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THE PRESENT STATE OF MANUFACTURING LIGHT WATER REACTOR PRESSURE VESSELS IN JAPAN

(PART 1. HEAVY SECTION RPV STEELS)

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The Present State of Manufacturing LWR Pressure Vessels in Japan

Part I, Heavy Section RPV Steels

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The present status of manufacturing the heavy-section steels for LWR pressure vessels in Japan is descrived, including the technology and steel properties. They satisfy the requirements for nuclear reactor pressure vessels. The report is prepared for presentation at the IAEA meeting to be held at Vienna in October 1974.

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日本における軽水炉圧力容器製造の現状
第１部　圧力容器用超厚鋼材

日本原子力研究所
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（１９７４年７月２３日受理）

日本における原子炉圧力容器鋼材は，原子炉の要求する品質を有している。本論文で，鋼材の製造および性能についてまとめたものであって，１９７４年１０月，IAEAのワーキング・グループ会議に提出する。

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The Present State of Manufacturing Light Water Reactor Pressure Vessels in Japan

Part 1. Heavy Section RPV Steels

Contents

1. INTRODUCTION

In Japan, construction of a nuclear power station was first started in 1961. Subsequently, with increase of the demands for electric power, one after another nuclear reactor plant has been built at rapid rate. As of April 1974, six nuclear power plants are in operation, with aggregate capacity of about 2,200 MWe, and those under construction are a total of 17, with about 13,600 MWe. In this way, it is expected that in 1985, the power generation by nuclear energy will reach about 25% of the total power generation in the country.

The power reactors in operation or under construction in Japan are nearly all either BWR or PWR. And from economic consideration, their capacities of the reactor are tending to increase. This leads to the increase in thickness of the steel plates used, and also in length and width, in order to reduce the welding joint lengths and further to simplify the manufacturing process. The size limit of thick steel plates manufactured in Japan is shown in Fig. 1.

For reactor pressure vessels in Japan, ASTM A533 Gr B Cl.1 steel plate is mainly used. However, with increase of the size of RPV accompanied by that in plate thickness, the steel plate of higher strength, A542 Cl.1 steel, is also being made in trial. For flanges, nozzles, etc., forging steels A508 Cl.1 and Cl.2, are employed. The production trends of RPV steels in Japan up to the present are shown in Fig. 2.

2. STEEL MAKING TECHNOLOGY

2.1 The course in improvement of steels

The steel making technology in Japan has been at high level sufficient to meet the needs of conventional pressure vessels in industries. As to the steels for RPV, however, the demands for such had been little up to 1960. So, the experiences in their manufacturing and the development efforts in this field are mostly those after 1960.

In building of Japan Power Demonstration Reactor (JPDR, with electric output of 12.5 MW, construction started in 1961, the first nuclear power plant in Japan, Mn-Mo steel (ASTM A302B) with much experience for boiler-use, having superior mechanical properties, to which Ni was added for ductility improvement, was employed. The steel plates thus used for JPDR PV were of maximum thickness about 85 mm. The impact values concerning ductility of the steels as normalized and tempered, followed by post-weld heat treatment, satisfied the requirements in those days; but they were not so enough, as viewed from the current specifications.

To cope with the problem of manufacturing thick steel plates exceeding 100 mm, the efforts were concentrated on increasing the strength and decreasing the thickness of steel plate. And further, since the notch ductility obtained by normalizing and tempering was not sufficient, the quenching and tempering process with good ductility was carried out. This type of steel is now specified as ASTM A533 steel.

Studies were furthermore made on the homogeneity of heavy section steel plate, and in 1963, 250 mm thick Mn-Mo-Ni steel with homogeneous structure was thus produced by means of electric furnace melting followed by vacuum degassing treatment. This steel was confirmed to well satisfy the various requirements for RPV use.

With this progress in the field, in the Tsuruga Nuclear Power Plant (BWR with output of 357 MWe), whose construction was started in 1966, was used improved A302B Ni-modified steel of thickness 78 - 187 mm with tensile strength 56 - 70 Kg/mm^2, as quenched and tempered.

Along with the development in RPV steel plates, research was made on the forged heavy section steel ring in its trial making. The improved A336 F1 steel of thickness 240 - 270 mm, produced by forging of an electric furnace ingot, vacuum treated, was thus found to be sufficiently homogeneous to even the center of thickness, with superior properties for RPV use. In the Tsuruga Power Reactor above mentioned, head flanges (about 28 tons/in unit weight flange), shell flanges (about 19 tons in unit flange) and various nozzles, made of improved A336 F1 steel, are used. Subsequently, the improved A336 F1 was replaced by ASTM A508 Cl.2; which now constitutes the main current of large forgings in RPVs. With these steels, varieties of flanges, forged shells and main nozzles for light water reactors, with maximum unit weight of about 100 tons, are now supplied. And further, those of 150 - 200 tons in unit weight are going to try in the stage before manufacturing.

2.2 Steel making

In steel making for RPV, the basic electric furnace is mainly used, and also in part the basic oxygen furnace. What must be considered first of all in this process is to choose strictly the raw material to minimize the contents of impurities. Among the impurity elements, as is well known, if the P and Cu contents are high, the neutron irradiation embrittlement becomes considerable. Then, P, Sb, As, Sn and Co are known to affect adversely the temper embrittlement S is deleterious in the respects of low temperature ductility, and weldablility. So this impurity element must be kept in content as low as possible.

For charging of scrap into the electric furnace or the basic oxygen furnace, therfore, its contents of the impurity elements above mentioned must be well known beforehand, so that it is made efforts in order to minimized the inclusion of impurities. The S content can be kept very low (0.05 - 0.08%) by using the deslfurized pig iron in the basic oxygen furnace. The P content can also be held sufficiently low (below 0.010%) by means of the double slag method in the basic oxygen furnace, as in the case of an electric furnace. As thus seen, there is no much difference between electric furnace steel and basic oxygen furnace steel, if the respective raw materials are properly chosen. The gas contents in steel vary considerably with the degassing method used, as described in detail later. Table 1 shows the chemical compositions of A 533 B steel produced by electric furnace tap degassing, electric furnace ladle refining and basic oxygen furnace RH degassing.

2.3 Degassing

The hydrogen in steels causes hydrogen embrittlement and also lowers characteristics of the material, though dependent on its content and distribution. If the micro-cavities in large steel ingot are subjected to hot working and then heat treatment, there may occur appreciable cracks at the tip of the cavities. Oxygen then tends to exist in the steel as deoxidation products or other oxide inclusions. It then causes the sand marks in steel, and deteriorates and the workability and weldability of steel, workability and weldability of steel, and also in mechanical properties.

From the requirements as the specification and also the manufacturer's own discretion for obtaining higher quality, in steel making for RPV, the molten steel, in all cases, is subjected to vacuum degassing process. These methods are as follows:

a) Stream vacuum degassing during pouring into the mold from a ladle,

b) Same as above, but during pouring into the ladle in tapping.

c) The double degassing; i.e. the combined two above,

d) Ladle vacuum degassing (such as the R.H., D-H or ASEA-SKF technique),

One of the four above is to be employed depending on the melting conditions, the size of steel ingot and so on. The tap degassing generally used in Japan is illustrated in Fig. 3.

The vacuum degassing process is mainly aimed at reducing the hydrogen content. For example, in basic electric furnace steel making, the hydrogen content in tapping is generally in 3 - 4 ppm, which is then lowered to 1 - 2 ppm by vacuum treatment; and it is further reduced to below about 1 ppm in heat treatment of the steel ingot or plate. The vacuum degassing in steel making also makes for lowering the oxygen content. The content in steel can thus be lowered to below 40 ppm, thereby improving the steel in cleanliness and facilitating the adjustment in such grain refining elements as Al. Figure 4 shows the distribution of hydrogen and oxygen contents in A 533 B molten steel.

2.4 Ingot making

Molten steel, after degassing, is cast into molds of 60 - 50 tons capacity. For steel plate, the mold is a big-end-up slab one, with pouring generally from the bottom. For forging steel, it is the big-end-up round mold, with pouring from the top. Great care is taken in both cases to minimize inclusions in the steel. Substantial inclusions present in steel result in deterious defects, so in RPV steels especially, particular caution is necessary in this respect. The consideration, therefore, must be given to the prevention from slag including in molten steel, from oxidizing the molten steel during pouring, and mixing of refratory material due to its failure, and also to desired floating of the deoxidized product.

2.5 Hot working

The hot working on RPV steels is either forging or rolling. For steel plate, the slab forged is then rolled to a form. For forgings, a steel ingot is directly forged. Capacities of the forging press and the heavy plate will in three RPV steel makers in Japan are shown in Table 2. For the former, the largest one is a 10,000 ton press, and for the latter, it is the equivalent of a product with width 4,800 mm.

2.5.1 Forging

(1) Forging of steel slab

In RPV steel plate making, the rolling process alone cannot eliminate the primary solidified structure such as dendrite or columnar crystal occurring in a large steel ingot or the micro-cavities existent in the interior of steel ingot. So, either of the two procedures is used: first, the forging of a round steel ingot into the slab; and second, the forging of a large slab ingot, followed by rolling into the final plate. Figure 5 shows a 8,000 ton press used for slab forging.

(2) Forgings

For RPVs, the followings are produced only by forging: flange, head flange, shell flange, bottom ring, shell nozzle, etc. For this, the large presses of 3,000 - 10,000 tons are generally used. For small pieces such as nozzles or bolt and nut, however, middle type of presses of 1,000 - 3,000 tons are also used.

2.5.2 Rolling

The forged slab as hot material is transfered to the rolling mill, where it is reheated in a batch furnace.

The slab is finished to the specified thickness by rolling. The rolling are performed with a four high reversible mill. The preliminary forging into the slab from a large steel ingot is general practice nowadays. This process contributes to refining of the loose structure in the cast ingot, and also partially to its homogenization.

2.5.3 Heat treatment

After forging or rolling, dehydrogenation process is carried out to the steel, either in a pit type furnace or a car type batch heat treatment furnace. Figure 6 shows the latter heat treatment furnace carrying out the process for steel plate after rolling. The example of heat treatment after rolling of A533 B steel plate is indicated in Fig. 7. In steel plate immediately after rolling, the rolled structure is not uniform and moreover hydrogen is localized in the nonmetallic inclusions or the non-uniform part of structure. Therefore, after austenitization for a short time by heating to a temperature T_1 in this temperature region, the dehydrogenation is carried out in the temperature range of ferrite where the diffusion rate of hydrogen is larger than in the austenite.

(1) Theories of dehydrogenation

In the dehydrogenation process for steel slab or plate, the temperature and the time of treatment are chosen by theoretical calculation on the hydrogen diffusion. Here, the volume diffusion of hydrogen in dehydrogenation process is merely through the volume of steel. And the variation in hydrogen concentration through plate thickness is obtained.

From Fick's second law,

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial t^2} \qquad (1)$$

With the initial and the boundary conditions, the equation (1) takes the following form,

$$\frac{C}{C_o} = \frac{4}{\pi} \sum^{\infty} \frac{(-1)^n}{(2n+1)} \exp\left\{ \frac{-D(2n+1)^2 \pi^2 t}{4\ell^2} \right\} \mathrm{Cos}\ \frac{2n+1}{2\ell}\ \pi x \qquad (2)$$

Where, C : hydrogen concentration at a distance x from the center of plate thickness after a time t,

Co: the initial hydrogen concentration,

: half the thickness of steel plate,

D : diffusion coefficient of hydrogen (1.4×10^{-3} exp(-3200/RT)cm^2/sec).

Figure 8 shows the variation of hydrogen concentration in C/Co from center of plate thickness to surface calculated from eq.(2) for steel plates of thickness 240 mm respectively in dehydrogenation at 650°C. Figure 9 then shows the variation in hydrogen concentration in the cases just mentioned and those measured in condition of dehydrogenation with initial hydrogen concentration 1.4 ppm at 550°C and plate with 0.71 ppm at 600°C for 150 mm steel. In Fig. 10 are compared between calculation and measurement in dehydrogenation for 240 mm thick steel plate with initial concentration 1.29 ppm at 650°C. As seen in the Figs. 9 and 10, agreement is relatively good between the calculated and the measured values. Hydrogen concentration along the plate thickness, after dehydrogenation treatment, can be estimated by means of the calculation described.

In Fig. 11 the occurrence of hydrogen defects revealed by the ultrasonic test is plotted versus the plate thickness and also the hydrogen content. It is seen that the hydrogen content needs to decrease with increase of the plate thickness. In consideration of this fact, the hydrogen content in molten steel must be controlled, and the dehydrogenation for both steel slab and plate are carried out accordingly.

