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KEYS TO SUCCESSFUL DRILLING IN MAHANAGDONG

Mario A. Talens, Edwin B. Herras, and Manuel S. Ogena

PNOC Energy Development Corporation
PNPC Complex. Merritt Road, Fort Bonifacio, Makati City, Philippines
ogena@edc.energy.com.ph

ABSTRACT

The Mahanagdong sector is one of the four development sectors within the Leyte Geothermal Production Field and has been developed to supply 180 MWe of steam capacity. Drilling activities in Mahanagdong began in July 1980 by dnlling the first deep well, well MG-1. To date, a total of thirty seven (37) wells have been dnlled in the area, twenty eight (28) for production and nine (9) for reinjection. The success rate of dnlling and completing deviated wells in the area to attain their geologic objectives is only 44%.

The principal cause of dnlling problems in the open hole section of wells in the Mahanagdong sector is the limited ability of the loss zones to accept cuttings despite initial massive mud circulation losses leading to a shift to drilling with water. The volume of cuttings generated with further dnliing and wluch can not be absorbed by these loss zones eventually leads to stuck pipe and subsequent early termination of the well.

A modified dnlling strategy, well design revisions and the use of the two-liner system are some of the solutions implemented which substantially improved the success rate of completing the last five wells and following the programmed design and objectives.

INTRODUCTION

The Mahanagdong sector is divided into two areas, Mahanagdong A and Mahanagdong B. A power plant has been constructed in each area with a generating capacity of 120MWe and 60MWe respectively.

The steam requirement for Mahanagdong A power plant has already been achieved after dnlling 13 production and 4 reinjection wells. In sector B, however, PNOC has been faced with a problem of supplying 60 MWe of steam due to the non-commercial value of the first four wells dnlled.. Faced with the dilemma of not producing sufficient steam in time for the commissioning of Mahanagdong B Power Plant in July 1997, the succeedmg sections discuss how PNOC approached tlus problem and the solutions that were eventually

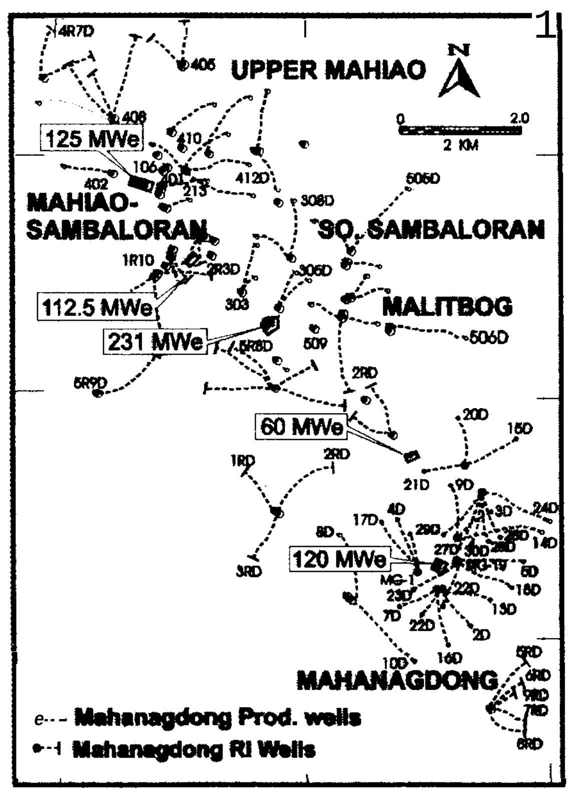

Figure 1. Development sectors of the Leyte Geothermal Production Field.

implemented. *An* innovative dnlling technique in the latter part of 1996 was adapted to be able **to** supply the required steam in the remaining time available and meet the supply contract to the Mahanagdong B plant. From April to December 1996, the last five wells were completed as programmed.

GEOLOGY

The Leyte Geothermal Production Field falls within a fault wedge formed **by** the left lateral Philippine Fault. This fault zone is characterized **by** three **to** five distinct NW-SE trending subparallel structures. Differential movements along these distinct faults developed intense secondary faulting, with most of the delineated permeable zones in each well in LGPF attributed to intersection of faults mapped from the surface.

