

"BARE BONES" PROPULSION
FOR
SMALL, LOW COST SATELLITES

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ABSTRACT

The radio amateur satellite community pioneered in the design, fabrication and launch of small, low-cost satellites. While these satellites became increasingly more sophisticated, they continued for years as piggyback passengers with no capability for orbital adjustment once released. Beginning with the Phase III spacecraft series an on-board propulsion capability was included permitting significant adjustments to the initial orbit. This paper describes the design of the propulsion modules of three Phase III spacecraft initially using a solid rocket motor and moving to a bi-propellant liquid propulsion system in following spacecraft. While the specific hardware and system design utilized may not be specifically applicable, the general approaches taken could point the way to satisfying the propulsion requirements of other small, low-cost satellites.

INTRODUCTION

On January 12, 1961, a small, simple telemetry beacon satellite was carried into orbit as a piggyback passenger on the Discoverer XXII launch. Battery powered, this satellite operated for only a few days sending crude telemetry signals to amateur radio operators around the world. The product of a group of California radio amateurs organized as Project OSCAR, this satellite was named OSCAR I, the acronym standing for, Orbiting Satellite Carrying Amateur Radio.

in the ensuing 25 years the amateur satellite community has

expanded internationally and the products of their labors have evolved into long-lived, sophisticated, communications satellites operated as free-access relays for amateur radio operators around the world. Since 1969 the Amateur Radio Satellite Corporation (AMSAT), an East Coast successor to Project OSCAR, along with its international affiliate organizations, have provided the focus for amateur radio satellite activity in the western countries. Beginning in 1978, a similar series of amateur radio satellites was initiated by amateur radio enthusiasts in the USSR.

Having demonstrated a capability for building and operating long-lived, multi-transponder communications satellites in low earth orbit, AMSAT groups in the U.S. and West Germany undertook the development of what was seen as the next step in the program, the Phase III series of spacecraft. This terminology derived from the categorization of the early, short-lived, beacon satellites as the Phase I program and the following long-lived, communications satellites in low earth orbit as the Phase II program. The PHASE III effort was directed to designing a sophisticated spacecraft with multiple transponders to be placed in a highly inclined elliptical orbit similar to one pioneered by the USSR Molniya satellites. This orbit would permit much greater communications coverage from its apogee of 35,000 Km and would extend visibility time for individual ground stations from the 20 minute average for the low orbiting satellites to as many as 10 hours at a stretch. In order to achieve this orbit, however, it would be necessary to bring into the design one capability never before incorporated into amateur radio satellites, on-board propulsion. The only available launch opportunities were for piggyback rides with commercial communications satellites on their way to geosynchronous orbits. The plan developed was to ride with the primary payload into a low-inclined geosynchronous transfer orbit and then use an on-board propulsion system to change the inclination of the orbital plane to 63 degrees. As part of the same operation, perigee would be raised a safe height while apogee was to be left at the 35,000 Km of the transfer orbit. The following paper describes the development of three propulsion systems to accomplish this goal.

THE PHASE III SPACECRAFT

The Phase III spacecraft is shown in Figure 1. and an exploded view of the second mission spacecraft in Figure 2. This distinctive three-armed structure, the shape of which was initially driven by space availability on an early launch possibility, has proven to be an excellent design both structurally and in optimizing the illumination of the six solar arrays. The cylindrical center section was sized

to house the spherical solid rocket motor that was available for the first mission. The spacecraft was spin stabilized with the spin axis coincident with the center line of the central cylinder. Attitude control with accurate pointing capability was essential both during the motor burn, and later for pointing the high-gain antennas toward earth at apogee. This was provided by an attitude control system utilizing magnetic torquing with earth and sun sensors for reference. An on-board computer, the Integrated Housekeeping Unit (IHU), had among its principle responsibilities the taking of data from the sensors, comparing the readings with three navigational reference systems resident in memory, determining the current spacecraft attitude, and activating the torquing magnets contained in the three spacecraft arms to move the spin axis to the desired orientation. While this system did not permit rapid change, experience has shown that it can effectively spin up the spacecraft from essentially no rotation to the 50 RPM necessary for motor burn and point the spacecraft with the necessary precision. In addition to controlling spin rate and attitude control, the IHU is responsible for overseeing a wide range of housekeeping duties that include: sequencing of the operating schedules for the communications transponders; storing ground commands for later implementation; controlling the charge rate from the solar arrays so as to keep the nickel-cadmium storage batteries at the proper charge level; and, most importantly from the propulsion standpoint, receive, verify, store, and issue motor firing commands at the specified time and point to the proper direction in space.

THE PHASE IIIA PROPULSION SYSTEM

The first Phase III propulsion system was designed around use of an available spherical solid rocket motor. Design, fabrication, handling, control, safety and operational results are addressed in the following.

The Motor

The Phase IIIA propulsion system was designed around the Thiokol TE-345, a 13 inch spherical solid rocket motor. This motor, originally designed as retro rocket for the Gemini spacecraft, was now being used in other space programs and arrangements were made for the donation of one motor to AMSAT. The total impulse available was calculated to be just sufficient to achieve the desired Phase III final orbit. Mounting required only providing the required attachment interfaces in the spacecraft structure and careful alignment of the motor nozzle with the spin axis.

The Motor Ignition Unit (MIU)

The electronics to initiate the ignition sequence were contained in the MIU module. The electronics in this box were designed to control the ignition sequence and to generate the high-current, low-voltage pulse necessary to assure igniter performance. The cabling associated with the MIU included a heavy-duty normally open relay in the igniter firing circuit, interconnection with the IHU computer, and a safe/arm plug that provided complete isolation of firing circuits prior to launch. After launch and determination of the initial orbit parameters, the spacecraft was spun up using the torquing magnets, and a series of firing commands were issued to the spacecraft. These included an enable code, a firing code, and the precise time for motor firing. These commands were stored in memory and at the appropriate time the ignition sequence was initiated by the IHU issuing the enable and firing codes in the proper sequence and timing. The MIU first compared the received codes against matching codes stored in its electronics and, then initiated the firing sequence. This involved first, closing the relay that had isolated the igniter circuits, then energizing the switching regulator in the MIU to generate the firing pulse. Any deviation from the planned timing or sequence of events triggered an immediate shut-down command.

