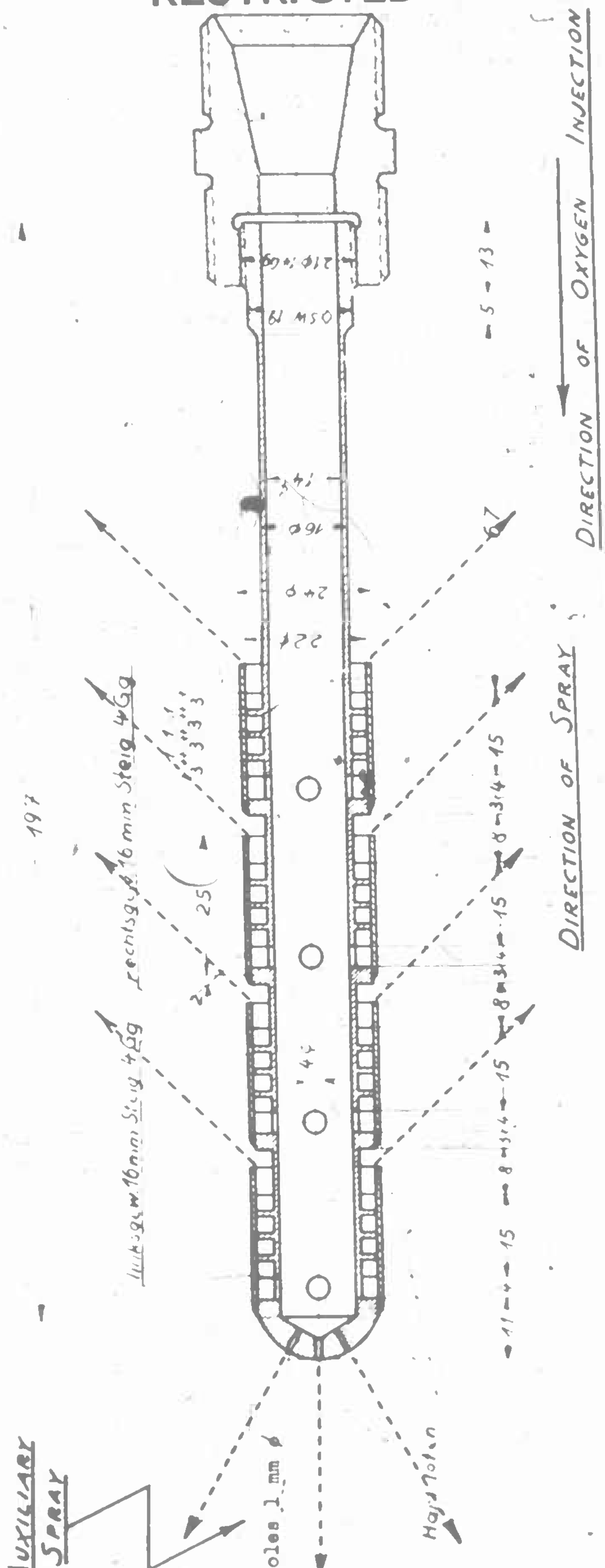


Fig. 53 - Counterflow Concentric Alcohol Twist Injector Detail

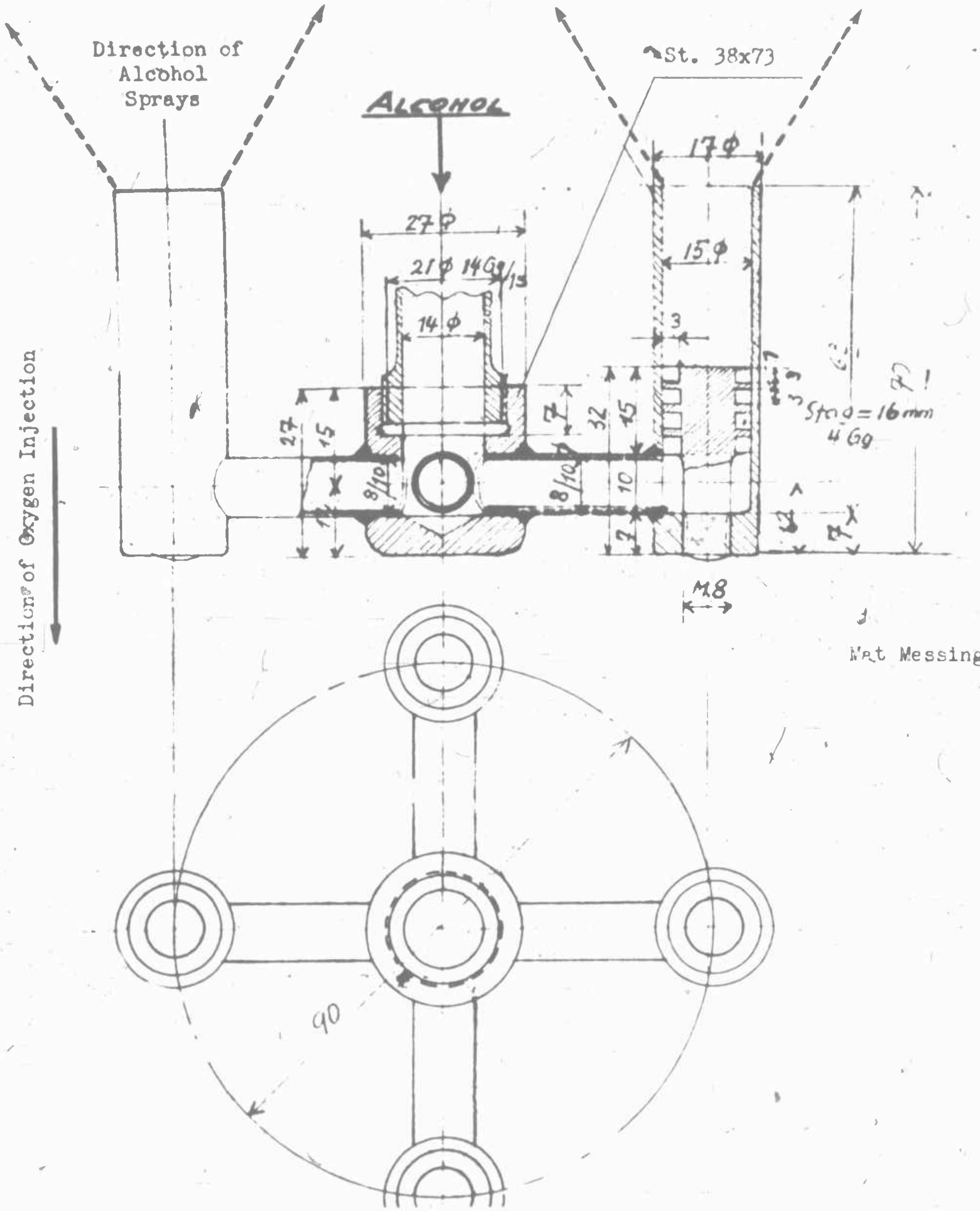


Fig. 54 - Counterflow Coplanar Alcohol Twist Injector

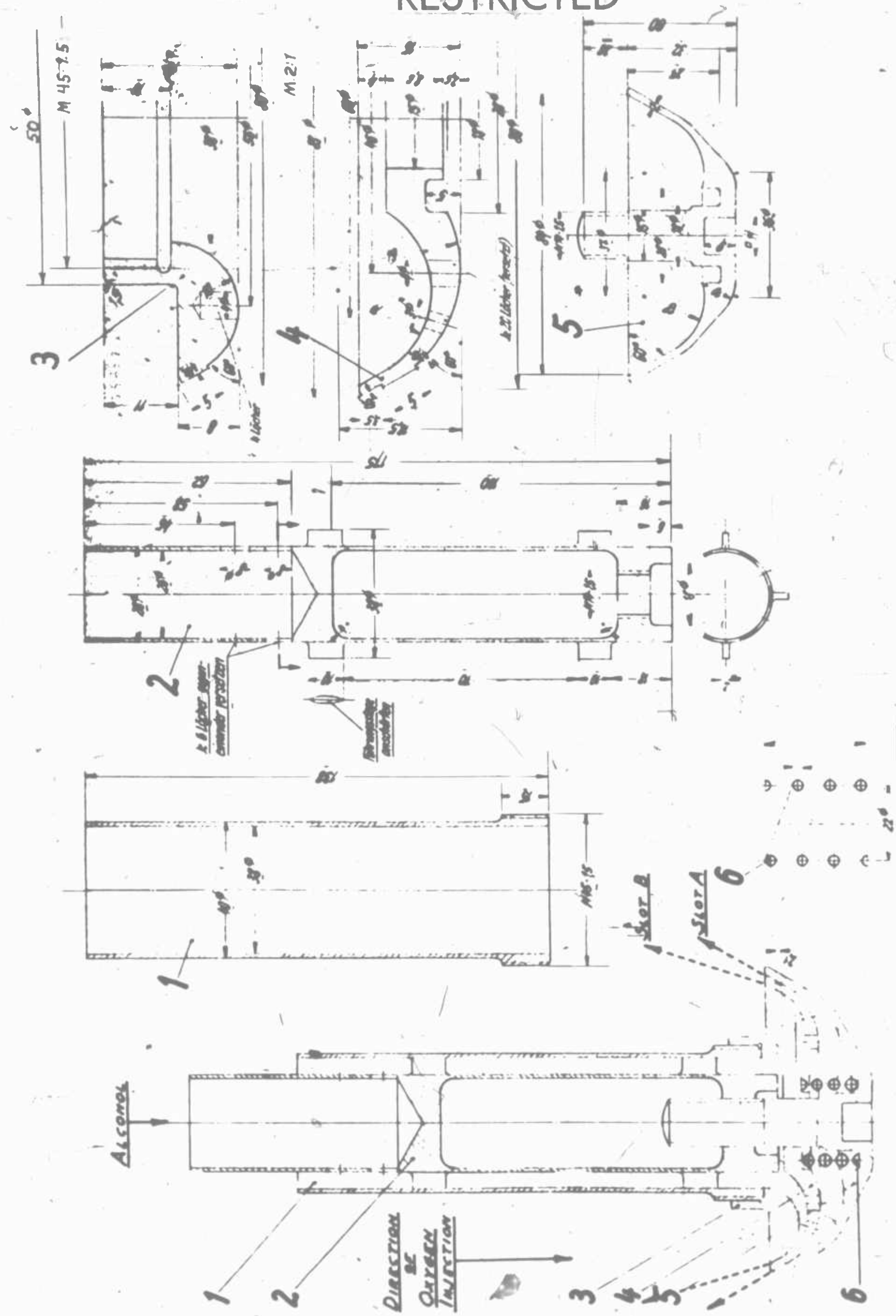


Fig. 55 - Counterflow 2200-Lb Self-Capping Injector

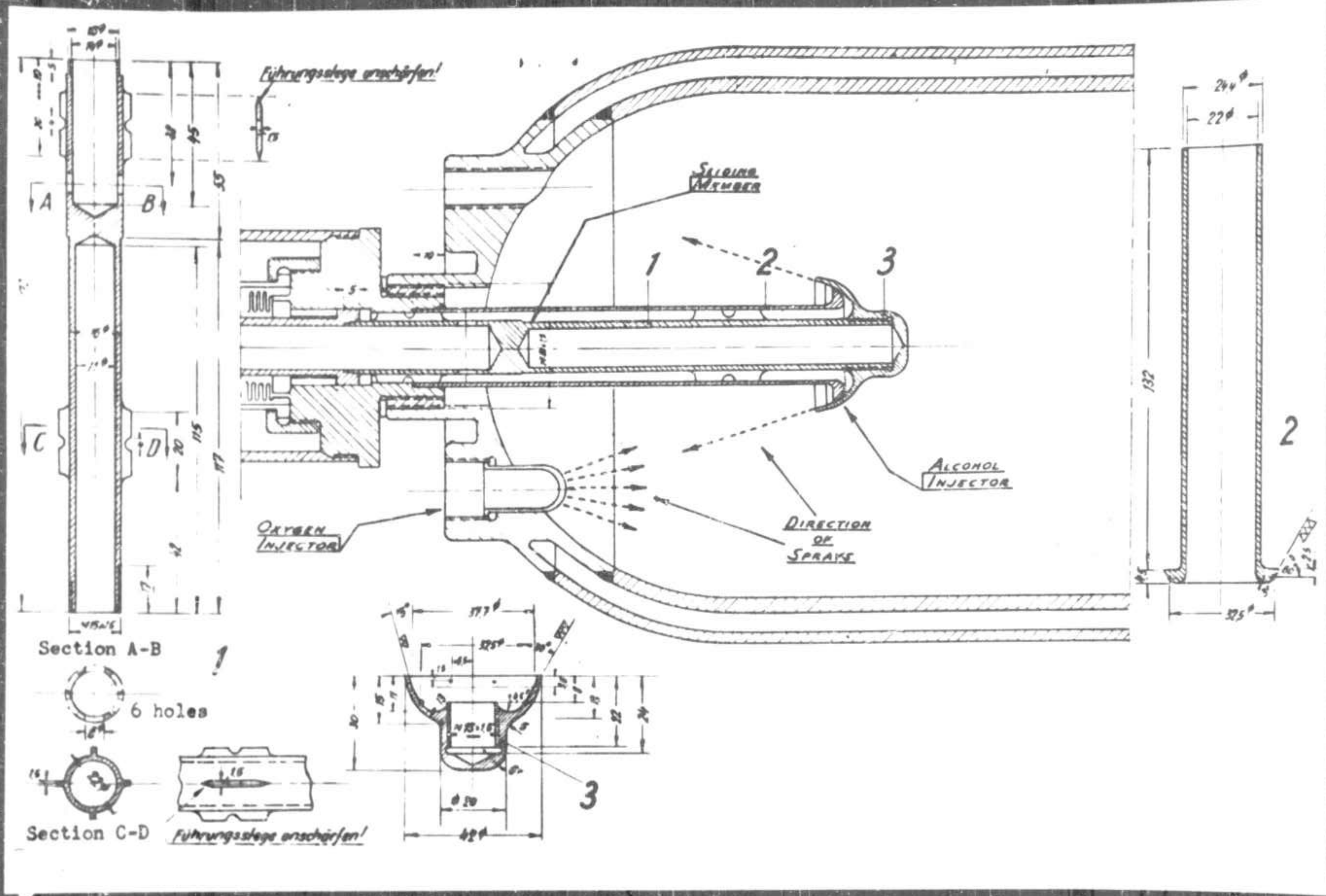


Fig. 56 - Counterflow Self-Centering Injector for 660-Lb Thrust

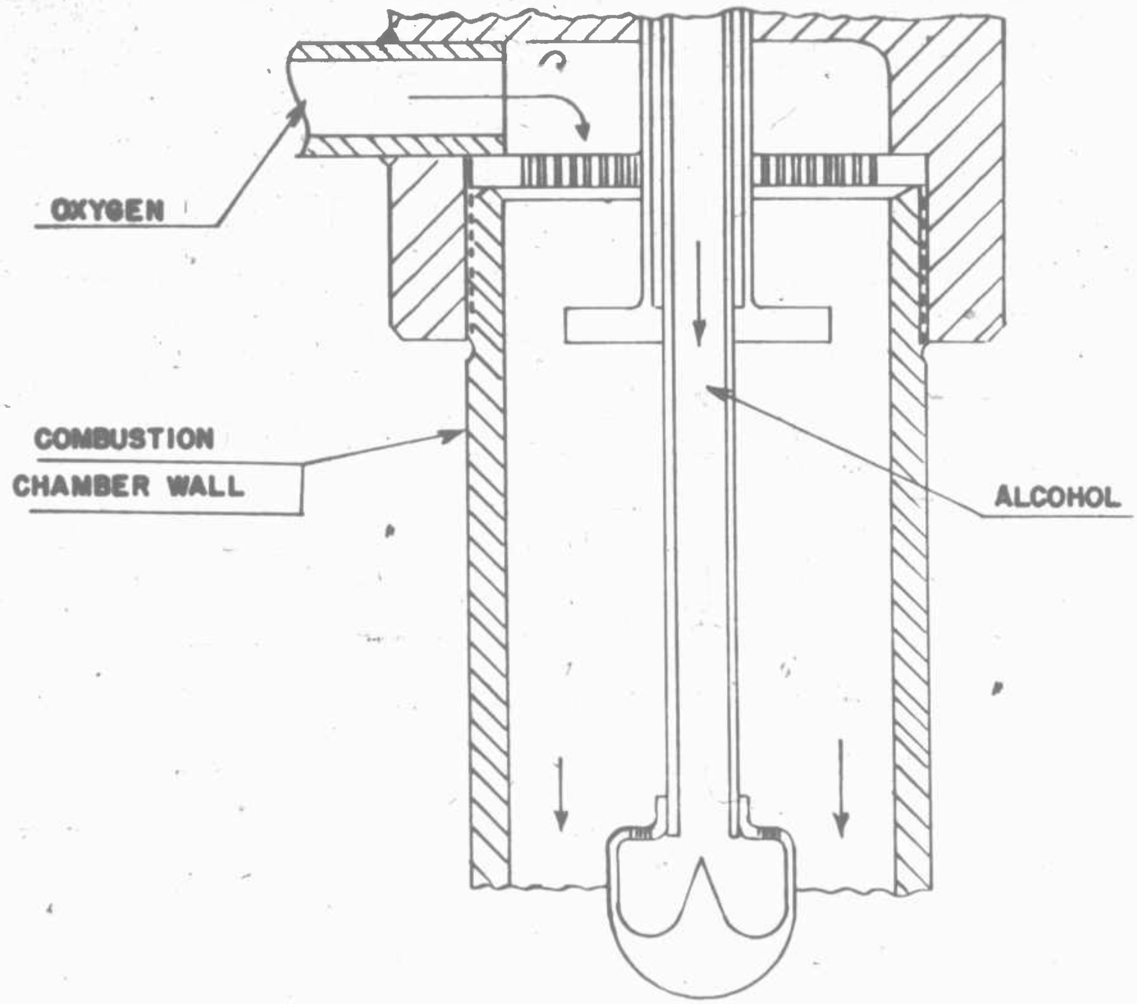


Fig. 57 -
