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MASTER'S THESIS

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Abstract

Stuck pipe is a major problem for the oil industry, and getting bigger as more complex horizontal and deviated wells are drilled. What causes this problem and the ways to avoid it are presented. The main tool to unstuck pipe is the accelerator and jar system, generating a strong shock that travels down the drill pipe. One of the main issues is to ensure that sufficient hammer weight is placed above the jar for high impact. This is usually done by mounting heavy weight drill pipe between the accelerator and the jar. A hydraulic jar-accelerator system is specified and simulated by a fast numerical method, and the main output, the shock transmitted down the BHA, is shown as material stress in the BHA as function of time. The most critical parameters affecting the maximum stress were found to be the lengths of the heavy weight drill pipe and hammer. After several simulations with different lengths and ODs, the stress is much higher when hammer length is short. On the other hand the length of HW drill pipe does not affect stress so much, even if its length increases several times. However, HW drill pipe length affects the time duration when stress is larger than 1000 bar. The longer HW, the longer time will the stress act on the string. The time is important to a successful jarring operation, since the stress shock acts on the stuck pipe only a short time. The longer the shock last, the longer the stuck pipe moves for each shock delivered.

Acknowledgements

I would like deeply thank my supervisor Mesfin Belayneh who motivated me during my work on the thesis, advised and supported me constantly, no matter what time is it, in the depth of night or early morning, he was always available and was ready to help instantly. A truly professional, patient and intelligent man. Special gratitude to my external supervisor Erik Skaugen who has been helpful and who guided me on this project. Without him this thesis could not be a reality. His brilliant mind and interesting point of view in several cases charged me to look at the problems wisely and from different angle. And I would like to thank my family and friends for their support and understanding.

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1 Introduction

Drilling string sticking is unpredictable event. However, in case the problem occurs it can be mitigated drilling jar, which is placed in the bottom hole assembly (BHA). As drilling string sticking occurs a drilling jar is used to create an impact and impulse force to jar free a stuck drill string. The mechanism is by converting strain energy into kinetic energy. This energy accelerates and causes the “hammer” to collide with the “anvil” to create a tremendous impact/shock wave/blow. During drilling deepening on the dynamic loading on the drilling string and jarring operation, the drilling string may reaches to yielding point and above which the drilling string may be damaged.

This thesis presents the theory and numerical calculations for the analysis of optimization of jarring operation. Case studies were considered for the analysis of jar. The theory part presents and consists of general overview of the causes of stuck, drilling and fishing operations, problem analysis, jars and jarring operation, wave equations theory and numerical calculations. The theory and numerical calculation is part is based on the study from Erik Skaugen’s compendium [1]

1.1 Background

Nowadays the oil and gas industry is showing a fast technological increase in explorations and production sectors. With the advancement also come more challenging environments such as in deep well drilling, HPHT, gas hydrates, extended reach wells, depleted formation can be mentioned.

Drilling with conventional methods in environments described above can cause several problems. They could be high torque and drag, well collapse, well fracturing, equipment failure, and kick.

These problems increase the nonproductive time (NPT). To avoid NPT and stuck pipe in general, the engineers must research possible failures and make a good plan for drilling/fishing operation.

Figure 1 shows study from 5900 wells in Europe obtained from 47 operators. As can be shown, the non-productive time accounts about 25-30% of the drilling cost [2]. As can be shown in Figure 2, as the depth increases the NPT also increases to about 30%.

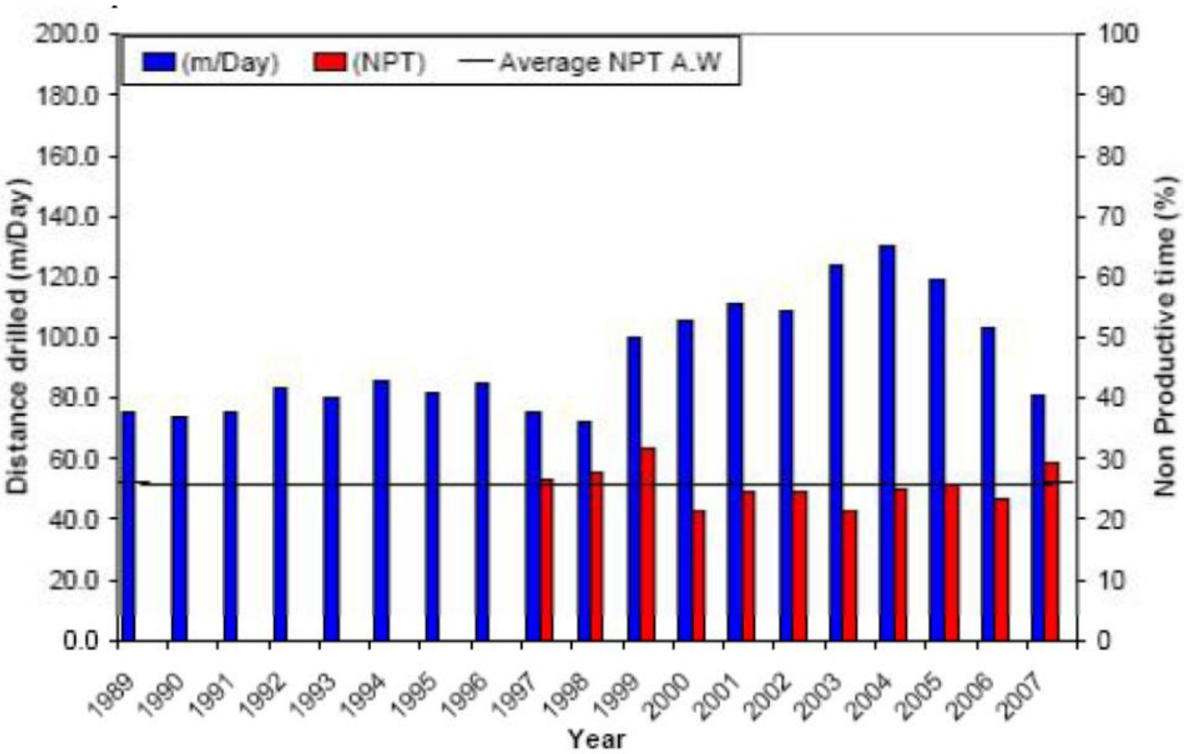


Figure 1: Reviewed non-productive time and drilling performance all type of wells [32]

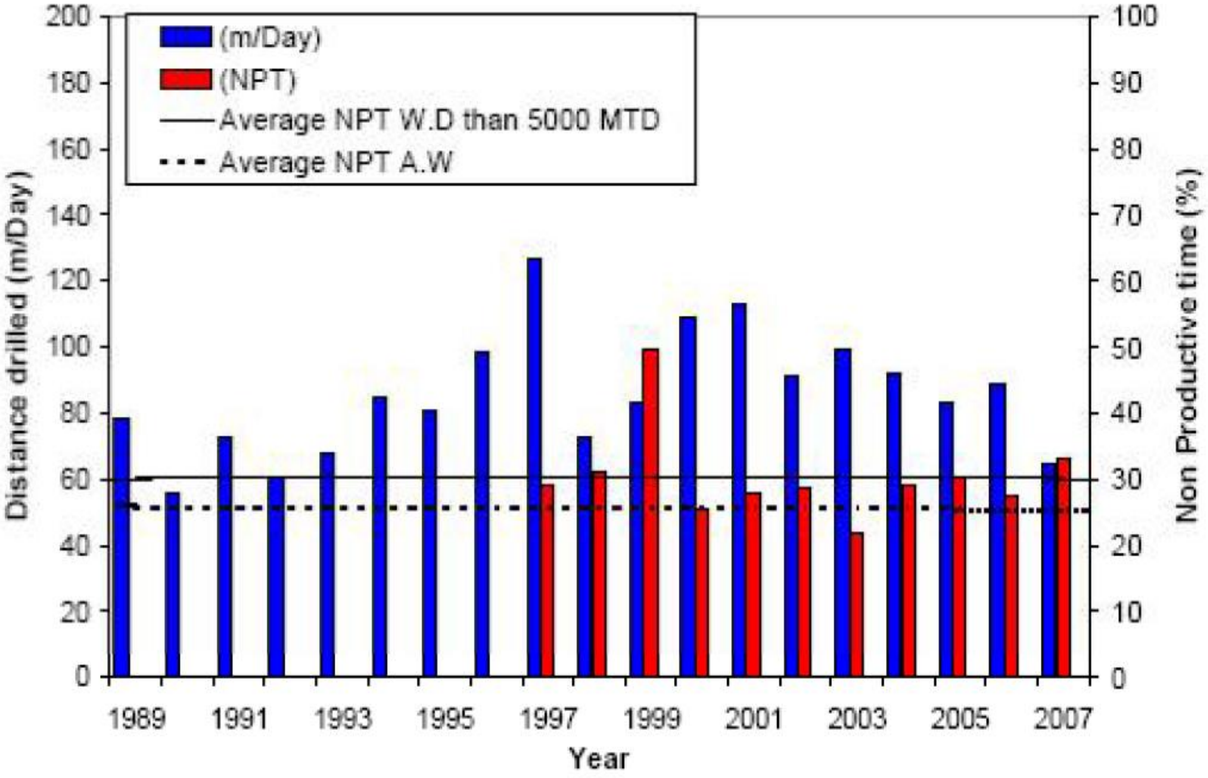
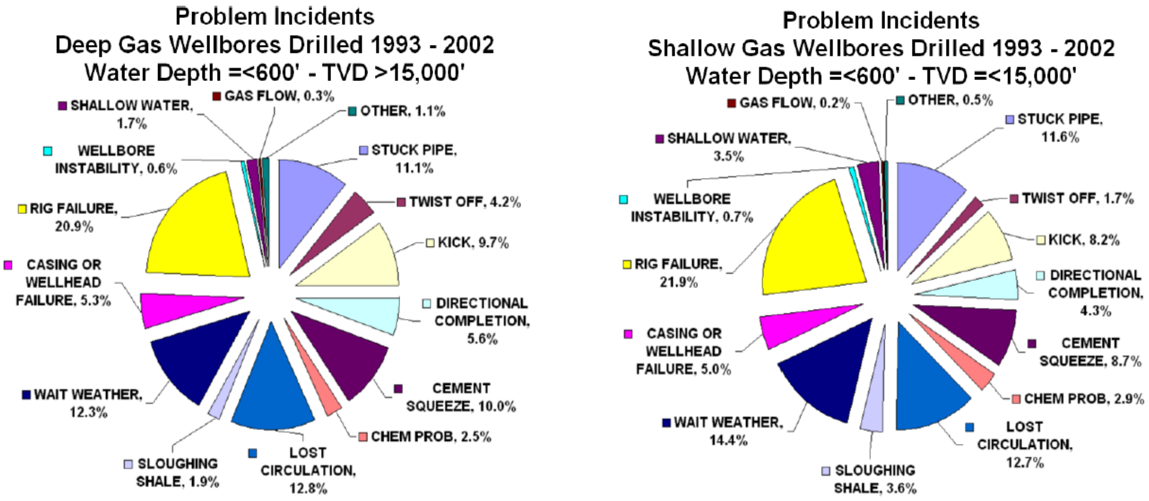


Figure 2: Reviewed non-productive time and drilling performance wells MD > 5000m [32]

Dodson 2004 [33] presented the study of NPT in the Gulf of Mexico, drilling in deep water and Extended Reach Drilling (ERD) wells. The data was taken from year 1993 and 2003 for gas wells as shown in Figure 3. The result shows that about 40% of NPT are because of pressure related problems such as kick, lost circulation etc. As can be seen about 12% of the NPT is caused by drill string sticking problems.