Fabrication

With the exception of the motor and its two igniters, all other components utilized in the Phase IIIA propulsion system were readily available from commercial sources consisting largely of cabling, connectors and small electronic components. The principal consideration was assuring absolute reliability of the design and the components used in the system to assure that the motor ignition would occur when commanded and not at any time before.

Safety Considerations

Any system that incorporates almost 40 kg of explosive material must be considered a hazardous device requiring careful handling and detailed safety planning. On the other hand, one advantage of using a solid rocket motor was the relative simplicity of handling from a safety standpoint. The motors currently in use have evolved to the point that they are relatively immune to ignition by static electricity discharge or low-level stray currents. The Motor Ignition Unit and associated cabling was carefully designed to assure the isolation of all firing circuits by open relay points, safe/arm plug interrupts and an absolute requirement for recognition of properly coded enable and firing keys. Hazardous operations were delayed until as late as possible in the launch campaign. However, beginning with the

installation of igniters in the motor, and continuing with all subsequent activities, hazardous conditions were assumed and extreme care was required to be exercised. The motor, spacecraft and handling personnel were all required to be connected to a common ground point. Any time that new structural components are brought together, they too were brought to the common ground. Equally important, in integrating the spacecraft with the launcher was the need to electrically check all cabling that could carry firing current to assure proper termination and absence of any voltage prior to mating connectors. The last action before final close-out for launch was to replace the "Safe" plug with the "Arm" plug to establish connections between the MIU, the spacecraft battery and the firing relay. This established all necessary wiring connections for motor ignition but still absent were the firing keys which are only communicated to the spacecraft after launch.

After detailed verification and extensive testing the system here described proved to operate in a consistently reliable manner. The importance of using reliable components and a solid system design cannot be overemphasized for this type of system. Particular attention should be given to identifying any individual components that could, through failure, initiate a firing sequence. Further, the adequacy of the design and operating procedures must be reviewed by and acceptable to the safety staff of the launch authority. Early interaction with the safety people is recommended to assure a complete understanding of the requirements for safety and to provide enough time to take any corrective action that may be necessary.

Operations

The proper operation of the Phase IIIA propulsion system, to the extent it could be tested on the ground, was completely verified through the testing program. The safety features of the design and ground handling procedures were reviewed and accepted by the safety staff of the Ariane launch authority. On May 23, 1981 final launch preparations at the Kourou launch site went smoothly without any major hitches. Shortly after liftoff, however, failure of one of the four first stage engines resulted in a catastrophic failure of the launcher and payloads. As a result, there was no opportunity to demonstrate the operation of the Phase IIIA propulsion system.

THE PHASE IIIB PROPULSION SYSTEM

Following loss of the Phase IIIA spacecraft, the design and construction of a replacement spacecraft was immediately undertaken. While the basic configuration and design of the

Phase IIIA was retained, a number of improvements were undertaken for the communications modules. Beyond these, the most significant change was in the propulsion system. With improvements adding weight to the spacecraft and a launch opportunity that would provide a lower initial orbit inclination, it was clear that the solid motor could not provide enough impulse to assure reaching the desired orbit. The decision was made to explore other approaches. A breakthrough was made when the German team, AMSAT-DL, was able to make arrangements with the German aerospace firm, Messerschmitt-Boelkow-Blohm, for donation of a 400 N bi-propellant motor with associated hardware and ground handling support. The availability of this hardware made possible a move to a liquid propellant system. Calculations clearly indicated that a significant improvement in total impulse could be achieved and that the capability for multiple motor burns added significant mission flexibility. On the other side of the ledger, the propulsion system would be more complex and potentially hazardous than the solid motor system used in the previous design. The configuration of the Phase IIIB spacecraft is shown in Figure 2. and the propulsion system configuration in Figure 3. The redesign utilized the total volume of the central cylinder for a two chambered propellant tank that was pressure fed by a high pressure helium bottle through a plumbing system designated the Propellant Flow Assembly (PFA). The propellants being hypergolic, ignition was achieved simply by opening the motor valves. Following is a discussion of the design and system components.

The 400 N Thruster

The motor provided by MBB had originally been developed as a vernier engine for the Europa European launch vehicle and was designed to give about 400 Newtons (95 Lb.) of thrust. The original propellants for this motor were the Nitrogen Tetroxide (N2O4) and Aerozine 50 (AZ-50) propellants utilized by the Europa first stage. Following cancellation of the Europa project, the motor was selected as the apogee motor for the Symphonie joint German/French communications satellite project with modification for use of Monomethyl Hydrazine (MMH) instead of AZ-50. In discussions with the MBB engineering staff it was decided to further modify the AMSAT engine to permit use of Unsymmetrical Dimethyl Hydrazine (UDMH) instead of AZ-50 because this propellant was more readily available at the launch site.

Material Compatibility

The propellants used raised major problems of material compatibility. N2O4 is not only extremely active and will readily attack most organic material, it is also easily contaminated. UDMH, while not as corrosive, is equally subject to contamination. Both are extremely toxic and cannot be handled without use of protective suits and air

filtering. To compound the problem, the close tolerance on valves and pressure regulators meant that both the gas and fluid flow transport systems were extremely vulnerable to contamination. Although MBB had agreed to provide certain key hardware items such as the pressure regulator, explosive valves, and a multiple check valve assembly, the remaining components had to be procured and the propulsion system designed and assembled by the AMSAT group. Materials that were to come in contact with the propellants were restricted to selected types of stainless steel and aluminum alloys with teflon for seal material.

The Propellant Tank

Initially it was planned to fabricate the two-chambered propellant tank from a special alloy of stainless steel. When it was found that this material could not be formed properly, the decision was made to go to an aluminum tank design. The most important requirement was to provide an intermediate bulkhead that would give absolute assurance that the two propellants could not come into contact through cracks or a poorly welded seams. The design that achieved this is shown in Figure 4. The tank was constructed in three sections milled from thick billets of aluminum alloy so that the intermediate bulkhead was an integral part of the center section and the welded seams were isolated to the individual propellant tanks. Thus, any seam was avoided that upon failure would result in propellant mixing. Drain points were located to keep the tube mouths covered by propellants through the effects of the spacecraft spin rate and the effects of propulsion thrust. The tank took advantage of the full volume of the central cylinder with only enough space at the top and bottom for tubing and cable access.