Schematic Arrangement - Injector for 44-Lb Experimental Unit (APJ Drawing No. 051-920-05-00)

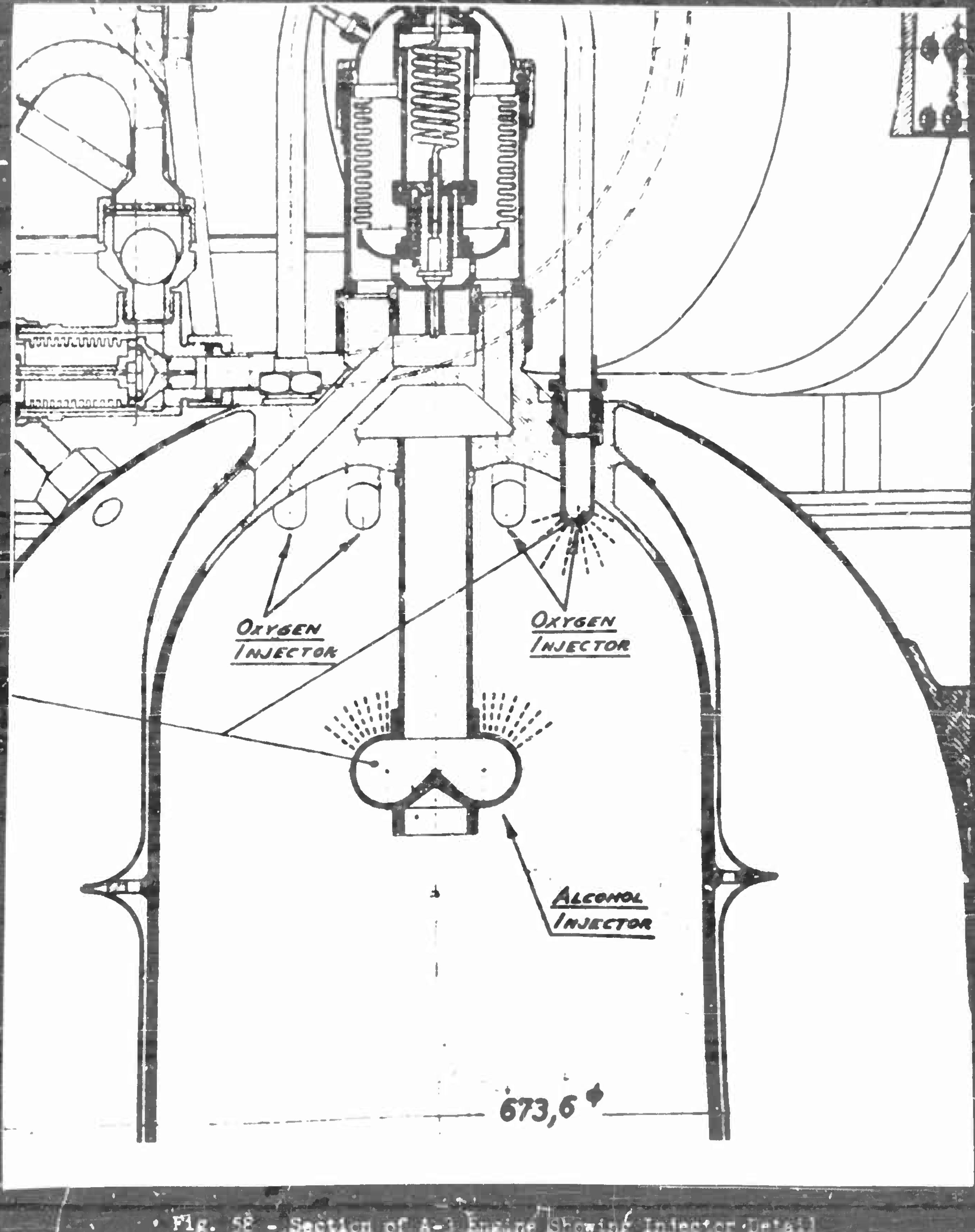


Fig. 58 - Section of A-3 Engine Showing Injector Detail

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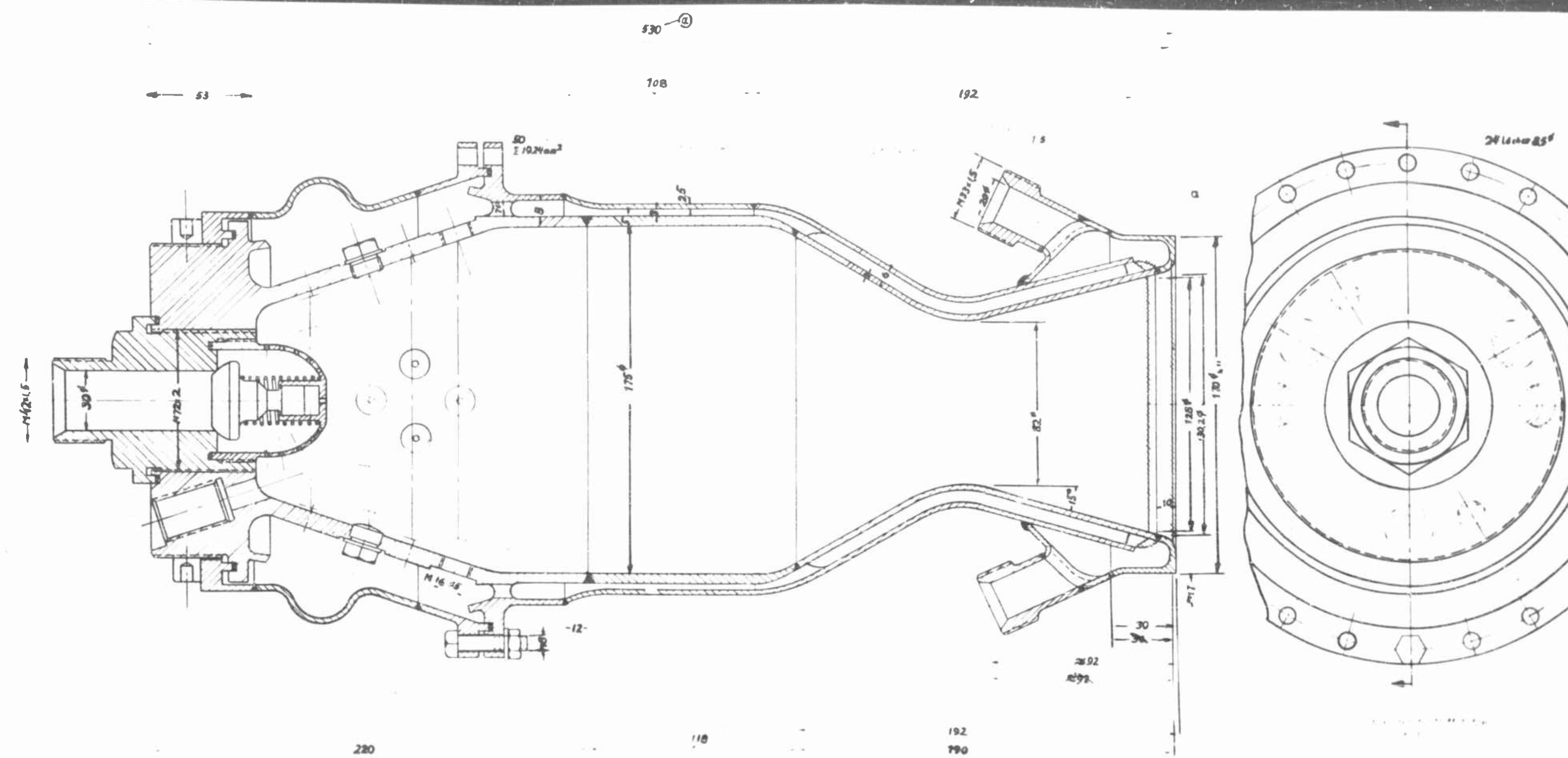

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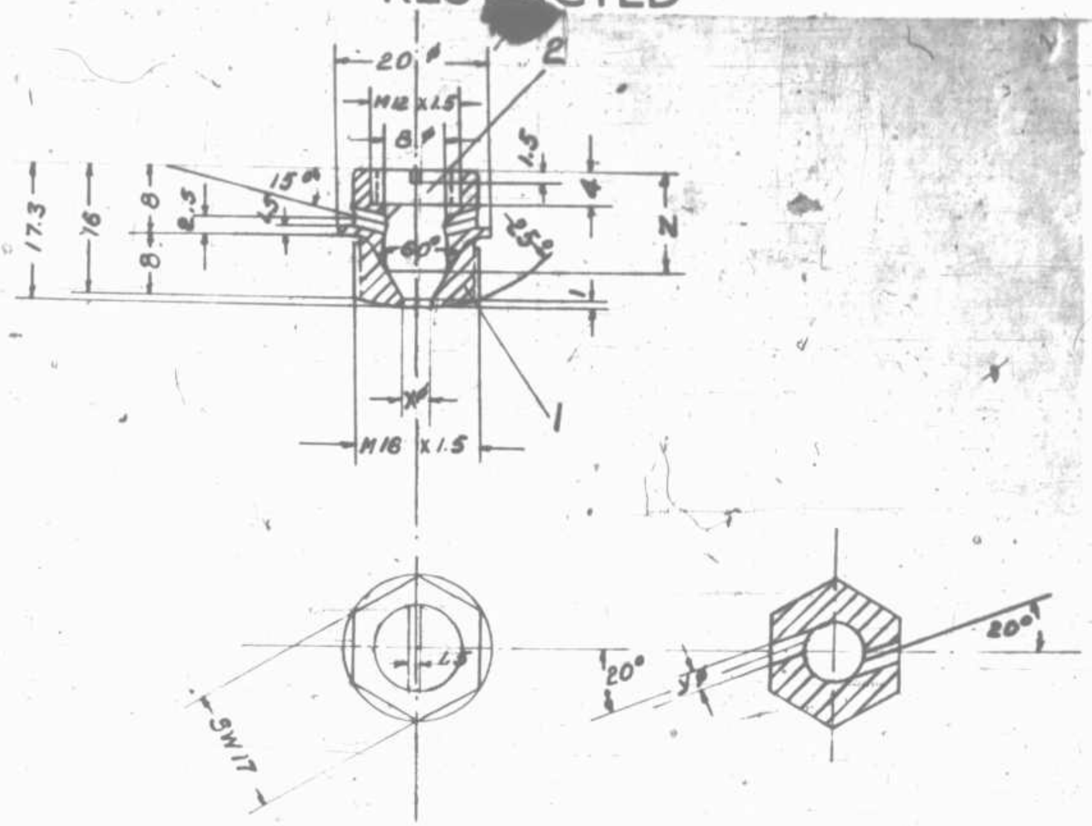
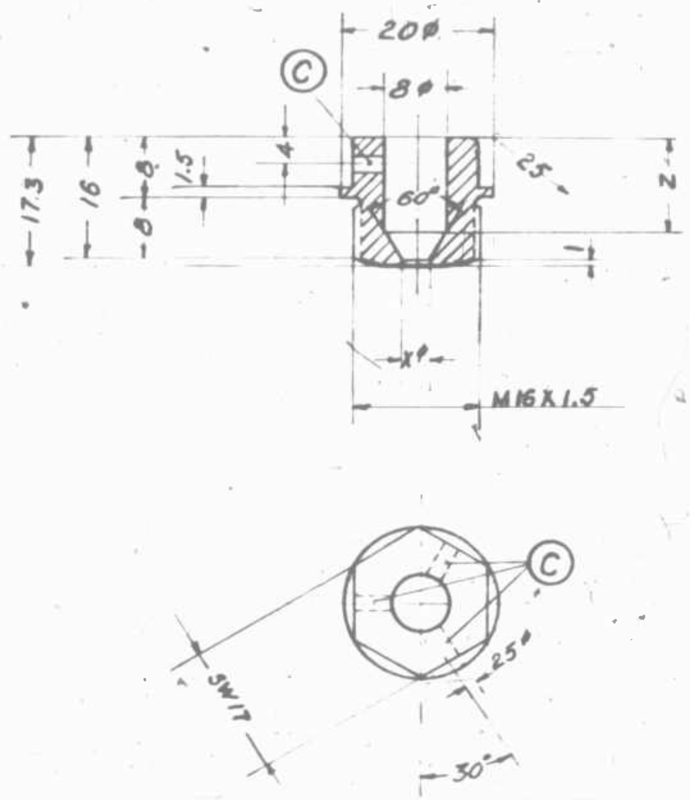
Fig. 60 - B-Series Injector Head on Test



