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SEA TRIALS AND SUPPORTING TECHNOLOGIES OF MANNED SUBMERSIBLE "SHINKAI 6500"

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Abstract

After the four years of development of the modern maximum depth submersible ,JAMSTEC has successfully completed the trainning dives of "SHINKAI 6500", a new manned submersible whose maximum operating depth is 6,500 meters, from June to October in this year.

"SHINKAI 6500" was constructed by Kobe Shipyard and Machinary Works of Mitsubishi Heavy Industries Ltd.(MHI) and marked 6,465m and 6,527m dives in the Japan Trench during the sea trials with the support vessel "YOKOSUKA" (built by Kawasaki Heavy Industries Ltd.) in August 1989.

This paper presents the results of the sea trials, trainning dives and the features of "SHINKAI 6500" with her supporting technologies.

1. Sea Tials in 1989

About twelve in August 11th 1989, the newly built research submersble "SHINKAI 6500" of JAMSTEC, grounded on the bottom of the east slope of Japan Trench after about two and a half hours of decending to the depth.

The depth was 6527 meters which could be dictated the world record among the latest submersibles. Up to the moment, the scheduled twenty seven dives were succesfully conducted as sea trials. The exciting voice from the depth really announced the accomplishment of the system development of "SHINKAI 6500" and simultaneously the beginning of research operation with the new powerful tool. According to the description acoustically transfered from the pilot in the spherical hull, the world of the 6,500 meters deep was relatively vivid with several creatures than we had imagined. And his voice could satisfy all engineers, designers and staffs who attended on the surface.

1.1 Trial dive sites and depth records

The sea trialw were composed of five sessions, which gradually increasing their depth from 25 meters and 100 meters of initial tests, to 6,500 meters of the maximum depth dive tests. The performace and property tests of several subsystems which should not depend on the depth pressure and temperature were planned to be examined in moderate depth. Their diving sites were carefully selected to be off Pacific coast along Japan Main Island with consideration of trasportation, weather and also traffic condition.

The final site of 6500m dives was decieded to be the east side slope of the Japan Trench about 250 kilometers off Kinkazan Coast.

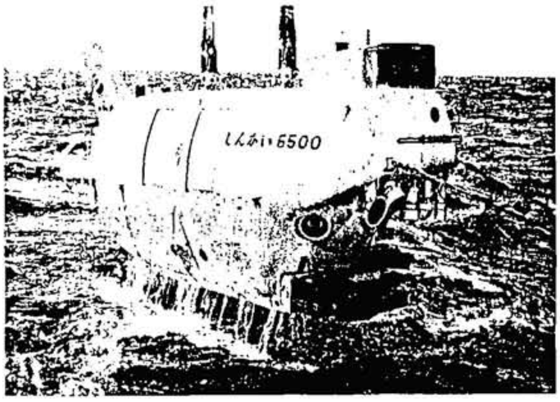

Photo 1. "SHINKAI 6500" Recovered at Trial Dive.

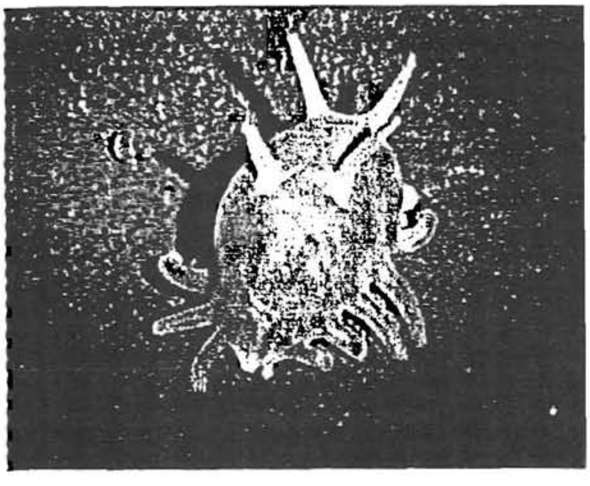

Photo 2. Deep sea holothurian *Scotoplanes globos* at 6,527m deep by TV Camera of "SHINKAI 6500"

The maneuverability test of the small sized submersible was performed mainly in about 100 meters depth off Kii Strait to the south.

The acoustical performance tests of communication between the surface support vessel through the underwater telephone and accurate subsea locationing by LBL acoustic system were extensively conducted in the bottom of 4,000 meters of Kumano Nada south-east off Kii Peninsula.

The sites of these trial dives are mapped in Fig. 1.