(2) Effect of dehydrogenation on ductility

As described, the dehydrogenation is carried out after rolling of steel plate. What must be noted, however, is the effect of dehydrogenation on the ductility. Figure 12 indicates such effect. By the dehydrogenation process, the size of AlN is occasionally increased markedly. And in the subsequent normalizing and quenching, the grown AlN inhabits the growth of austenite grains, and seen in the figure, the ductility is considerably decreased by the growth of austenite grains. In applying the dehydrogenation process, therefore, adequate caution must be taken in the respect of its adverse effects.

2.6 Inspection

In manufacturing the RPV steel plates etc., stringent inspection is carried out in each stage. For the surface defects, internal structure and homogeneity, nondestructive testings are utilized. These are ultrasonic test, magnetic particle test and liquid penetration test; of which, the ultrasonic test is used the most commonly. For heavy section steel plate, the ultrasonic testing method with a normal pulse reflection type apparatus is employed. The surface of plate must be smooth so as not to hamper the determination in ultrasonic test. Scale etc. attaching on the surface of rolled or forged plate are thus removed by grinding. As the contact medium, machine oil is generally used, but when the surface is rough particularly, water glass is occasionally is applied. The frequencies used are 2.25 - 3.00 MHz. For adjusting the sensitivity in defect detection, a standard specimen is utilized. In the final determination, the areal broading of defect wave, the attenuation of bottom reflected wave and so on, must be taken into consideration. Figure 13 shows the internal defects due to micro-void revealed by ultrasonic test in the top portion of a steel ingot.

The nondestructive testing methods for RPV steel plate etc. are applied essentially over the whole surface and the whole volume. Therefore, a forged flange, nozzle, etc. must be simple in shape, to enable 100% volume test before the heat treatment. And further, workable shape must have for the subsequent followed quenching. Large nonmetallic inclusions as detected by ultrasonic test in the top portion are shown in Fig. 14. These two cases of defect are existent localized, but the defects by hydrogen are observed on a relatively wide area of the steel plate. While the ultrasonic test is aimed at detecting defects at the depths of steel plate, magnetic particle test and liquid penetration test are for the defects appearing on the surface. For the former, the plod technique is usually used by continuous magnetization with direct current, using fluorescent particles. The magnetizing current between the plods at interval 200 mm is 800 - 1,000 amp. In this detection method, the caution must be taken to so-called false defects. Figure 15 shows the magnetic flux pattern as microstructure. It is the banded structure due to primary segregation in a low alloy steel ingot during the solidification. In fact, the structure is none deleterious in RPV use.

2.7 Heat treatment of separate test coupon

Among the items of testing required of RPV steel plate are the following: check analysis, sulfur print, measurement of austenite grain size, tensile test, charpy impact test, drop weight test, and bending test. In RPV steel manufacturers, although the hot working and the heat treatment, including quenching, temperating and post-weld heat treatment, are carried out, in order to insure the mechanical properties at the time of delivery, the tests above mentioned are performed with test coupons subjected to the same heat cycles. For the purpose, two different types of procedure are available; i.e. the 3t-test, and the programed heat treatment test. In the former method, a test specimen, whose thickness is the same as or larger than the actual plate manufactured, that is, 6 x 3t (t is the steel plate thickness), is heated and then quenched in the quenching bath. In the latter method, the programmed heat treatment is performed with test coupons, which is capable of providing one or more specimens for the tensile, impact and drop weight tests, respectively. In the programmed heat treatment test, as specified in the ASME code, section III, the heat treatment must be carried out with the temperature and time precisions within 25°F and 20 sec, respectively, concerning the master curves used in actual heat treatment in the factory. Figure 16 depicts the scene of quenching a 3t test specimen in the quenching water bath with a stirrer.

In the 3t-test, not only the testing apparatus is large in size, but the test specimens themselves are substantial; this results in lowering of the manufacturing yield. Therefore, in recent years, the programmed heat treatment test with small specimens is used more commonly。 Such apparatus for the programmed test is shown in Fig. 17. In Fig. 18 are then compared the cooling curves between programmed heat treatment and 3t test coupons. Agreement is seen to be sufficiently good, the programmed heat treatment meeting the requirements of ASME Code.

2.8 Quality assurance system

In manufacturing RPV steel plate etc., which must meet the requirements to insure the integrity and reliability on the reactor pressure vessel use, a thorough quality assurance system, based on the ASME Code, Section III, is carried out in the manufacture. The fundamental of the system is that the needs of a customer should be fully grasped, which are then reflected in the products. In the system are involved the following:

(1) The organization, with responsibilities and authorities well defined,

(2) Documents control, including specification, manual etc.

(3) Operation control, including the facilities and instruments,

(4) Management of the inspecting personnel.

The flow chart in this connection is given in Fig. 19. Manufacturing, inspection and testing are thus carried out with swift activity in each stage, prevention of unacceptable products and measures to improve the quality.

3. STEEL PROPERTIES

3.1 Fundamental properties

3.1.1 Adjustment in chemical composition

In RPV steel plate etc., proper balance has to be maintained between strength and ductility. The impurity elements, and also main alloying elements, are adjusted in their contents within much narrower a range than general specification, according to the thickness of steel plate and the heat treatment applied respectively. As seen in Table 3, A533 Gr B, and A508 Cl.1, steel which are currently used as RPV steels. A508 steel is slightly inferior in workability for heat treatment. In their heat treated structure of plate thickness over 100 mm, the variation is considerable with lower bainitic microstructure to upper bainitic one with pro-eutectoid ferrite from surface to the middle of steel plate. In such heavy section bainitic steel plate, the efforts are made to refine the structure by addition of a proper amount of Al and also to improve the ductility value and the weldability of steel plate. Adjustments in Mn, Cr and Mo contents are then made within the ranges not to impair the workability for heat treatment appreciably, including strength and toughness characteristics. C contributes to increasing the strength as shown in Fig. 20, but on the otherhand, affects adversely the ductility in base metal after post-weld heat treatment and, further, increases the difficulty in welding. To cope with this problem, the attempt is made by lowering the C content while the Mn content is increased. Mn is considered recently to be effective in preventing the reheat cracking at welds in low-alloy steel. Therefore, the employment of A508

Cl.3 steel for RPV use forgings is being considered with similar chemical composition to that of A533 Gr B Cl.1 steel at present.

3.1.2 Effect of heat treatment

In the past, RPV steels have been mostly used as normalized and tempered. With increase in thickness of the steel plate in recent years, however, the mere air cooling in normalizing cannot give specified mechanical properties since the colling rate in this case is too low. Therefore, recently, to meet the needs for higher strength and ductility in heavy section steel plate, the forced cooling with steel having excelent characteristics is being used.

The relation between cooling rate and plate thickness for the different methods of cooling from the austenitizing temperature is shown in Fig. 21. In low-alloy heavy section steel plate, the alloying elements extend its bainite transformation range and shift the nucleation line of pro-eutectoid ferrite to longer hours. The effects of cooling rate from the austenitizing temperature on the mechanical properties of low-alloy steel are indicated in Figs. 22, 23, 24 and 25. The austenitizing temperature differs with the kind of steel; it is 860°C - 930°C for A533 B Cl.1, A508 Cl.2 and Cl.3, and 900°C - 950°C for A542 Cl.1 steels. In heavy section steel plates, the swift handling of the materials from their tapping to water dipping is one of the essentials in working control of heat treatment.

In heavy section RPV steel plates etc, there occurs the problem of change in the irreversible properties in the prolonged post-weld heat treatment and also the problem of tempering embrittlement. It is reported in this connection that there is certain correlation between the impurity elements and the alloying elements such as Mn, Ni, Cr, and Mo to hold the specified mechanical properties. In A533 B and A508 Cl.2 steels manufactured for light water reactors in Japan, however, the tempering embrittlement is hardly observed.

3.1.3 Mechanical properties

Differing from the case of conventional pressure vessel steels, the steels for RPV, due to neutron irradiation, are encountered with the problem of shift in the brittle-ductile transition temperature and decreasing in the upper-shelf energy. For the steels, therefore, sufficiently high ductility are required to withstand the unstable fracture during RPV hydraulic test, to insure RPV integrity to the irradiation embrittlement during reactor operation.

From the safety point of view concerning the unstable fracture, the technological standard of Ministry of International Trade and Industry (MITI) on RPV steels, and also ASME Code, Section III, specifies that the RPV should be used at a temperature over NDT + 33°C (60°F) and the reactor containment vessel at a temperature over NDT + 17°C (30°F) on the base of Pelinni's conception. In ASME Code, Section III, the ductility requirement for RPV steels was further revised in its 1972 Summer Addenda, considering the safety design in fracture. It is that in the V-charpy test performed at NDT + 60°F, the absorbed energy and the lateral expansion should be over 50 ff-lb and 35 mils, respectively. If, then, this is not satisfied, NDT should be that temperature which is obtained by subracting 60°F from the minimum temperature for 50 ff-lb and 35 mils in V-charpy test. V-charpy characteristics and NDT of heavy section A 533 Gr B steel for Japan-made nuclear reactors satisfy sufficiently the requirements described, as shown in Fig. 26. In A 508 Cl.2 forging steel also, the transitions of 50 ff-lb and 35 mils are in the ratio of nerly 1 : 1, as shown in Fig. 27.

3.2 Homogeneity

With increase in size of a steel ingot, there tends to occur the internal defect, caused mainly by the differences in solidifying rate. For heavy section steel plates, therefore, due consideration must be taken in this respect, i.e. the problem of homogeneity.

3.2.1 Ingot internal defect

In Japan, presently, as heavy section steel plates, the slab ingots and polygnal steel ingots are 120 and 220 tons in maximum unit weight, respectively, while the polygnal steel forgings reach about 500 tons. In the meanwhile, highly homogeneous quality steel plates are required for RPV use. Therefore, great cautions are taken in their manufacturing technology.

An important problem in the process of the large steel ingots making is the micro segregation (V-segregation and inverse V-segregation), sand marks, micro-cavity and the heterogeneity due to segregation in the chemical composition. As well known, the segregations occur unavoidably in the interior of a large steel ingot. The typical segregation pattern in this case is depicted in Fig. 28. In the V-and inverse V-segregations, there occur macroscopic defects due to large amount of micro-cavities. The micro-cavities localized in the inverse V-segregation in the top portion of a low-alloy slab ingot of about 60 tons, which was vacuum treated, are far larger in volume than the sound portion in their vicinity, even about ten times as large. These defects of micro-cavity in large steel ingots are successfully eliminated by means of the hot working such as to give proper plastic working reaching to the plate center.

The improvement of internal structure in the hot working is shown in Fig. 29. The elimination of macro segregations in the state of steel ingot is highly significant, concerning the reduction in defects due to micro-cavity, the mitigation in sulfide inclusions and the improvement in mechanical properties. The distribution of segregations is influenced by factors as the shape of mold, the chemical composition of molten steel, the smelting process, pouring temperature and cooling condition. To reduce the V-segregations, the means currently taken is to use the small diameters ratio to have uniform solidification, and to increase the taper of steel ingots; whereby good results are obtained. Besides, the reduction in P and S contents in smelting process, followed by application of the vacuum degassing, of course contribute to reducing the segregations.

In order to remove the internal defects inherent in a large steel ingot, about 5% of the steel is cut out from the top portion, including the most concentrated V-segregation, during the process of hot working, and further, about 10 - 15%

is done so in the bottom portion, including the negative segregation and sand inclusion. Figure 30 shows such practice for the quality control of heavy section RPV steel. On the strength of improvement in the accuracy of forecast information, the proper cut-out control for top and bottom portions of steel ingots is now possible; in which evaluation of the internal structure is made according to the kind of steel and the conditions of steel making and ingot making, and the requirement of homogeneity is also taken into consideration.

3.2.2 Impurities

The impurity contents in RPV steel must be held as low as possible, for the reasons listed below.

a) The tempering embrittlement in base metal and the embrittlement after post-weld heat treatment are to be minimized,

b) The occurrence of fine cracks at welds of thick steel plate is to be prevented as far as possible,

c) Neutron-irradiation embrittlement is to be held to a minimum.

In this connection, the U.S.AEC's Tentative Regulatory, Suplementary Criteria for ASME Code — Construction, specifies: for the RPV ferritic steel used closed to the reactor core, where the neutron irradiation is over 1×10^{17} n/cm^2 (>1 MeV), the P and S contents as revealed by ladle and check analysis should be $P < 0.012\%$ and $S < 0.015\%$. From the necessity of homogeneity for large steel ingots already described, proper material is chosen to minimize the P and S contents and also the exhaustive quality control in smelting etc. is carried out. In recent years, the effects of P and Cu in irradiation embrittlement are bing appreciated, and also there has arison the problem of reheat cracking in the weld of high tensile steel where tehre exists considerable constraint. The current trend is thus to be more and strict concerning the impurity contents. The chemical composition histograms of A 533 B steel manufactured in Japan are given in Fig. 31; it is seen that the impurity contents are held very low.