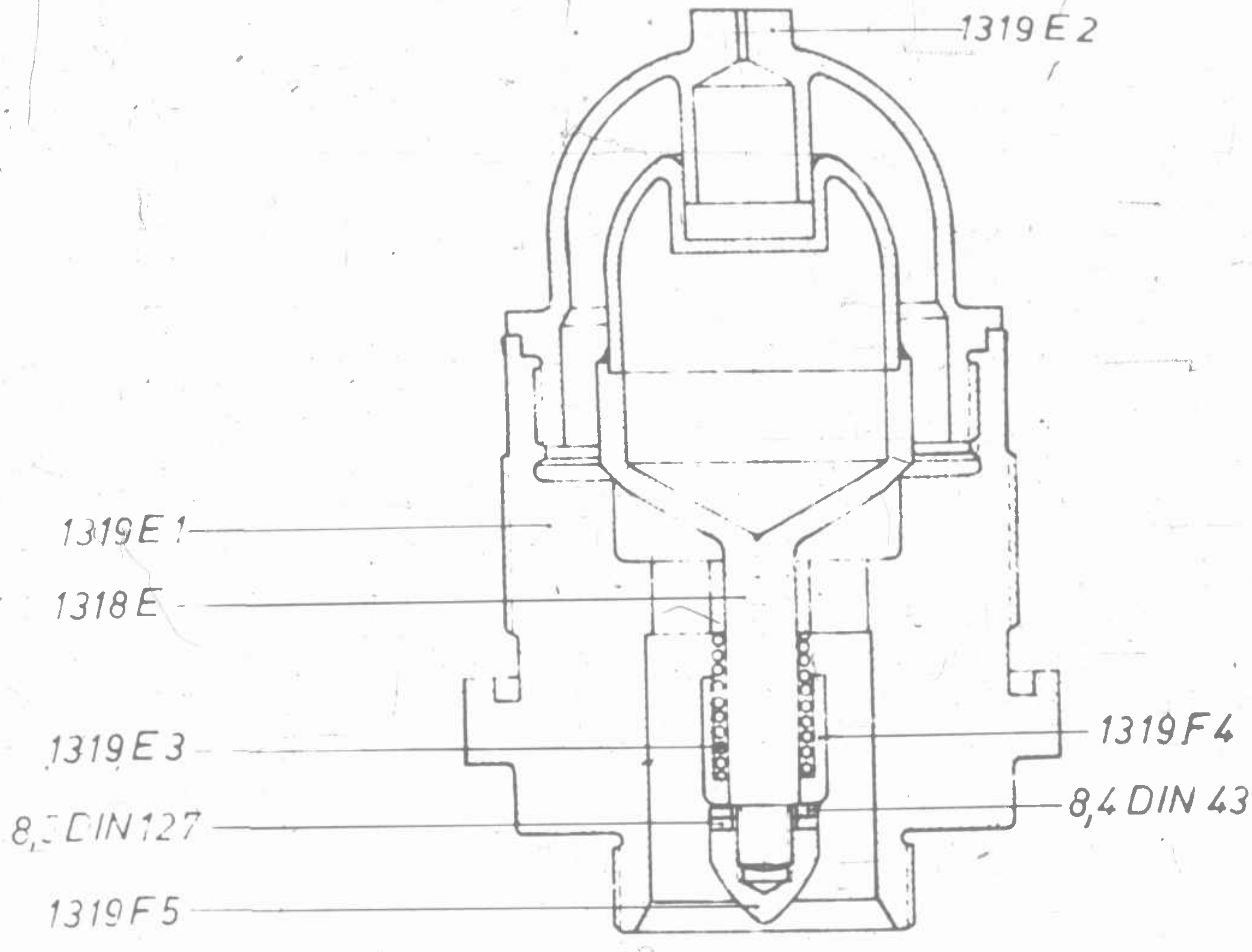
Types			
Injector Designation in 1/10 mm	Exit Hole Diameter x in mm	Tangential Hole Diam. y in mm	z in mm
15	1.5	1.0	10.7
20	2	1.4	11.1
25	2.5	1.6	11.5
28	2.8	1.8	11.8
32	3.2	2.0	12.1
35	3.5	2.5	12.4
38	3.8	2.4	12.7
42	4.2	2.7	13
45	4.5	2.9	13.3
48	4.8	3.1	13.6

Fig. 61 - Centrifugal Spray Nozzle Detail



Types		
Injector Designation in 1/10 mm	Exit Hole Diameter x in mm H7	z in mm
15	1.5	10.7
20	2	11.1
25	2.5	11.5
28	2.8	11.8
32	3.2	12.1
35	3.5	12.4
38	3.8	12.7
42	4.2	13
45	4.5	13.3
48	4.8	13.6
23	2.3	11.3

Fig. 62 - Orifice Nozzle Detail

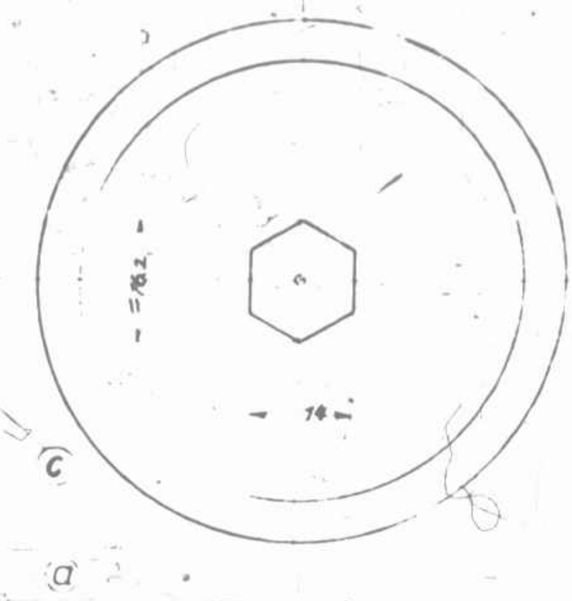


B-/B7
R

Fig. 63 - B-4/7 Oxygen Injector Assembly

Model	Row	No. of Holes	Diam. of Hole
B	7	1	1
	6	6	2 H7
	5	8	
	4	10	
	3	12	
	2	14	
	1	18	
A	7	1	1
	6	8	1.5 H7
	5	8	
	4	12	
	3	15	
	2	20	
	1	20	

Rows of holes 1 - 6 are offset in relation to one another.



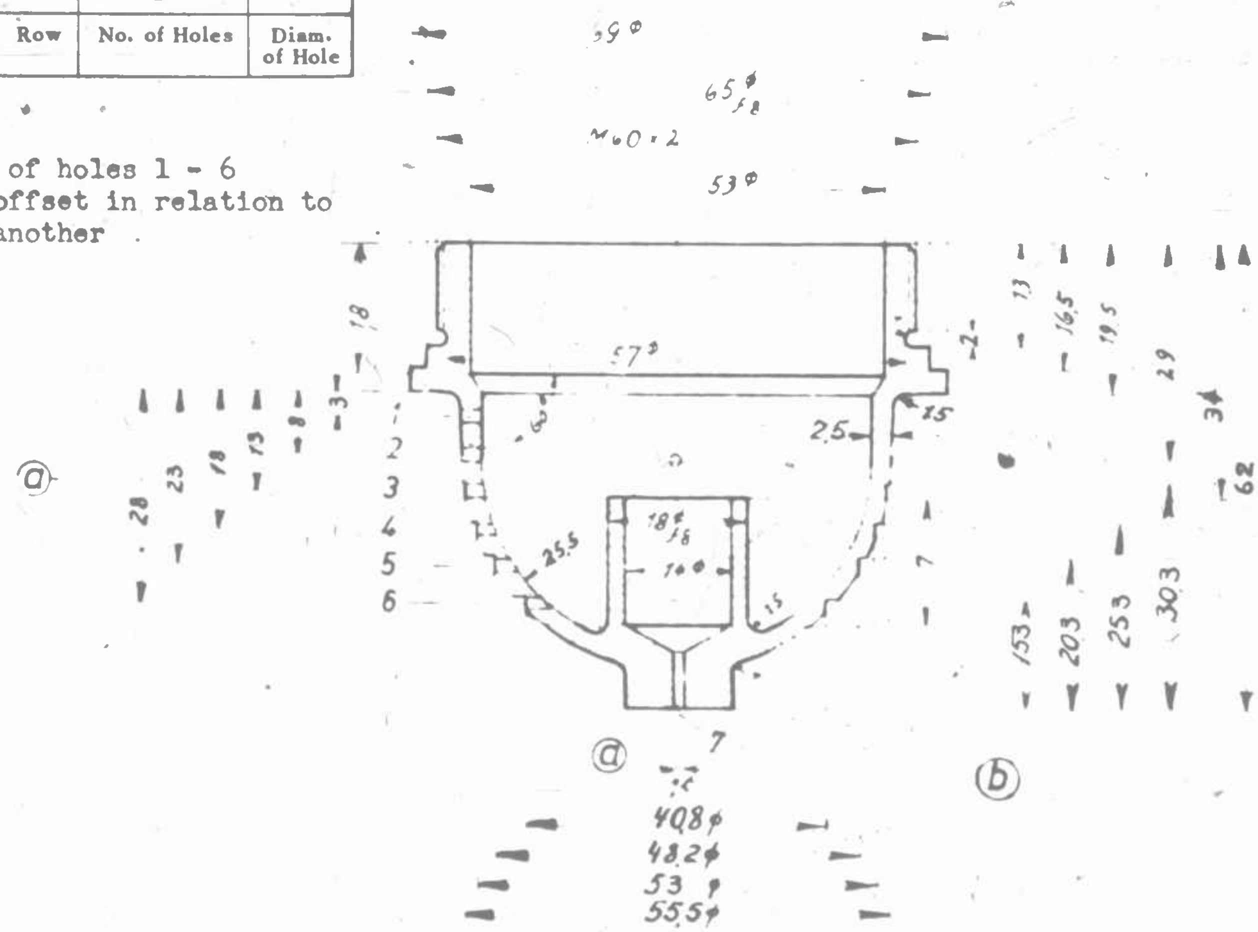


Fig. 64 - B-4/7 Oxygen Atomizing Cup Detail

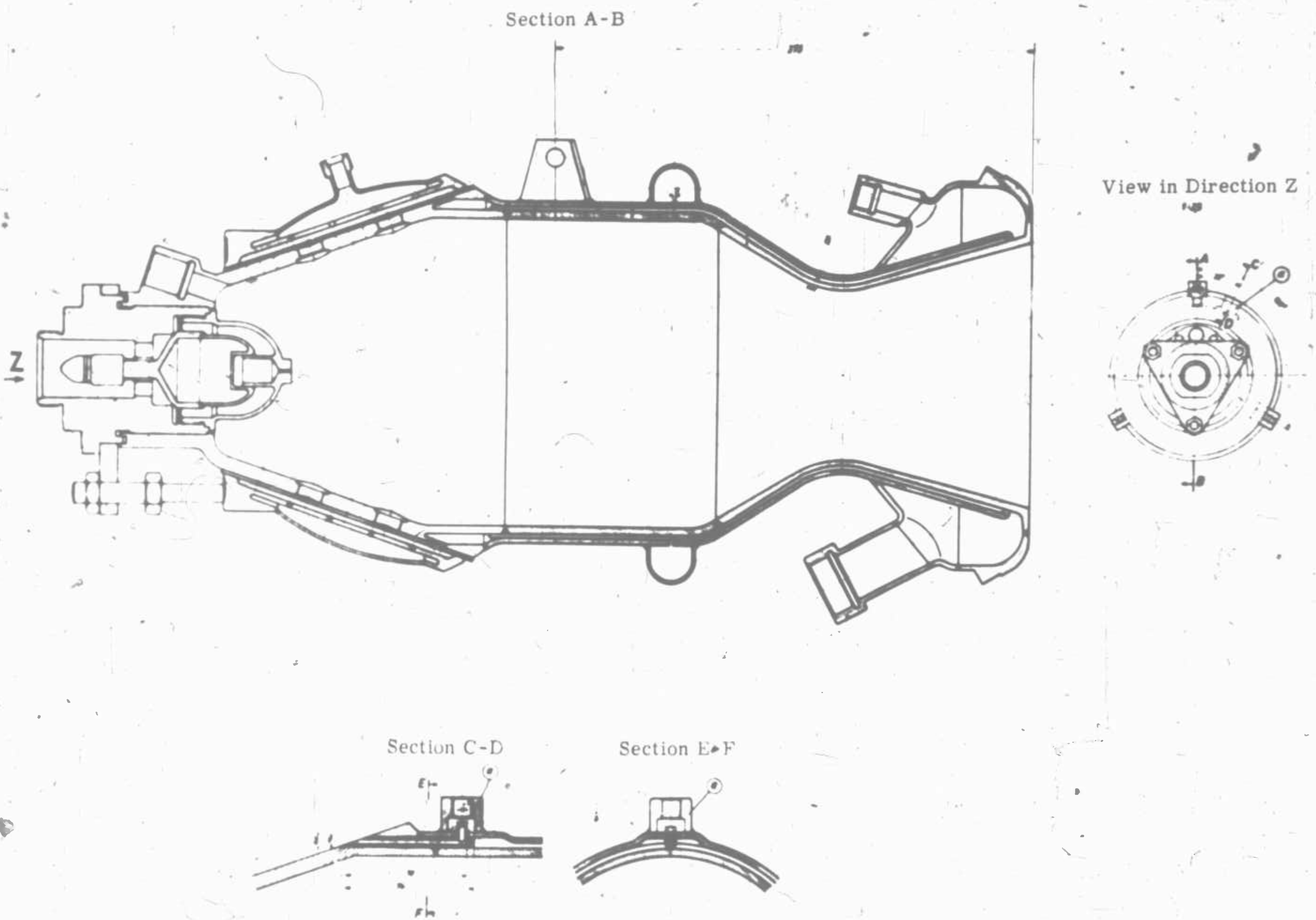
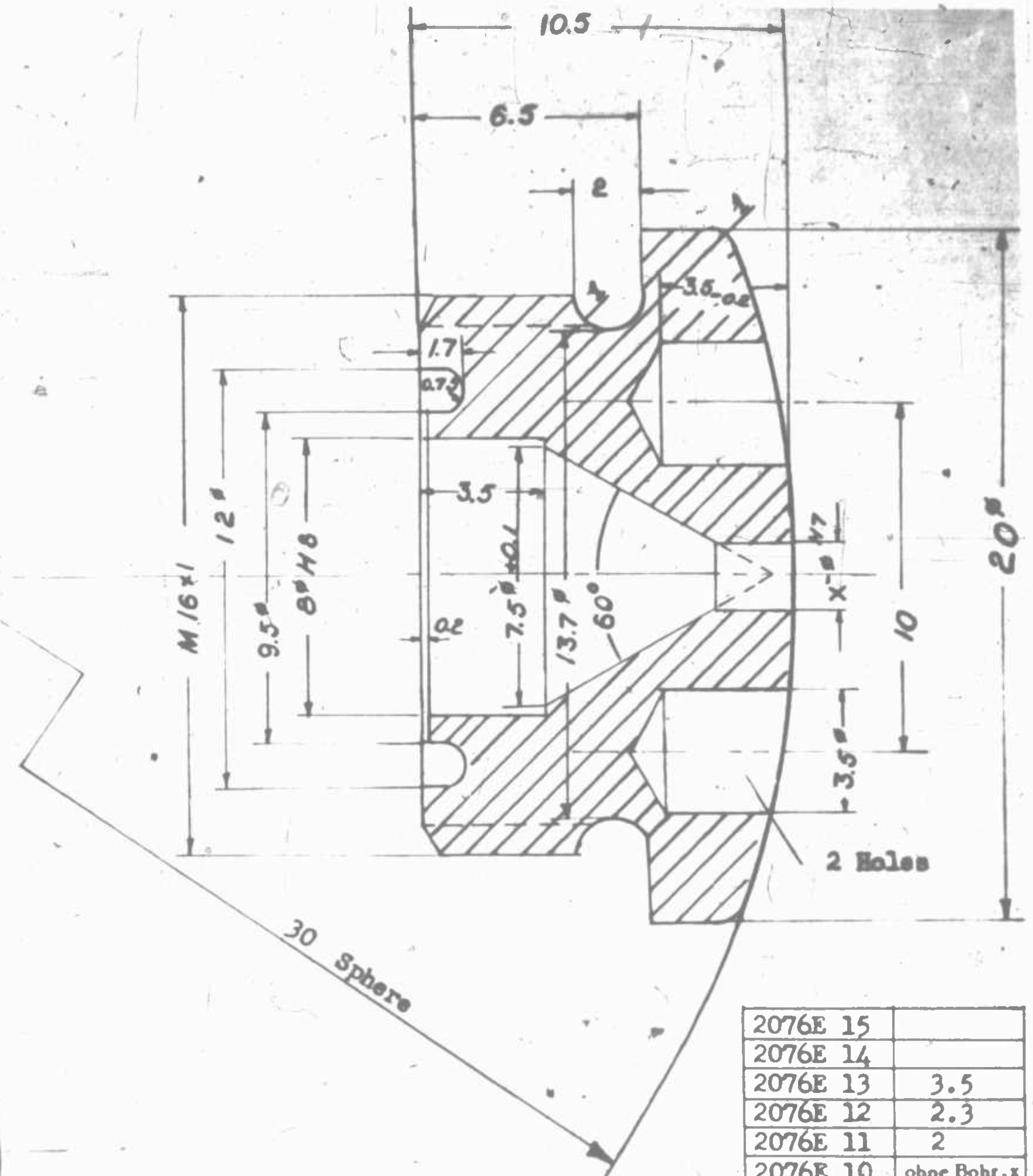