The Helium Bottle

The flow of propellants to the motor was forced by helium pressure. In order to provide sufficient helium gas to assure total displacement of the propellants it was necessary to store the helium at a very high pressure. Since a commercial bottle was not available in a usable configuration and at an affordable cost, a low-cost, but effective alternative was developed. This is shown in Figure 5. The AMSAT-DL group located a metal bottle that was inexpensive and commercially produced as a fire extinguisher bottle. The problem was that this bottle was rated to a pressure well below the helium storage bottle requirement of 400 atmospheres (6,000 psi.). The solution was to encase the length of the bottle with carbon/epoxy fiber windings and thereby increasing the burst pressure of the bottle to a demonstrated 1132 atmospheres.

The Liquid Ignition Unit (LIU)

The electronics module for initiating and controlling the motor burn for the Phase IIIB spacecraft was designated the LIU to differentiate it from the Phase IIIA MIU. Its purpose was similar to that of the MIU but with one important additional requirement. This unit not only was responsible for controlling the ignition sequence, it was now also required to control the burn time of the motor. To do this the LIU design included a counting capability in 50 millisecond intervals to meter the duration of an individual burn.

Propellant Flow Assembly (PFA)

With the exception of the electronics package, tankage, and interconnecting tubing, the remaining components of the propulsion system were assembled on a single mounting plate as shown in figure 6. As can be seen from the drawing, the PFA was a consolidated module containing all fill valves, pressure regulation, filtering and check valves to prevent backflow in the pressurization lines. It also included three normally closed explosive valves to isolate the high pressure helium tank and the two sections of propellant tank until the initial firing sequence was commanded in orbit. Also included in the PFA design was a precision pressure transducer to measure the low pressure side of the system and transmit its measurements by telemetry to the ground. A much more coarse measurement of the high pressure helium bottle was made using a strain gage attached to the wall of the bottle. In designing the PFA every effort was made to minimize the number of wrench-tightened fittings and to use welded connections wherever possible to reduce the possibility of leaks. In addition, all subassemblies were pressure and leak tested before assembly and the total system was thoroughly leak tested when finally assembled. The ignition sequence, following receipt of validated keys and commands from the IHU, involved actuating the explosive valves in the proper sequence, allowing the system to stabilize, and then opening the motor propellant valves. Valve operation in the 400N thruster is initiated electrically but activated by helium pressure. Following ignition, the LIU counted the commanded time intervals and then initiated a shutdown sequence. The Phase IIIB mission profile included two major burns to achieve the desired orbit with enough residual fuel for trimming maneuvers, if required.

Safety Considerations

All of the safety considerations addressed for the Phase IIIA spacecraft apply to the Phase IIIB system. To these was added the problem of safely handling very toxic, self-igniting propellants. This required even more detailed and careful planning for ground handling at the launch site

including hazardous propellant transport, complex filling operations, and subsequent careful ground handling of the loaded spacecraft. A close interaction with the launch authority safety staff before arrival at the launch site and during the launch campaign was essential. In addition, arrangements had to be made with the launch authority for provision of protective suits and transport of propellants. Once fueled, the spacecraft required constant monitoring to assure that there were no hazards to personnel from release of toxic vapors. Finally, there was the problem of cleaning the ground support equipment used to fill the spacecraft after the tanking operation was complete. A new safety feature initiated with the Phase IIIB mission was a CRT safety display driven by the spacecraft computer that was located at the range safety officer's station showing in green and red the status of the firing keys in memory, which plug was in the safe/arm connector, what parts of the system were powered up, and how much time had elapsed since the last telemetry update.

Operations

The Phase IIIB spacecraft and its propulsion system were successfully launched on an Ariane rocket from the Kourou launch site on June 16, 1983. Initial orbital operations were disrupted by an unplanned collision between the spacecraft and the third stage that resulted in damage to an antenna, change in the spacecraft orientation and reduction in the spin rate. Despite this initial difficulty, the spacecraft was reoriented, spun up to the proper rate using the magnetic torquing system and the propulsion system commanded into its first burn. Telemetry following the successful burn indicated some deviation from the expected burn time, but otherwise the operation of the system appeared nominal. The orbit actually achieved with the first burn was, as planned, intermediate to the one finally desired. Action then was initiated by the ground stations to reorient the spacecraft in preparation for the second burn. During this somewhat lengthy process, telemetry indicated a steady drop in helium pressure. By the time the spacecraft was reoriented for the second burn, the helium pressure had fallen below the level necessary to actuate the motor valves. Thus, the intermediate orbit became the final orbit for this mission. The problem is thought to have been caused by a leak in the seal of the high pressure helium bottle triggered by the rapid cooling of the bottle during the first burn. The orbit achieved proved to be very useful if not as effective as the one desired. The Phase IIIB spacecraft, renamed OSCAR 10 once in orbit, achieved most of its mission objectives. It provided effective communications for the world amateur radio community for three years. It is only now nearing the end of its operational life due to damage to the computer memory from the effects of radiation.

THE PHASE IIIC PROPULSION SYSTEM

At the time the decision was made to undertake the PHASE IIIB development a policy was established that two of each of the electronic modules would be produced. This was done to provide redundancy in case of last minute problems with the prime modules and to provide the key hardware for a follow-on mission. Not long after OSCAR 10 began orbital operations, the development of the Phase IIIC spacecraft was initiated. As with the Phase IIIB system, improvements and augmentations were made in the design of the communications subsystems. For the propulsion system, it was decided to continue with the 400N thruster. MBB agreed to make available another motor, but was not able to provide the supporting hardware beyond a minimum number of fill and drain valves since supplies had been exhausted in supporting the previous mission. The challenge, therefore, in developing the Phase IIIC propulsion system was to come up with a redesign of the Propellant Flow Assembly that used available and affordable hardware. The results of this redesign effort are shown in figure 7. With the exception of the 400N thruster and three specialized fill and drain valves, the complete system was designed using commercially available and relatively inexpensive hardware. The design is an absolutely bare bones approach emphasizing simplicity and economy. The propellant and helium tanks were used without change except for a modification in the propellant tank to accommodate use of AZ-50 rather than UDMH as the fuel and modifications to the helium tank to preclude a repeat of the leak experienced with the PHASE IIIB system. The major changes were in the PFA.