1.2 Verification of Capabilities

In each dive in every session, the submersible could demonstrate the designed function and performance successfully. Consequently the supervisiers from JAMSTEC and the inspectors from Nippon Kaiji Kyoukai (NK, the classification society of Japan) could clarify the excellent property of the submersible.

Combined with the data of the preceeding tests on land, in the tank and in the dock, the following functions and performance of individual subsystems were systematically examined and verified.

(1) Propulsion and Maneuverability

- Her tactical (turnning) performance is illustrated in Fig. 2 which suggests the enough moving capability to locate and sample any subsea objects.
- The crabwise movement (traversing sideways keeping almost the same heading) in Fig. 3 proved delicate accessbility when precise observation is required.
- The advancing movement with full load thruster was clarified to be over three knots. A part of speed mesurement is tabled below.

Revolution of Main Thruster(RPM)	175	110	60
Speed Planned(kt)	2.75	1.7	0.9
Speed Measured(kt)	3.0	2.0	1.0

- The operator in the pressure hull could adequately monitor these movement with Integrated Information Display System (IIDS) which displays the heading of the submersible and revolutions of each thruster.

(2) Ballasting and Trimming Capability

- The enough elevation speed over 44 meters per minutes from/to bottom was successfully demonstrated which would secure the sufficient time of observation (over three hours at the bottom). The speed enables the crew to travel between the surface to the bottom in two and a half hours which considered to be the maximum one while keeping the good stability.
- The submersible consumes up to one ton of steel ballast plates for decending and ascending elevation to save energy for observation activity with limited electricity.
- Trimming by shifting mercury between bow and stern could control her longitudinal attitude

Period	Site	Depth
1st 2nd	#1	25-500m
3rd	#2	1250m
	#3	2000m
4th	#4	3000m
	#5	4000m
	#6	5000m
5th	#7	6000m
	#8	6500m

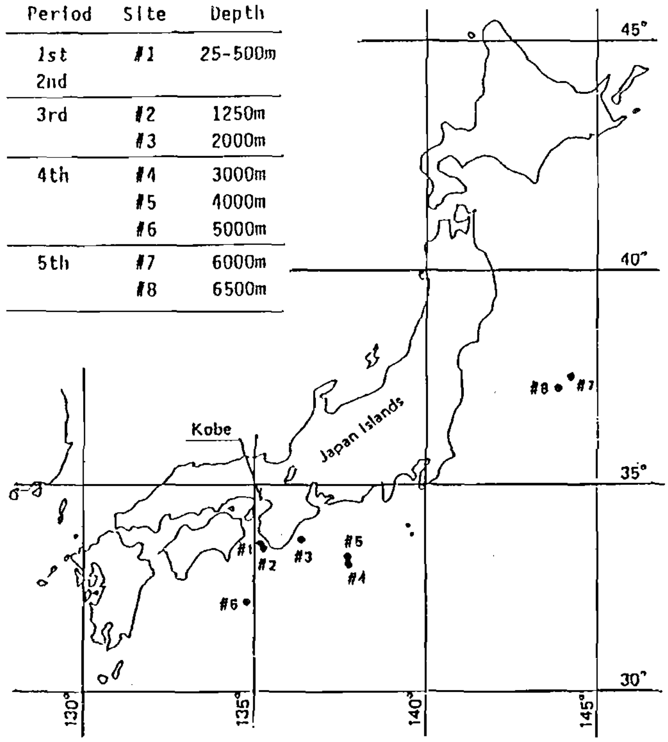

Fig. 1 Trial Diving sites of "SHINKAI 6500"