In general, the impurity contents in A 533 B and A 508 steels manufactured in Japan, which are used for RPV close to the reactor core, range in the following: $P < 0.012\%$, $S = 0.015 - 0.020\%$, $Cu = 0.10 - 0.15\%$ and $V = 0.01 - 0.05\%$. Excessive addition of the grain refining elements is then considered to affect adversely the notch ductility and cleanliness. Therefore, the current move is to control their amounts properly.

It is well known that P and S act adversely in ductility of low-alloy steels. Figure 32 gives the data in this connection for A 533 Gr B Cl.1 steel. The P, S and Cu contents in A 533 B steel manufactured in Japan are decreasing yearly in average value, as shown in Fig. 33. These values all satisfy those specified in various specifications in the world.

ACKNOWLEDGEMENTS

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Table 1 Chemical Analysis of A533B steel melted by various methods

Chemical composition (%)

Furnace	Degassing	Plate thickness (mm)	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	As	Sn	Sb	Co	T.Al	T.N	T.O	H
Electric	Tap degassing	165	.20	.26	1.40	.007	.006	.04	.63	.10	.52	.007	.014	.002	.018	.020	.0105	.0032	ppm 1.60
Electric	Ladle refining furnace degassing	170	.19	.30	1.35	.013	.007	-	.69	-	.54	-	-	-	-	.032	-	.0020	1.53
Basic oxygen	RH	150	.21	.24	1.46	.010	.006	.02	.63	.029	.53	.004	.010	.001	.001	.025	.0039	.0037	1.72

Table 2 Hot working facilities for reactor pressure vessel steels in Japan

Facilities		Steel manufacturer		
		A	B	C
Press	Capacity	8,000 TON	10,000 TON	6,000 TON
	Type	2 columns, push down	4 columns, push down	4 columns, push down
	Max. ingot (Ton)	400	500	200
Plate mill	Type	4-high, reverse	4-high, reverse	4-high, reverse
	Mill power	Motor DC 4,500kw × 2	Steam engine 30,000 ps	Motor DC 3,750kw × 2
	Max. thickness (mm)	300	350	300
	Max. width (mm)	4,500	4,800	4,500

Table 3 Chemical composition and parameters for hardenability and weldability of nuclear pressure vessel steels

Steel		Chemical composition (%) (1)													
JIS	ASTM		C	Si	Mn	Ni	Cr	Cu	Mo	V	D_1 (2)	Ceq (3)	PcM (4)	△G (5)	P_{SR} (6)
G3120	A302-B	MAX.	.25	.32	1.55	.20	.15	.20	.64	-	6.821	.717	.402	+0.262	-0.37
SQV 1	A533-A	MIN.	.16	.15	1.10	-	-	-	.41	-	1.438	.452	.247	-0.647	-1.18
G3120	A302-C	MAX.	.25	.32	1.55	.73	.15	.20	.64	-	8.048	.730	.410	+0.262	-0.37
SQV 2	A533-B	MIN.	.16	.15	1.10	.37	-	-	.41	-	1.632	.461	.253	-0.647	-1.18
G3120	A302-D	MAX.	.25	.32	1.55	1.03	.15	.25	.64	-	8.741	.737	.415	+0.262	-0.37
SQV 3	A533-C	MIN.	.16	.15	1.10	.67	-	-	.41	-	1.788	.469	.258	-0.647	-1.18
-	A533-D	MAX.	.25	.32	1.55	.43	.15	.20	.64	-	7.355	.722	.405	+0.262	-0.37
		MIN.	.16	.15	1.10	.17	-	-	.41	-	1.527	.456	.250	-0.647	-1.18
G3212	A508	MAX.	.35	.35	.90	.20	.15	.20	.06	.05	1.953	.568	.436	-1.247	-1.03
SFVV1	C .1	MIN.	.16	.15	.40	-	-	-	-	-	0.322	.233	.185	-2.000	-2.00
G3212	A508	MAX.	.27	.35	.90	.90	.45	.20	.70	.05	8.285	.726	.426	+1.165	+0.55
SFVV2	C .2	MIN.	.16	.15	.50	.50	.25	-	.55	-	1.777	.450	.247	+0.065	-0.65
G3212	A508	MAX.	.25	.35	1.50	.80	.15	.20	.60	.05	7.704	.718	.412	+0.535	+0.05
SFVV3	C .3	MIN.	.16	.15	.20	.40	-	-	.45	-	1.860	.489	.262	-0.515	-1.10
-	A508	MAX.	.23	.30	.40	3.90	2.00	.20	.60	.03	-	.959	.478	+2.223	-
	C .4	MIN.	.10	.10	.20	2.75	1.50	-	.40	-	-	.606	.261	+0.820	-
-	A542	MAX.	.15	.32	.63	.20	2.62	.20	1.15	-	-	1.085	.413	+4.415	-
	C .1	MIN.	.10	.13	.27	-	1.88	-	.85	-	-	.739	.268	+2.685	-
-	A543	MAX.	.23	.37	.40	3.32	2.06	.20	.60	.03	-	.959	.474	+2.283	-
	C .1	MIN.	.10	.18	.20	2.53	1.44	-	.45	-	-	.605	.260	+0.925	-

(1) For the elements which are not specified, following values are estimated as the maximum content in the electric furnace steel. Ni;.20 Cr;.15 Cu;.20 MO; 0.6 V;0.0

(2) D ; Hardenability of steels (Ideal diameter)
Grain size used in this calculation : MAX. A.G.S.No.5
MIN. A.G.S.No.8

(3) Ceq; Carbon equivalent for weldability
$Ceq = C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14$ (%)

(4) PcM; Susceptibility for cold cracking of welds
$PcM = Pc - (H/60+t/600)$ (%) t; Section Thickness
$Pc = C+Si/30+Mn/20+Ni/60+Cr/20+Cu/20+Mo/15+V/10+5B+H/60+t/600$ (%)
Calculated Preheating Temperature (°C) = 1440 Pc (%) - 392

(5) △G; Susceptibility for reheat cracking
$\triangle G = Cr+3.3Mo+8.1V-2$ $G \geq 0$ Cracked
$G < 0$ Not cracked

(6) P_{SR}; Susceptibility for stress relief cracking
$P_{SR} = Cr+Cu+2Mo+10V+7Nb+5Ti-2$ $P_{SR} \geq 0$ Cracked
$P_{SR} < 0$ Not cracked