The New Propellant Flow Assembly

As shown in the schematic in Figure 7. and the drawing in Figure 8., significant changes were made in the design of the PFA. First, the normally closed explosive valve that had isolated the high pressure helium bottle was replaced by two high quality, low leakage, electrically operated valves. Further, when the system is actuated, one of the valves is held open to initiate the flow of helium, the other is operated in a feedback loop with the pressure transducer to provide pressure regulation in a "bang-bang" mode. In this operation, the valve is opened when pressure falls below a set level and closed when the desired pressure is reached. Should the pressure rise above the expected level, the role of the valves is reversed with the suspect regulator valve now held open and the other operated in the regulating mode. A further safety feature was provided by adding a relief valve set to operate if the propellant tank pressure rises significantly above the operating pressure. Anticipating undesirable pressure fluctuations from the pulsing of the regulating valve, an accumulator was incorporated. The explosive valves and the specialized check valve assembly

used in the Phase IIIB design to prevent backflow from the propellant tanks was replaced by redundant commercial check valves. The result of this redesign is a significantly different Propellant Flow Assembly in appearance, but one that is expected to functionally duplicate the operation of its predecessor.

The New Liquid Ignition Unit (LIU)

The redesign of the PFA drove significant redesign of the LIU. While the firing command verification and motor burn timing functions were retained without change, the circuitry required to fire the explosive valves was deleted and new circuitry was incorporated to control the operation of the pressure regulating valve system.

Current Status

All hardware supporting the new propulsion system has been fabricated, tested at the subsystem level, and assembled into the Phase IIIC spacecraft. Final testing of all spacecraft systems including the propulsion system has been delayed by the schedule slips associated with the Ariane mission V18 failure and recovery activity. Integrated spacecraft testing has now been resumed with a vibration test scheduled for early November. At this time, a total check-out of the propulsion system short of actual ignition will be accomplished. Following a launch that is currently scheduled for early 1987, it is expected that the Phase IIIC propulsion system will function as designed and accomplish the first fully successful orbital maneuver in the Phase III spacecraft series.

REFERENCES

1. J. A. King, "The Third Generation"
Part 1, Orbit, Vol. 1, no. 3, Sept./Oct. 1980, pp. 12-18
Part 2, Orbit, Vol. 1, no. 4. Nov./Dec. 1980, pp. 12-18
2. M. A. Schwende, "Development of Bi-Propellant Orbit Injection and Attitude Control System", Paper No. 78-1092, AIAA/SAE 14th Joint Propulsion Conference, Las Vegas, Nevada, July 25-27, 1978.



Figure 1

AMSAT PHASE III B

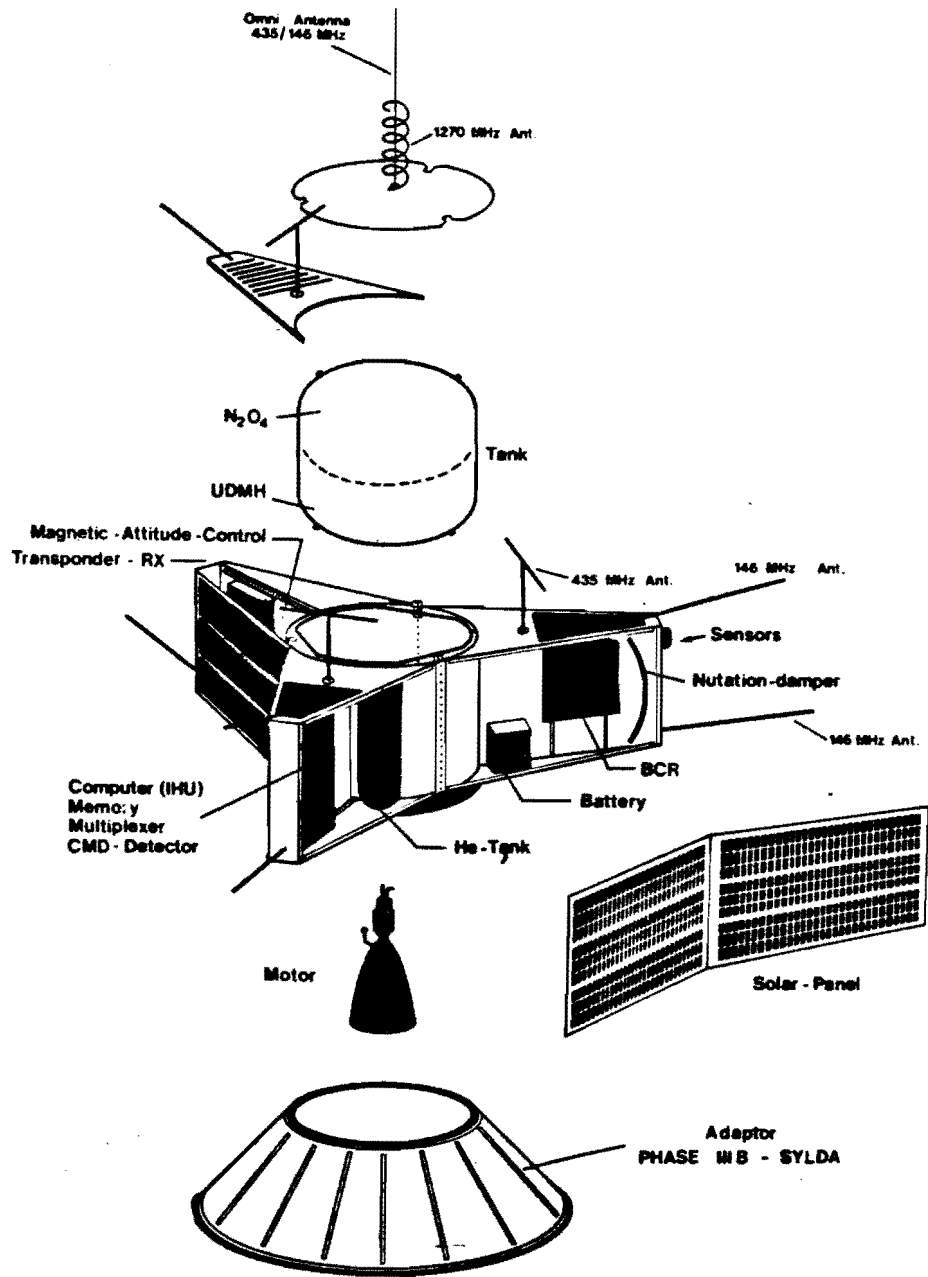
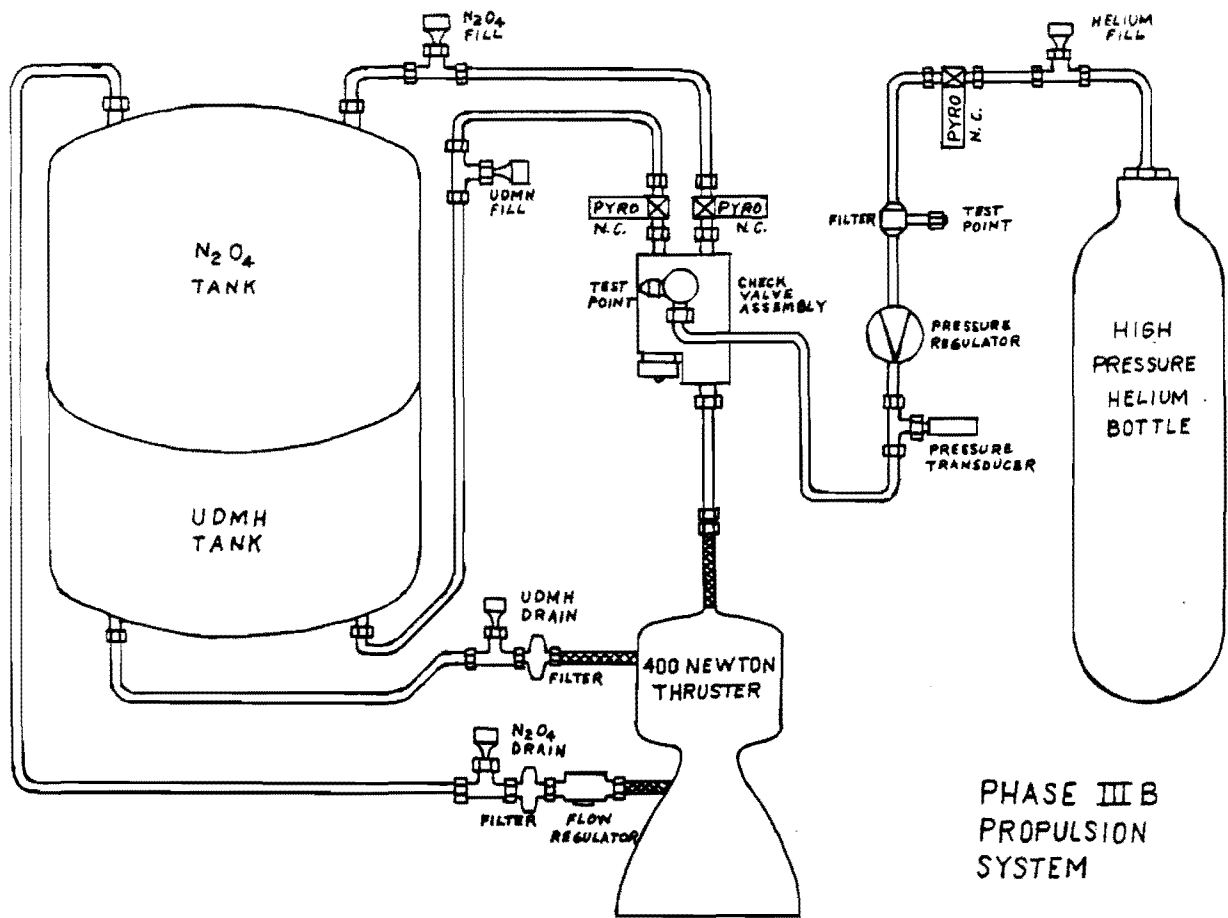