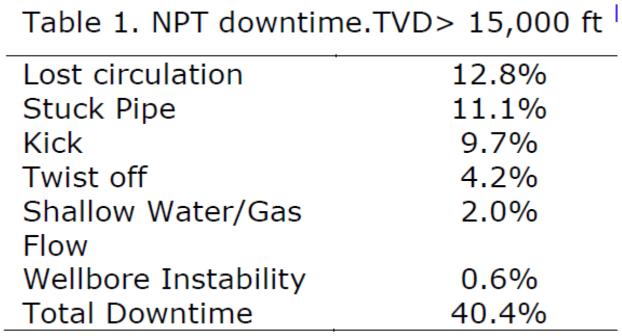


Table 1. NPT downtime.TVD> 15,000 ft

Lost circulation	12.8%
Stuck Pipe	11.1%
Kick	9.7%
Twist off	4.2%
Shallow Water/Gas Flow	2.0%
Wellbore Instability	0.6%
Total Downtime	40.4%

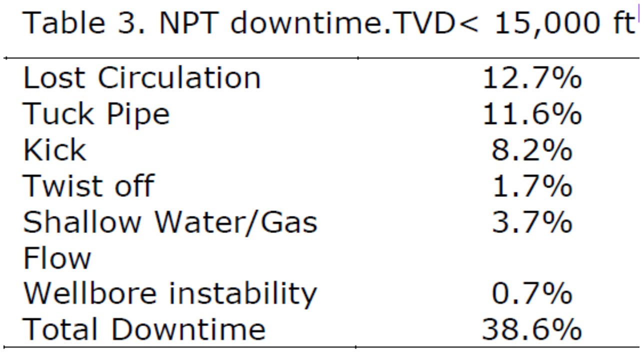


Table 3. NPT downtime.TVD< 15,000 ft

Lost Circulation	12.7%
Tuck Pipe	11.6%
Kick	8.2%
Twist off	1.7%
Shallow Water/Gas Flow	3.7%
Wellbore instability	0.7%
Total Downtime	38.6%

Figure 3: Contribution of different drilling problems [33]

1.2 Scope and Objective

Equipment failure is one of the factors that increase the NPT in terms of solving the problem. For instance the problem caused by mechanical sticking requires jarring operation in order to detach from the stuck. However the performance of the jarring and optimization is an important issue to be considered in order to design the accelerator and jarring systems. Therefore this thesis addresses issues such as

- main causes of the mechanical sticking
- performance of jarring
- optimize jarring operations

The scope and objective of the thesis is limited to literature study, modelling and numerical calculations. The activities of the thesis are:

1. To review causes of sticking and jarring operation
2. To present the theory behind jarring modeling
3. To present simulation case study to analyses upper and lower part of jar and accelerator house

1.3 Readers guide

- Chapter 1 presents background of the thesis focusing on non-productive and various factors contributing for the downtime
- Chapter 2 presents main causes of drill string sticking and jarring operations
- Chapter 3 present the theory of jarring modelling to be used for optimization study
- Chapter 4 presents jarring optimization simulation studies
- Chapter 5 presents summary and conclusion

2 Literature review

This chapter presents issues such as causes of drill string sticking, stuck point determinations modelling, jarring operations and methods how to solve sticking problem.

2.1 Causes of drill string stuck

The cause of stuck has been a huge problem in the history of the petroleum activities. The causes of drill string sticking may be categorized in to two namely due to differential sticking and due to mechanical sticking.

2.1.1 Differential sticking

Differential sticking occurs when the drill string gets embedded in a mudcake and is stuck to the borehole wall by the differential pressure between the mud and formation. Figure 4 shows differential pipe sticking.

This type of sticking gets progressively worse with time. Differential sticking of a pipe is caused by the differential pressure forces from an overbalanced mud column acting on the drill string against a filter cake deposited on a permeable formation. Conditions for differential sticking:

- Permeable zone covered with mud cake/ porous, permeable formation must exist.
- Stationary string
- Increased risk when making connection/survey/formation pressure measurement

The sign of differential pipe sticking are:

- Increased torque and drag when drilling depleted or permeable zones.
- Capability to circulate drilling fluid with inability to rotate drill string.

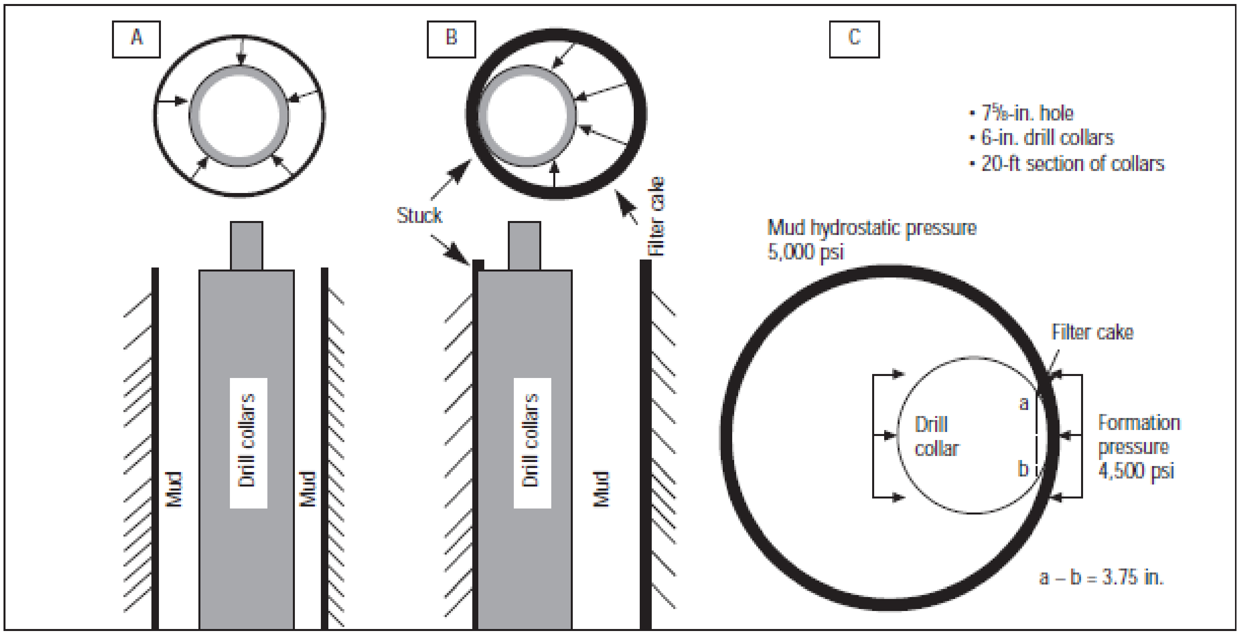


Figure 4: Differential pressure pipe sticking [34]

The differential pressure acting on portion of the drillpipe that is embedded in the mud cake can be written as:

$$\Delta P = P_m - P_{ff} \tag{1}$$

Where,

- P_m – Mud pressure (psi)
- P_{ff} – Formation fluid pressure (psi)

In terms of mud density the differential pressure can be calculated as:

$$\Delta P = 0.052 * \rho_m * TVD - P_f \tag{2}$$

where

- ρ_m - mud density (ppg) and
- TVD – True Vertical Depth (ft)

Sticking force

Mud sticking force is usually caused by the settling out of solids in the mud. Cuttings produces when drilling a well must be circulated out sufficiently to keep the hole clean. Otherwise, they will accumulate and causing sticking. The sticking force is calculated by the product of the differential pressure and the drill collar contact area

$$F = \mu \Delta P * A. \qquad 3$$

Where, μ is coefficient of friction, ΔP is differential pressure (Equation 2) and A is contact area.

The following present the determination of contact area. The figure below illustrates the differential sticking of a pipe.

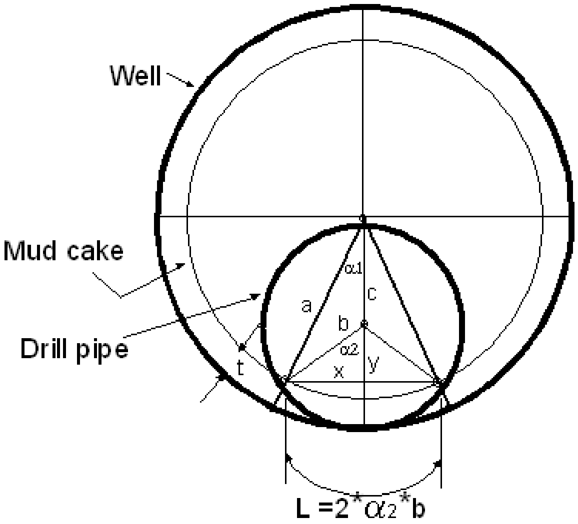


Figure 5 Illustration of drill collar without centralizer sticking in a well

$Sin\ \alpha_2$ is calculated from the given cosine angle, which reads:

$$\alpha_2 = \cos^{-1}\left(\frac{a^2 - b^2 - c^2}{2bc}\right) = \cos^{-1}\left(\frac{(R_w - t)^2 - R_p^2 - (R_w - R_p)^2}{2R_p(R_w - R_p)}\right) \qquad 4$$

For the computation of contact area, some companies use an arc length and some other use a chord.