Fig. 65 - Assembly Drawing of a B-8 Chamber Showing Injector Head



1:1

2076E 15	
2076E 14	
2076E 13	3.5
2076E 12	2.3
2076E 11	2
2076E 10	ohne Bohr.x
Draw. No.	x⌀H-7

Fig. 66 - B-8 Orifice Nozzle

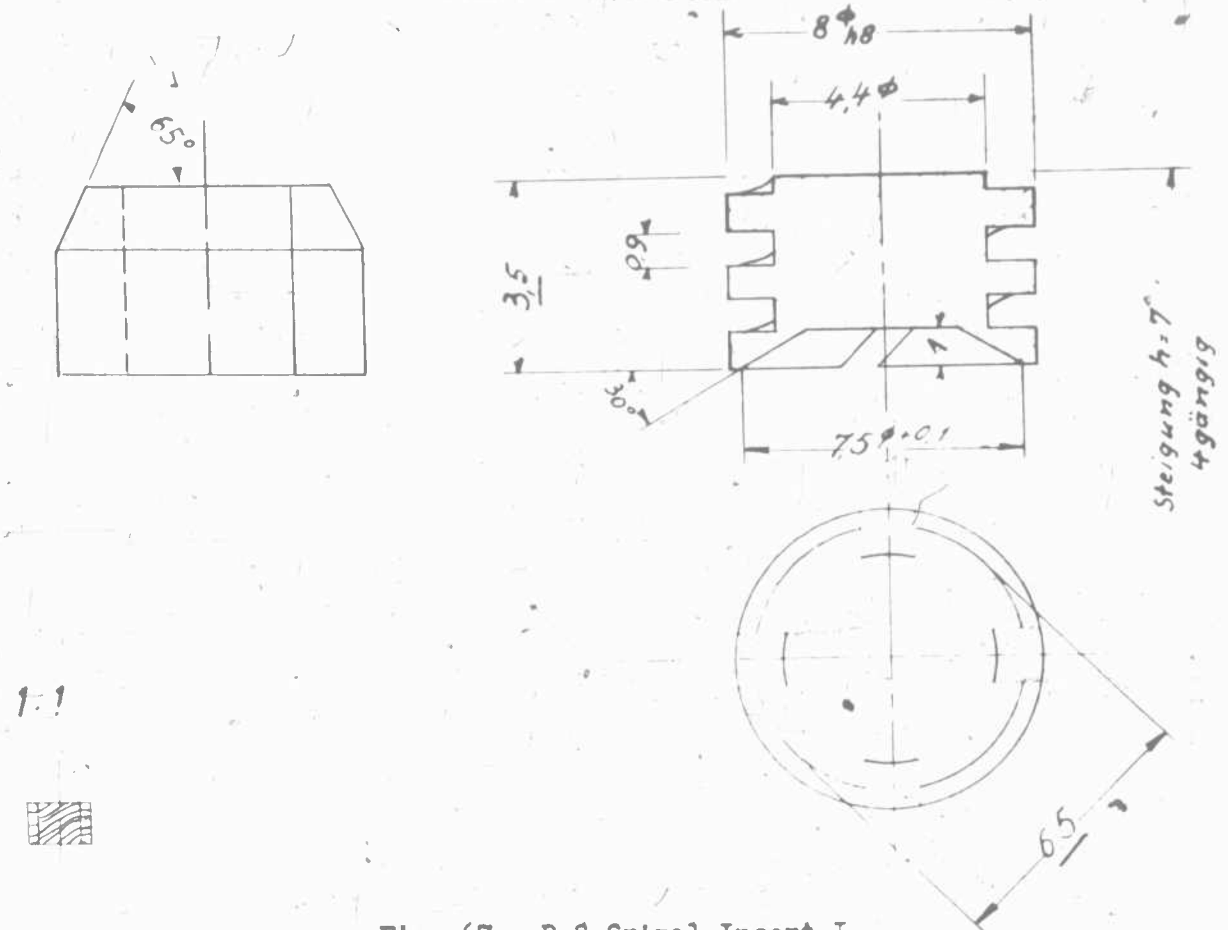


Fig. 67 - B-8 Spiral Insert I

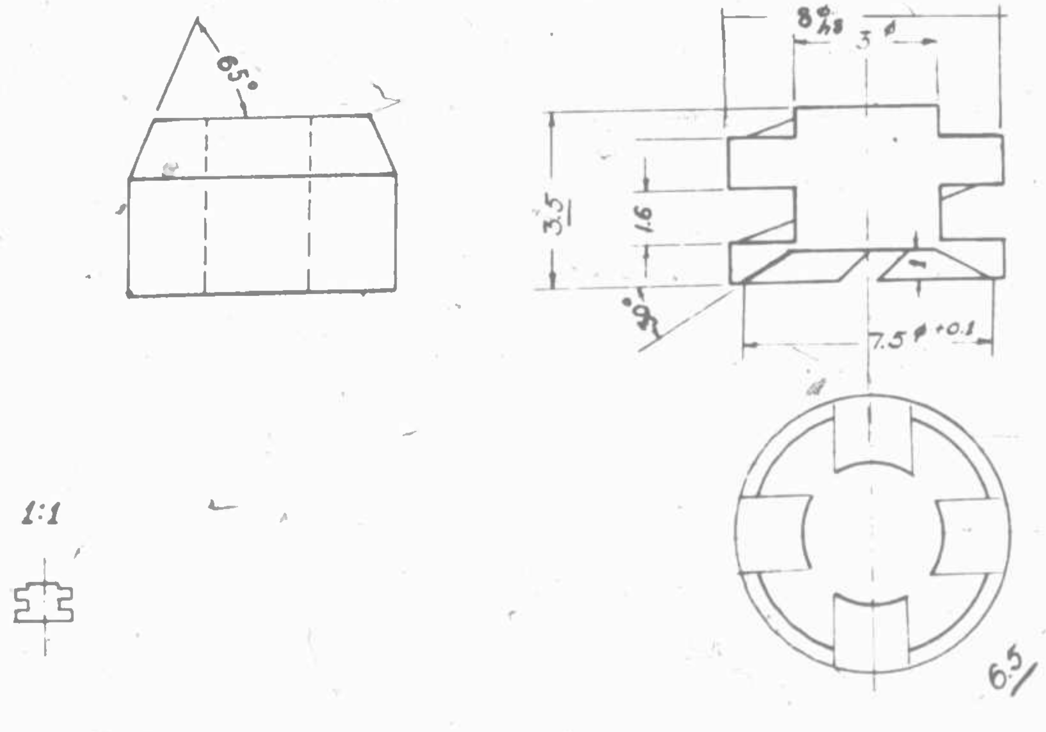


Fig. 68 - B-8 Spiral Insert II

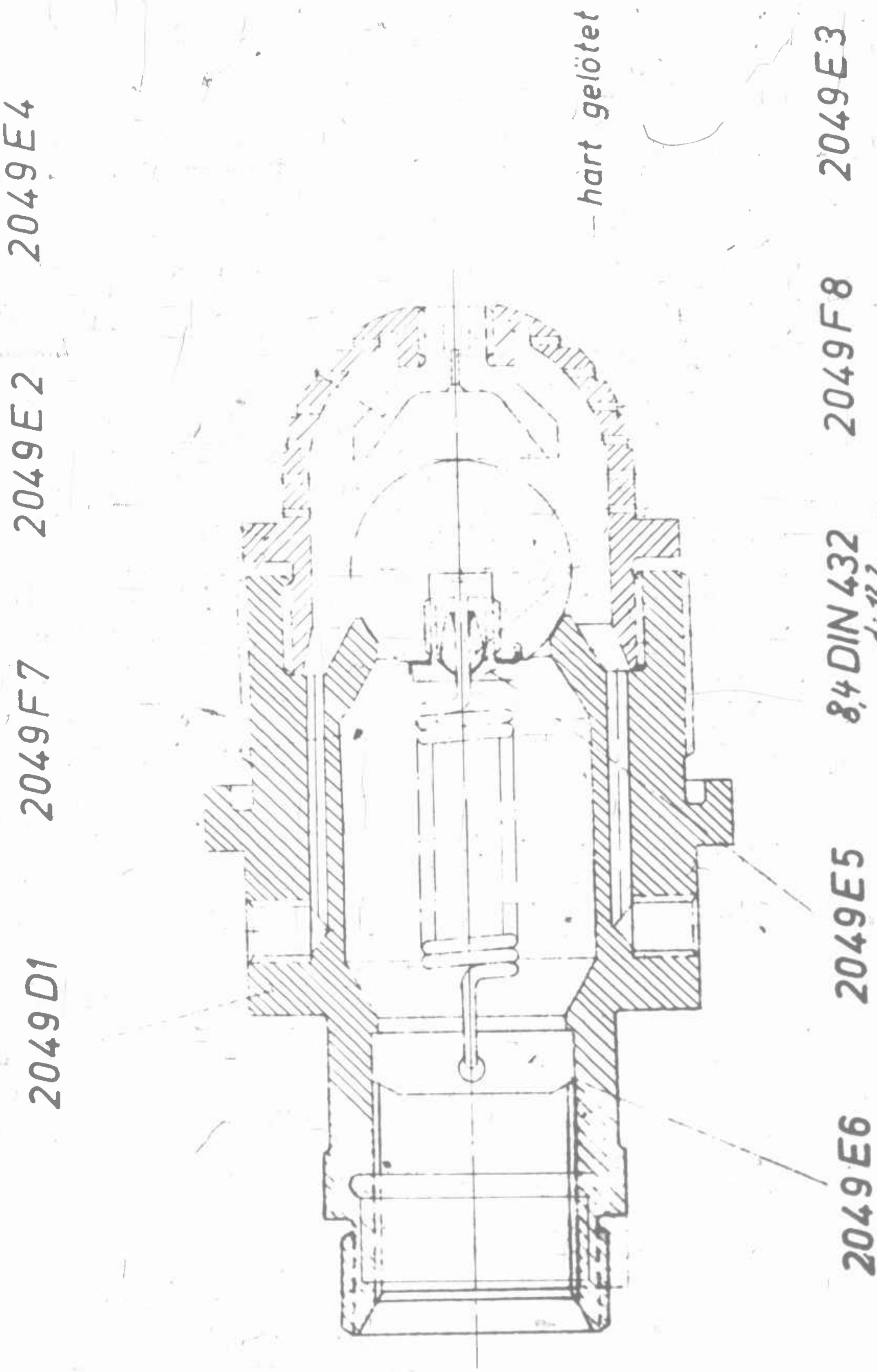
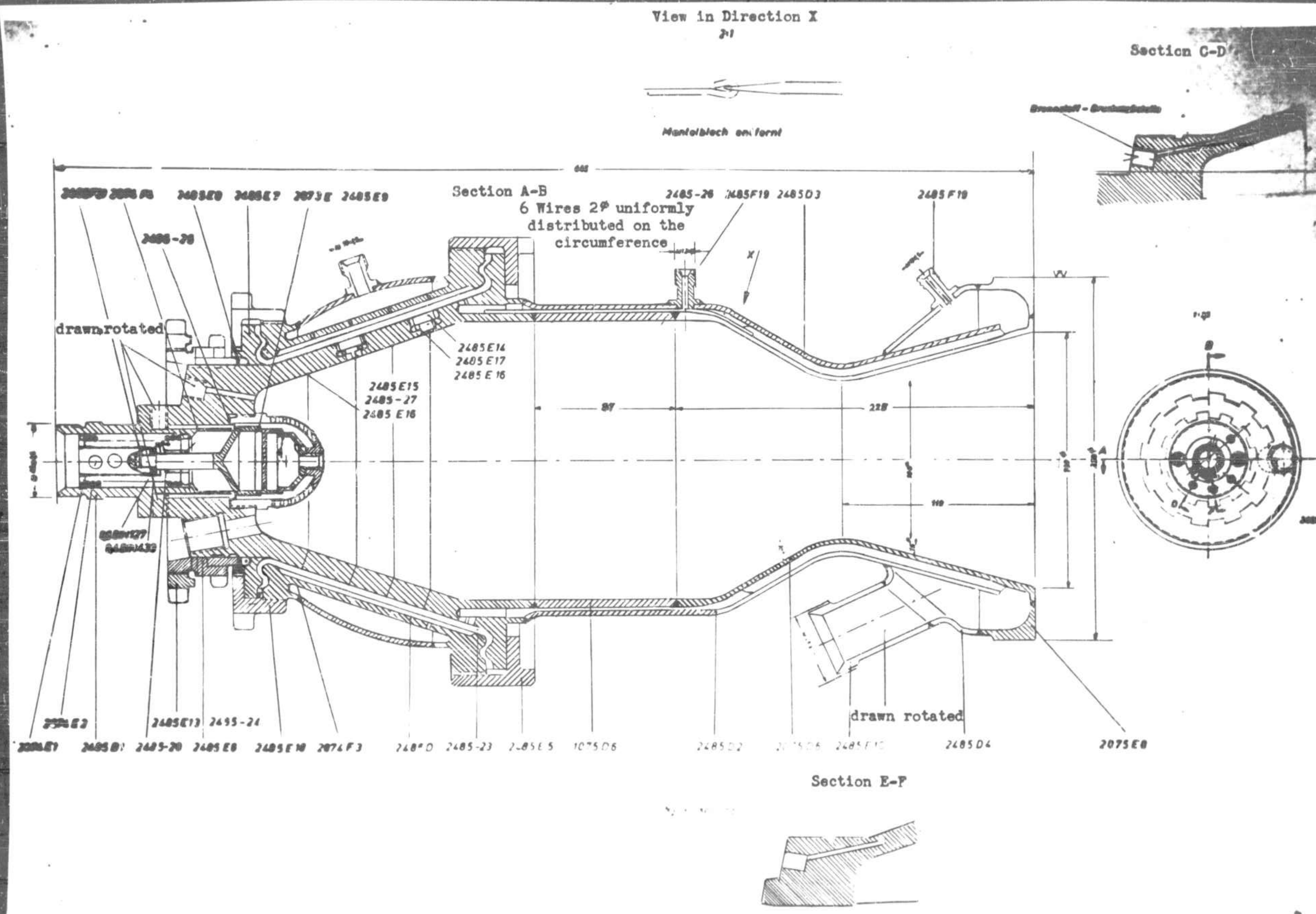
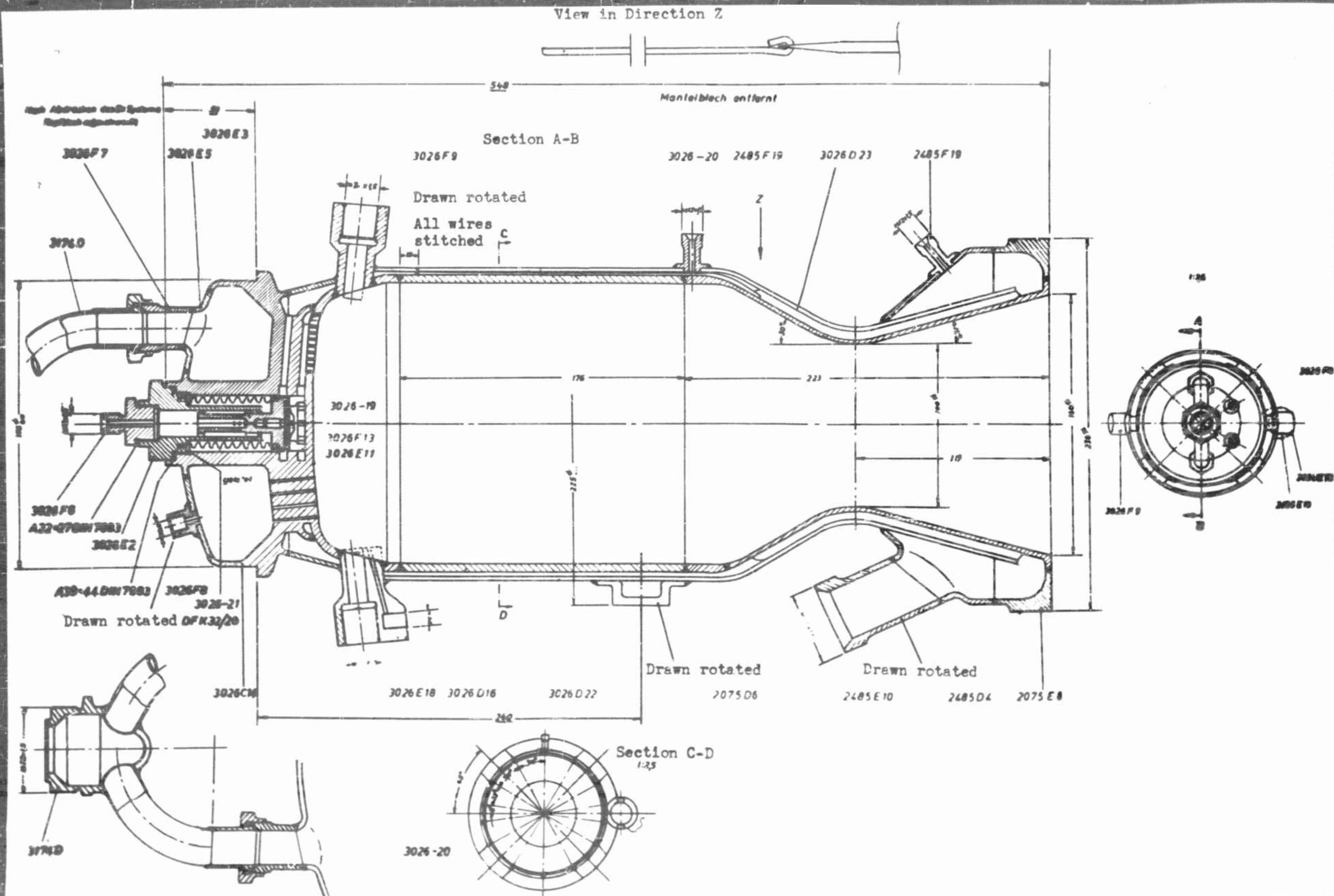


Fig. 69 - B-8 Oxygen Injector With a Ball Valve


View in Direction X
Section C-D
Mantelblech umformt
Section A-B
6 Wires 2Ø uniformly distributed on the circumference
drawn rotated
2485 E14
2485 E17
2485 E16
2485 E15
2485-27
2485 E16
2485-26
2485F19 2485D3
2485 F19