The area is typically underlain **by** basement metamorphic and ultramafics rocks. These are overlain **by** conglomerates and sedimentary breccias with clasts consisting mainly of microdiorite and quartz monzodiorite termed as the Mahiao Sedimentary Complex (MSC). Overlying the MSC are andesite lavas, hyaloclastites and tuffs breccias intercalated with fine grained clastics of the Mamban Formation (MF). Surface rocks in LGPF consists of fresh to weakly weathered andesite lava flows and associated pyroclastics.

Since the major source of permeability in the LGPF are faults, these have been the pnmary targets in PNOC geothermal dnlling. Drilling through these structures lead to partial and frequently to total loss in circulation. This is what is unique in geothermal dnlling, although losses in the 12%' or 8%" production hole sections are welcome from the productivity point of view, at times these **pose** dnlling problems especially in the Mahanagdong sector. Hole problems in Mahanagdong can not be related **to** a group or any particular structure. These problems are prevalent throughout the sector.

WELL DRILLING PERFORMANCE VS. PROGRAM

The thirty seven (37) wells drilled in the Mahanagdong sector **as** of December 31, 1996, have been grouped into four categories (Table 1-4). The degree of success of each dnlled well is gauged on whether it has intersected all the programmed target structures in the open hole section of the well: dnlled within the target limits prescribed, attained a total depth of plus or minus one hundred meters relative to the well's program target depth. and satisfied all geologic objectives, as defined in the well design and geologic prognosis.

There are two vertical wells MG-1 and MG-19 found in the first category (Table 1). wtuch were able **to** reach the program target depth and intersect all target structures. Wells in the second category (Table 2) were dnlled with full mud returns or incurred minimal circulation losses in the open hole section. These wells were non commercial. The third category (Table 3) is comprised of successful wells that were able to intersect all target structures, attained the geologic objectives and dnlled down or almost to programmed target depths. Majority of the wells dnlled in Mahanagdong are in the fourth category (Table 4). There are fourteen (14) wells that did not reach the programmed target depth nor attain the geologic targets and objectives.

EVALUATION OF DRILLING PROBLEMS

Our evaluation focuses on the third and fourth categories involving twenty five (25) wells which includes both production and reinjection wells. Wells in categories 1 and 2, because either one was vertical or was dnlled with full mud returns can not be compared to those wells in categories 3 and 4.

As indicated in Tables 3-4, the rate of drilling success at Mahanagdong is only forty four percent. This trend persisted up to the early part of 1996 and became alarming with the reality of not being able to supply the required steam for Mahanagdong B plant commissioning. A review of the well design, dnlling strategy and procedures were conducted in early 1996 **to** improve dnlling success.

Total Depth

The average total depth reached **by** wells that failed to attain the geologic objectives (Table **4)** was 2155 meters and wells that attained the geologic objectives (Table 3) was 2414 meters. Their difference is 259 meters. Comparing the average total depth attained **by** wells in both categories against their respective programmed target depth, those wells in the third category were short in attaining their average target depth of 2495 meters **by 81** meters, while those

Table 1. Vertical Wells

Well Name/ Year Drld	# TS/ # SI	No. of Days Drilled	Prog. TD (PTD)	Actual TD (ATD)	ATD-PTD	PCS	PTD-PCS Depth	KOP	Drift Angle Prog.	Act.	GPM
MG-1 (1980)	3/3	62	2100	2339	239	908	1192				675
MG-19 (1994)	1/1	77	2500	2500	0	1198	1302				750
AVERAGE	2/2	69.5	2300	2419	119.5	1053	1247				

Table 2. Wells with FMR or Minimal Losses

Well Name	# TS/ # SI	No. of Days Drilled	Prog. TD (PTD)	Actual TD (ATD)	ATD-PTD	PCS	PTD-PCS Depth	KOP	Drift Angle Prog.	Act.	GPM
MG-8D (1993)	8/6	54	2562	2700	138	1542	1020	200	31	31	550
MG-10 (1993)	3/3	66	2450	2709	259	1670	780	249	38	38	650
MG-14D (1994)	3/3	47	2400	2445	45	1194	1206	410	32	32	600
MG-17D (1994)	2/2	70	2550	2600	50	1581	969	700	35	38	600
MG-24D (1996)*	3/3	114	2650	2838	188	1396	1254	400	38	35	800
MG-1RD (1992)	3/3	56	2050	2559	509	1481	569	200	44	47	500
MG-2RD (1993)	2/2	159	2700	2703	3	1458	1242	350	34	43	500
MG-3RD (1994)	4/3	69	2800	2379	-421	1295	1505	750	38	49	550
MG-4RD (1994)	2/2	42	1400	1406	6	669	731	120	45	43	550
AVERAGE	3.3/3	75.2	2396	2482	86	1365	1031	375	37	40	