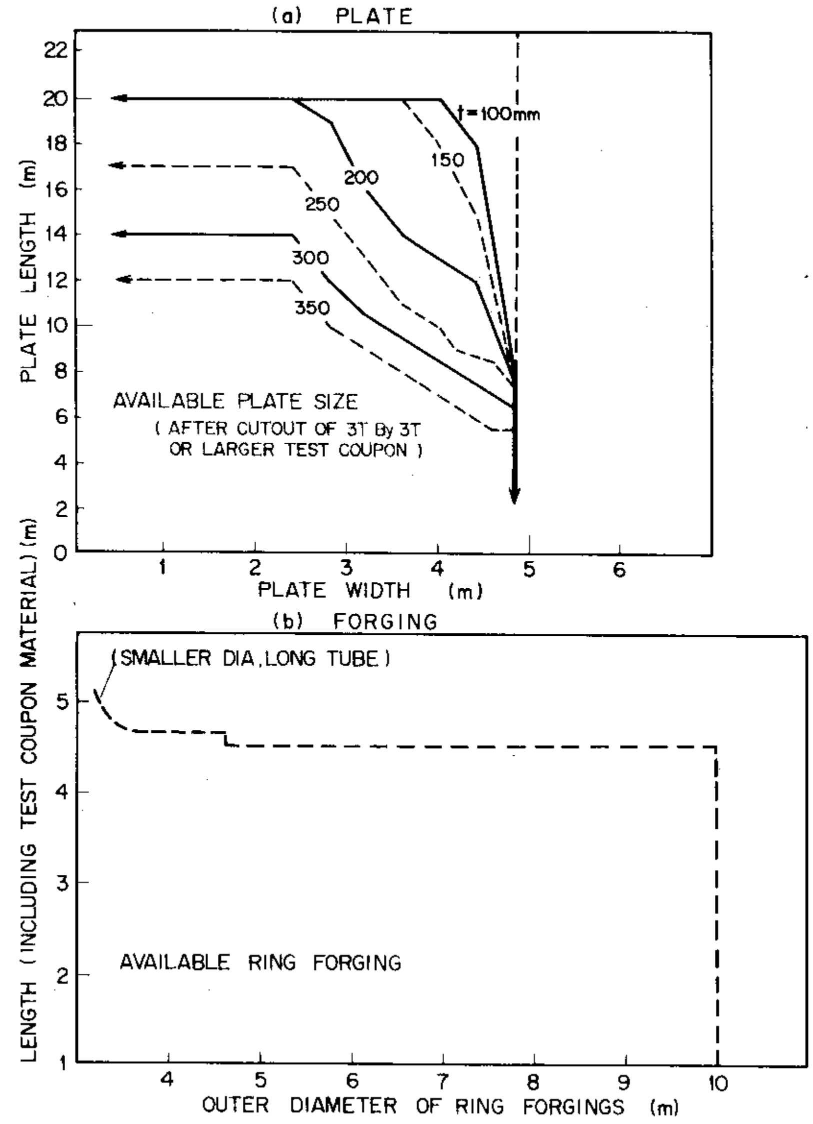


FIG.1 SIZE LIMIT DIAGRAM OF LOW ALLOY HEAVY SECTION PLATES AND RING FORGINGS

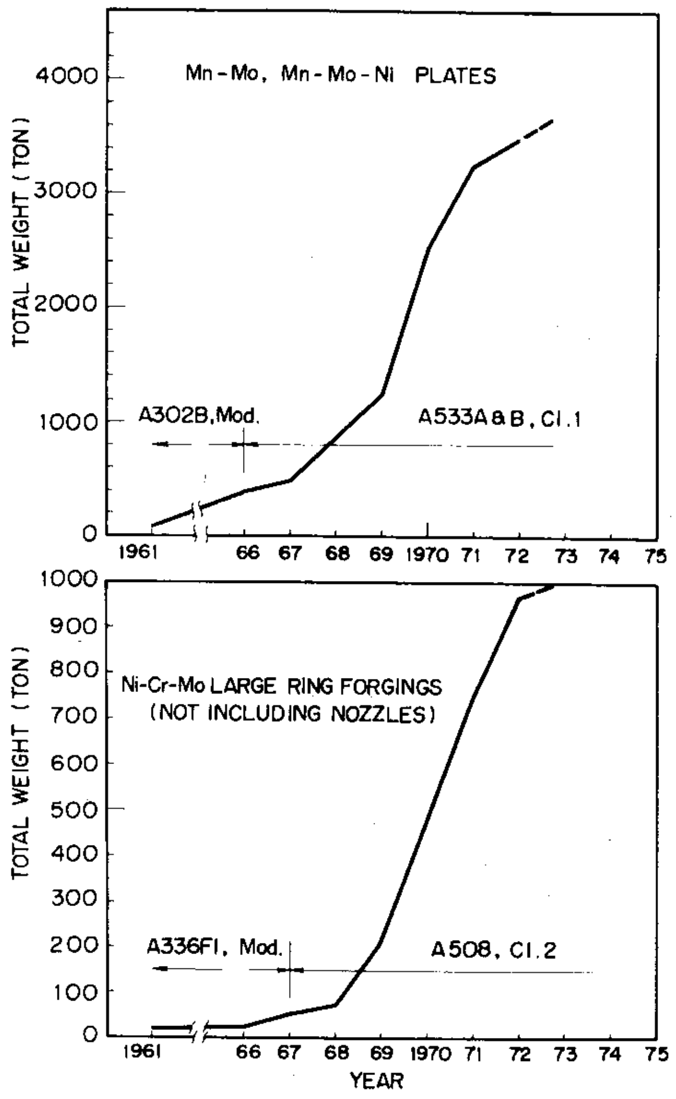


Fig.2 PRODUCTION TRENDS OF HEAVY SECTION STEELS FOR LIGHT WATER REACTOR PRESSURE VESSELS AND COMPONENTS

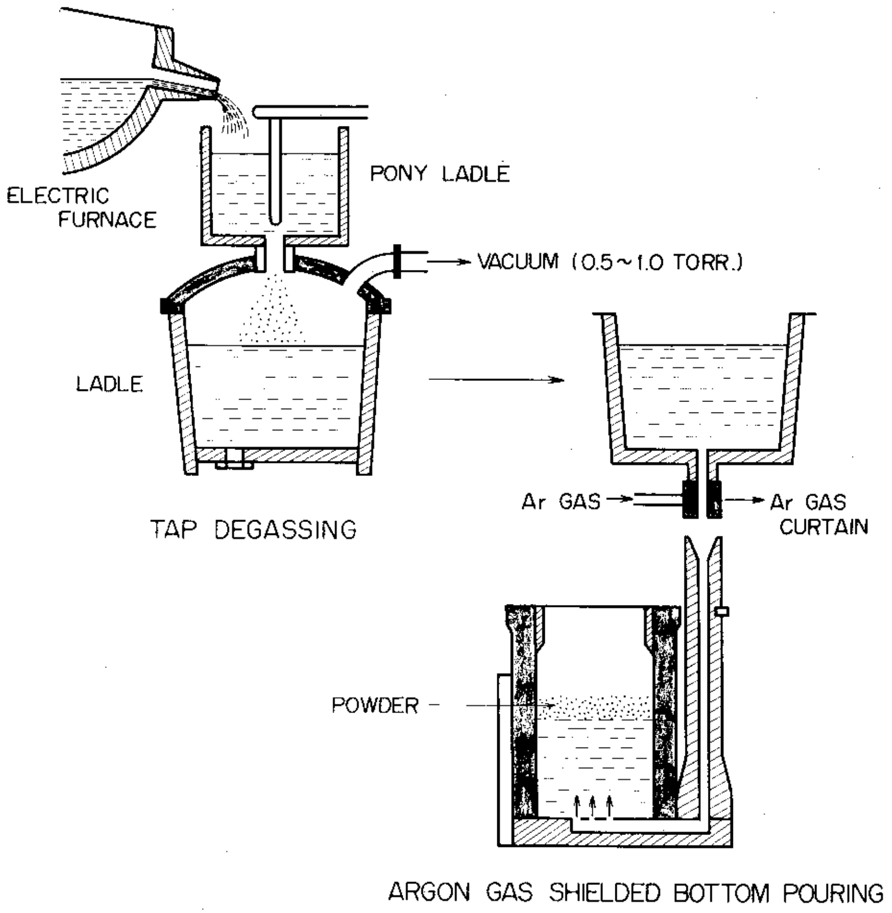


FIG. 3 SCHEMATIC DRAWING OF TAP DEGASSING AND BOTTOM POURING FOR RPV STEEL

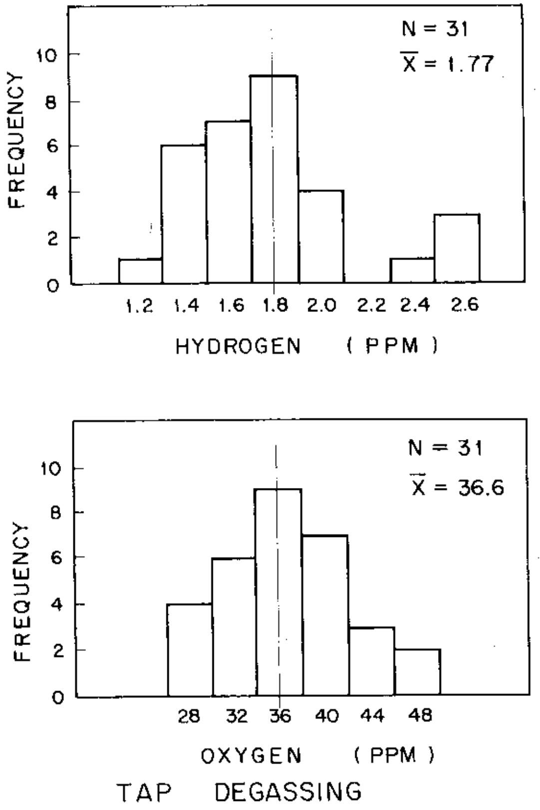


FIG.4 DISTRIBUTION OF GAS IN MOLTEN A533B STEEL

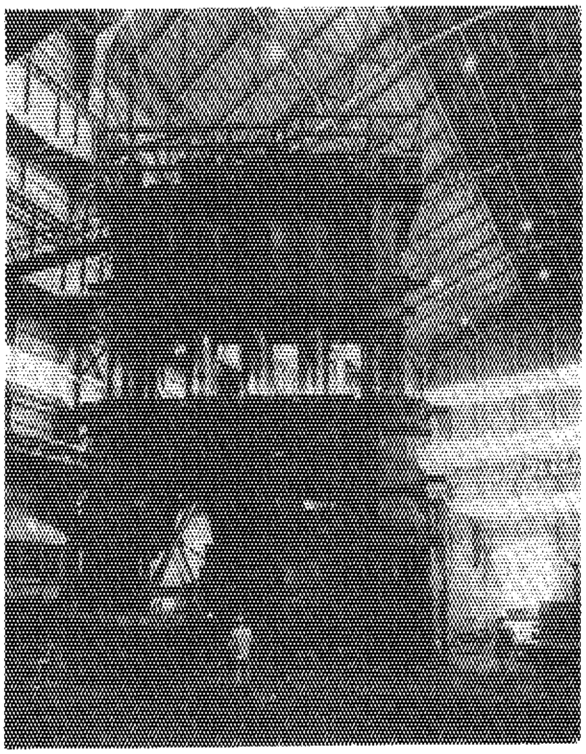


Fig. 5 SLAB FORGING WITH 8000 TON PRESS

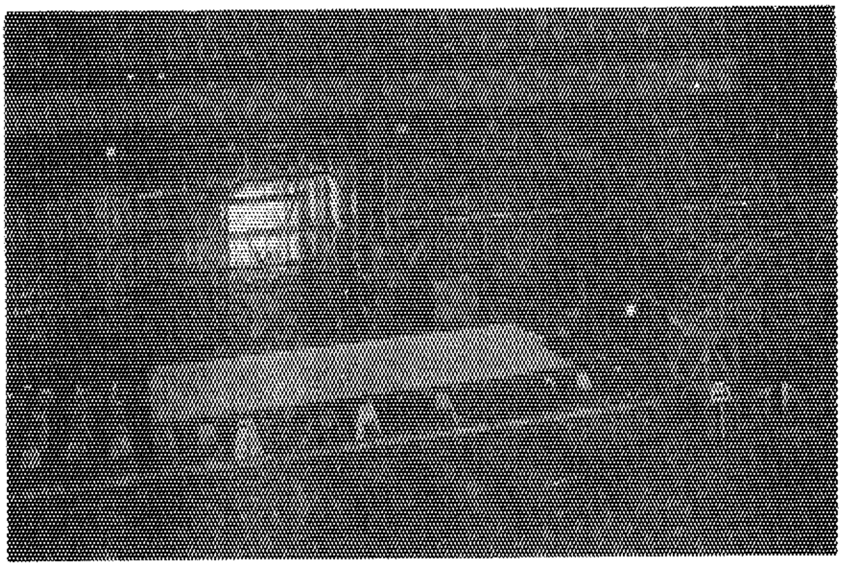


Fig. 6 CAR TYPE BATCH HEAT TREATMENT FURNACE

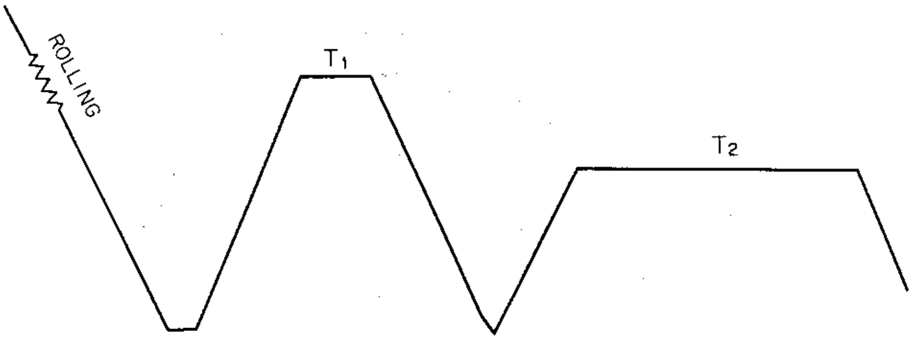


FIG. 7 EXAMPLE OF HEAT TREATMENT OF PLATE AFTER ROLLING

D_H^{α} (650°C) = 2.45 x 10^{-4} cm^2/sec

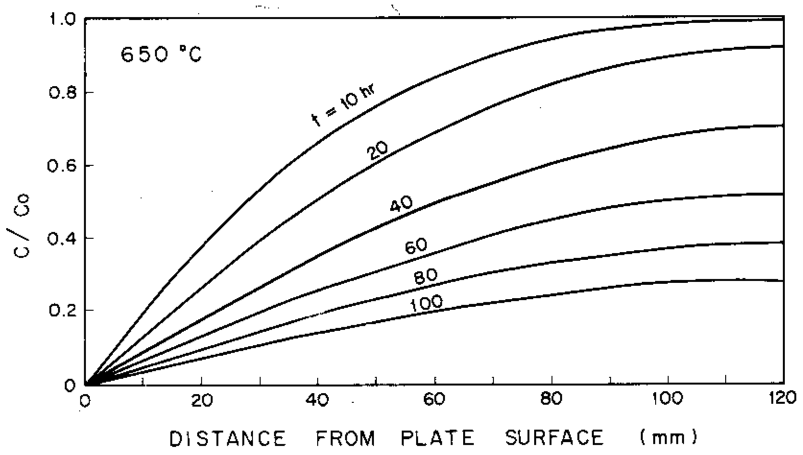


FIG. 8 VARIATION OF HYDROGE CONTENT IN PLATE (240^{MM} THICK) TREATED AT 650°C

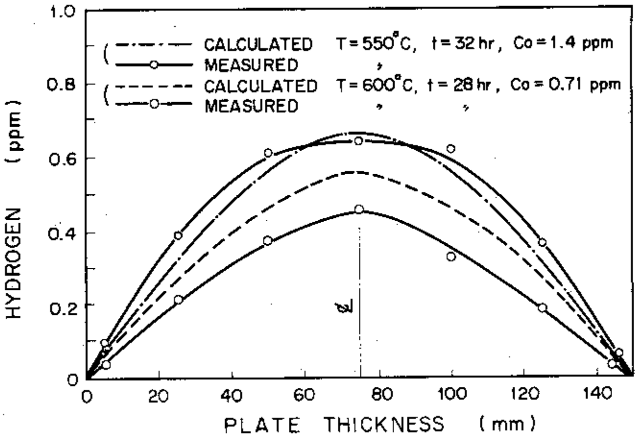