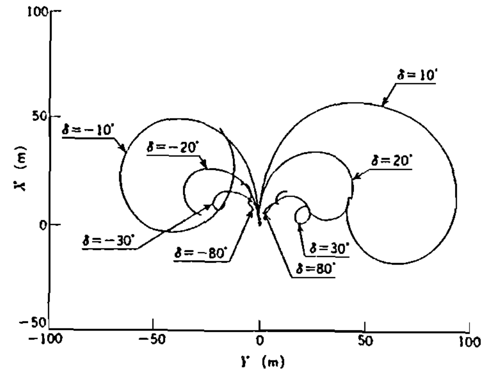

Fig. 2 The results of Turning Tests of Steering the Main Propeller

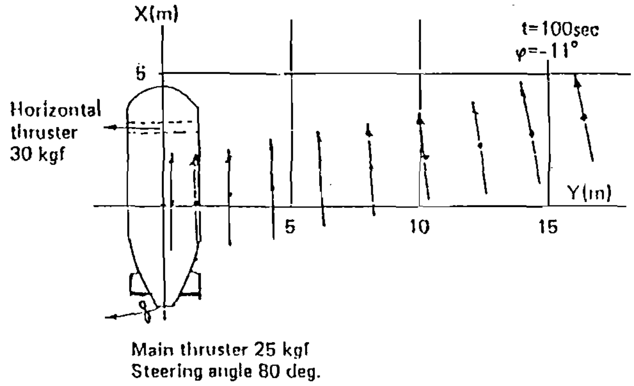

Fig. 3 Lateral Movement of "SHINKAI 6500" by Calculation

with considerable inclination (up to 10 degrees) in suitable response.

(3) Navigation and Telemetry Ability

- The navigation instrumentations such as acoustic positioning, acoustic underwater telephone, altitude sonar, observation sonar and current meter as a speed log could compose their human control link with expected accuracy. The excellent man-machine interface with pilot could be attained.
- The sea-bed acoustic positioning link with transponder network(LBL), which is to be calibrated to global sattelite network, could be realized with its excellent accuracy. Being compared with the result of the acoustic positioning by the the support vessel, the accuracy of these measurements are almost coincident.
- Acoustic communication with the support vessel "YOKOSUKA" was proved to be of good sensitivity and quality. While running in 1~2 knots, the submersible could keep clear communication with the vessel within the range of 9,000 meters. This owes truly to the noise control efforts payed in both submersible and the surface vessel.
- A newly developed acoustic imaging sonar was equipped with the submersible to attain not only ability of obstacle avoidance but also long distance observation of seabed profile. The operator compose the three dimensional configuration of the forward world with vertical and horizontal topographic images. The conventional acoustic PPI mode survey was either performed with this instrument. In the recovery simulation practiced on the way back to her mother port after final trial, the observation sonar could locate and capture the small transponder with the diameter of about 200mm in the range of 80~200 meters. The transponder had been left on the bottom in the former dive because of the malfunction of the releasing mechanisum.

(4) Observation and Sampling Status

- Many kinds of improvement in optical observation capability were established based on the experiences with "SHINKAI 2000".
- The three view ports are so carefully arranged as to secure enough sight angle forward and below the submersible for three curious occupants.
- Two color TV cameras with high resolution record wide and zoomed bottom images of high quality for reseachers' later reference.
- The dual manipulators with multi-degree-of-freedom (seven and five D.O.F individually) are installed just like human arms. And master-slave-control mechanisms with force feedback of her right hand could equip the soft sampling capability to keep the sample's quality.

During the sea trials by the builder, the every subsystems and software are thoroughly examined and adjusted to perform the designed quality and quantity. And also their operational manuals were carefully reviewed.

2. Trainning Dives

Accepting the delivery of the verified "SHINKAI 6500" system, JAMSTEC has conducted training dives by their regular operators and crew who have well-established experience with "SHINKAI 2000". Totally thirty six dives were performed around Japan from June to October 1990 while several dives were interrupted by some seasonal typhoons swept around Japan. Consequently the operators, crew and even staffs could recognize the versatility and availability of this newly initiated submersible system.

The details of this trainning dives are listed below.

Depth rate	No. of dives	period
1000 meters	15	6/ 5~ 7/10
2600 meters	9	8/ 7~ 8/29
3000 meters	5	9/25~10/ 5
6500 meters	4	10/13~10/18
1700 meters	3	10/23~10/25

Although training, these dives gradually revealed the strange world of the deepsea with her three spectacles and two TV cameras. The submersible located the living organisms not only fish or sea cucumbers (holothurian) but also the possibility of micro bio-structures.

All through this training period, the operation procedures and manuals are reviewed precisely from the aspect of safety and efficiency.

3. Background of The Development

In 1969, reflecting the uprising world trend to ocean develoment, an advisery board for the prime minister of Japan submitted the report on the general policy and programs of ocean development in Japan. In the report the necessity of development of a 6000 meter class manned deep research submersible as a most useful tool for ocean development was insisted as a most critical issue. This actually initiated the development of the manned research submersibles in Japan.

Since then the research and development on the associated key technogies were started in governmental research organization and some private companies with the support of some funds of such as Japan Marine Machinary Development Association(JAMDA), Ministry of Transport and also Science and Technology Agency of Japan (STA). Those key technologies includes the structure and material of pressure hulls, bouyancy material, high energy density batteries and acoustic navigation systems.