drawn rotated
Section E-F
2485E13 2495-24
2485 B1 2485-20 2485 E8 2485 E18 2074 F3
2485-23
1075 D6
2485 D2
2485 D4
2075 E8


View in Direction Z
548
Manteiblech entfernt
Section A-B
3026 E3
3026 F7
3026 E5
3026 F9
3026 - 20
2485 F 19
3026 D 23
2485 F 19
Drawn rotated
All wires stitched
C
Z
3076.0
176
223
3026 - 19
3026 F 13
3026 E 11
119
3026 F8
3026 E2
A39-44 DIN 7603
3026 F8
3026-21
Drawn rotated DFK 32/20
D
Drawn rotated
Drawn rotated
3026 C 16
3026 E 18
3026 D 16
3026 D 22
2075 D6
2485 E 10
2485 D4
2075 E 8
260
Section C-D
1:2,5
3076 D
3026 - 20

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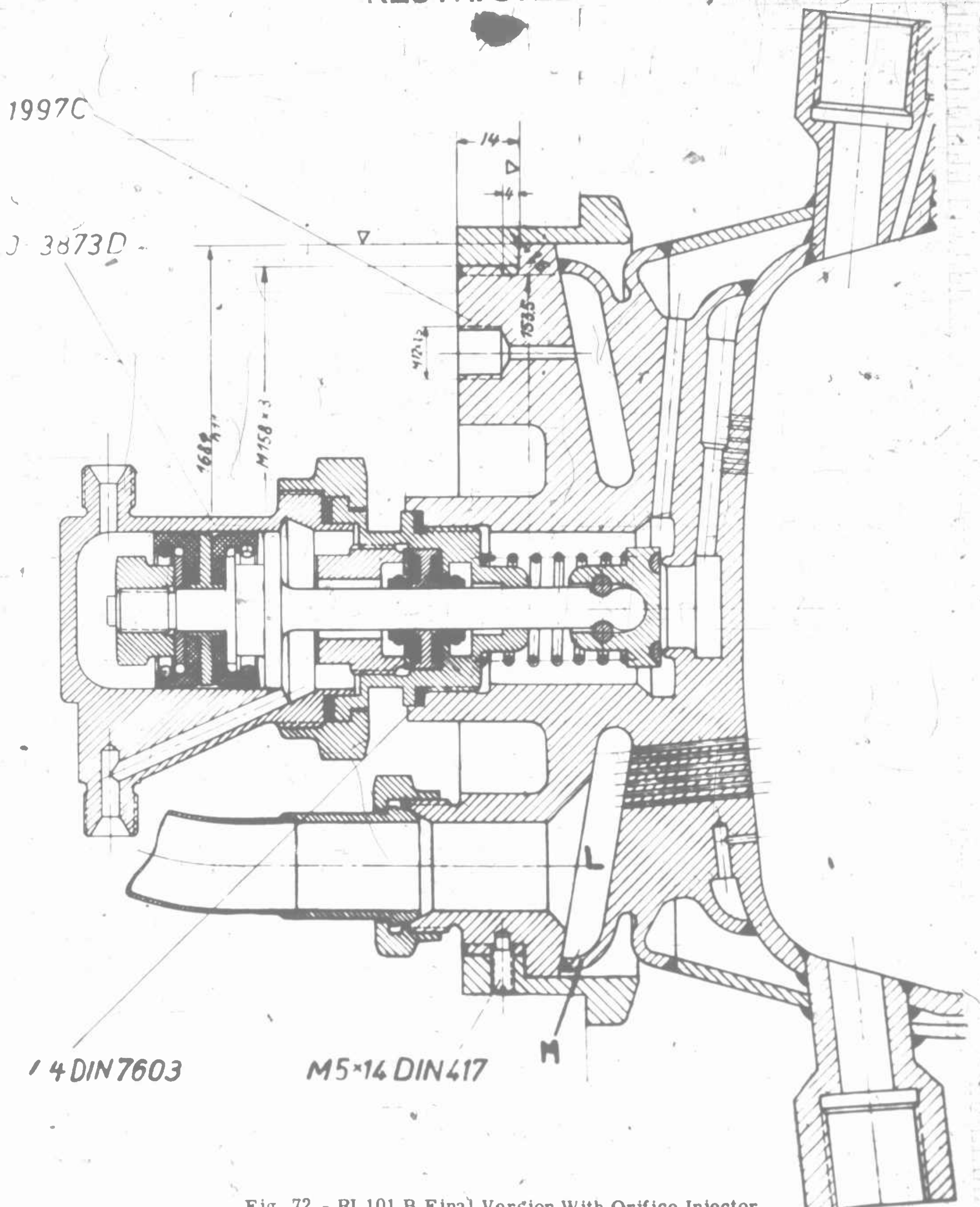
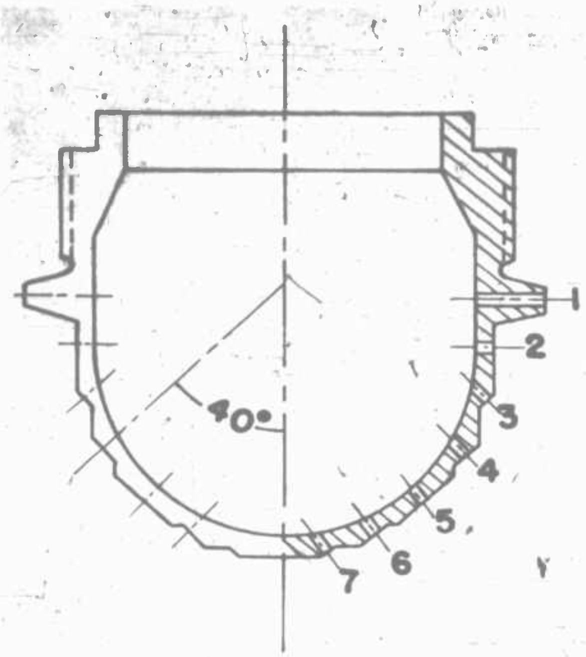
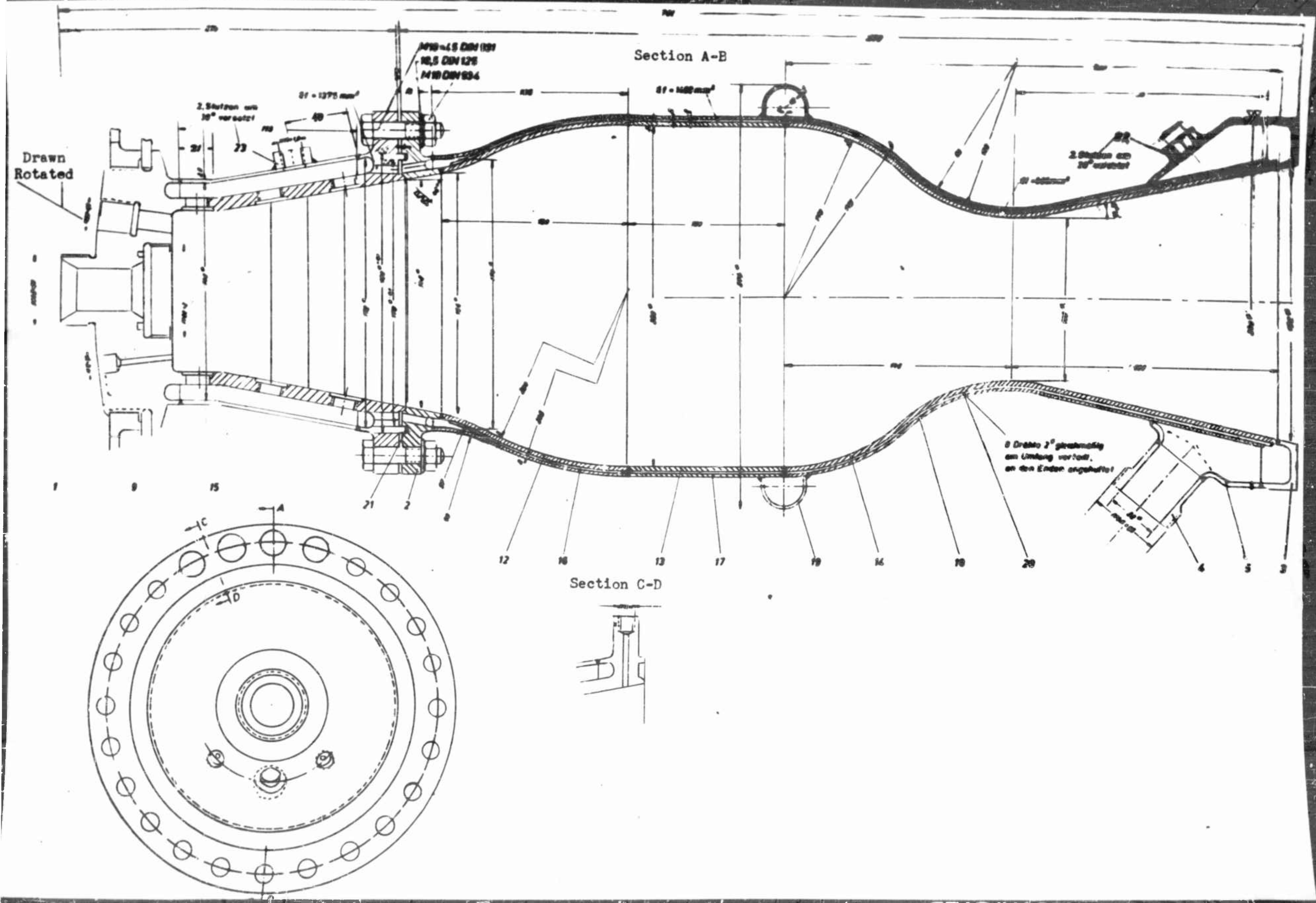