Figure 2



PHASE IIIB PROPULSION SYSTEM



PHASE IIIB
PROPULSION
SYSTEM

Figure 3

PHASE III PROPELLANT TANK

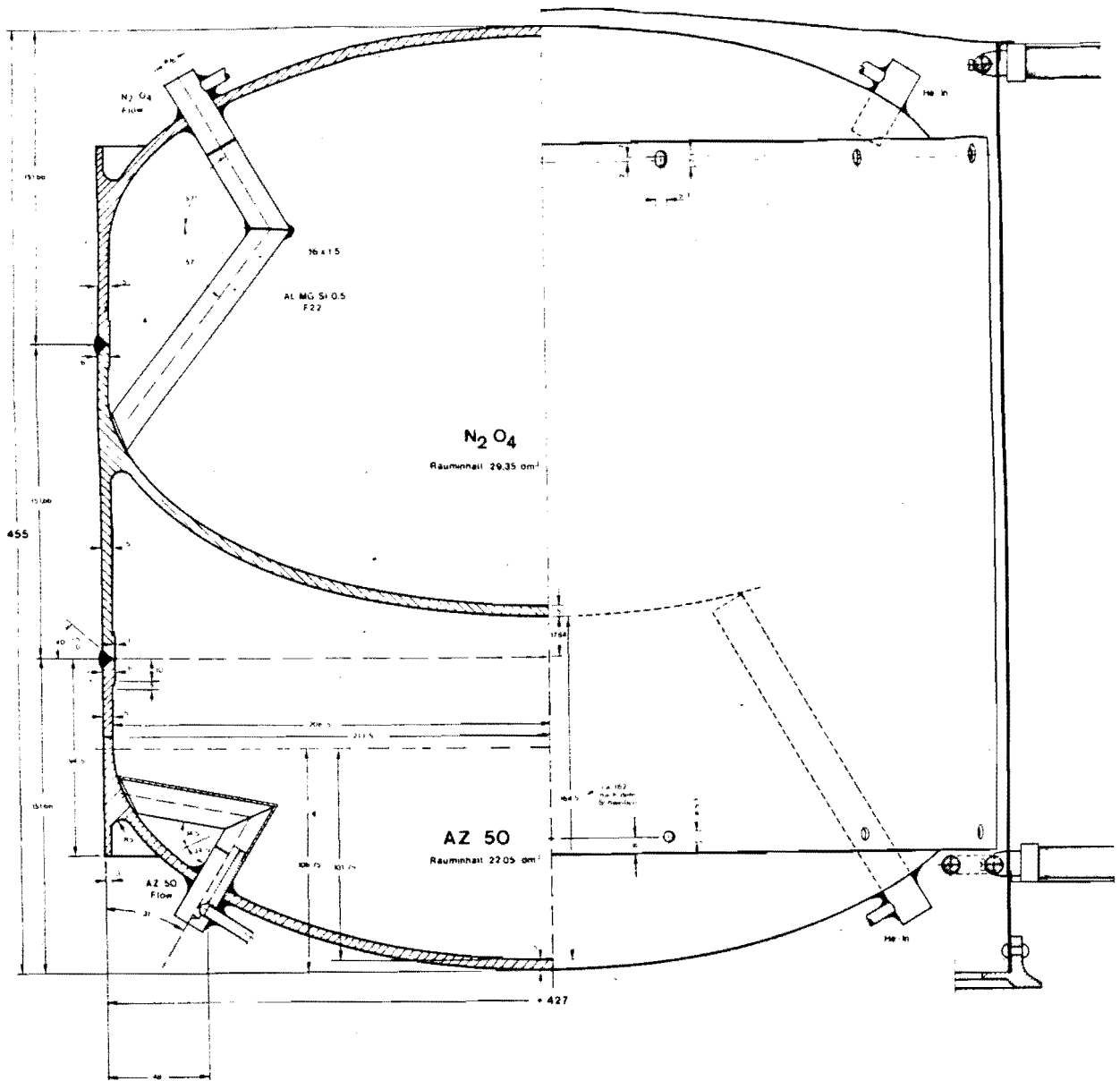
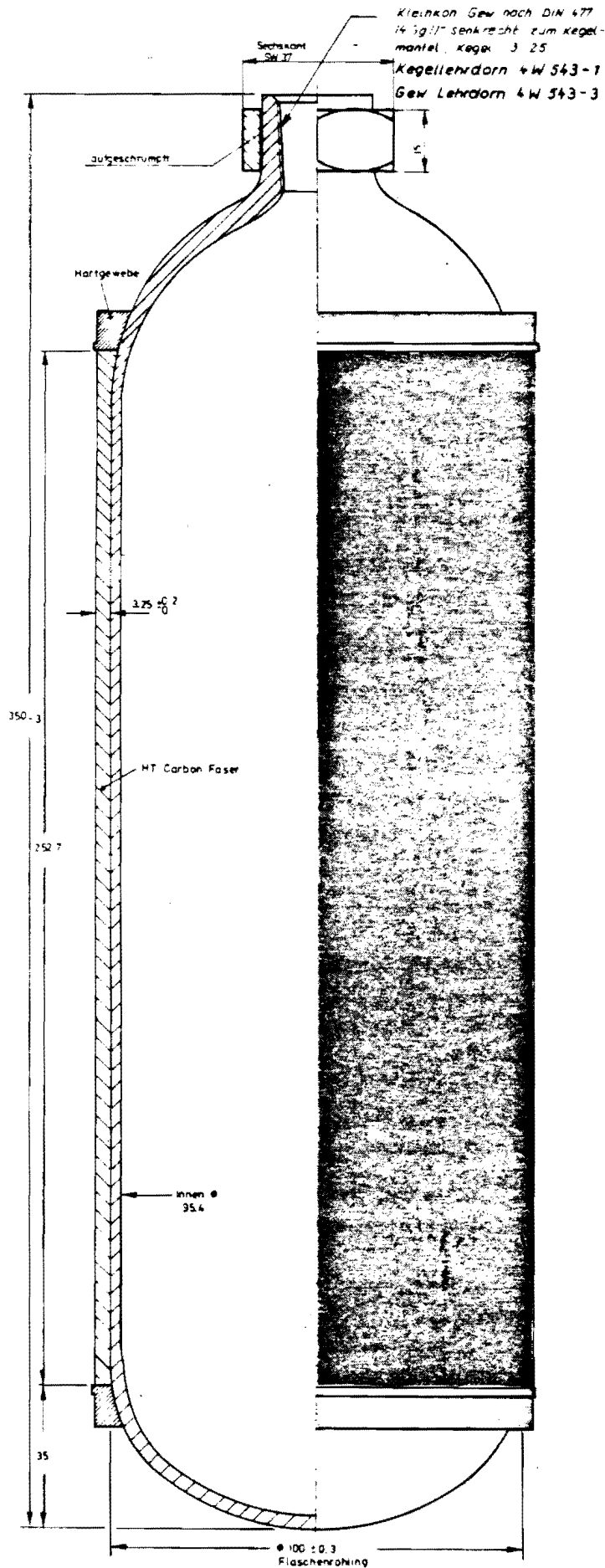


Figure 4

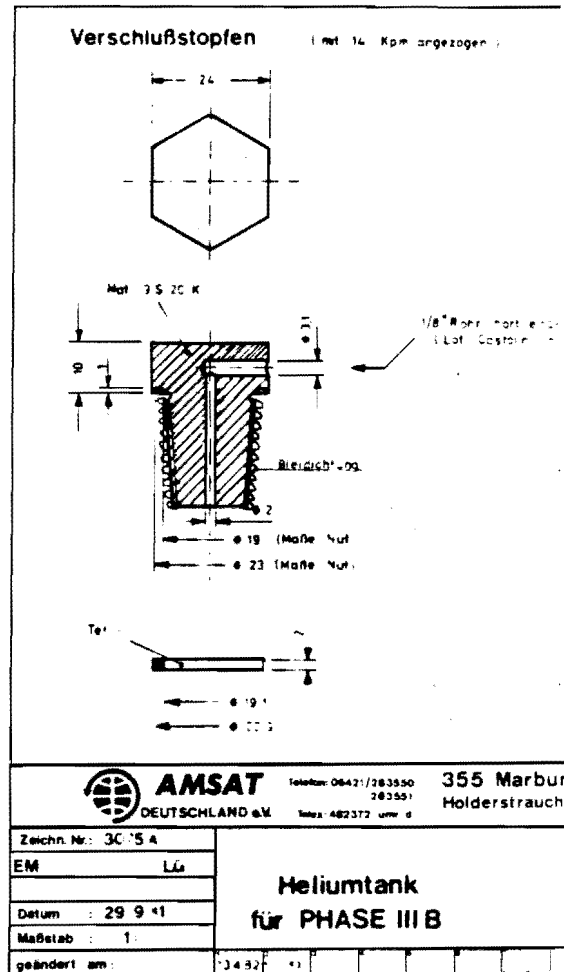


Vorgegeben:

Wanddicke	= 3,25 mm ± 0,1
Faservolumenanteil	= 65 Voll %
Fasertyp	= T 300 / T 3000
Faserquerschnitt	= 2x 0,11 mm ²
Faserquerschnitt/mm	= 3,25 x 0,65 = 2,11 mm ² /mm
Vorschub / Windung	= 2,5 mm
Anzahl der Lagen	= 24
Wickellänge	= 252,7 mm
Anzahl der Schritte	= ± I 1250
Anzahl der Schritte	= - I 361200

- A Auf den Rohling werden 2 Lagen Vlies T 1747 gewickelt
- B Die Fadenspannung in 4 Stufen verändern
 bis zur 8. Lage = 1,4 Kp
 bis zur 13. Lage = 1,5 Kp
 bis zur 18. Lage = 2,0 Kp
 bis zur 24. Lage = 2,5 Kp
- C zum Schluß werden 2 Lagen Abreifgewebe aufgebracht

Harz: 162 - Larenin 260 c = 100 : 38
 Kohlerohlingverbrauch : ca. 326-327 gr.
 Harzverbrauch : ca. 250-300 gr.
 Flaschengewicht leer : ca. 245c - 2490 gr.
 Gewicht der aufgebrauchten Kohlefaser : 492 gr.