Tabh 3. Attained geologic objectives

Well Name	# TSI # SI	No. of Days Drilled	Prog TD (PTD)	Actual TD (ATD)	ATD-PTD	PCS	PTD-PCS Depth	KOP	Drift Angle Prog.	Act.	GPM
MG-5D (1983)	2/2	117	3000	2914	-86	1147	1853	370	24	26	500
MG-16D (1994)	3/3	41	2400	2301	-99	1288	1112	300	35	34	800
MG-18D (1994)	4/4	35	2450	2450	0	1343	1107	600	28	34	700
MG-21D (1995)	3/3	45	2500	2332	-168	1155	1345	591	20	21	700
MG-27D (1996)*	3/3	71	2400	2301	-99	1242	1158	250	32	36	600
MG-28D (1996)*	3/3	70	2500	2405	-95	1285	1215	550	25	27	900
MG-29D (1996)*	1/1	77	2500	2414	-86	1477	1023	150	26	30	750
MG-30D (1996)*	2/2	63	2450	2453	3	1542	908	270	24	24	800
MG-31D (1996)*	2/2	81	2350	2297	-53	1399	898	597	31	31	800
MG-5RD (1995)	2/2	54	2400	2383	-17	1298	1102	500	38	38	600
MG-9RD (1996)	2/2	55	2500	2300	-200	1400	1100	750	20	22	650
AVERAGE	2.5/2.5	64.4	2495	2414	-81	1325	1165	448	28	29	

Table 4. Wells that failed to attained geologic objectives

Well Name	# TS/ # SI	No. of Days Drilled	Prog. TD. (PTD)	Actual TD (ATD)	ATD-PTD	PCS	PTD-PCS Depth	KOP	Drift Angle Prog.	Act.	GPM
MG-2D (1986)	4/2	78	2500	2217	-283	997	1503	350	30	32	500
MG-3D (1992)	5/3	94	2400	2042	-358	1331	1069	650	40	36	750
MG-4D (1990)	3/2	122	2660	2258	-402	1167	1493	500	38	43	500
MG-7D (1990)	4/3	68	2600	2519	-81	1459	1141	370	32	39	700
MG-9D (1993)	4/2	118	2415	1940	-475	1441	974	250	34	36	550
MG-13D (1994)	2/2	43	2550	2078	-472	1401	1149	189	39	42	750
MG-15D (1994)	5/3	77	3000	2353	-647	1546	1454	500	38	35	850
MG-20D (1995)	3/1	106	2800	2301	-499	1341	1459	565	37	33	750
MG-23D (1995)	3/2	77	2500	2160	-340	1400	1100	380	36	38	1027
MG-25D (1996)	5/2	114	2500	1998	-502	1215	1285	450	25	24	800
MG-26D (1996)*	5/2	83	2600	2075	-525	1353	1249	120	28	26	1150
MG-6RD (1995)	2/1	75	2700	2347	-353	1299	1401	400	40	39	900
MG-7RD (1995)	3/2	65	2600	1815	-785	1221	1379	550	35	35	1100
MG-8RD (1996)	2/1	70	2500	2066	-434	1398	1102	150	23	26	825
AVERAGE	3.6/2	85	2595	2155	-440	1326	1268	387	34	35	

# TS/# SI	number of target structures/ number structures intersected
PCS	production casing *shoe*
	big hole wells

belonging to the fourth category were 440 meters short of the average target depth of 2595 meters. This translates to ninety seven percent (97%) and eighty three percent (83%) success in drilling actual total depth versus program target depth for the two categories.

The welltracks for wells in both categories were within the cone defined by the target limits prescribed in the well design and dnlling program. The problem for wells in the fourth category was not related to the geometry of the well, but rather failure to attain the program target depth. The cause and solution to this will be Qscussed at the latter part of this paper.