Chord (X=2x, where x = b*sin α_2) is given as:

$$X = 2b^*\sin\alpha_2 = 2R_p^*\sin\alpha_2 \qquad 5$$

$$X = 2R_p\sqrt{1 - \cos^2_{\alpha_2}} = 2R_p\sqrt{1 - \left\{\frac{(R_w - t)^2 - R_p^2 - (R_w - R_p)^2}{2R_p(R_w - R_p)}\right\}^2} \qquad 6$$

Arc length is given as:

$$L = 2R_p\cos^{-1}\left\{\frac{(R_w - t)^2 - R_p^2 - (R_w - R_p)^2}{2R_p(R_w - R_p)}\right\} \qquad 7$$

Both (Chord Eq. 6) and (Arc length, Eq. 7) use the thickness of the mud cake is an input parameter.

The area in the absence of centralizer is calculated as the following.

a) Using Chord

$A = X.DC_{Length}$ where X is given as Equ.6 8

b) Using Arc length

$A = L.DC_{Length}$ where, L is given as Equ7 9

2.1.2 Mechanical sticking

Poor hole cleaning leads to the overloading of the annulus between the drill string and the borehole wall with cuttings, causing the drill string to get stuck. Keyseats, or grooves cut in the borehole wall by the rotating drill pipe stick the larger diameter drill collars when trapping out. Occasionally, the casing may collapse as a result of excessive formation pressure causing sticking of the drill string.

Formation related such as unconsolidated formations such as loosely compacted sands and gravel can collapse into the wellbore forming a bridge around the drill string. Mobile formations like salt and plastic shales flow into the wellbore when restraining stresses are removed thereby jamming the drill string. Rig site indications among others are [39] [29]:

- Increase in pump pressure.
- Fill on bottom.
- Overpull on connections.
- Shakers blinding.
- Increase torque and drag

The following presents the mechanical drill string sticking.

2.1.2.1 Mud sticking

Mud sticking may occur in open and cased holes. For whatever reason, the solids that make up part of the mud can settle out of suspension. Solids can be barite particles or cuttings. In a high temperature well, the mud can lose the fluid phase (filtrate) leaving the solids packed around the string. In addition, sometimes contamination, such as acids or salts, can alter the mud properties. This can lead to the loss of suspension properties of the mud.[13]

2.1.2.2 Undergauge hole sticking

An undergauge hole is any hole that has a smaller diameter than the bit that drilled that section of hole as shown in Figure 6. One potential cause of an undergauge condition is drilling a high clay content plastic shale with a fresh water mud. If an oil- based mud is used, a plastic salt formation can "flow" into the wellbore. If the wellbore fluid has a hydrostatic pressure less than the formation pressure, the shale or salt will slowly ooze into the wellbore [13], [34]. It is a slow process, but one that can stick drilling tools of the unwary.

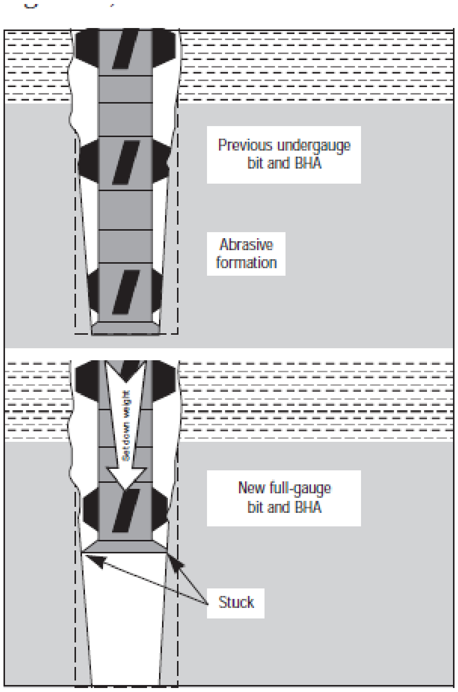


Figure 6: Undergauge hole sticking [34]

An undergauge hole can also occur after a drill bit is worn smaller as it drills through an abrasive formation. In this case, the hole is undergauge because the bit drilled it that way. If a new bit is run, it can jam into the undergauge section of the hole and become stuck. This is often called tapered hole sticking. The presence of a thick filter cake, described in Stuck Drill String Problems, Differential Pressure Sticking above, can also cause an undergauge hole. The filter cake can become so thick that tools cannot drag through it.

2.1.2.3 Key Seat sticking

When a well deviates from the vertical, the subsequent rotation of the pipe and particularly the hard banded tools joints in the area of the “dogleg” wear a slot in the well bore that is smaller than the gauge hole (Shown in figure below). This undersize slot creates a hazard in “tripping” the pipe in and out of the hole. Frequently when pulling the pipe out of the hole, the larger drill collars are pulled up into this key seat and stuck [13] [34][13][5]. There is a natural tendency on the part of driller to pull harder as he observes the pipe tending to stick. This, of course, merely makes the situation worse. Figure 7 shows keyseat in openhole.

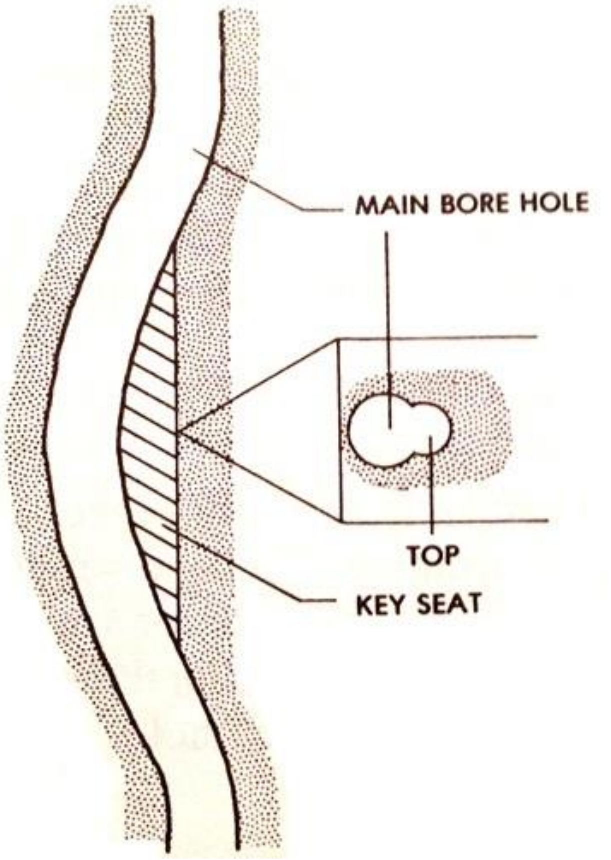


Figure 7: Keyseat cut in the open hole [5]

2.1.2.4 Cement sticking

It can occur because of leak, human factor, intentional cementing or mechanical failure in equipment. For cement sticking usually flash setting or premature is blamed. If cuttings are allowed to settle out of the fluid they will stick the pipe momentously.

Another thing is also that cement around casing shoe or open hole squeeze becomes unstable and finally chunks of cement fall into a wellbore [13][34]The drill string will be stuck if there will be a lot of cement in the annulus. Figure 8 shows cement block leaks through rathole below casing shoe and causes stuck pipe.

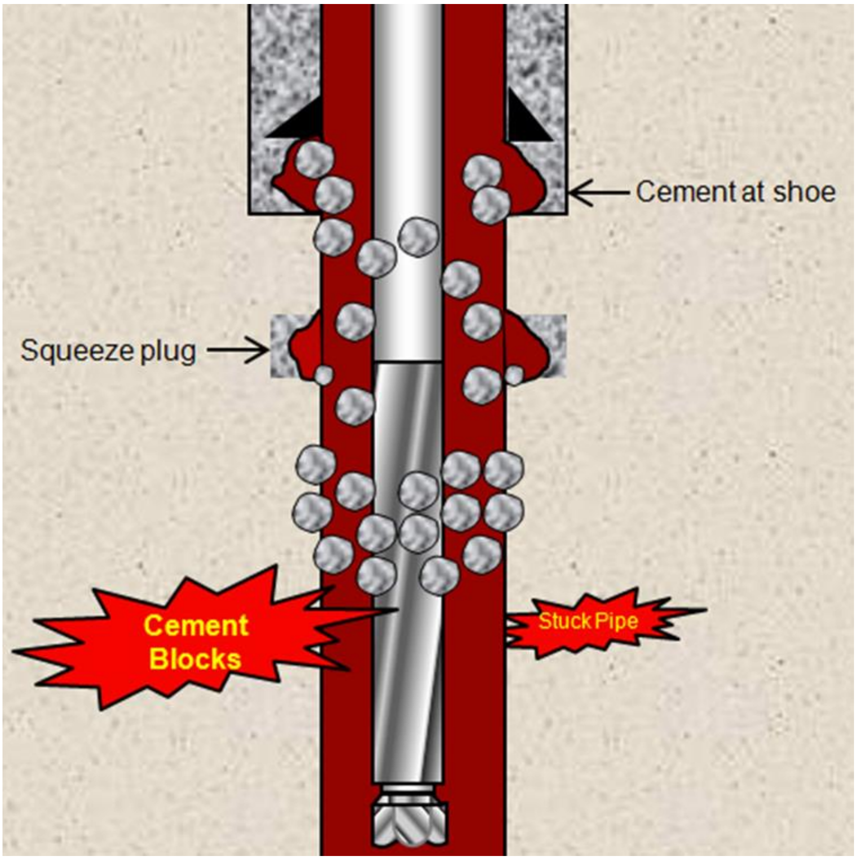


Figure 8: Cement blocks causes stuck pipe [13]

2.1.2.5 Sloughing hole sticking

Sloughing hole sticking occurs after the hole wall sloughs off. For example, water sensitive shale that has been invaded by water will swell and break. If circulation is stopped, the broken pieces will collect around the drill string and eventually pack the drill string in place. Figure 9 illustrate drill string sticking caused by reactive formations [13] [34].