FIG. 9 DISTRIBUTION OF HYDROGEN CONTENT ALONG PLATE THICKNESS (150 mm) AFTER DE-HYDROGEN OF A533B PLATE

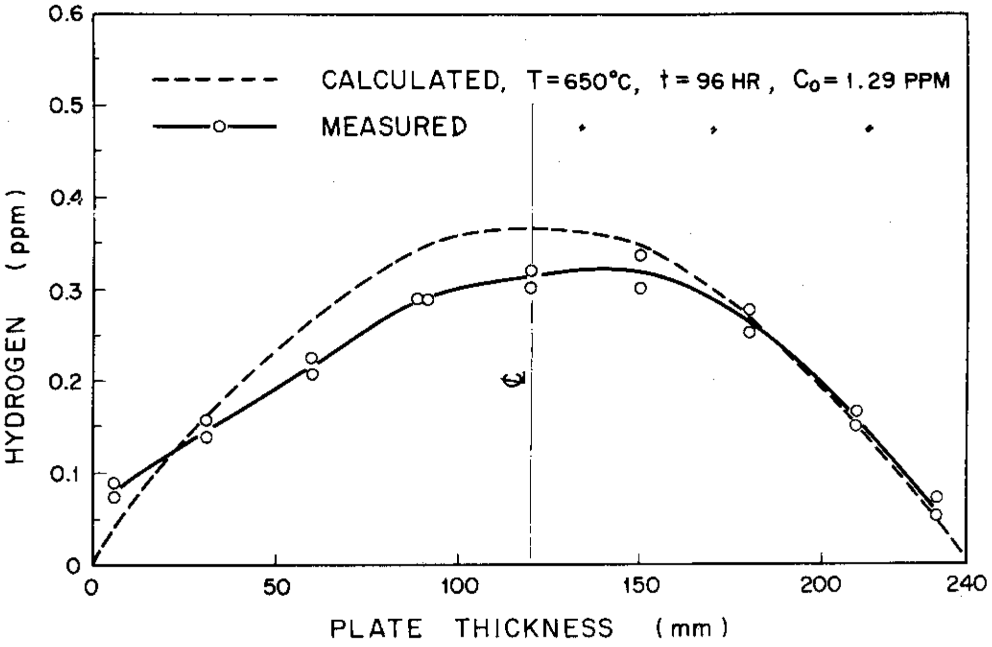


FIG.10 DISTRIBUTION OF HYDROGEN CONTENT ALONG PLATE THICKNESS (240 mm) AFTER DE-HYDROGENATION OF A533B PLATE

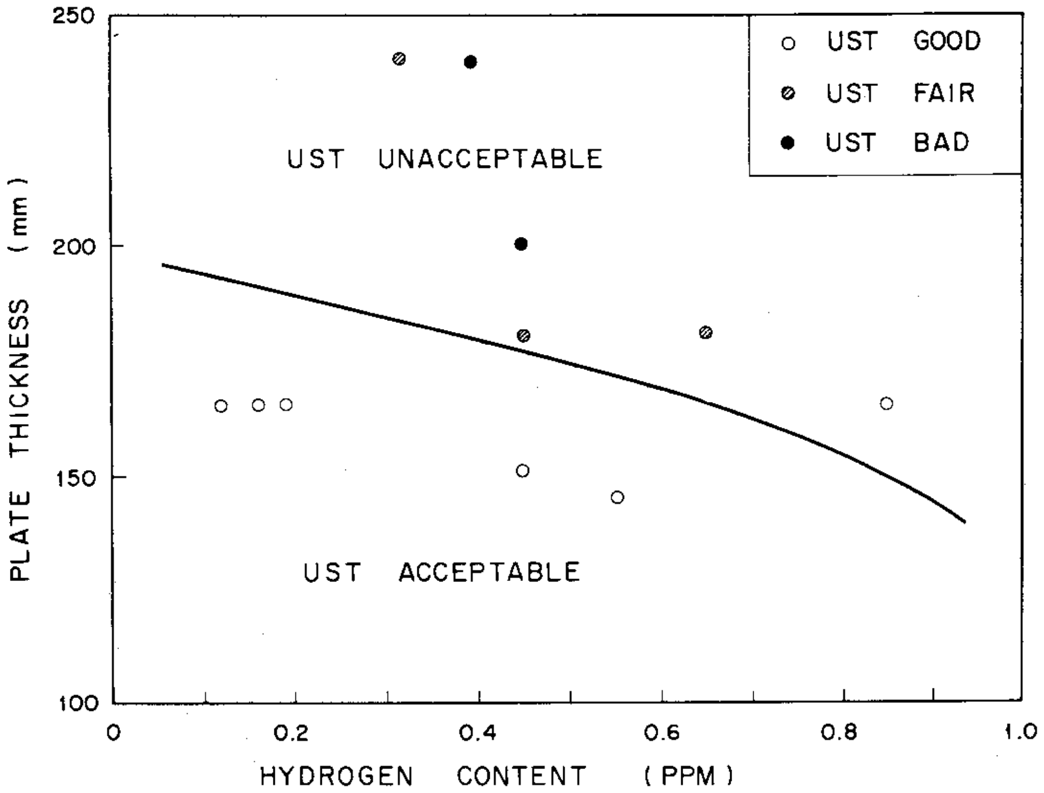


FIG. 11 RELATION BETWEEN HYDROGEN CONTENT AND A533B PLATE THICKNESS FROM POINT OF VIEW OF ULTRA SONIC TEST

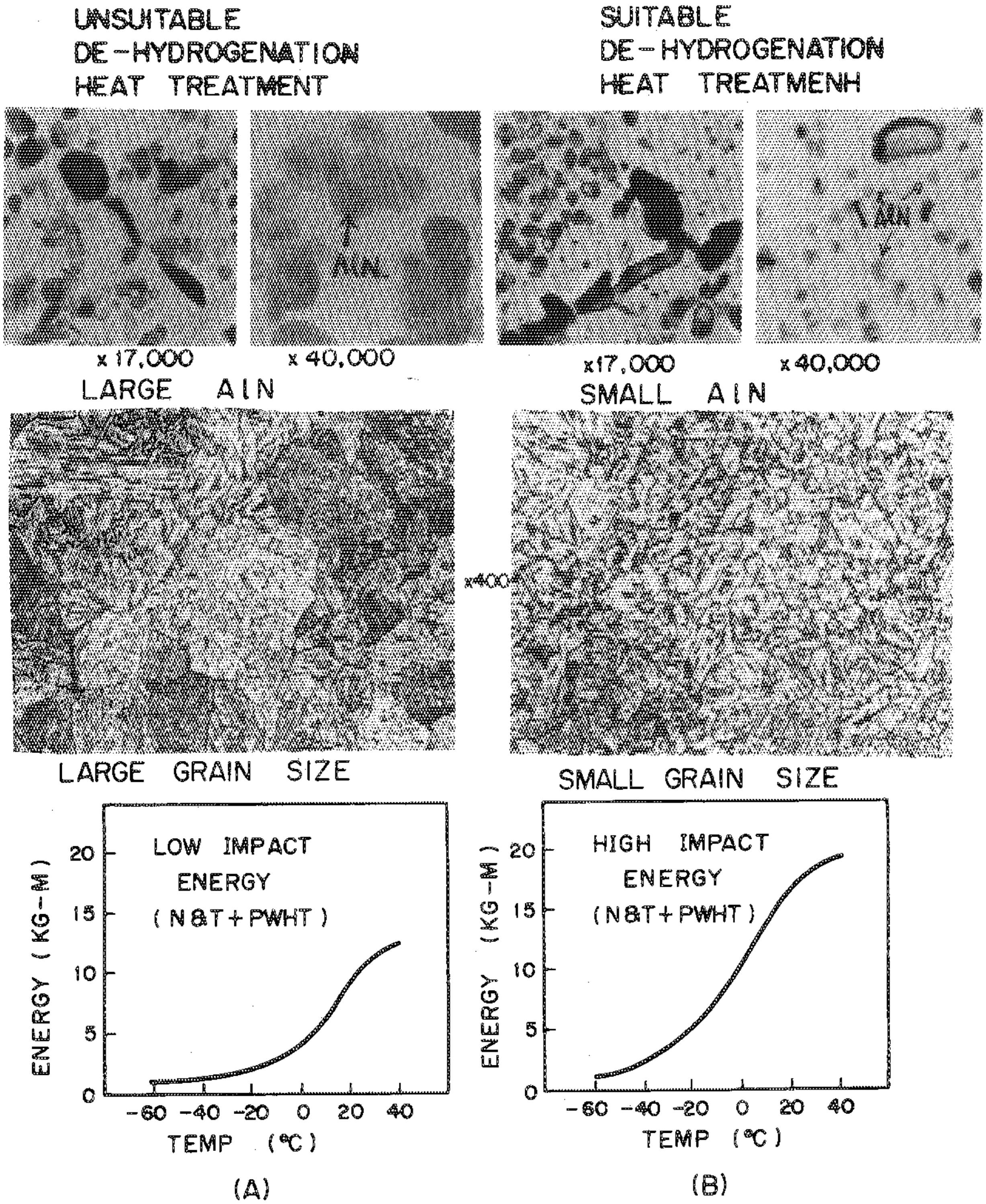


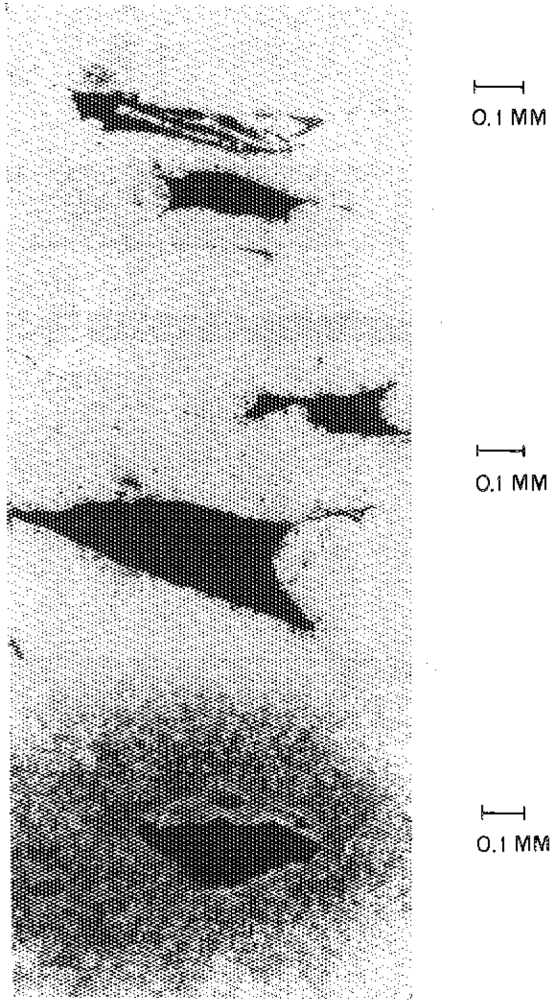
FIG. 12 EFFECT OF DE－HYDROGENATION HEAT TREATMENT ON THE IMPACT TOUGHNESS OF A533B PLATE (165 MM THICK)

2.25 MHz
SENSITIVITY
V15-2.8 = 100%

F_1/B_1 = 25 ~ 50%

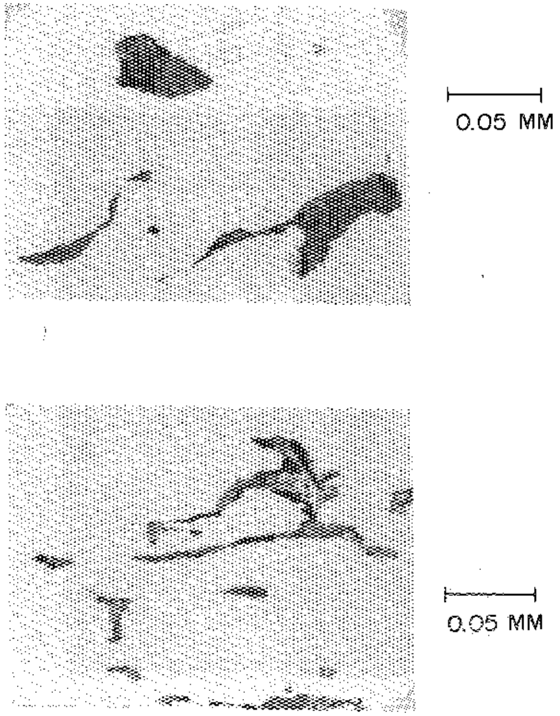
F_1/B_1 = 25 ~ 50%

F_1/B_1 = 0 ~ 25%



A 533 B
STEEL PLATE
(240 MM THICK.
TOP PORTION
OF INGOT)

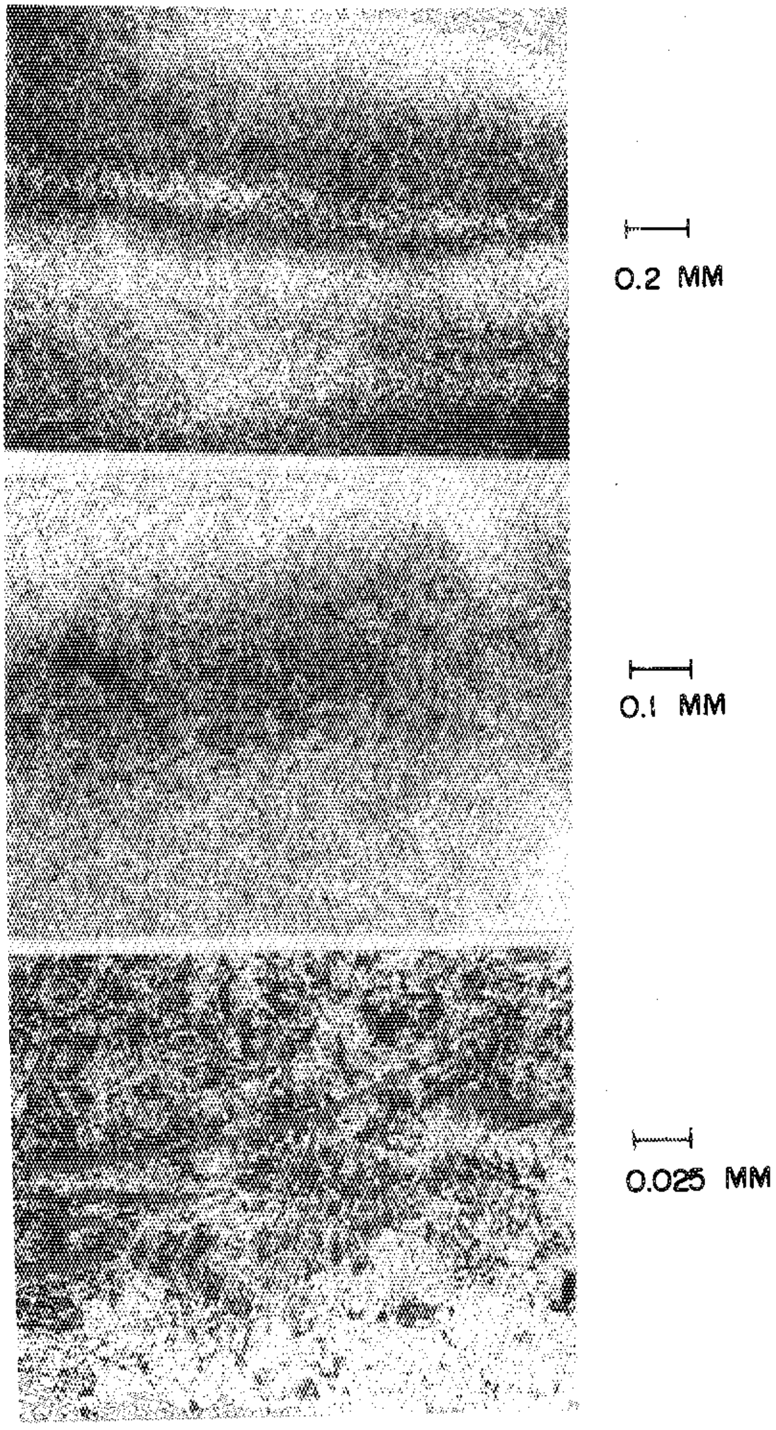
FIG. 13 MICRO-VOID DETECTED BY ULTRA-SONIC TEST



A533 B STEEL PLATE (240 MM THICK.)
(TOP PORTION OF INGOT)