The target limits for wells in Mahanagdong sector ranges from fifty (50) to one hundred (100) meters around the programmed target depth. If welltracks for these wells stay within the prescribed cone, to dnll and attain geologic objectives, depth variance relative to programmed target depth is plus or minus one hundred meters. This means , if a particular welltrack is above the programmed line, it will bottom out the last targeted structure earlier in the range of one hundred meters or less. On the other hand, if it is below the line, total depth needed to bottom out the last target structure will be deeper by one hundred meters maximum.

For wells in the third category (Table 3), majority of the welltracks were slightly above the programmed profile thus structures were intersected and bottomed our earlier. Thus, the variance of 85 meters between programmed target depths and total depth attained for wells in the tlurd category falls within the target limits of the well designs.

Drift Angle and Kick-Off Point (KOP)

The drift angles and kick-off points in well designs are Qctated by the temperature at the production casing shoe depths and the attitude of the Qfferent target structures at the open hole section. For long-throw wells, it is best to kick-off at shallow depth to minimize the dnft angle. Often, the Qp and well-fault Qstance of target structures does not fit this ideal combination. Since Qp and well-fault Qstance are fixed, the parameters that can be changed for the well design to satisfy the objectives is to vary kick-off points and dnft angles.

In wells belonging to the fourth category, we evaluated wells with dnft angles less than 30°, those in the range of 31°-35° and those above 36°. The results were surprising. When the actual versus programmed target depths for tlus grouping were compared, the results were almost identical, 82.7%, 82.4%, 83.8%, respectively. This is consistent with the 83% success rate of attaining target depths as discussed earlier.

Hydraulics

In the open hole in geothermal drilling, we seek zones of loss circulation, the higher the rate of circulation losses, the better chance of getting a good well.

When the rate at wtuch a loss zone can accept drilling fluid is less than the pumping rate at which the rig pumps deliver, this is called partial loss circulation (PLC). PLC is gauged in terms of percent of dnlling fluid that circulates back to the surface tanks. When massive losses are encountered and dnlling fluid is greater than the volume at which the rig pumps can deliver, this is called total loss circulation (TLC).

When TLC or PLC are encountered in the open hole, attempts are made to regain full circulation. However, when TLC persist, the common drilling practice is to dnll ahead using water with intermittent mud sweeps of high viscosity called mud slugs to lift cuttings into the loss zones.

PNOC EDC implemented a hydraulics program for blind dnlling with water using low pump rates in the range of 500-650 gpm (8%"hole) and 650-800 gpm (12¼" hole) in 1978-1986. A total of 107 wells were drilled during tlus period. Ths compares with the total 135 wells drilled during the period 1987-1996.

The new hydraulics program implemented in the 90s was to pump water during blind drilling at higher pumping rates. This is 700-800 gpm at the 8%"hole section and 800-1100 gpm in the 12¼" hole section. The concept was that higher pumping rates will provide better lifting capacity especially for multiple loss zones. An increase in hydraulic pressure correspond to an increase in pumping rates. Therefore, there is greater pressure acting behind the cuttings to push it farther away from the wellbore. This is also means that more cuttings can be possibly pumped into higher loss zones. Correspondingly, an increase in pumping rate results and in other hydraulic parameters such as increased annular velocities both between the bottom hole assemblies and the formation and around the dnll pipes. Bit hydraulic pressure also increased. Whether higher pumping rates was a solution or a part of the problem at this sector at this point and time is still debatable.

Majority of the wells in the fourth category were conventional wells. Of the eight conventional wells. two were dnlled using low pumping rates. All six big holes dnlled utilized high pumping rates. In the third category, six were conventional wells. Of these, five were drilled with high GPM. The four big holes drilled used low GPM. In both categories, there seemed to be no definite trend whether using low or high GPM gives a better chance of attaining target depths.

POSSIBLE CAUSED OF HOLE PROBLEMS

In Mahanagdong, PNOC EDC has been faced with the persistent problems of being unable to penetrate more than one production zone after encountering irrecoverable losses from the first zone encountered. Drilling ahead blind with water has only been the strategy. The following are the common causes of stuck pipe in the open hole section while blind dnlling with water based on the assessment of several problematic wells in Mahanagdong.