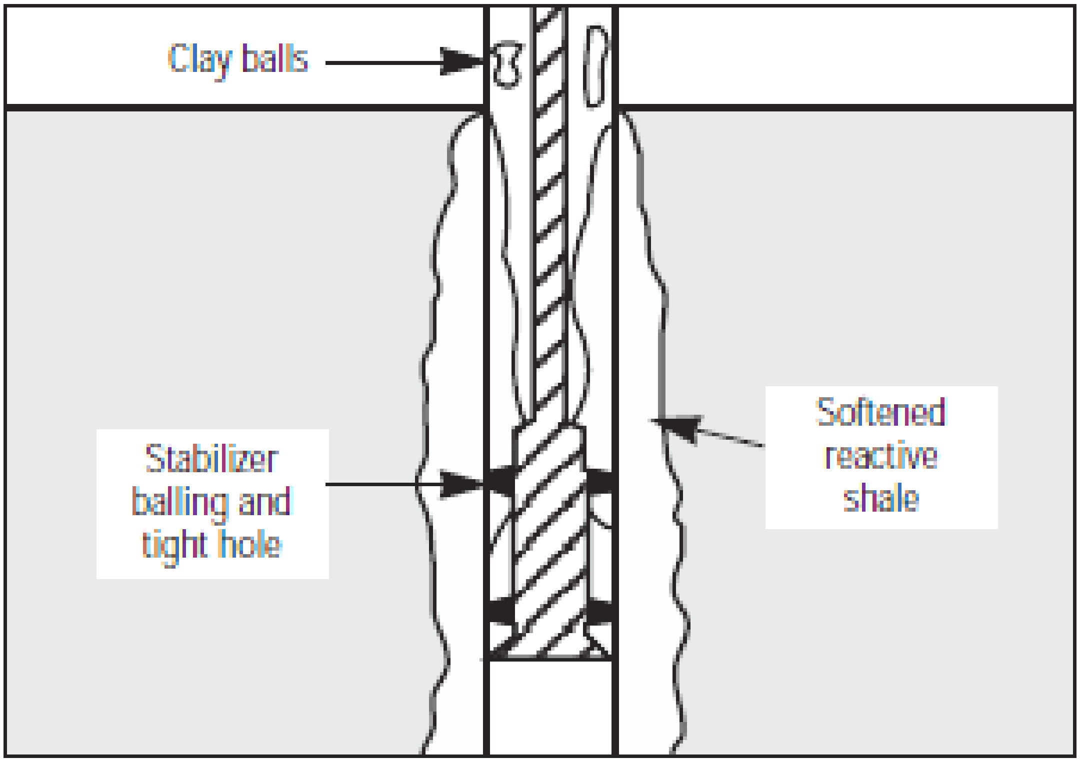


Figure 9: Reactive formations [34]

Shales under high formation pressure can slough as well. In this case, the formation pressure is greater than the wellbore hydrostatic pressure. Because the shale has a very low permeability, no flow is observed. The rock, having a high pressure differential toward the well bore, shears off the hole wall. This can be seen as large cuttings on the shale shaker screen. Sometimes, the borehole curvature can be seen on the cuttings, a classic sign of entering a high pressure zone. If too much sloughing occurs or the wellbore is not cleaned properly, the drill string can become stuck. More than likely, circulation will cease and no movement will be possible.

Steeply dipping and fractured formations also can slough into the hole. Drilling in over thrust belts is notorious for this problem. Also, if there are cavities in the wellbore, cuttings can collect there. After the circulation stops, the cuttings in the cavities may fall back into the hole.

2.1.2.6 Inadequate hole cleaning sticking

Inadequate hole cleaning sticking occurs after the flow rate of the circulation fluid slows to the point that the solids' carrying capacity of circulation fluid has been exceeded by the force of gravity. If the fluid is not viscous enough or flowing fast enough, the drag forces on the solids are less than the gravity forces. This means that the solids flow down the hole, instead of up and out of the hole. The hole fills up with solids that build up around the string, eventually sticking the string.

This flow rate can slow down for a number of reasons including:

(i) the driller may not be running the pumps fast enough;
(ii) there could be a hole enlargement in the drill string that slows the flow rate (e.g. a washout); or,
(iii) the amount of solids may become overwhelming as a result of sloughing shales, unconsolidated formations, or lost circulation.

Figure 10 illustrates the accumulation of cutting in a well due to poor hole cleaning.

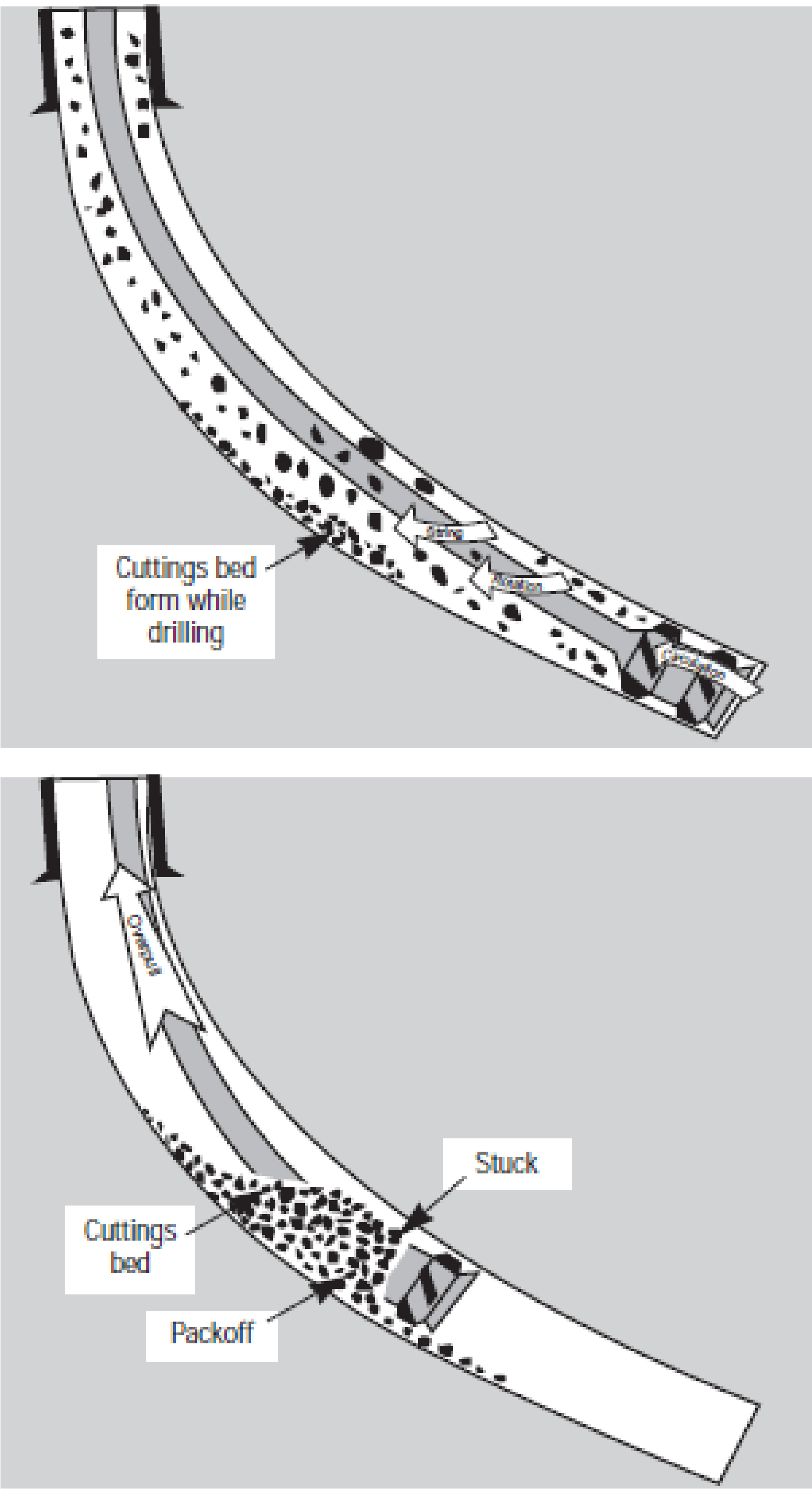


Figure 10: Settled cuttings [34]

2.1.2.7 Unconsolidated formation

It is occur during drilling operation into different unconsolidated formations as sand, gravel, etc. Particles in the formation will separate and fall down hole, since the bond between particles are not strong. The drillstring can also be packed off if there are a lot of unconsolidated particles in the annulus.