ULTRA SONIC TEST
2.25 MHz SENSITIVITY $V_{15-2.8}$ = 100 %

FIG. 14 NON-METALLIC INCLUSION DETECTED BY ULTRA-SONIC TEST



MAGNETIC
PARTICTE
TEST

PROD. TEST

DIRECT
CURRENT

$$\frac{800\sim1000\ \text{AMP}}{200\ \text{MM}}$$

A533B PLATE (240 MM THICK)

FIG. 15 MICRO-SEGREGATION DETECTED BY MAGNETIC PARTICLE TEST

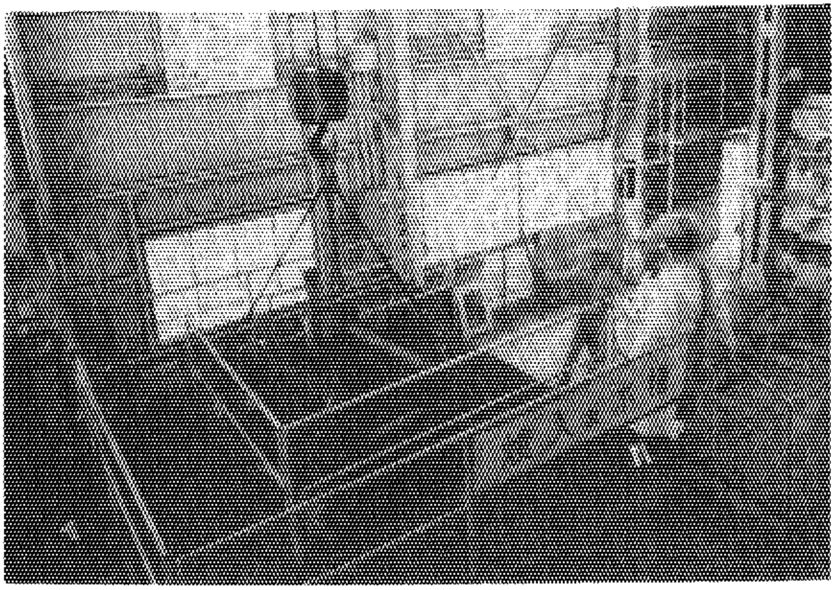


Fig. 16 WATER QUENCHING FOR PROGRAMED HEAT TREATMENT

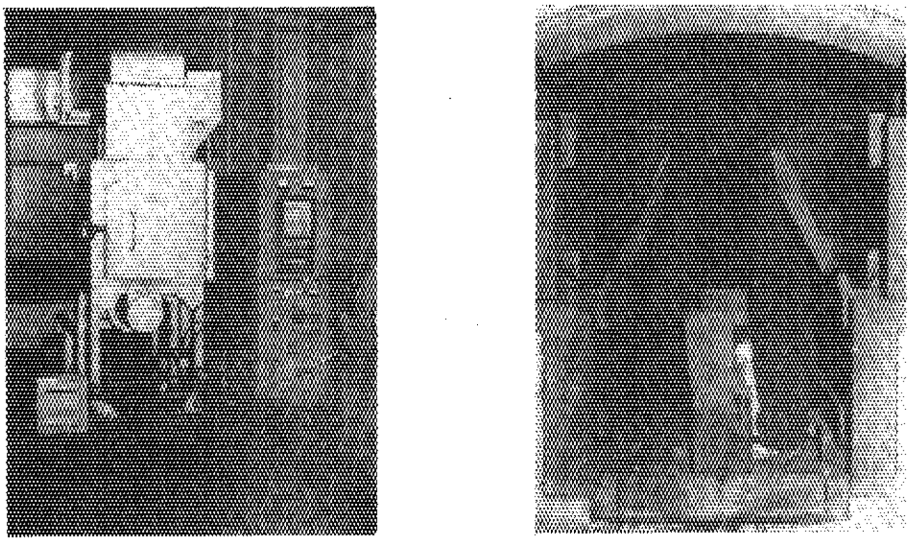


Fig. 17 PROGRAMMED HEAT TREATMENT FURNACE

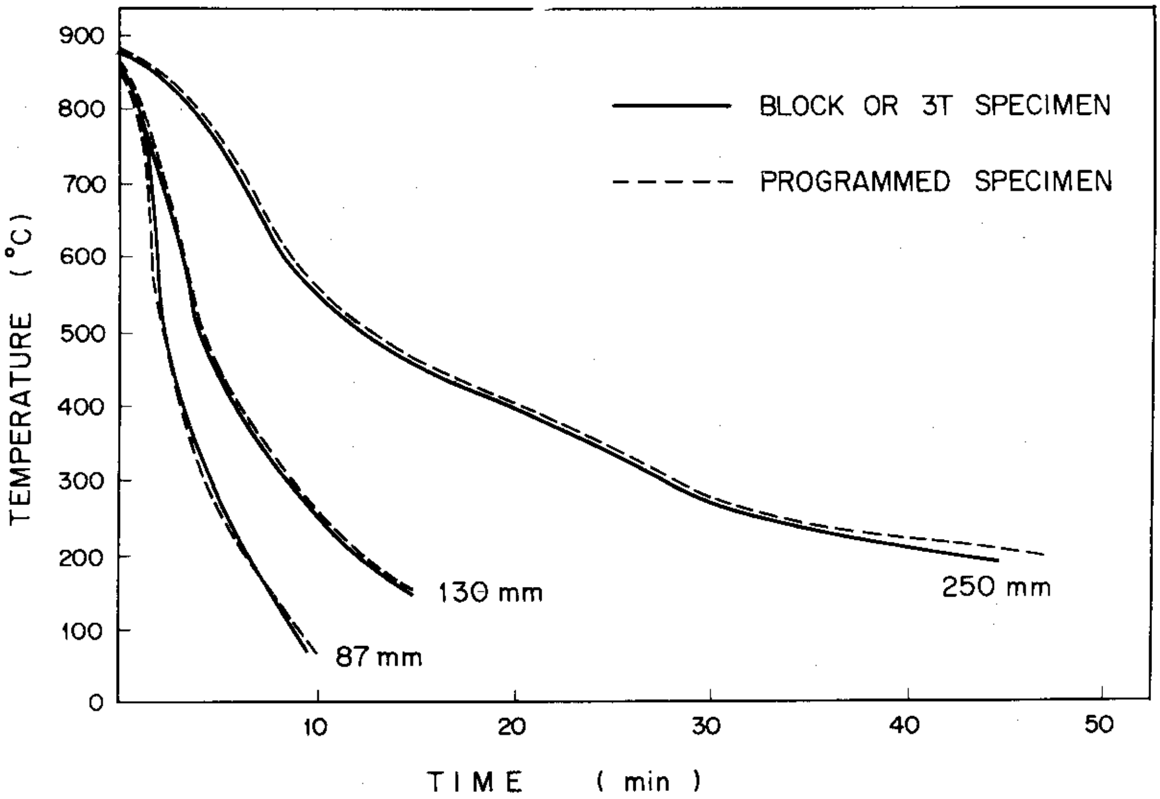


FIG.18 COMPARISON OF COOLING CURVES

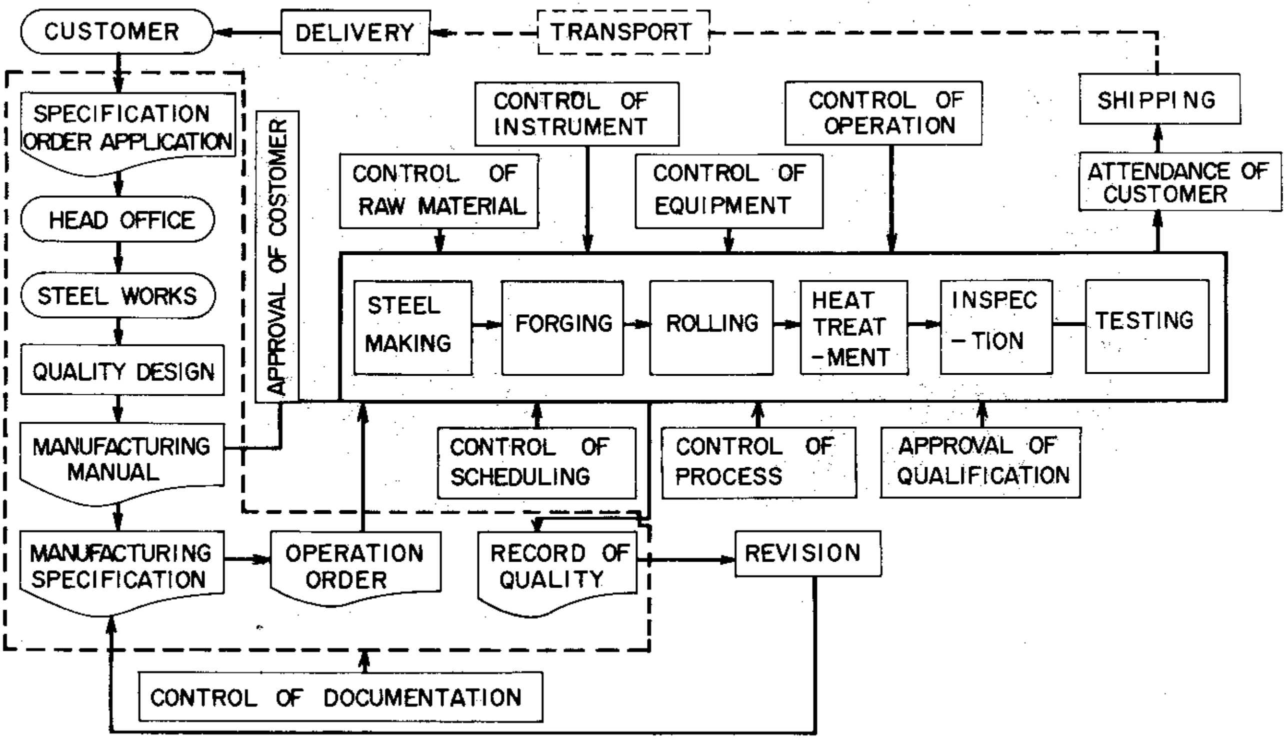
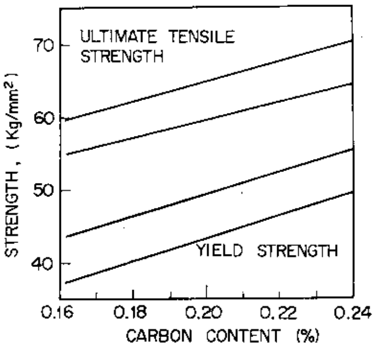


FIG. 19 FLOW CHART OF QUALITY ASSURANCE SYSTEM FOR MANUFACTURING OF RPV STEEL

(a) A508 Cl.2 RING FORGINGS WITH SECTION THICKNESS OF 300-500mm AT 20mm BY 40mm



(b) A533B Cl.1 PLATES WITH SECTION THICKNESS OF 250~300mm AT A QUARTER THICKNESS

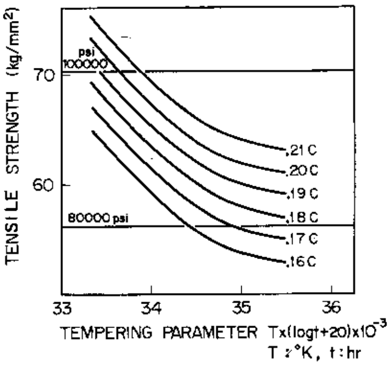


FIG.20 EFFECTS OF CARBON ON THE TENSILE STRENGTH OF HEAVY SECTION NUCLEAR PRESSURE VESSEL STEELS- DIP WATER QUENCHED, TEMPERED AND STRESS RELIEVED