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Zechn. Nr.: 3C 15 A
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Datum : 29 9 '11
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Heliumtank für PHASE III B
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Figure 5

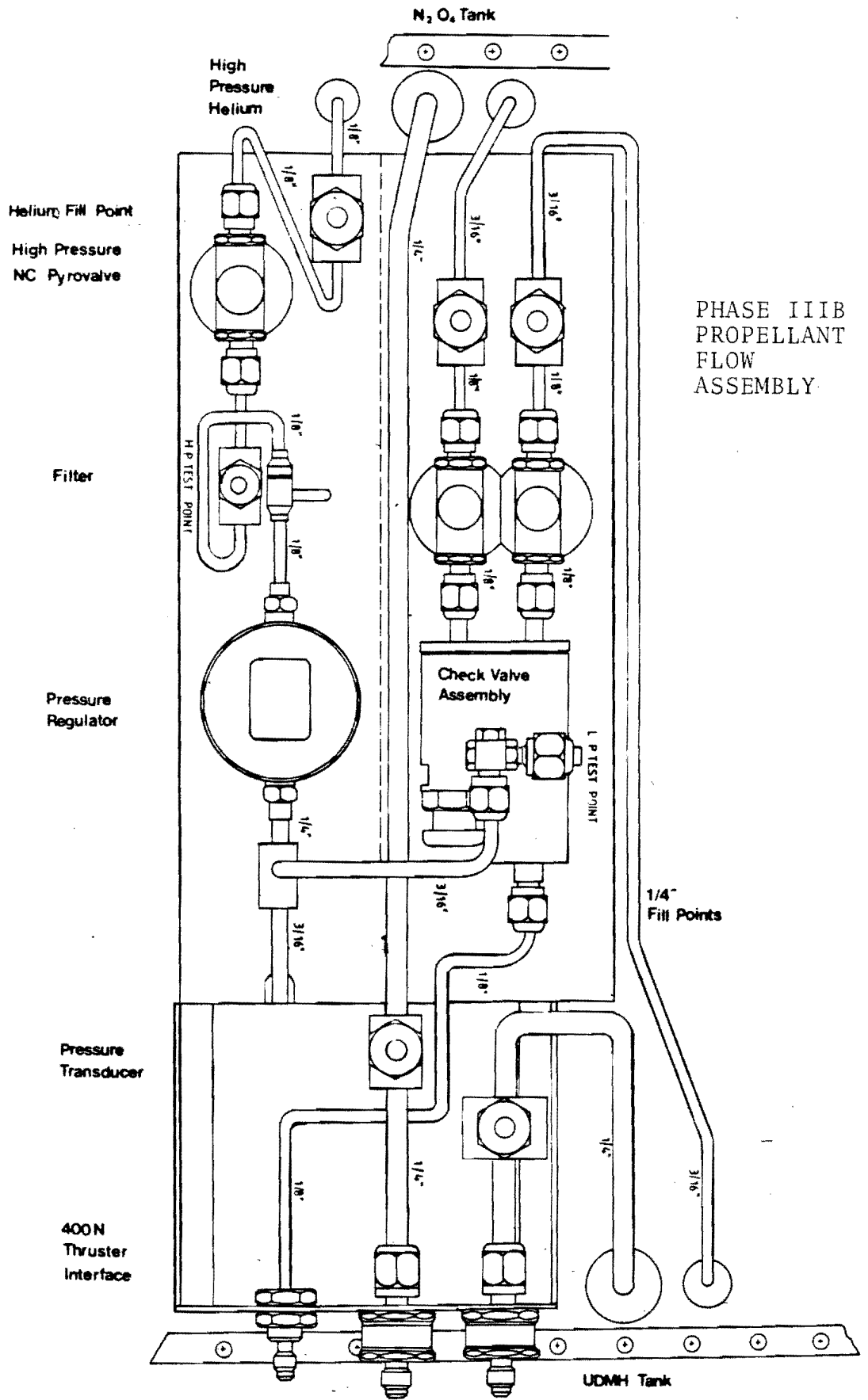


Figure 6

PHASE IIIC PROPULSION SYSTEM

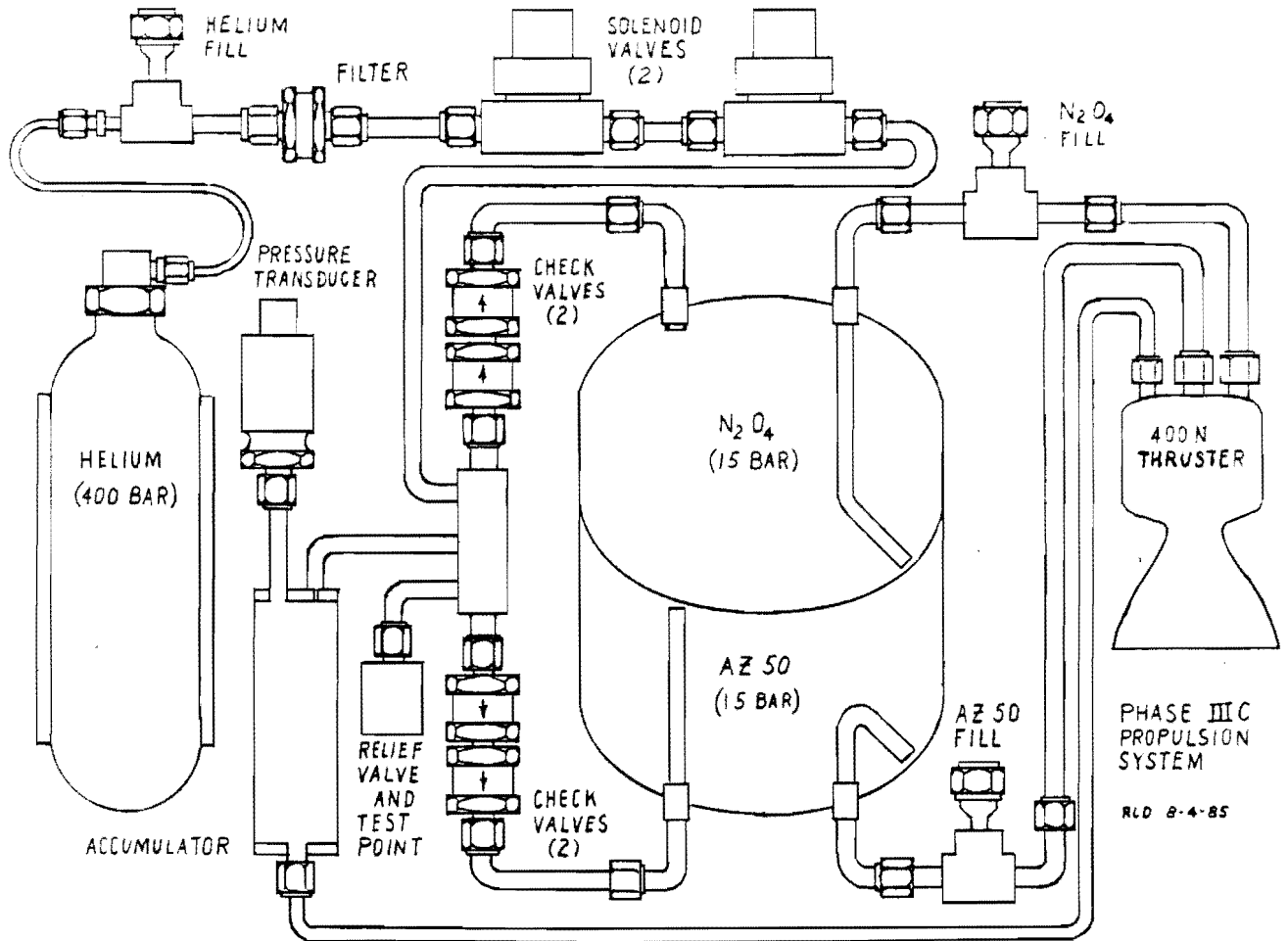


Figure 7

PHASE IIIC
PROPELLANT
FLOW
ASSEMBLY

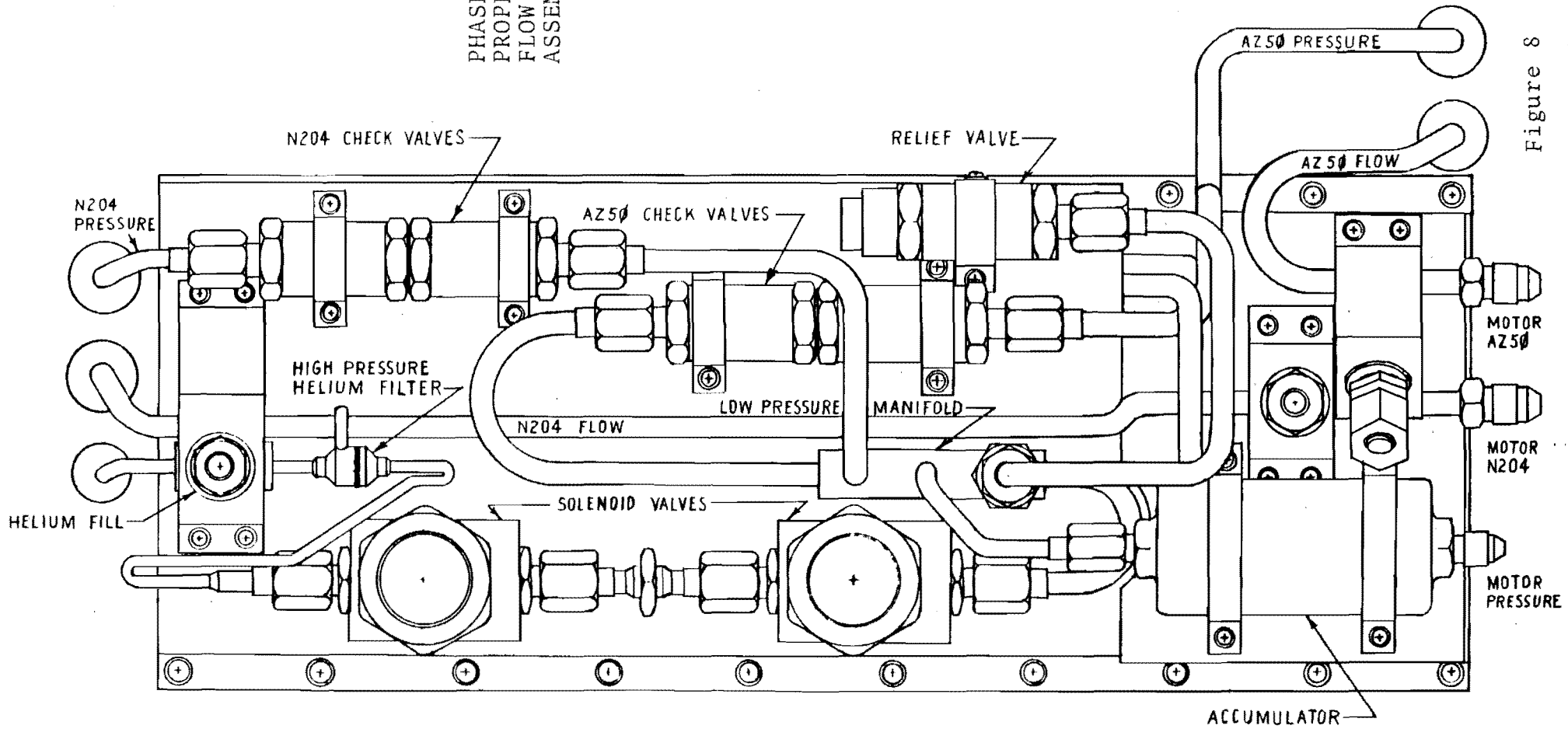


Figure 8