Wellbore Instability

A primary drawback with using water is its inability to "weight up" and stabilize collapsing formation. When the hole collapses, high flowrates (1000-1200 gpm) are not sufficient to clean the slouglung wellbore. Collapse happens only when the formation pressure exceeds the hydrostatic pressure exerted by the dnlling fluid. There is usually a pressure build up when a collapse occur. This is caused by sufficient volume or rock particles packed either around the bottom hole assembly or the dnllpipes which restrict the migration of dnlling fluids up the annulus. Usually this problem persist around a particular depth. Hole enlargement follows until such time that something is done to stabilize the wall of the hole. Most often, the roof of the enlarged portion of the hole continue to fall. In cases of total loss of circulation, it is very difficult to stabilize the wall. Rarely do we see collapse in a volcanic environment.

It is likely that slouglung or collapsing formation were the cause of drilling problems in the Mahanagdong sector. There were instances because of partial returns, dnll cuttings were collected during stuck pipe situations. The size of dnll cuttings were consistent or typical products of dnll bit action against formation. If it was collapse. pebble or bigger rock particles should have been recovered or the size distribution of rock particles collected should be uneven.

Hole Cleaning

Another disadvantage of using water as dnlling fluids is its low capacity to lift cuttings and the inability to hold cuttings in suspension as it does not have the thixotropic property inherent in drilling mud. There is a tendency for cuttings to build-up in the lower section of the bore which is usually a prelude to stuck pipe.

During blind dnlling deviated wells, there is a tendency for cuttings to build up in the low side of the bore creating beds cuttings. Thus. during static conditions there is tendency for this cuttings to slide downwards. This, however with proper hydraulics and sufficient mud sweeps can be thrown to the loss zones.

The cause of the problems encountered in the open hole section was the limited ability of the loss zones to accept cuttings as realized in the Mahanagdong sector. It was observed that after sometime, hole cleaning problems can be attributed to cuttings either not accepted or pumped to formation or cuttings that flow back into the wellbore from the loss zones.

Stratigraphy and Multiple Structural Targets

The multiple loss zones encountered in the wells are almost always related either to structural intercepts or stratigraphic permeability. With available technology, it is almost impossible to determine the volume or the maximum size of cuttings that these loss zones can accept. However, there were consistent trends that hole problem occurs five days after exposure to blind dnlling. Approximately this translates to five hundred to six hundred meters of hole drilled. This parameter was used as a yardstick to dnll the open hole sections of the production wells MG-27D, MG-28D, MG-29D, MG-30D, MG-31D and MG-9RD beginning second half of 1996.

In the reinjection sector, the problem was related to collapse and sloughing formation. Once the Mahiao Sedimentary Complex (MSC) is intersected, after sometime, collapse follows. The MSC was intersected at an average vertical depth of 1787 meters in wells drilled from MG-RD1/B pad. Wells MG-6RD, MG-7RD and MG-8RD encountered problems inferred to be due to collapse of the MSC near the bottom of the well. In all instances five days after intersecting the MSC, tight hole and stalling of the rotary, plus continues fill with occasional increase in pump pressure were noted. IN MG-7RD and MG-8RD stuck pipes led to fishes downhole which were later abandoned.

The typical characteristic of the MSC is relative past rate of penetration ranging from eight to twelve meters per hour. Unlike in the production sector in Mahanagdong, samples recovered at depths were hole problems occur were not drill cuttings but bigger rock particles with uneven size distribution.

Based on current data, the maximum number of structures successfully intersected and bottomed out in the open section of any well in the Mahanagdong sector was realized at MG-18D. However, this is only one out of ten, and can be considered an exception. As shown in Table 3, three structures is the maximum number that should be programmed for intersection in the production wells in this sector. The average number of structures targeted for wells in the third category was 2.5, while those in the fourth category was 3.6. It will be shown that this was part of why majority of the wells in Mahanagdong failed to attain the target depths.

KEYS TO SUCCESSFUL DRILLING IN MAHANAGDONG

By the end of the first quarter of 1996, five wells, MG-15D, MG-20D, MG-21D, MG-24D (BH) and MG-26D (BH) have been dnlled to supply steam for the Mahanagdong B power plant. Unfortunately, the first three wells were acidic. The succeedmg two big hole wells were non-commercial most probably due to the fish left in hole. Thus, it was a must that the next well dnlled should attain the geologic objectives to maximize steam production and ensure steam availability for the power plant at the shortest time possible.