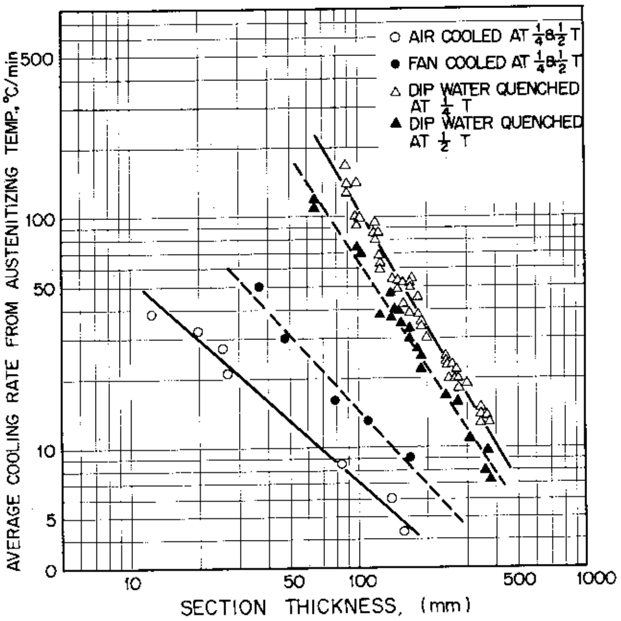
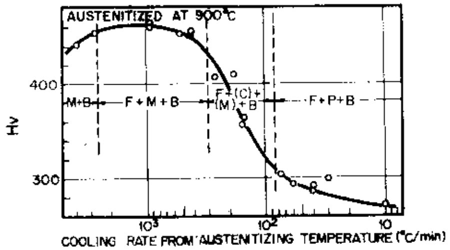
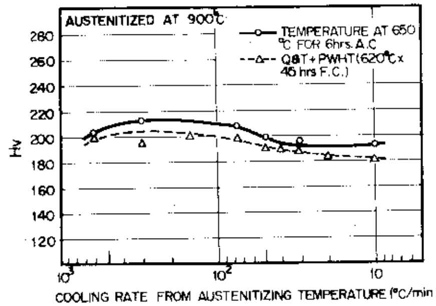


FIG.21 COOLING RATE DATA OF HEAVY SECTION LOW ALLOY STEELS FOR PRESSURE VESSELS

(a) AS-QUENCHED HARDNESS



(b) HARDNESS IN TEMERED AND TEMPER PLUS PWHT'D CONDITION



(c) CHANGE OF IMPACT VALUE

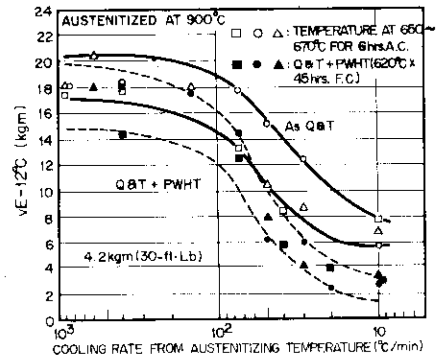
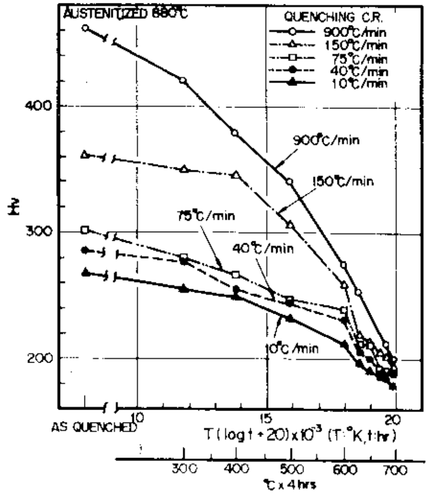


FIG.22 EFFCTS OF COOLING RATE FROM AUSTENITIZING TEMPERATURE ON THE HARDNESS AND IMPACT VALUES OF Mn-Mo-Ni STEEL-0.20C, 0.25 Si 1.32Mn, 0.68Ni, 0.54Mo

(a) HARDNESS SOFTENING CURVES



(b) TEMPERING VS. V CHRPY ABSORBED ENERGY AT-12°C

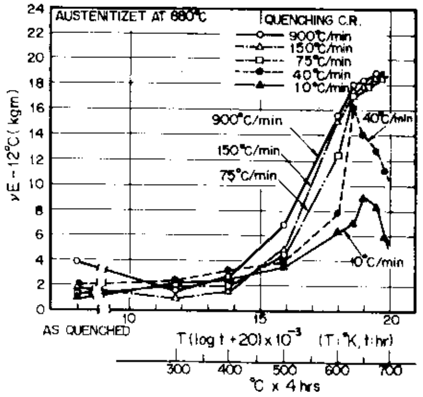
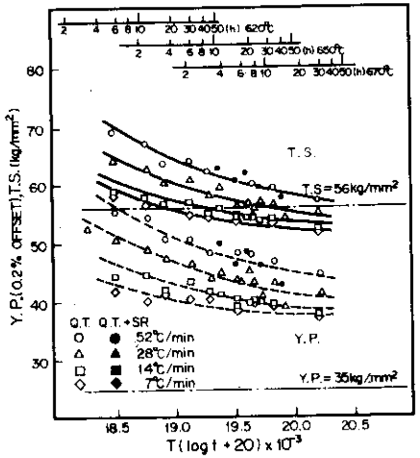


FIG. 23 EFFECTS OF TEMPERING ON THE HARDNESS AND IMPACT VALUES OF Mn-Mo-Ni STEEL-0.20C, 0.25Si, 1.32Mn, 0.68Ni, 0.51Mo

(a) QUENCHING COOLING RATE, TEMPERING AND POSTWELD HEAT TREATING VS. STRENGTH



(b) POSTWELD HEAT TREATING VS. 'V' CHARPY ABSORBED ENERGY AT-12°C

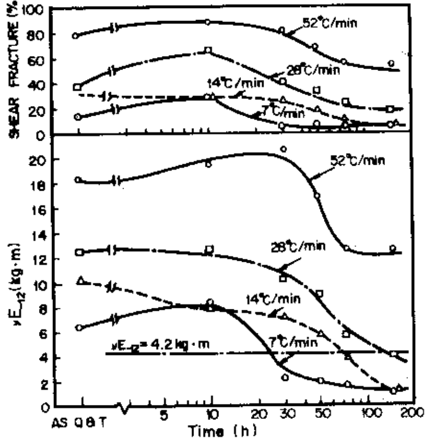


FIG. 2.4 HEAT TREATMENT AND MECHANICAL PROPERTIES OF A508 Cl.2 STEEL -0.17C, 0.34 Si, 0.63Mn, 0.81 Ni, 0.26Cr, 0.61 Mo

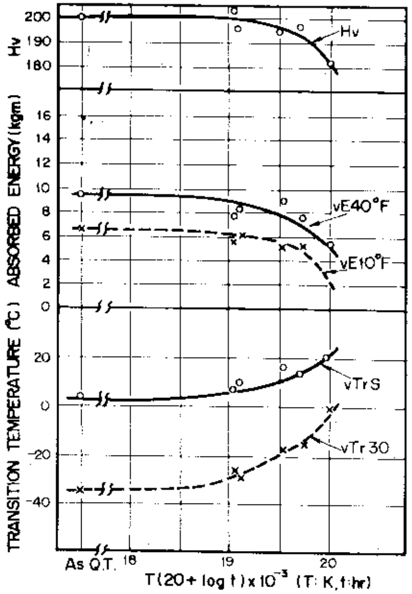


FIG. 2.5 PROLONGED PWHT VS. HARDNESS AND IMPACT PROPERTIES OF 165MM THICK A533B Cl.1 PLATE AT A QUARTER THICKNESS, LONGITUDINAL, 0.19C, 0.27Si, 1.34Mn, 0.63Ni, 0.50Mo

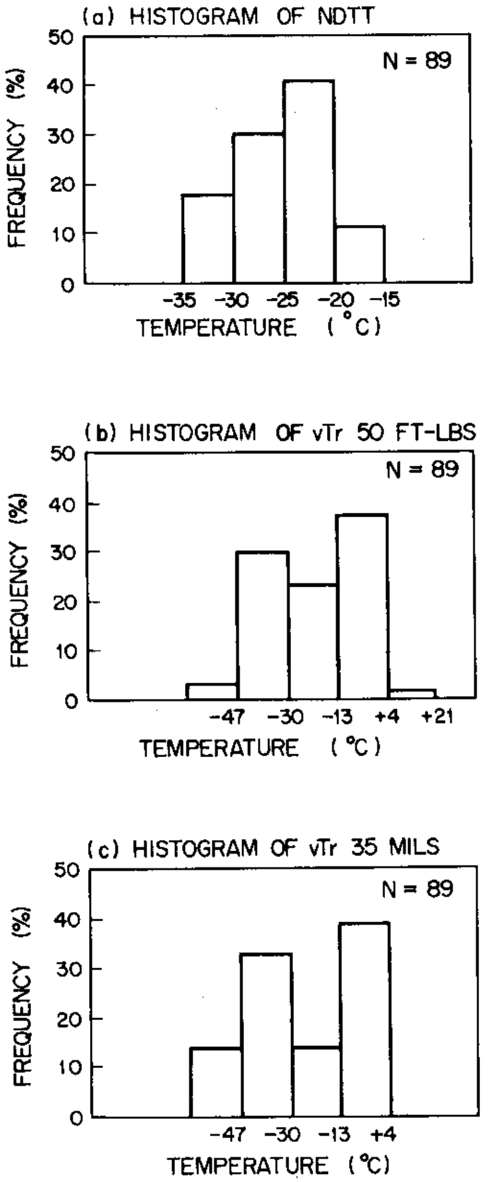


FIG.26 RECENT TRANSVERSE NOTCH TOUGHNESS FOR 100 TO 200 mm THICK. A533B CL.1 PLATES

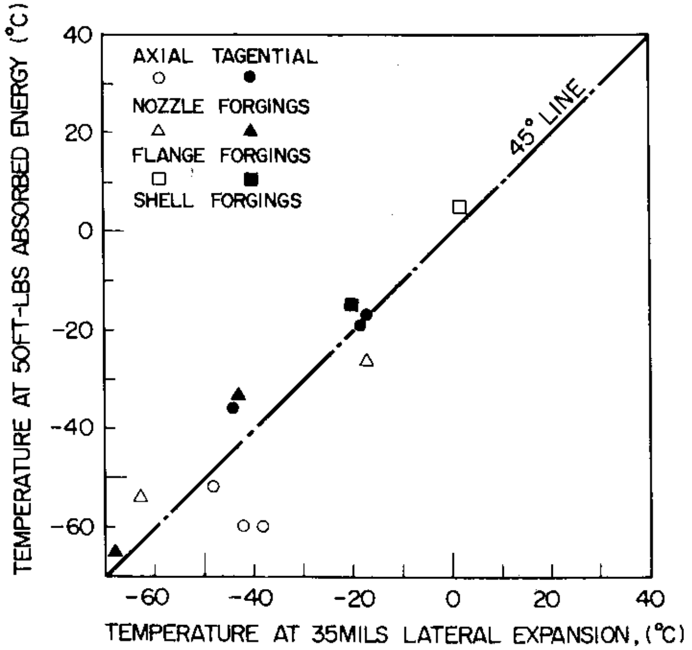


FIG.27 SOME EXAMPLES OF TRANSITION TEMPERATURE RELATIONSHIP - ABSORBED ENERGY VS. LATERAL EXPANSION OF V CHARPY TEST
LOCATION OF SPECIMEN : FLANGE AND NOZZLE FORGINGS......t by 2t (t=20mm)
SHELL FORGINGS......T by $\frac{1}{4}$T (T=SECTION THK.)