Fig. 72 - RI 101 B Final Version With Orifice Injector



ROW	NO. OF HOLES	DIAMETER
1	18	.079
2	12	.079
3	30	.059
4	24	.059
5	16	.059
6	12	.059
7	8	.059

Fig. 73 - Hole Arrangement A-4 Oxygen Injector


Drawn
Rotated
Section A-B
Section C-D
M18×4.5 DIN 1191
18,5 DIN 125
M18 DIN 934
2. Stutzen um
30° versetzt
2. Stutzen um
30° versetzt
8 Drähte 2° gleichmäßig
am Umfang verteilt,
an den Enden angeheftet
1
9
15
21
2
8
12
16
13
17
19
14
18
20
4
5
3
23
A
C
D

RESTRICTED

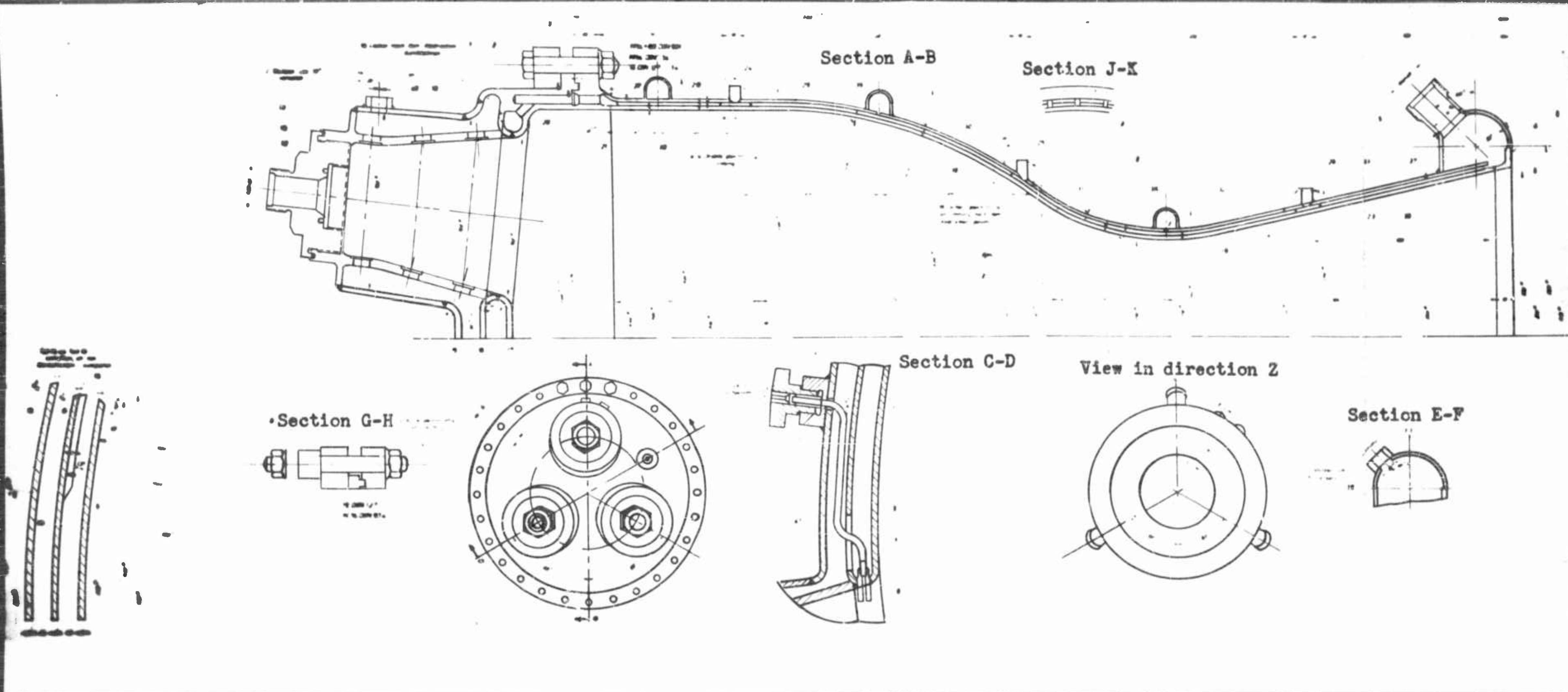


Fig. 75 - Assembly of [illegible]-lb [illegible] Prototype Chamber With Three Injector Heads

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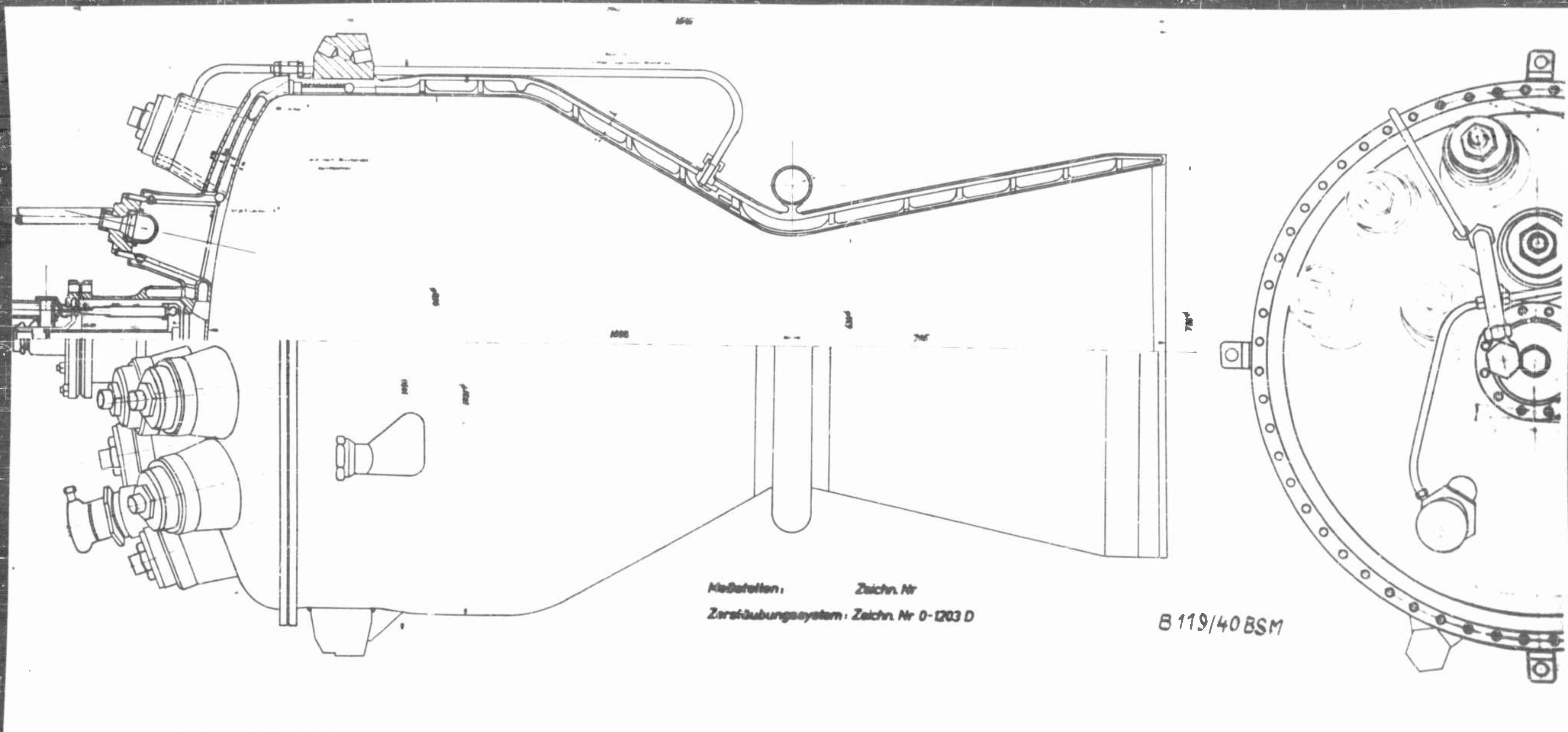

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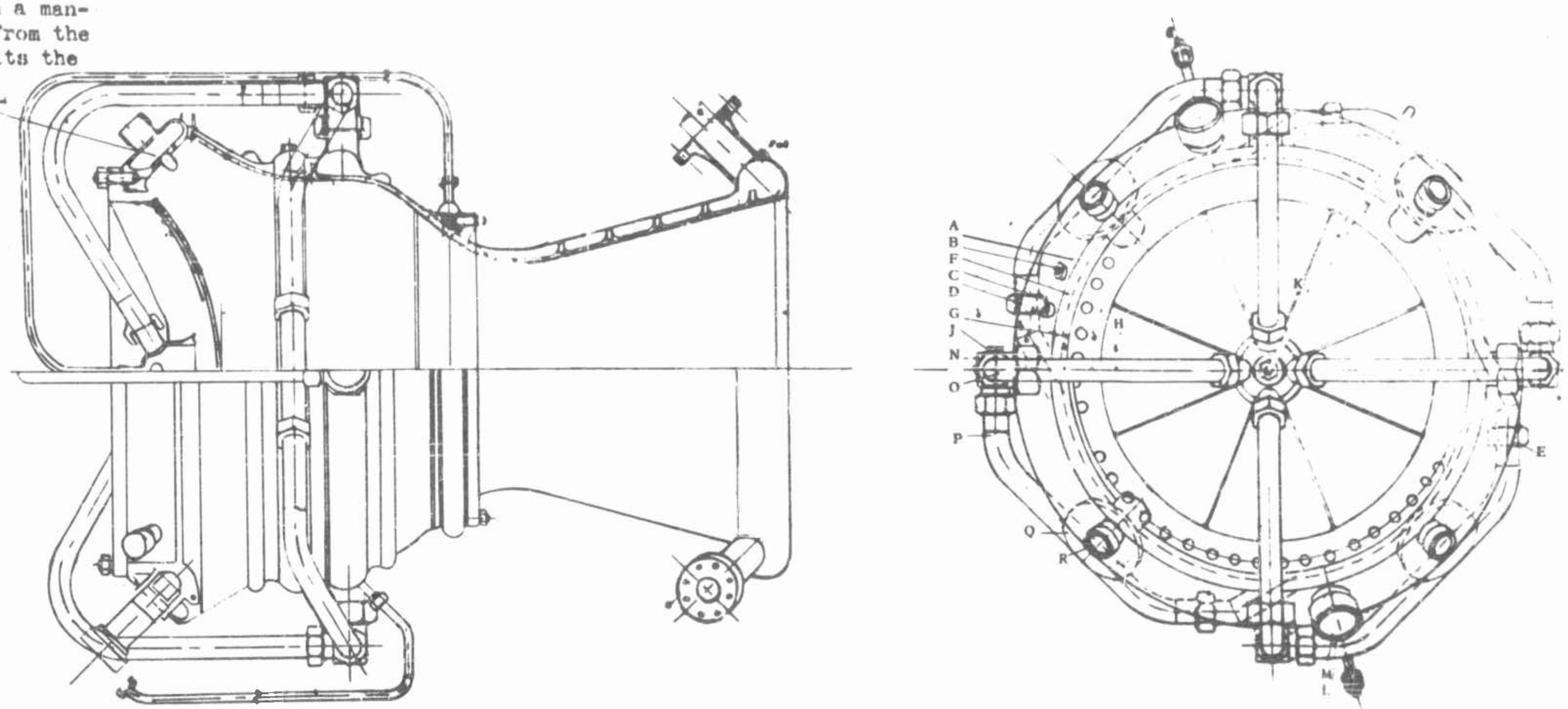
The O_2-injector is to be screwed in in such a manner that the jet from the orifice exactly hits the opposite chamber



Fuel: Lower Chamber

368 Spray nozzles	2.2 mm Diam
294 Jet nozzles	2 " "

Upper Chamber

213 Spray nozzles	2.2mm Diam
236 Jet Nozzles	2 " "
4 Extra orifices	1 " "
50 " "	1 " "
62 " "	1 " "
110 " "	1 " "
2 Igniters per 24 orifices	1 " "

Oxygen

38 0_2 Injectors per 46 orifices 1.5 mm Diam

R : O_2 Inlet
Q : Fuel Inlet
P : Line to Lower Chamber
O : Line to Upper Chamber
N : Distributor
M : Igniter Inlet
L : Igniter Cooling Line
K : Film Cooling Line

Measuring Points:

J : Fuel Temperature
H : Fuel Pressure
G : Fuel Temperature
F : Fuel Pressure
E : Chamber Pressure (Cooled Measuring Line)
D : Chamber Pressure (Cooled Measuring Line)
C : O_2 Temperature
B : O_2 Pressure
A : Fuel Pressure

Fig. 77 - Assembly of Chamber With Injector Heads Spaced About Periphery of Chamber Head