JAMSTEC was established in 1971 with the mission of ocean development under supervisory of the STA of Japan, and it started the development and verification of the 6,000m class research submersible system succeeding the former projects.

After deep consideration of the state-of-art technologies to realize the development, the advisory board of STA and JAMSTEC decided to develop a 2,000m manned submersible as an important interim to the final goal of the 6,000m class manned submersible. Thus the 2,000m deep manned research submersible "SHINKAI 2000" and its support vessel "NATSUSHIMA" were constructed in 1981 to verify key specific technologies and to accumulate operation experiences. Inviting many researchers not only around Japan but also foreign countries, JAMSTEC has operated this "SHINKAI 2000" system almost for ten years totally to make about 500 dives.

While constructing "SHINKAI 2000" system JAMSTEC and the ship building company were still running the development program of such key technologies as titanium alloy pressure hull and bouyancy material with high strength and low density to realize a deeper manned submersible.

Summerizing all of the research and development results, JAMSTEC has evaluated the possibility of development and research operation of the new submersible. The result was most promising applying the design requirement of the maximum depth capability of 6500 meters which reflected most of the scientists' needs.

The preliminary design of the new submersible started in 1985. Simultaneously to the design work the following verification programs were implemented intensively.

—Arrangement verification with mock-ups:
The wooden full-size models of spherical pressure hull and whole structure were assembled and simulated.

—Strength verification of pressure hull:
A scaled model of the titanium pressure hull was manufactured to be pressurized to collapsing after cyclically pressure loading. The model stood against over 1,370kgf/cm² pressure before its collapse just expected in design, which demonstrated sufficient strength.

In 1987 the construction of "SHINKAI 6500" was started and it was launched on January 1989. In last summer, the sea trials with her support vessel were successfully conducted as described previously.

4. Supporting Technologies

The required properties of "SHINKAI 6500" is pressure resisting and rapid ascending/descending performaces. Although the system of this submersible is relatively small, the assigned functions and performance in the deep sea environment are necessarily to be supported by several advanced technologies.

The principal mission objectives required to the submersible could be described as follows:

(1) To keep enough observation duration of at least three hours at the maximum operation depth.

(2) To keep enough observation capability to fulfill uprising research demand.

(3) To secure the safty operation

4.1 Reduction of weight for fast elevation

To stay in almost the same weight as "SHINKAI 2000", the following measures and technologies are inevitably required to be developed and applied in design and construction.

(1) Adoption of the high strength-weight ratio materials for pressure resistant structures

(2) Imoprovement of fabrication and assembly procedures and technologies for the new and high performance materials to attain high accuracy reducing the redandant scantling.

For the weight saving, based on the laborious research and development, the pressure hull of titanium 6Al-4V alloy was adopted instead of the conventional ultra-high tensile steel. The design procedure of the titanium alloy hulls were verified through the series of model tests on the creep property, cyclic pressurising and collapse strength. At the same time the fabrication and assembly procedure of titanium alloy hulls were established through the clarification with trial production of the proto type model. In such manner the procedures such as hot-press forming of the titanium hemispheres, electron beam welding for thick titanium sections and precise three dimensional machining to improve the sphericity were systematically developed and applied.

(3) Development of the advanced bouyancy material with high pessure resistant property and low density.

The property of the bouyancy materials installed has a great effect on the weight and size of the submersible. The syntactic foam with binary mixture composition of glass microballoons was succeesfully developed and applied. This unique structure of binary mixture enables almost saturated packing which results in low density. The specific gravity of the new buoyancy material was reduced to 0.54, which is nearly the same as that of "SHINKAI 2000" in spite of the nearly doubled higher collapse strength.

(4) From pressure resistant vessels to oil-immersed pressure compensated vessels.

"SHINKAI 6500" has inverters to change the direct current of the batteries to the useful alternative one as "SHINKAI 2000" has. Whole parts of inverters of "SHINKAI 2000" were accommodated in the pressure vessels because of the fragile electric components. The weight of the pressure vessels could apparently increase enoumously as the operating depth comes to 6,500 m because of the required scantling. To avoid this, the new inverters with electric components operable in high pressure environment were developed. The main circuits of the inverters, consisting of power transistors, capacitors, reactors were put into the oil to consist the pressure compensated structures. It could save the weight by about three tons including the buoyancy material supposed to compensate the weight in water.

4.2 Strengthen Observation Capability

To integrate the observation capability, the following tactics are considered to be useful.