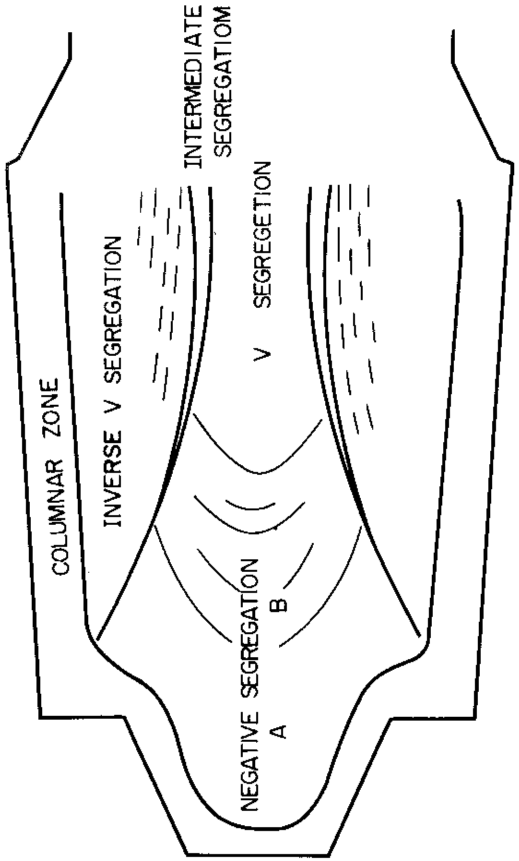


FIG.28 TYPICAL SEGREGATION PATTERN OF LARGE INGOT

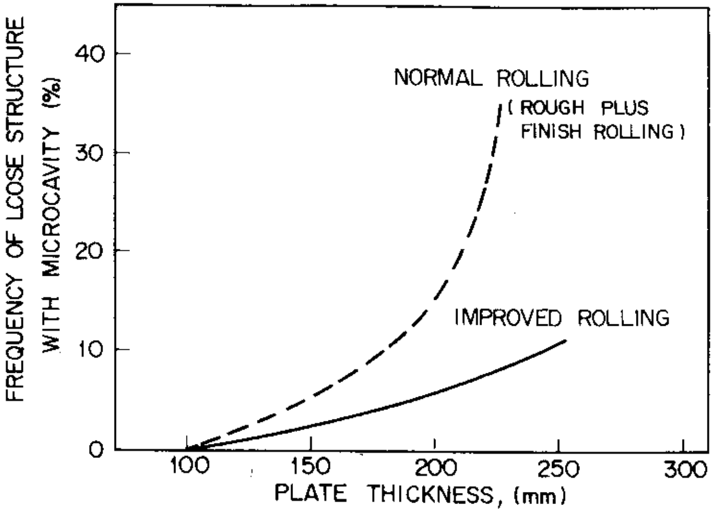


FIG.29 EFFECTS OF HOT WORKING OF SLAB INGOTS BEFORE ROUGH ROLLING ON THE MODIFICATION OF LOOSE STRUCTURE-MANY HEATS AND TESTS OF A533 PLATES

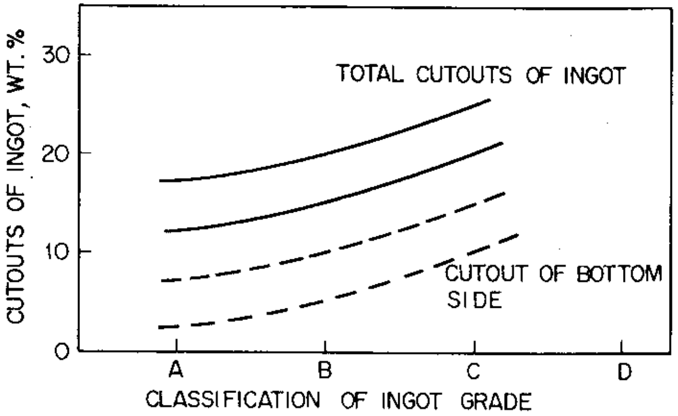


FIG.30 AN EXAMPLE OF INGOT CUTOUT CONTROL FOR CLEANLINESS AND HOMOGENEITY OF HEAVY SECTION PLATES BEING CONDUCTED IN JAPANESE PLATE MILL

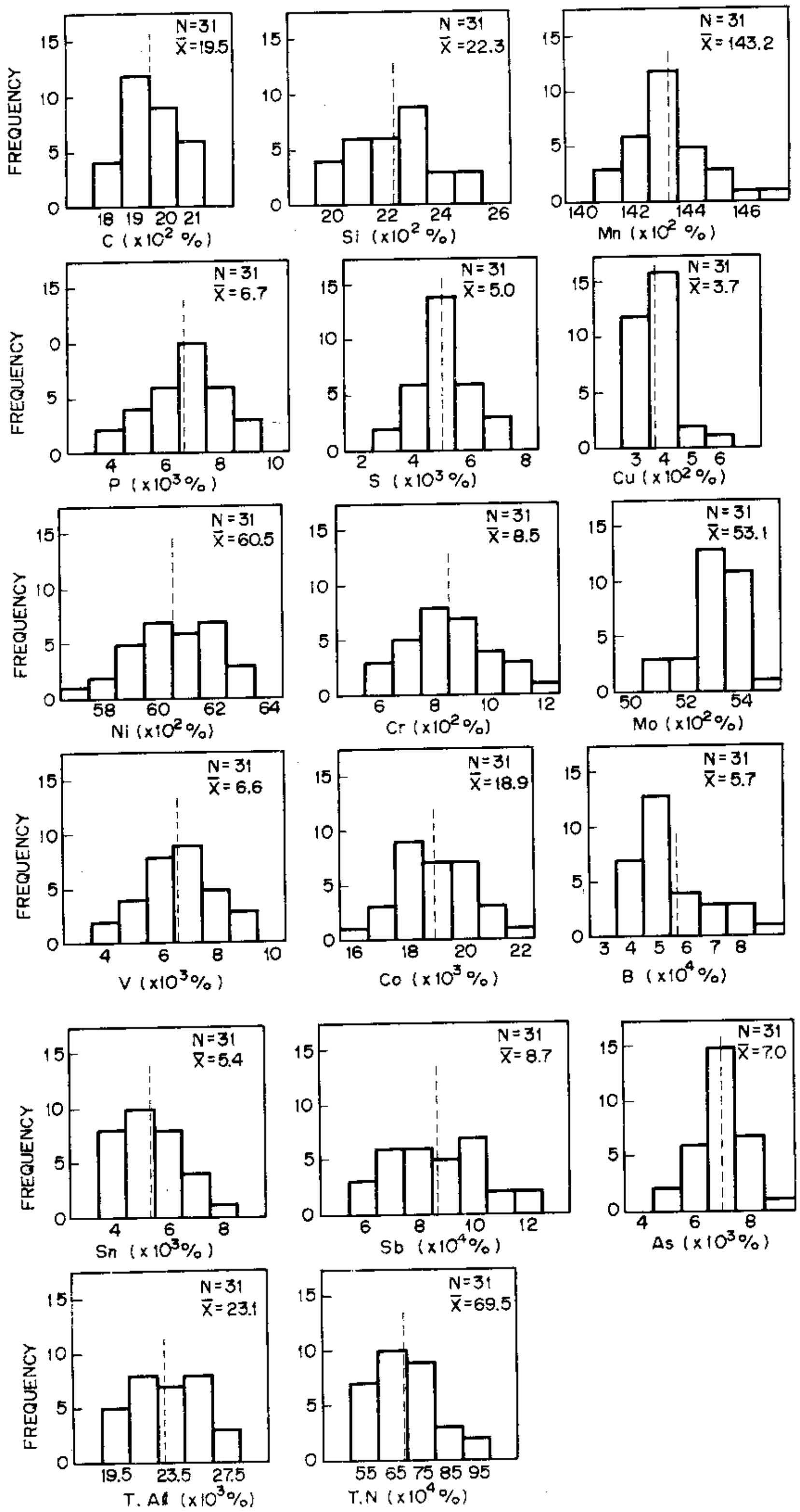


FIG. 31 HISTOGRAM OF CHEMICAL COMPOSITIONS OF A533B STEEL PLATE

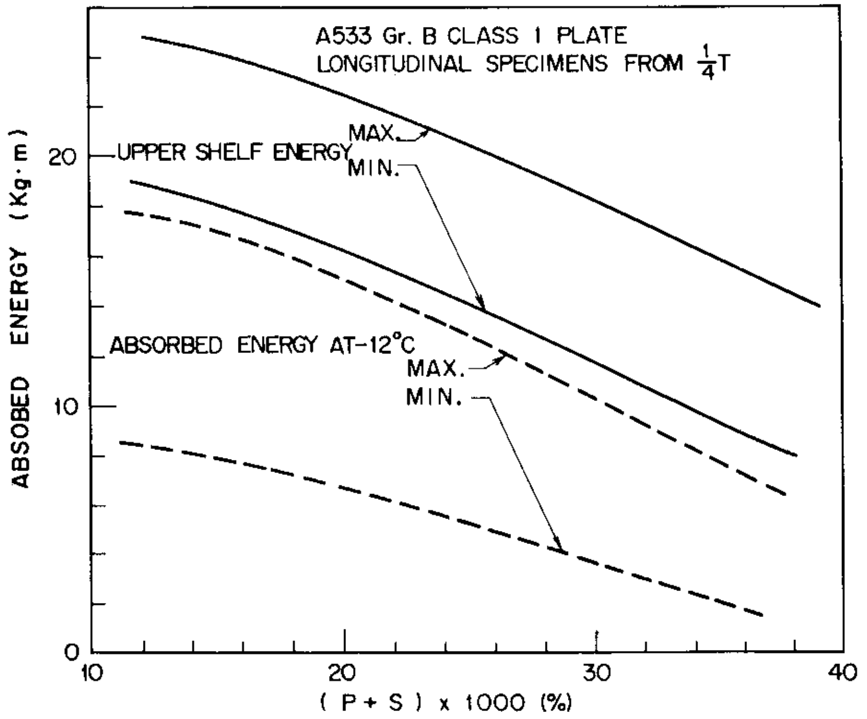


FIG.32 EFFECTS OF (P+S) CONTENTS ON THE "V"CHARPY IMPACT VALUES–MANY HEATS AND TESTS OF 140–175mm THICK PLATES, QUENCHED, TEMPERED AND POSTWELD HEAT TREATED

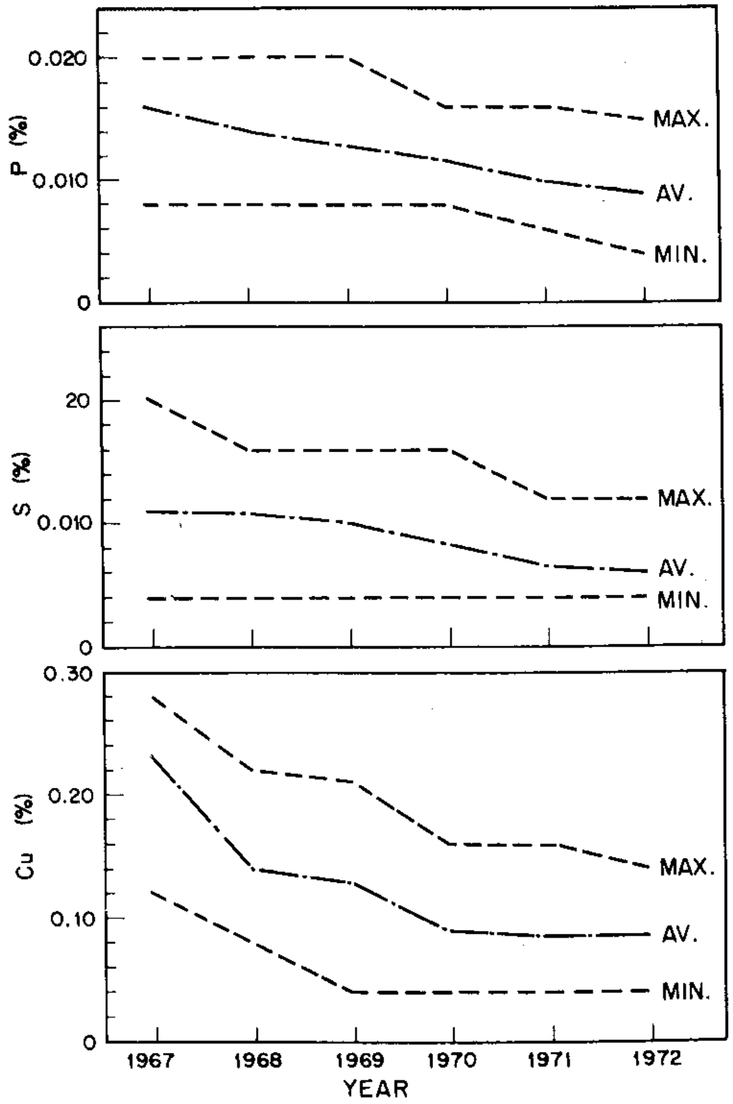


FIG. 3.3 P, S AND Cu CONTENT TRENDS IN HEAVY SECTION A533 B PLATES FOR RPV