Unconsolidated formations such as loosely compacted sands and gravel can collapse into the wellbore forming a bridge around the drillstring. Highly Unconsolidated sand formation falls into the well bore because it is loosely packed with little or no bonding between particles, pebbles or boulders. [39]

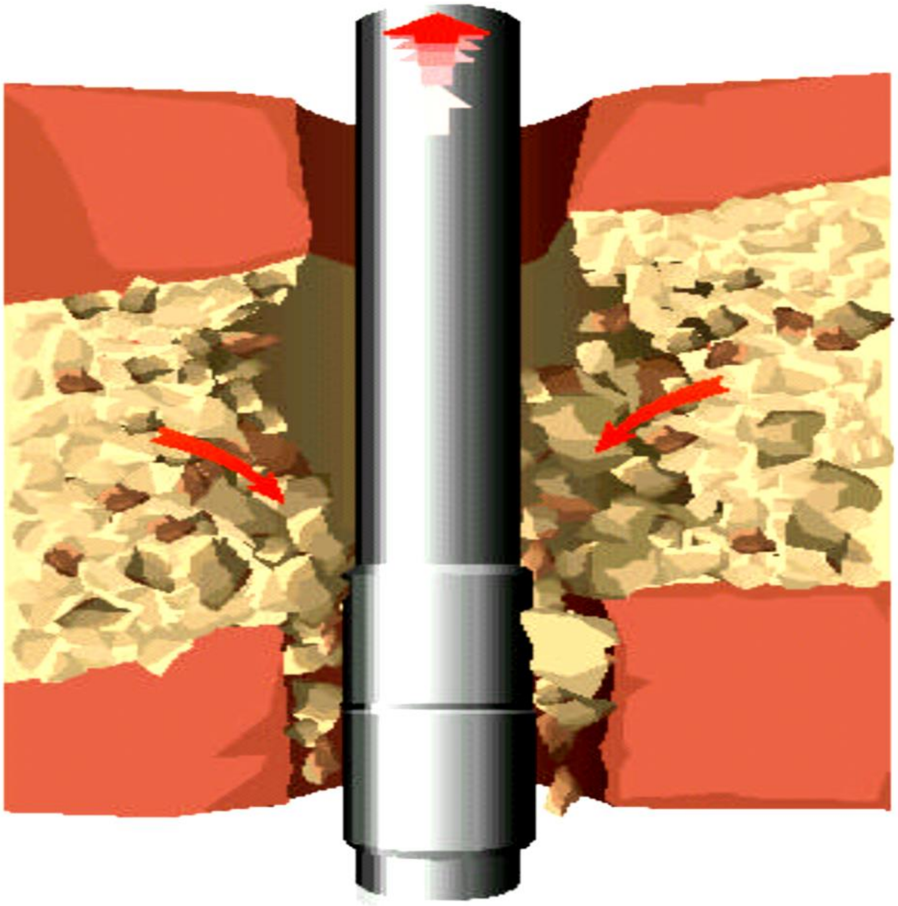


Figure 11: Unconsolidated formation and packoff [39]

Figure 11 illustrates unconsolidated formation and the resulting pack-off at tool joint. The collapse of the formation is caused by removing the supporting rock as the well is drilled. This is very similar to digging a hole in sand on the beach, the faster you dig the faster the hole collapses. It happens in a well bore when little or no filter cake is present. The un-bonded formation (sand, gravel, small river bed boulders etc.) cannot be supported by hydrostatic overbalance as the fluid simply flows into the formation. Sand or gravel then falls into the hole and packs off the drill string. The effect can be a gradual increase in drag. This mechanism is normally associated with shallow formations. Examples are shallow river bed structures at about 500m in the central North Sea and in surface hole sections of land wells.

Preventative Action

These formations need an adequate filter cake to help stabilize the formation. Seepage loss can be minimized with fine lost circulation material. If possible, avoid excessive circulating time to reduce hydraulic erosion.

- Spot a gel pill before POOH.
- Slow down tripping speed to avoid mechanical damage with BHA.
- Start and stop the pumps slowly to avoid pressure surges being applied to unconsolidated formations.
- Use sweeps to help keep the hole clean.

A method successfully used in the North Sea is to drill 10m, pull back to the top of the section and wait 10 minutes. Note any fill on bottom when returning to drill ahead. If the fill is significant then ensure the process is repeated every 10m [39].

2.1.2.8 Fractured formation

This happens when drilling operations occurs into fractured formations, then the particles of formation will fall down in the annulus and stuck drill string. Figure 12 shows drilling through faulted chalk formation and the resulting bridging. [34]

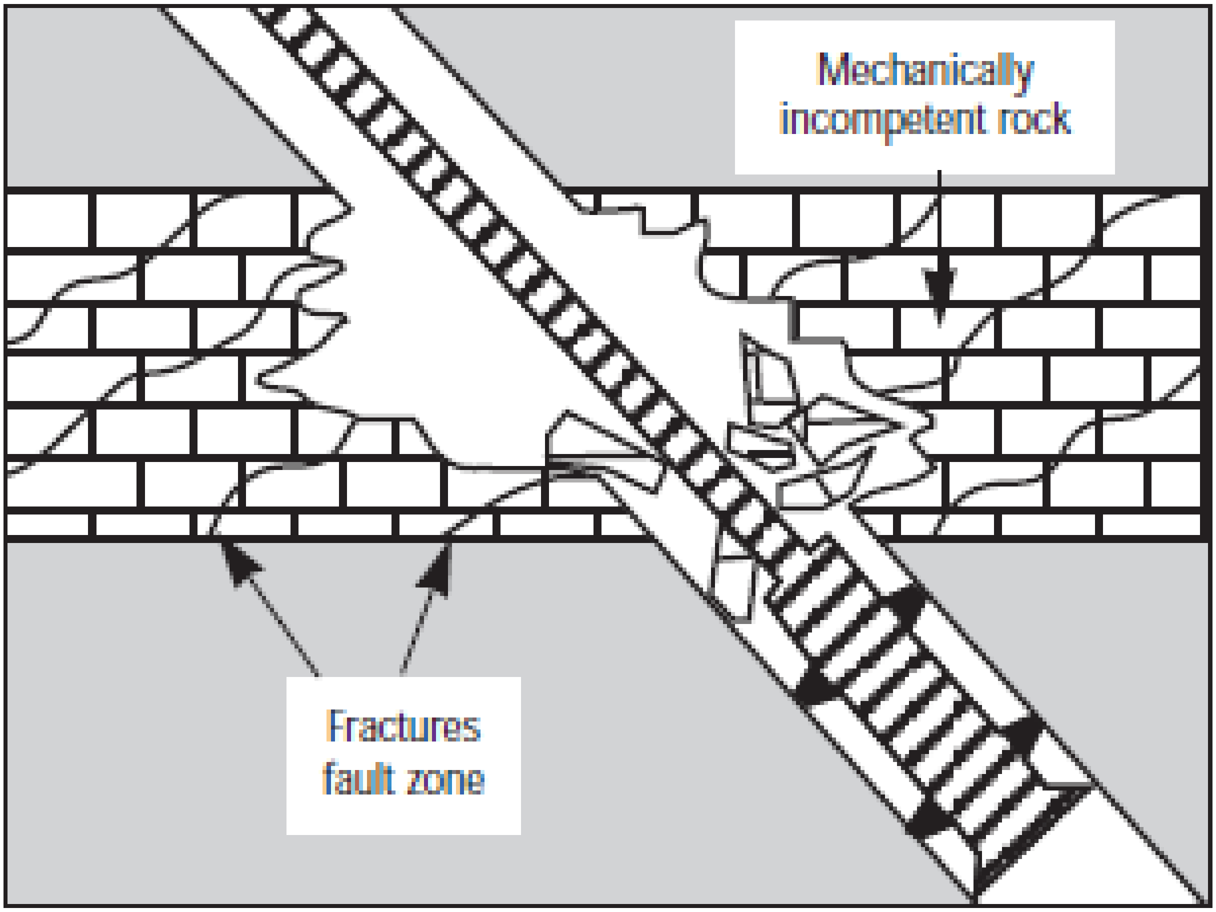


Figure 12: Fractured am faulted formation [34]

2.1.3 Techniques for freeing the drillstring

There are a number of techniques employed by the drilling industry to free stuckpipe. They range from the use of gentler measures like using spotting fluids, hole conditioning and changes in hydrostatic pressure to more brute force methods like jarring. Spotting fluids essentially change the down hole conditions so as to weaken the bond between the mudcake and the pipe. Hole conditioning involves increasing the mud flow rate or changing mud physical properties. Reduction in hydrostatic pressure is used mainly to free differentially stuck pipe. When the gentler methods of persuasion fail to produce the desired results, jarring is resorted to.

Jars are impact tools run in the drill string to free stuck pipe and the process of attempting to free stuck pipe is called jarring. A jar looks like a drill collar and it consists of a mandrel inside a sleeve which accelerates upwards and downwards. Once the mandrel has traversed the stroke length of the jar, it collides with a shouldered sleeve also known as the anvil. This impact creates a shock wave that traverses up and down the drill string and to the stuck region. The intention is to break the drill string loose from the stuck region.[5][6]

Freepoint tool

For more accuracy the free point tool (FP tool) can be used. But make sure that wireline tool must be run inside the drill string. The FP tool includes electromagnets or spring loaded drag blocks and set of strain gauges that rub against the string inside it. The string has tension applied or torsion when the free point instrument is run into the string. During pipe movement the degree of that comes to the surface through the wireline. When the FP tool is below the stuck point no movement of the string will be detected [2] [5]

Buoyancy

The buoyancy force must be dealt with constantly in drilling wells and to a lesser degree in producing wells or cased holes. It may be a considerable factor in determining such variables as the number of drill collars to run. As an example, a drill collar has a buoyed weight of only approximately three-fourths of air weight in 16 ppg mud. However, when pipe is stuck, the buoyant forces are being exerted against the stuck section, and therefore there is no effective buoyant force at the surface. Immediately when the pipe is freed, the buoyant forces are again in effect and are to be reckoned with accordingly. This method is ignoring the cumulative length of the tool joints or couplings and the small hydrostatic forces tending to buoy them.[2] [5]

Stuck pipe logs

By using stuck pipe logs method the length and severity of stuck pipe can be measured. The pipe recovery log expresses the sticking condition as a percentage, as shown below. A vibration is used and measured by a receiver. At stuck intervals, the sonic vibrations decrease in proportion to the severity of the sticking. The downhole tool is calibrated in known free pipe, normally near the bottom of the surface pipe. The pipe recovery log gives a complete record of all stuck intervals and possible trouble areas in a sting of stuck pipe. This information is very useful in evaluating conditions to determine whether to jar on the stuck section, to wash over the fish, or in some cases, to sidetrack. It may be used in drill pipe, tubing, casing, or washpipe. [5]