It was at this stage that the next five wells MG-27D, MG-28D, MG-29D, MG-30D and MG-31D were successfully drilled. These wells attained all its geologic objectives and 100% successfully executed the dnlling program. All wells were dnlled as big holes.

Modified Well Design Parameters and Hydraulics Program

The first key to successful dnlling in Mahanagdong was to identify the likely causes of hole problems that led to premature TD of the wells. Next was to find solutions and accept the geologic and dnlling limitations in the sector.

Prior to these five wells, data shown in Table 4 indicate that a total target depth of 2300 meters to 2450 meters is achievable. It was therefore safe to assume another 100 meters extension up to a maximum target depth of 2500 meters is likewise attainable. Thus, the programmed target depths for the five wells mentioned above ranges from 2400 meters to 2500 meters.

The length of the open hole section, as much as possible was minimized.

The number of target structures in the open hole section were limited to three.

Dnft angles were minimized and designed to be less than 35". Although there was no substantial evidence of dnft angles relating to drilling problems, we Qd not discount the fact that the wells dnlled by PNOC EDC during the first half of the 1980's were quite successful. What these wells had in common were fairly low dnft angles in the range of 25" to 35".

Similarly, the argument above holds for the hydraulics program applied. Low pumping rates were used in the succeeding wells. Once in the open hole, a very conservative dnlling approach was adapted by the dnlling personnel. Since it has been defined that structures had limited ability to accept cuttings, once dnlling rates became fast, as much as possible, penetration rates were held at a maximum of one single or nine meters per hour. The use of mud sweeps was increased to possibly suspend cuttings and arrest back flows from loss zones. The early identification of this hole cleaning problem by site staff has been critical in the success of implementing such hydraulics program. In both MG-27D and MG-28D, tight holes were encountered as early as three hundred meters before their respective total depths were attained. Liberal use of mud sweeps was made and reaming was conducted every 30-50 meters of dnlling progress.

Use of Two-Liner Svstem

With the concept that structures in the sector had limited ability to accept cuttings, an innovative solution was presented, executed and eventually resolved the Mahanagdong enigma. These were for wells with multiple target structures in the open hole.

For these wells, after setting the production casing shoe and bottoming out the first target structure, 9-$^5/_8$" blank liners were ran into the hole to temporarily isolate the first massive loss zone. The last two joints of the solid liners are cemented in place to prevent the bottom portion of the liner string from unscrewing.. By temporarily "casing off' the first permeable zone, circulation is regained thereby ensuring effective hole cleaning with mud until the next permeable zone is encountered. With the fractured permeable formation cased-off, potential collapsing formation is isolated, and possible collapse are stabilized because of the presence of the hydrostatic head of the mud. Moreover, by casing-off of the first loss zone, possible re-entry of cuttings into the well is arrested and mechanical disturbance of the wellbore is minimized. It was therefore, more re-assuring to proceed dnlling to programmed target depth. Furthermore, after completion of the well in the 8%" hole, if the discharge results prove to be sub-commercial, there is an option to perforate the liner for additional production. This approach has proven to be quite successful.

The successful application of this technique was best demonstrated in MG-27D, MG-28D, MG-29D MG-30D and MG-31D as indicated in Table 3

USIONS AND CO

Hole problems encountered in Mahanagdong wells were related to the limited ability of the loss zones to accept cuttings. Despite the premature TD of the wells due to persistent problems, the dnlling of the last five production wells using the two-liner design has been successful in intersecting the major targeted producing zones. These wells have a combined output of 58.7 MWe.

Following are the recommendations for future wells to be dnlled in the Mahanagdong sector:

- Limit programmed target depth to a maximum of 2500 meters.
- Minimize the length of the open hole section between 1000-1300 meters.
- Limit the number of target structures in the open hole section to a maximum of three.
- Limit the drift angle of the well to less than 35°.
- Use lower pumping rates of drilling fluids sufficient to maintain an annular velocity of 115-120 ft/sec.
- Increase the frequency and volume of mud sweeps in the open hole at the initial sign of tight hole conditions under blind dnlling.
- Conduct regular wiper trips to ensure the hole is clean, especially just before intersecting a structure
- Assign experienced drilling and geologic staff familiar with the signature of the problems while drilling the open hole section of the well.
- Use of two-liner system.

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