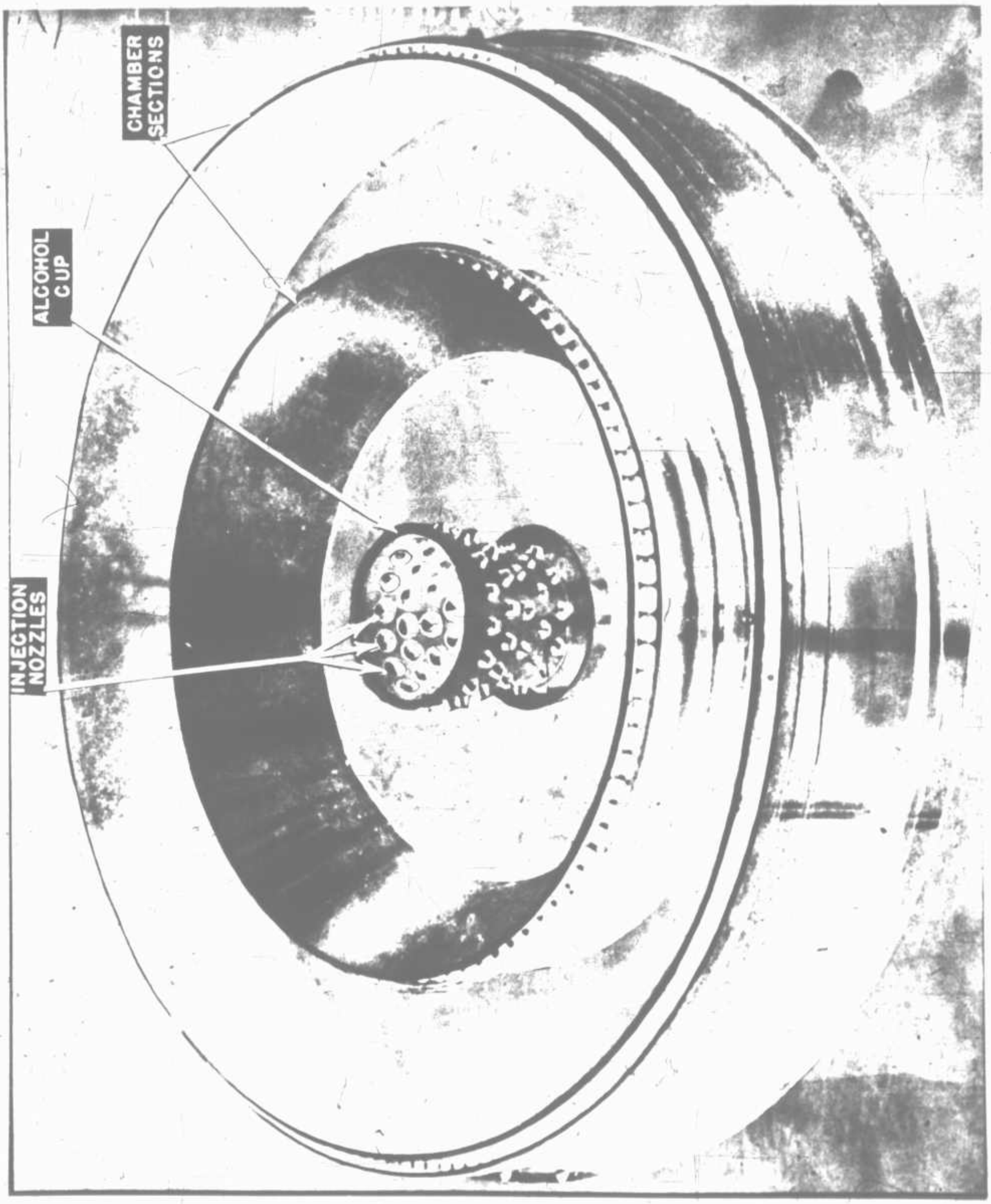
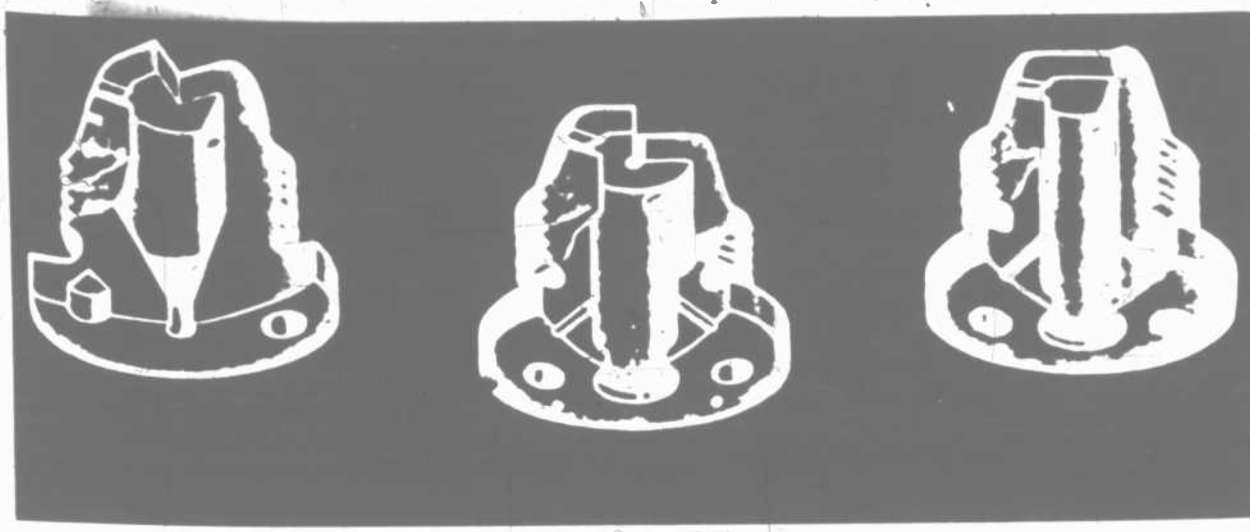


Fig. 78 - Alcohol Injection Cup of A-4 Showing Injection Nozzles

Alcohol Combustion Cup Feed Nozzles



C B A

Fig. 80 - Alcohol Injection Nozzles

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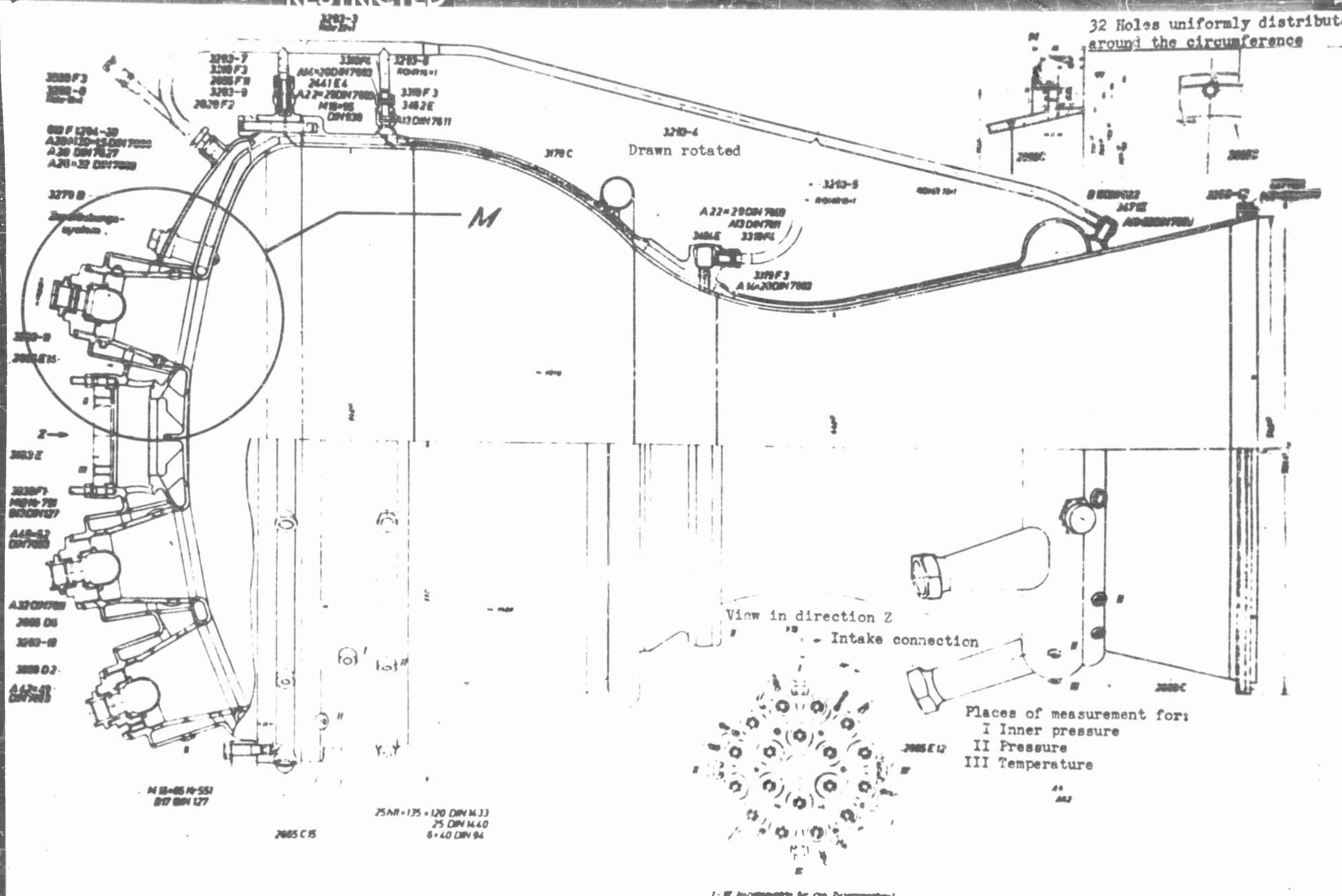

Fig. [illegible] Assembly Drawing of [illegible] Chamber Showing Injector Heads

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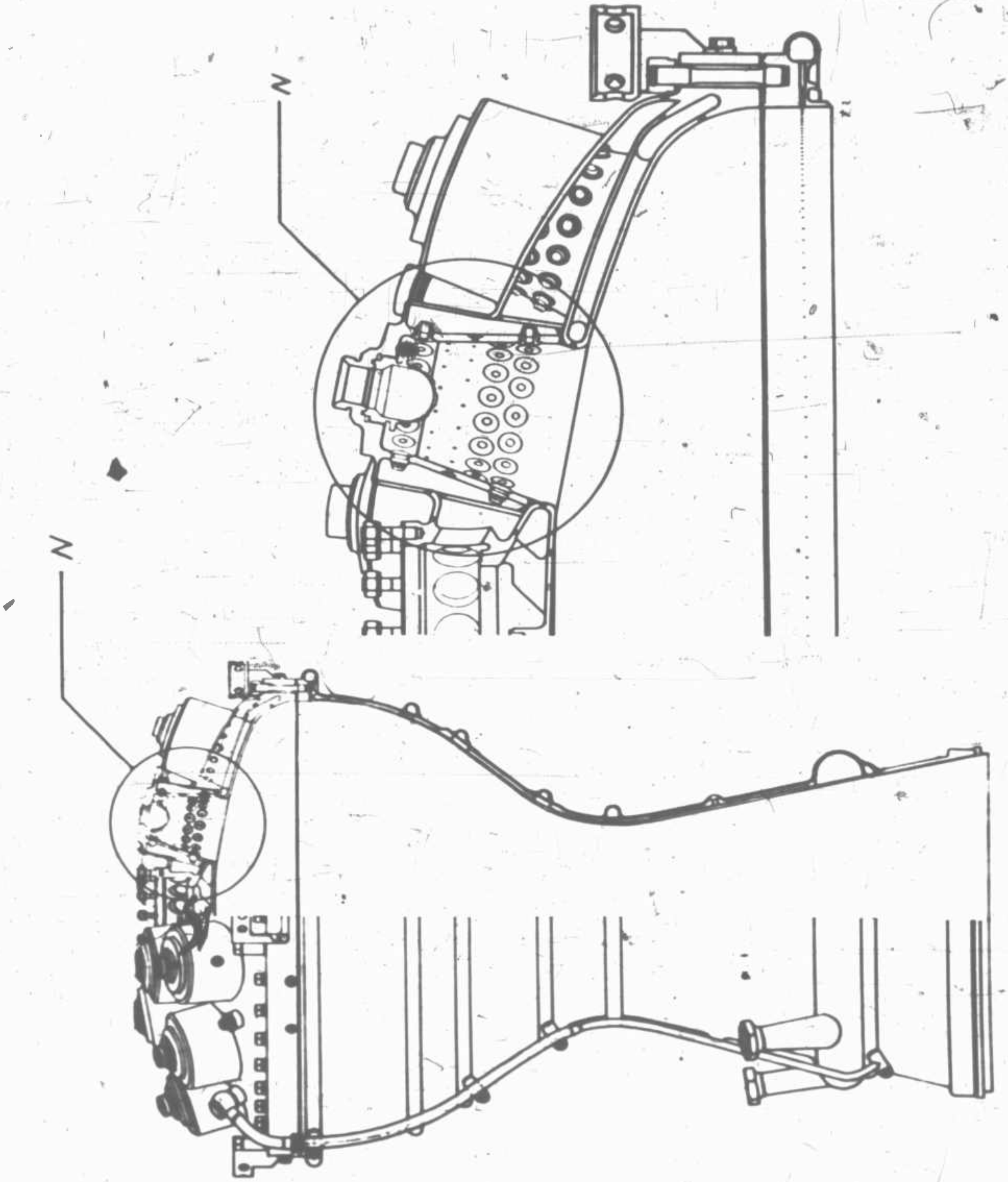
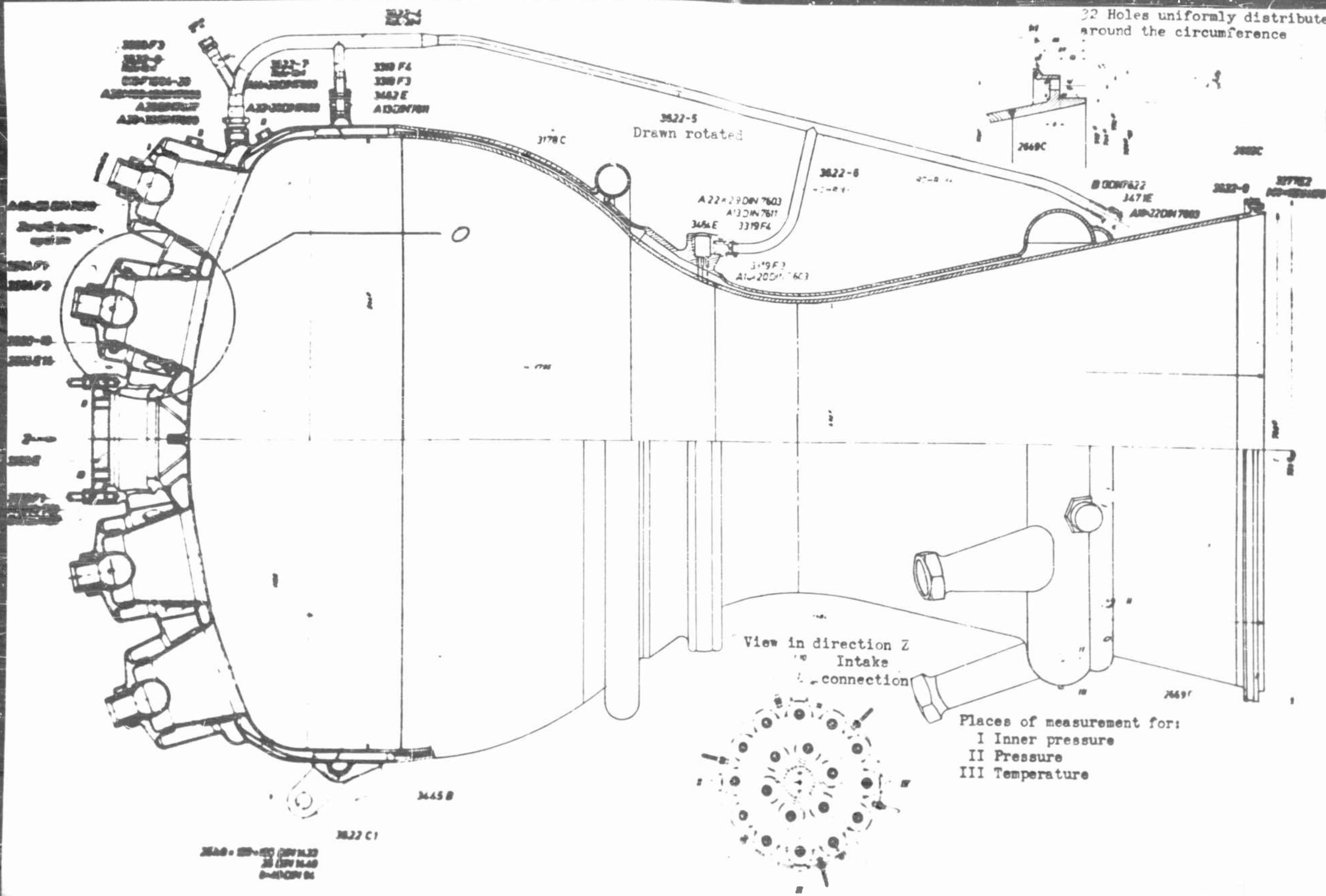
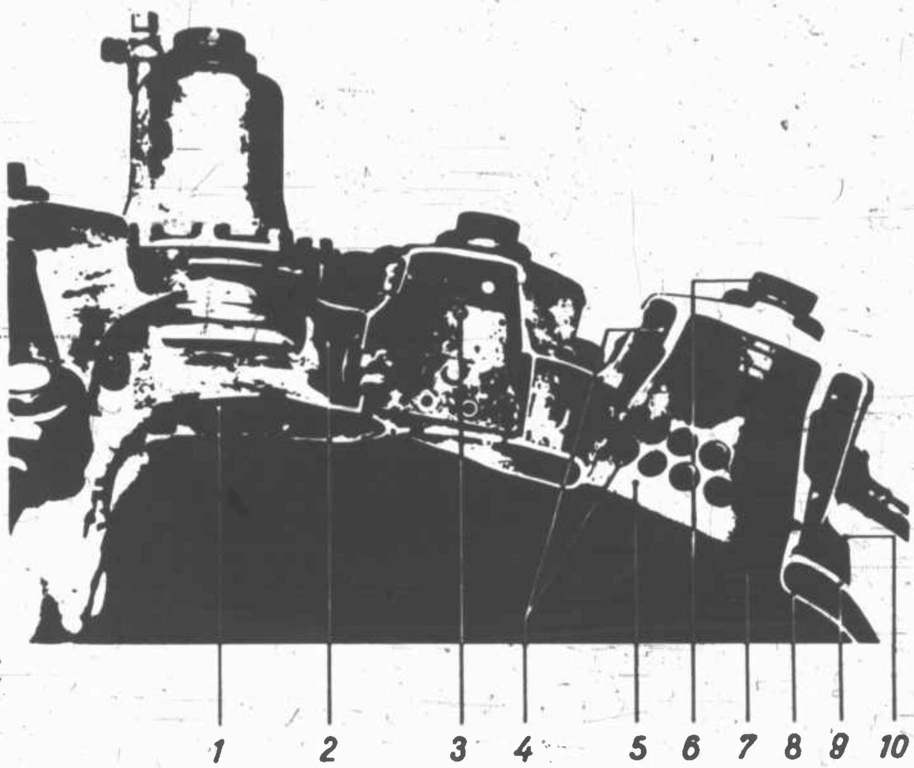