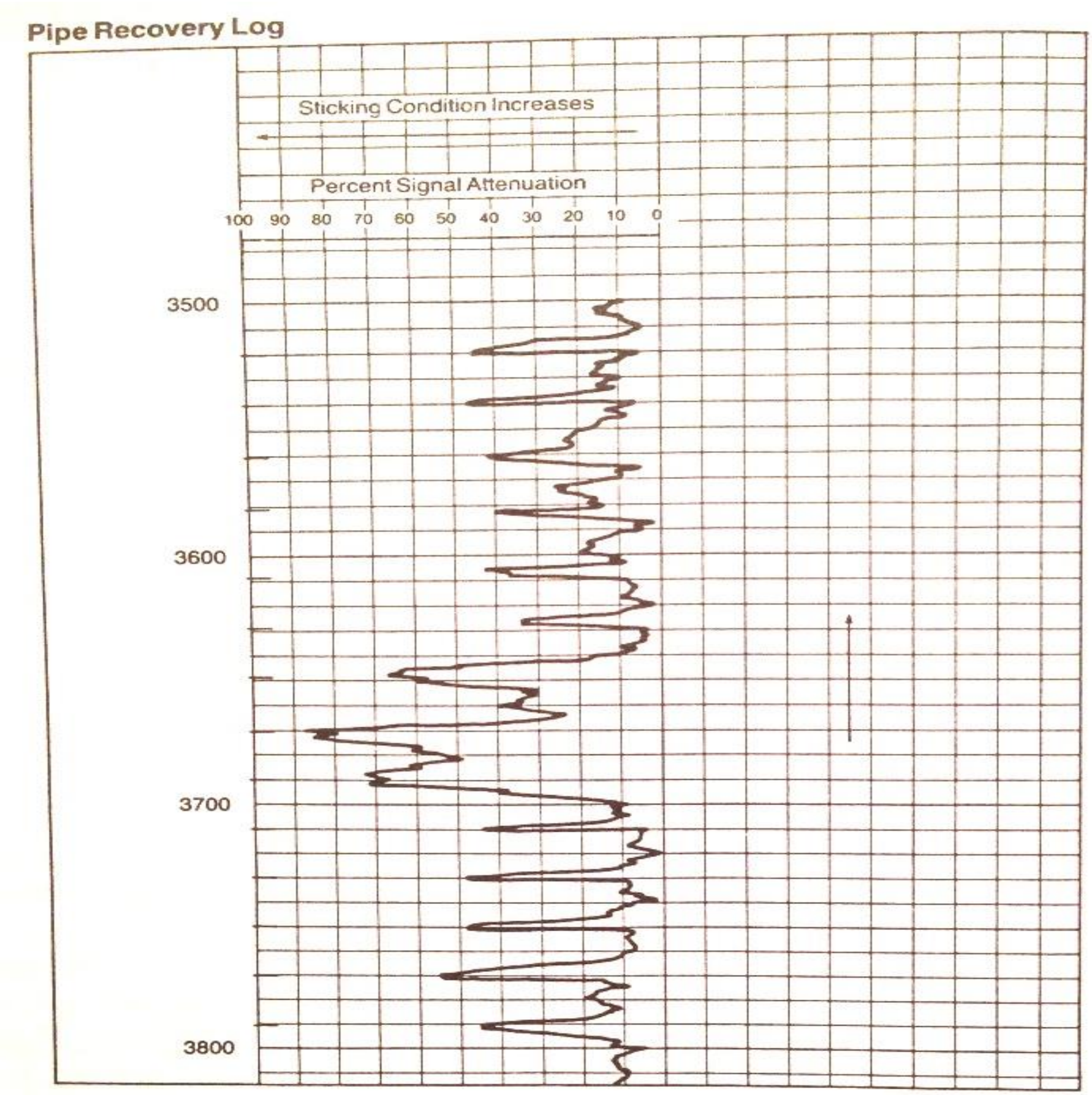


Figure 13. Pipe recovery log [5].

2.1.4 Stuck point determination

There are techniques that can be used to determine the location at which the string is stuck (the "stuck point"). They involve either stretching the string with a known load or running a special wireline tool. The best method depends on the time available and the accuracy needed.

When pipe becomes stuck for any of the reasons described, the first step is to determine at what depth the sticking has occurred. Stretch pipe can be measured and a calculation made to estimate the depth to the top of the stuck pipe. The following presents the stuck point determination models for vertical and deviated wells.

2.1.4.1 Vertical section

A stretch calculation is the quick method of determining the stuck point. This test assumes that the same type of string is connected from the surface to the fish. To run this test, the string is pulled to a given tension on the weight indicator and a mark is made on the string opposite the rotary table top. Then more tension is pulled on the string and another mark is made on the string opposite the rotary table. There should be some distance between the two marks. That distance is proportional to the load pulled and the length of the string that is free if buckles have been removed.

2.1.4.2 Deviated well

The Aadnøys model can be applied for different well geometries.

Vetical section-one sized drill pipe and n-elements

- Calculate: Static load and apply extra load that overcome the static load.
- Measure the extra force: dF, and measure dL, elongation

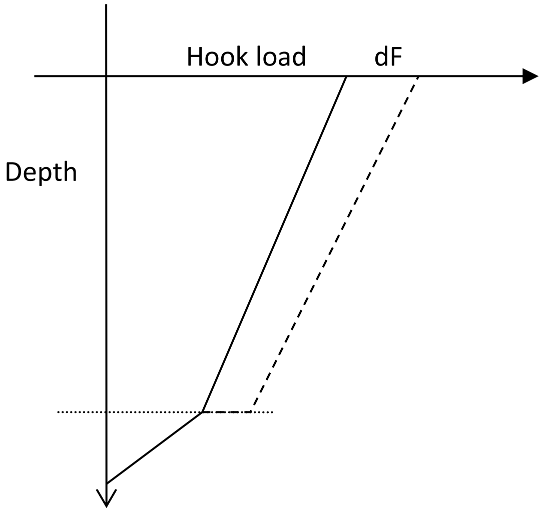


Figure 14: Vertical well geometry [35]

i elements

Assuming no friction (μ =0)

For *i* elements and for the measured *dF* and *dL*, one obtain:

$$dL = \frac{1}{E}\sum_{n=0}^{i}\frac{L_n}{A_n}dF_i \qquad 10$$

One element

Since the BHA part is stiff, then above will use one drill pipe as:

$$L = EA\frac{dL}{dF} \qquad 11$$

<u>Vetical/bend/sail section-one sized (A1) dril pipe</u>

Figure 15 shows the force in drill strings, which are combination of vertical, bend and sail section of a wellbore. Using the similarly test procedure, we measure the top differential load that overcomes the static load, and measure the corresponding elongation dL.

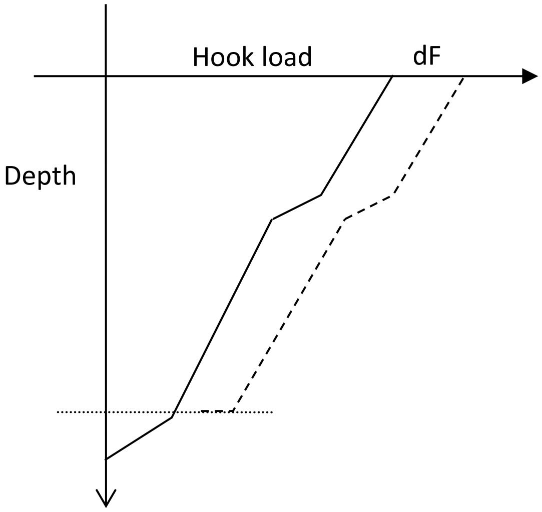


Figure 15 Vertical/bend/sail section-one sized (A1) dril pipe [35]

In their analysis, they neglected the effect of Drag. The application pull load increase the friction on the belt, and one can write:

One element

The depth of stuck pipe (If one drill pipe is used, A)

$$L = AEe^{\mu\alpha}\frac{dL}{dF} - \left(e^{\mu\alpha} - 1\right)\left(L_1 + \frac{1}{2}\alpha R\right) \qquad 12$$

Where,

L_1 = length in vertical section, R = Radius of curvature, A = cross sectional area

2.1.4.2 Vertical/bend/sail section-two sized (A1 and A2) dril pipe

The depth of stuck pipe (If two drill pipe are used, 1 = top, and 2 = bottom) the above Eq. 12 will be given as:

$$L = A_2Ee^{\mu\alpha}\frac{dL}{dF} - \frac{A_2}{A_1}\left(e^{\mu\alpha} - 1\right)\left(L_1 + \frac{1}{2}\alpha R\right) - L_2\left(\frac{A_2}{A_1} - 1\right) \qquad 13$$

L = Total length and L_1 = length in vertical section

2.2 Jarring and fishing operations

This chapter presents the causes of drill string sticking, jarring operation and methods how to solve sticking problem.

During planning of a well it is always calculates approximately costs of possible troubles. For example, for stuck pipe in deep wells it can be significant part of the overall budget. Drill string sticking occurs in two ways. These are Due to mechanical (Pack off and bridging) and Differential sticking

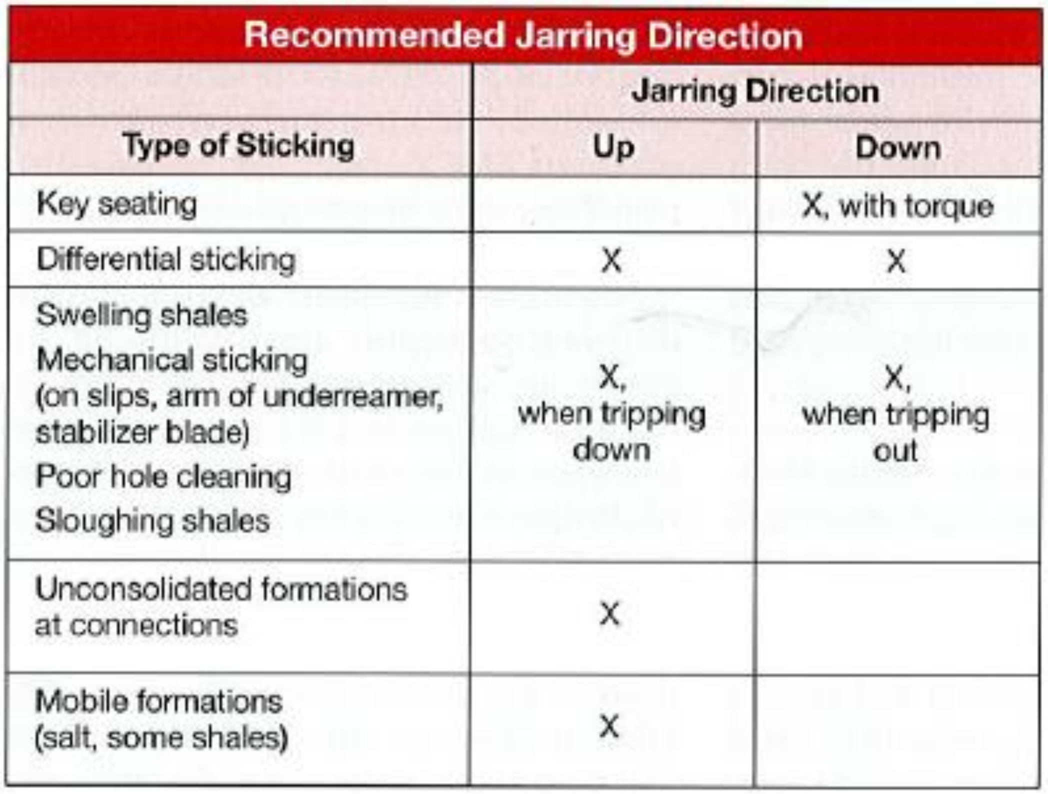
There are several problems during operations. Many of the causes that happens to drilling/fishing operations can be prevented by professional planning and following the drilling operation process for possible unusual data from indicators which may indicate problems in the borehole. The most well-known causes of fishing operations will be discussed below.