(1) Integrated Acoustic Instrumentation and Noise Control
In utilizing the acoustic instruments, to

improve sensitivity and accuracy is one of the most critical issue in submersible system development. The following instrumentation was extensively implemented to realize an ultrasonic systems on the submersible.

—Acoustic Subsea Locationing
It was successfully proved that the acoustic subsea link with LBL locating algorisms could be the most precise underwater measurement procedure where no electromagnetic wave or light could transmit in some reasonable distance. The manned submersible which could independently sense her own trajectory would possibly expand the range of her activity and improve the accuracy of locationing. Being free from the conventional acoustic positioning link from surface to the bottom, the support ship could conduct her own survey, for instance bathymetry survey with multi-narrow beam profiling, while the submersible is making contact survey at the bottom.

—Observation Sonar
The newly developed observation sonar is composed of acoustic transmitters and receivers arranged vertically and horizontally individually. The transmitting arrays in vertical line generate a horizontal thin fan beam while the receiving array in horizontal a vertical thin receiving beam. Resultantly the narrow pencil scanning beam is formed just like TV frame. The range (the distance) to the object is resolved by referring the time lag of the reflecting acoustic pulse. Consequently three dimensional hologram as phase and amplitude distribution is to be constructed through adequate signal processing. This procedure of sector-cross-fan beam scanning with high speed signal processing enables the size of the system to be practical for installation.

This acoustic imaging instrument supplies an excellent means to figure out and observe obstacles in rather long distance beyond the range of light transmission. The several sensing modes of this acoustic procedure are illustreted in Fig.4.

—Noise Reduction and Control
To assure the performance of the acoustic instruments, any possible noise from machinary components has been controlled to allowable level since the very early stage of parts assembly through its final stage of her sea trial. The emission of the noise from main motors and pumps were strictly measured and evaluated not to disturb performance of the acoustic equipments. The target noise level of under -8dB for LBL positionning receiver and 2dB for underwater telephone were satisfied in almost all operational condition. Conventional noise control measures were applied to the full extent not only for the submersible but also for the support vessel.

—Integration of Data Acqusition and Infomation Display
As submersible Alvin of Woods Hole Oceanographic Institution adopts the new data acquisition system, an efficient up-streamming system of observed data from the submersible

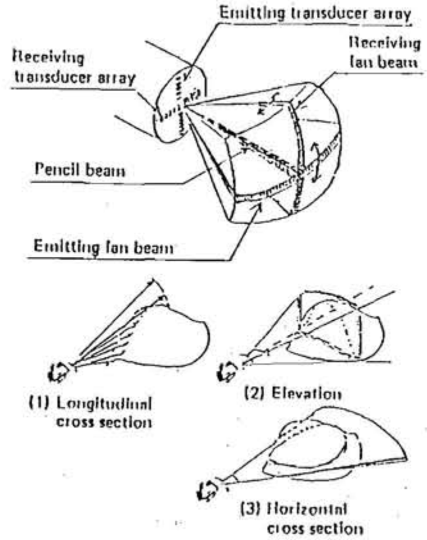

Fig. 4. Principle of the Acoustic Imaging Sonar

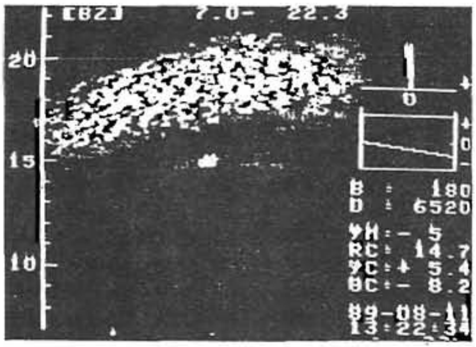
Photo 3. Display of the Acoustic Imaging Sonar

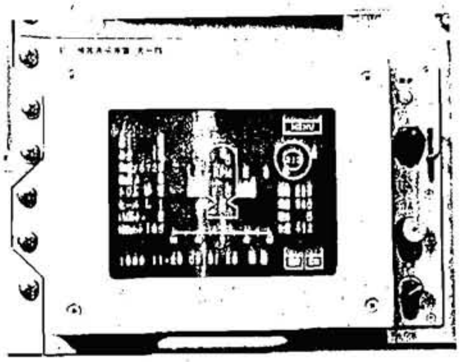
Fig.5. The Integrated Display of Navigation Data