Fig. 82 - A-4 Chamber Showing Details of Injector Heads


32 Holes uniformly distributed around the circumference
3622-5
Drawn rotated
3622-6
3178 C
3319 F4
3319 F3
3482 E
A 22×2 DIN 7603
3456 E
3319 F4
3445 B
3622 C1
2669 C
View in direction Z
Intake
connection
Places of measurement for:
I Inner pressure
II Pressure
III Temperature

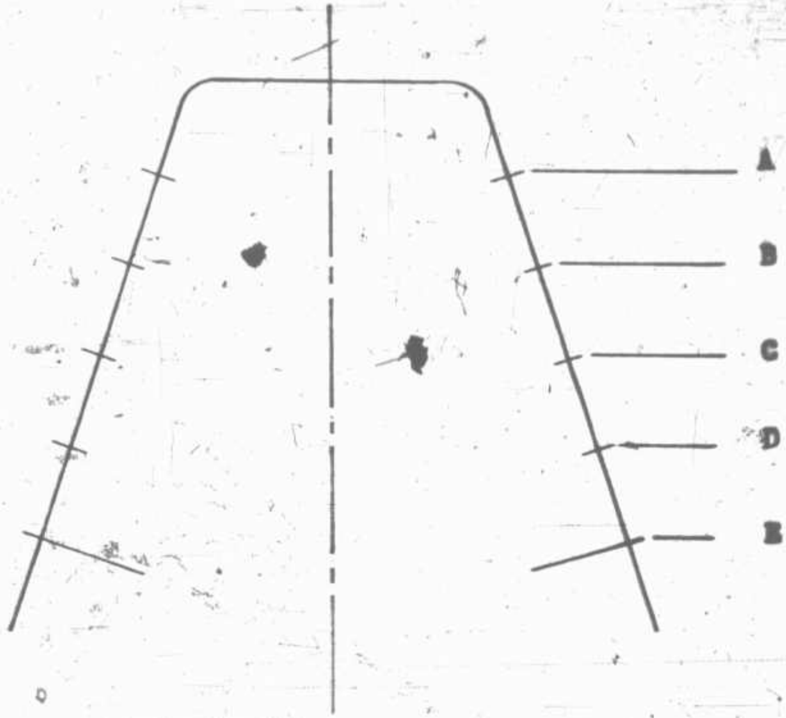
RESTRICTED

Part of the Head of Combustion Unit With Head Element, Cutaway

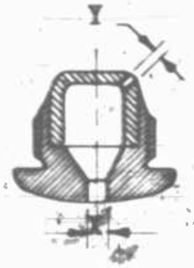


1	Lower head chamber	6	Nipple for oxygen feed line
2	Upper head chamber	7	Oxygen atomizer
3	Jet bore	8	Inner shell
4	Fuel spray nozzles	9	Middle shell
5	Head element	10	Outer shell

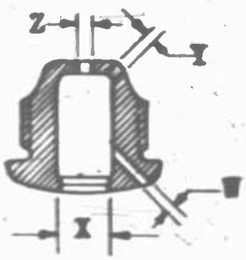
Fig. 84 - Photograph of A-4 Head Section Showing Injector Installation



Head Element - Row 1-2



A



D & E

ROW		NO. OF ORIFICES PER HEAD ELEMENT	TYPE OF ORIFICE	HOLES*			
				X	2×Y	Z	×W
	A	12	Spray nozzle	.079	.055	—	—
I	B	12	Drilled hole	6×.091 6×.079	—	—	—
II	C	12	Drilled hole	6×.091 6×.079	—	—	—
	D	16	Spray nozzle cooled		.055	—	—
	E	16	Spray nozzle cooled		.055	.039	.031

*Diameter

Fig. 86 - Hole Arrangement A-4 Alcohol Injector

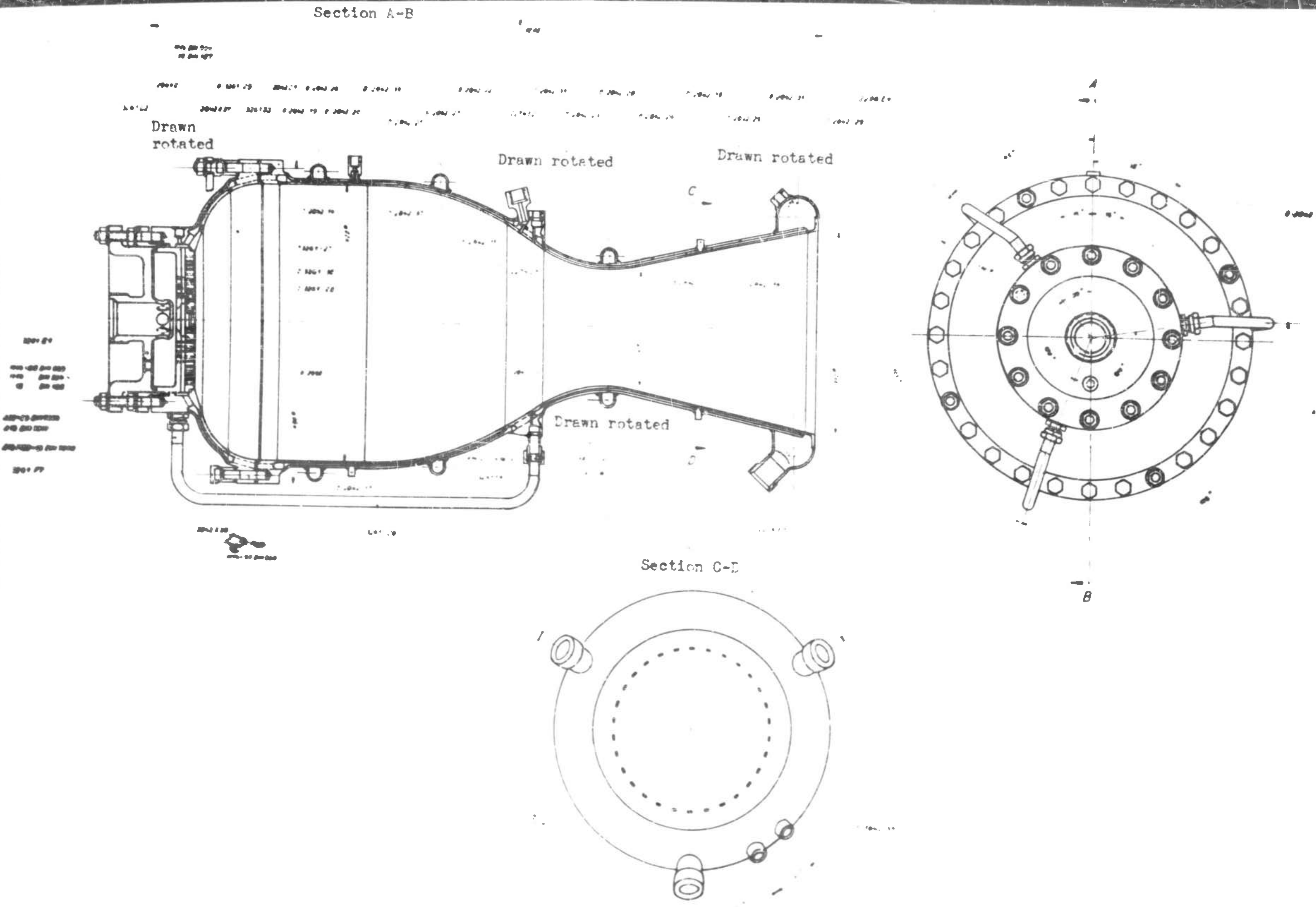


Fig. 87 - Assembly of [illegible] Chamber Showing Spray Plate Injector

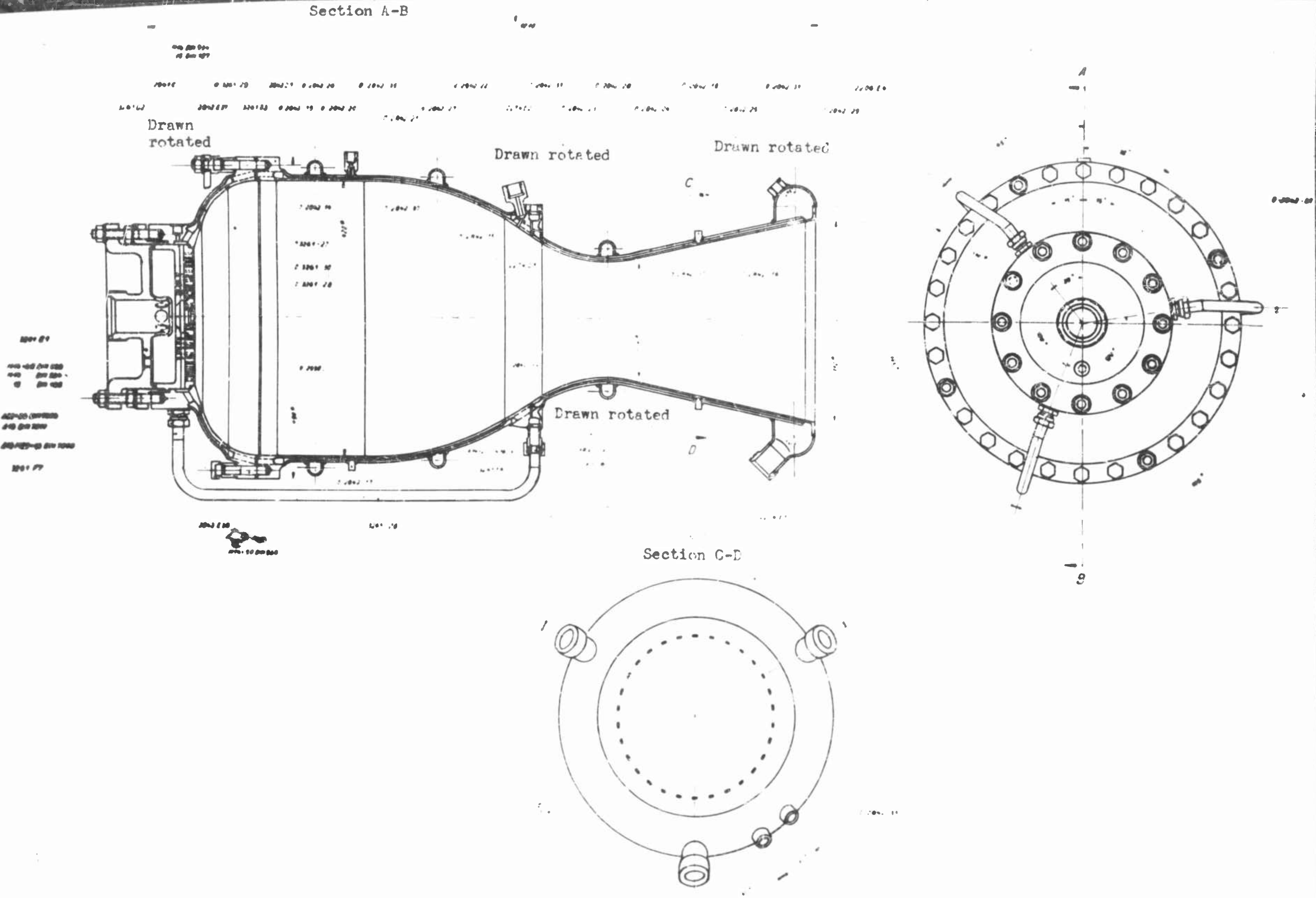


Fig. 87 - Assembly of A-4 Chamber Showing Spray Plate Injector

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ANALYSIS AND EVALUATION OF GERMAN ATTAINMENTS AND RESEARCH IN THE LIQUID ROCKET ENGINE FIELD - VOL. IV PROPELLANT INJECTORS

FEB'51 136PP DIAGRS, DRWGS

AMC, WRIGHT-PATTERSON AIR FORCE BASE, DAYTON, O., USAF CONTR. NO. W33-038-AC-17485 AND AF33(038) 3636(F-TR-2251-IA)

GUIDED MISSILES (1) 4 ENGINES, ROCKET - GERMANY
PROPULSION (1) 12 PROPELLANT INJECTORS

CFSTI, auth: FTD ltr, 12 Sep 68

AD-A800 145

AIR FORCE-WPAFB-L-18 DEC 50 210M

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AUTHOR(S): Fuel Injection Engines

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PUBLISHING AGENCY:	P.A. NO.:
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