2.2.1 Jars and Jarring Operations

A jar is a device used down hole to create and deliver an impact to the stuck point by releasing energy stored in a stretched drill string.

One of the most important things in jarring operations is the correct interpretation of surface measurements.

Oil jars or hydraulic jars are designed to jar upward and free a fish. It is important to have these jars as close to the stuck point as possible. To get the benefit of the jarring action, it is important to know the jarring strength of the jars in use. This is important as not to exceed this weight. Bumper jars are designed to jar downward on a fish by dropping the string very rapidly and stopping it quickly just as the jars close. This gives a downward slapping action; these jars should be as close to the stuck point as possible. Bumper jars are very helpful in other ways. When fishing, they give an exact weight at the depth they placed by working the string up and down. In open hole, once the fish is engaged the work string can be moved up and down the length of the jar travel. Quite often this prevents wall sticking. Accelerator jars or intensifier jars are used to increase the effectiveness of hydraulic jars. They are run above the hydraulic jars with a specified number of drill collars to get the desired weight between them and the hydraulic jars. They move this mass upward much faster when the hydraulic jars hit, therefore, increasing the upward blow to the fish. Table 1: shows recommended jarring operations [14] [36]



Recommended Jarring Direction

	Jarring Direction	
Type of Sticking	**Up**	**Down**
Key seating		X, with torque
Differential sticking	X	X
Swelling shales Mechanical sticking (on slips, arm of underreamer, stabilizer blade) Poor hole cleaning Sloughing shales	X, when tripping down	X, when tripping out
Unconsolidated formations at connections	X	
Mobile formations (salt, some shales)	X	

Table 1: Recommended jarring operations [36]

2.2.1.1 Main components of jar assembly

There are some basic components in a fishing tool, such as jars, bumper subs and intensifiers. The bumper sub uses to withstand displacements and sustained bumping loads in drilling and fishing operations. The design of those tools allows 10 to 60 inch vertical strokes downward. The ease of the stroke could be affected; on other hand the stroke is always available in the tool. For high circulation pressures should be used the lubricated bumper sub. Figure 16 shows the components of jar

Bumper subs can help to free drill collars, drillpipe, bits, etc that become keyseated, lodged or stuck. The drillstring stretch must be utilized for the speed for the impact; it is uses for best possible impact.

- Drill pipe
- Jar connecting pipe
- Mud passage
- Anvil (Ambolt)
- Seal
- Hammer
- Splines
- Drill collar

.

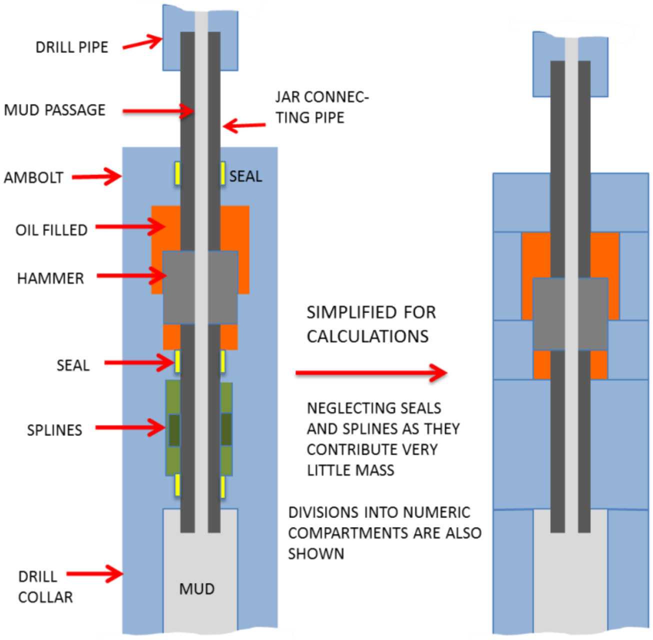


Figure 16 Simple drawing of the jar string

2.2.1.2 Performance of jars

A jar contains a hammer and anvil to deliver an impact (like a slide hammer) and a trigger mechanism. Under the influence of an applied load (drill string tension or drill string weight), when the jar trigger trips, the hammer travels the length of the jar's up or down free stroke as appropriate and strikes the anvil. The resultant impact is several times greater than the applied load. To jar again, the jar is re-cocked and the procedure is repeated until the drill string comes free. The description "mechanical" or "hydraulic" refers to the trigger mechanism. Apart from the trigger, mechanical and hydraulic jars are very similar.