Seq. No.	Item to be Jettisoned	Buoyancy Obtained	Trim by Stern	Remark
1	Ballast Weight for decending	458kgf	0°	Neutral buoyancy
2	Ballast Weight for ascending	608	appr. 1°	
3	Sample basket or Payload rack	167 (includes 120kgf Payload)	appr. 11°	
4	Manipulator	72	appr. 18°	
5	Grabber	55	appr. 23°	

Table 1. Sequence of Emergency Jettisonning for "SHINKAI 6500"

to the surface research equipments is one of the very important issues to establish an efficient research system. At the same time, while diving, it is quite demanding for the operator to be able to monitor the operational condition of the major equipments and environment of the submersible. To attain this objective, the submersible equips Integrated Information Display System (IIDS) as an advanced human interface. Every two seconds observation data such as CTDV and the position of the submersible are automatically recorded for the future reference by scientists. And the operator would be continuously acknowleged with operational condition with this alarming-installed system for the safe and efficient operation. An example of the display for navigation mode is illustrated in Fig.5.

5. Safty Features

To prevent an unexpected critical situation, represented by entanglement at the bottom, the submersible is designed and constructed in the following concept and principle.

(1) Based on the systematic reliability analysis procedures such as "FTA", "FMEA" and "Boundary Analysis", the integrated design and construction were carried out since the very early stage of its planning. "FTA" stands for Fault Tree Analysis and "FMEA" for Failure Mode and Effect Analysis. And "Boundary Analysis" procedure is used to be applied in safety evaluation in the fields of nuclear power system.

(2) The important subsystems strictly concern her safety are to install the following adequate redundancies with consideration of fail-safe and back-up concept.

- The submersible has a pair of main batteries parallely lined to the load so as to be operated with either battery in case of trouble of the other. And to supply the power to emergency operation, a minimumly required emergency battery is installed in the pressure hull in case of emergency.
- Powerful life support system which supplies oxygen and absorbs carbon-dioxide is prepared for three men in the hull.
- As for ballasting four sets of steel plate are to be released/jettisoned by tripple procedures and mechanisms, which suggests hydraulically releasing mechanism as normal operation, inflationary-gas-actuated releasing mechanism coping with the hydraulic or mechanical troubles and electro-magnetic release in valves when electric power would be failed.
- Two sets of the same UQC underwater telephone systems are installed in double.

(3) The selected heavy fittings like manipulators, sample basket/payload instrumentations and also ballasting weight system could be jettisoned with possible electricity sources. The sequence and the weight of this emergency jettisoning are summarized in *Table 1* as self-contained escape measures.

(4) If the submersible would not be able to ascend despite of all efforts such as releasing heavy components mentioned above, the submersible should release the rescue buoy from the depth for the final rescue by entanglement and lift by remotely operated vehicle or so. The final rescue buoy is illustrated in Fig.6.

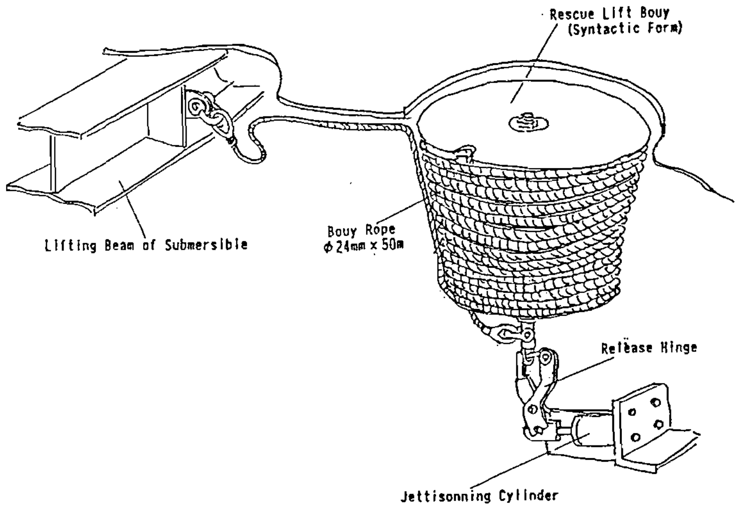

Fig.6. Rescue Buoy System

6. Conclusion

JAMSTEC has completed "SHINKAI 6500" system, consisting of a fully developed submersible and its support vessel, and also completed the preparation to make research dives from coming 1991.

It is, however, still an important issue for us to achieve more effective and beneficial exploration of prosperous deep oceans, taking advantage of these excellent technologies and systems. Now the fruitful accomplishment of studies and researches in the field of biology, geology, geophsics, marine mineral resouces are highly expected.