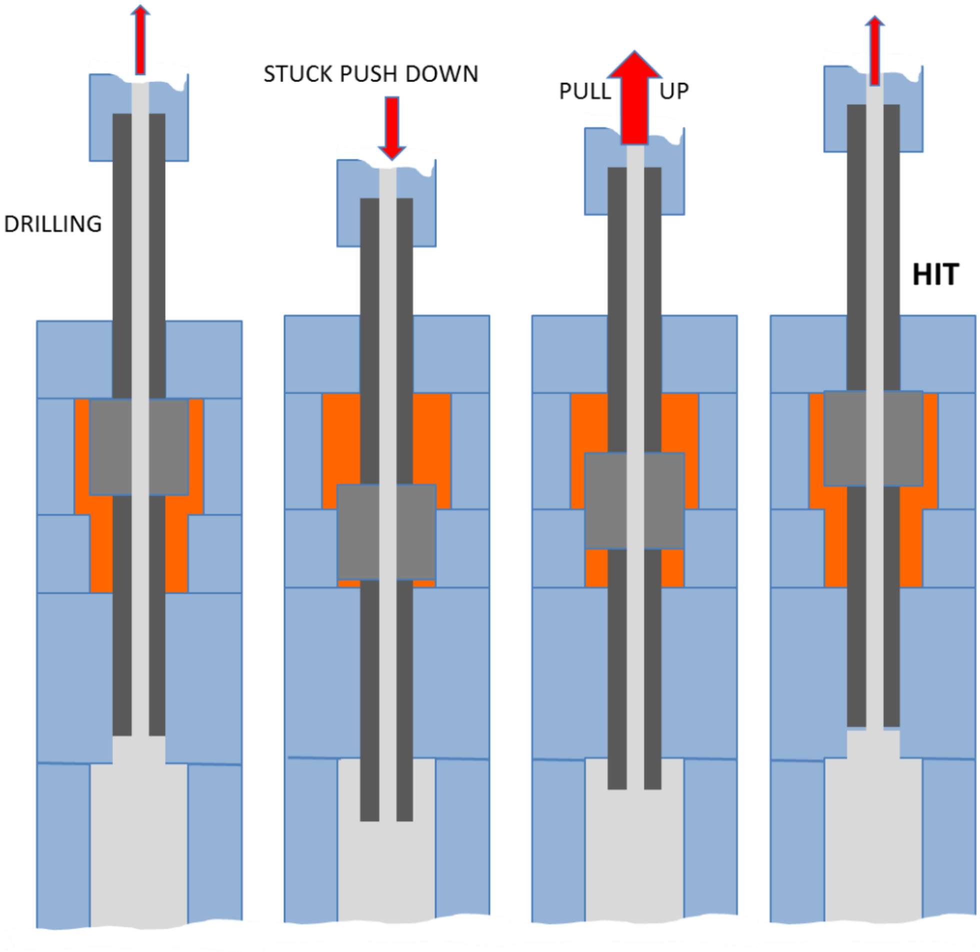


Figure 17 The drawing shows how to simplify the string for easy calculation

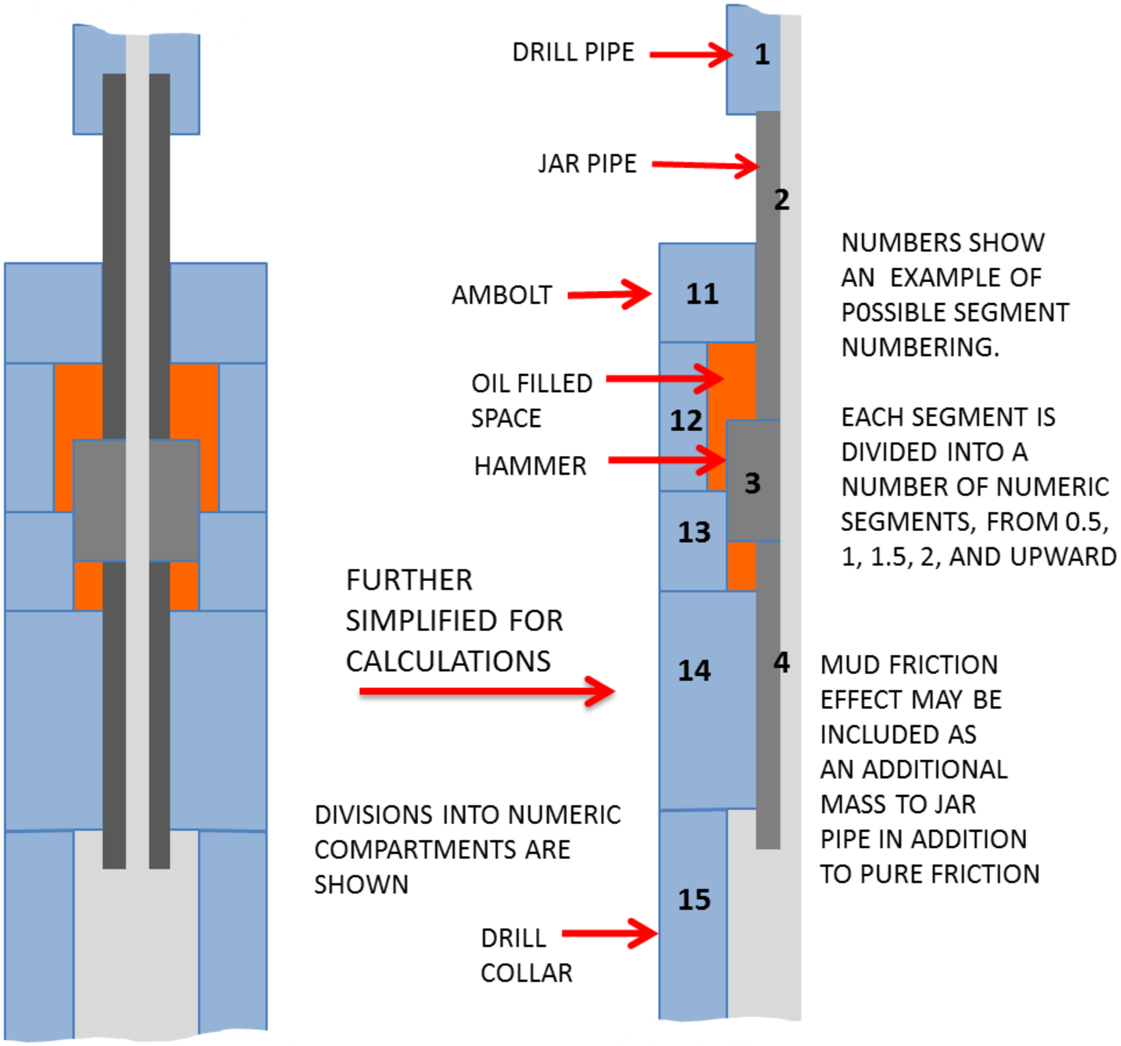


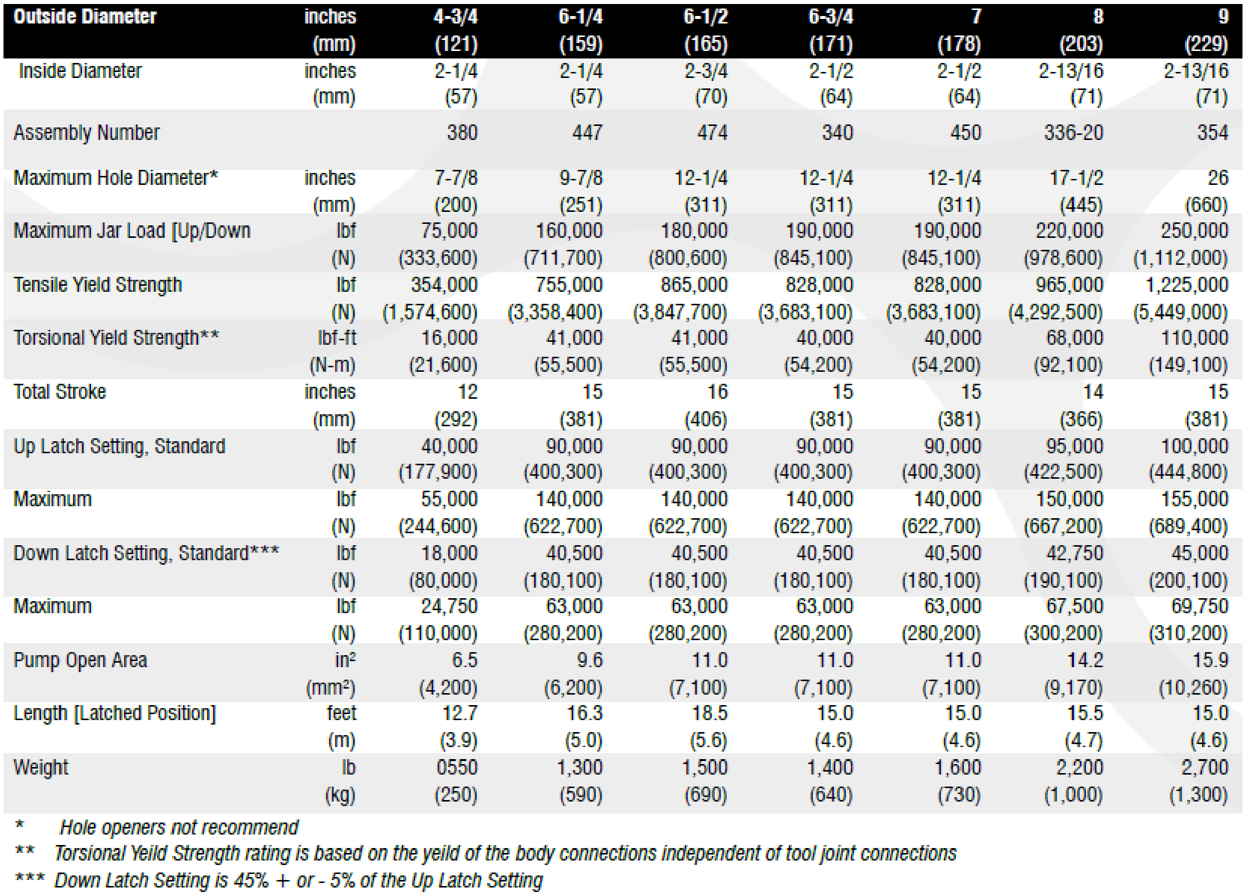
Figure 18: How the jar string works

2.2.2 Types of jars

There are three types of jars. These are [18]:

- Mechanical jars
- Hydraulic jars
- Hydro-mechanical jars

But only mechanical and hydraulic jars used mostly in jarring operation. Table 2 shows n example of the specifications for hydraulic/mechanical drilling jars [32].



Outside Diameter	**inches**	**4-3/4**	**6-1/4**	**6-1/2**	**6-3/4**	**7**	**8**	**9**
	(mm)	**(121)**	**(159)**	**(165)**	**(171)**	**(178)**	**(203)**	**(229)**
Inside Diameter	inches	2-1/4	2-1/4	2-3/4	2-1/2	2-1/2	2-13/16	2-13/16
	(mm)	(57)	(57)	(70)	(64)	(64)	(71)	(71)
Assembly Number		380	447	474	340	450	336-20	354
Maximum Hole Diameter*	inches	7-7/8	9-7/8	12-1/4	12-1/4	12-1/4	17-1/2	26
	(mm)	(200)	(251)	(311)	(311)	(311)	(445)	(660)
Maximum Jar Load [Up/Down	lbf	75,000	160,000	180,000	190,000	190,000	220,000	250,000
	(N)	(333,600)	(711,700)	(800,600)	(845,100)	(845,100)	(978,600)	(1,112,000)
Tensile Yield Strength	lbf	354,000	755,000	865,000	828,000	828,000	965,000	1,225,000
	(N)	(1,574,600)	(3,358,400)	(3,847,700)	(3,683,100)	(3,683,100)	(4,292,500)	(5,449,000)
Torsional Yield Strength**	lbf-ft	16,000	41,000	41,000	40,000	40,000	68,000	110,000
	(N-m)	(21,600)	(55,500)	(55,500)	(54,200)	(54,200)	(92,100)	(149,100)
Total Stroke	inches	12	15	16	15	15	14	15
	(mm)	(292)	(381)	(406)	(381)	(381)	(366)	(381)
Up Latch Setting, Standard	lbf	40,000	90,000	90,000	90,000	90,000	95,000	100,000
	(N)	(177,900)	(400,300)	(400,300)	(400,300)	(400,300)	(422,500)	(444,800)
Maximum	lbf	55,000	140,000	140,000	140,000	140,000	150,000	155,000
	(N)	(244,600)	(622,700)	(622,700)	(622,700)	(622,700)	(667,200)	(689,400)
Down Latch Setting, Standard***	lbf	18,000	40,500	40,500	40,500	40,500	42,750	45,000
	(N)	(80,000)	(180,100)	(180,100)	(180,100)	(180,100)	(190,100)	(200,100)
Maximum	lbf	24,750	63,000	63,000	63,000	63,000	67,500	69,750
	(N)	(110,000)	(280,200)	(280,200)	(280,200)	(280,200)	(300,200)	(310,200)
Pump Open Area	in²	6.5	9.6	11.0	11.0	11.0	14.2	15.9
	(mm²)	(4,200)	(6,200)	(7,100)	(7,100)	(7,100)	(9,170)	(10,260)
Length [Latched Position]	feet	12.7	16.3	18.5	15.0	15.0	15.5	15.0
	(m)	(3.9)	(5.0)	(5.6)	(4.6)	(4.6)	(4.7)	(4.6)
Weight	lb	0550	1,300	1,500	1,400	1,600	2,200	2,700
	(kg)	(250)	(590)	(690)	(640)	(730)	(1,000)	(1,300)

* *Hole openers not recommend*

** *Torsional Yeild Strength rating is based on the yeild of the body connections independent of tool joint connections*

*** *Down Latch Setting is 45% + or - 5% of the Up Latch Setting*

Table 2: An example of the specifications for hydraulic/mechanical drilling jars [38].

2.2.2.1 Mechanical jars

Mechanical jars consist of a series of springs and lock & release mechanisms. The jar trips when the axial force reaches a preset value. The tripping load can be set either at the surface or down hole depending on the jar design. Figure 19 Mechanical jar. [18]

The jar trigger is mechanical and the load to trip the trigger up or down is preset. The jar will trip only when the applied load exceeds the setting and will then fire immediately. The jar is normally used latched at mid-stroke ready to jar up or down, but can be used fully open or fully closed. If any load on the jar would tend to open it, the jar is "in tension." If the load tends to close it is "in compression."

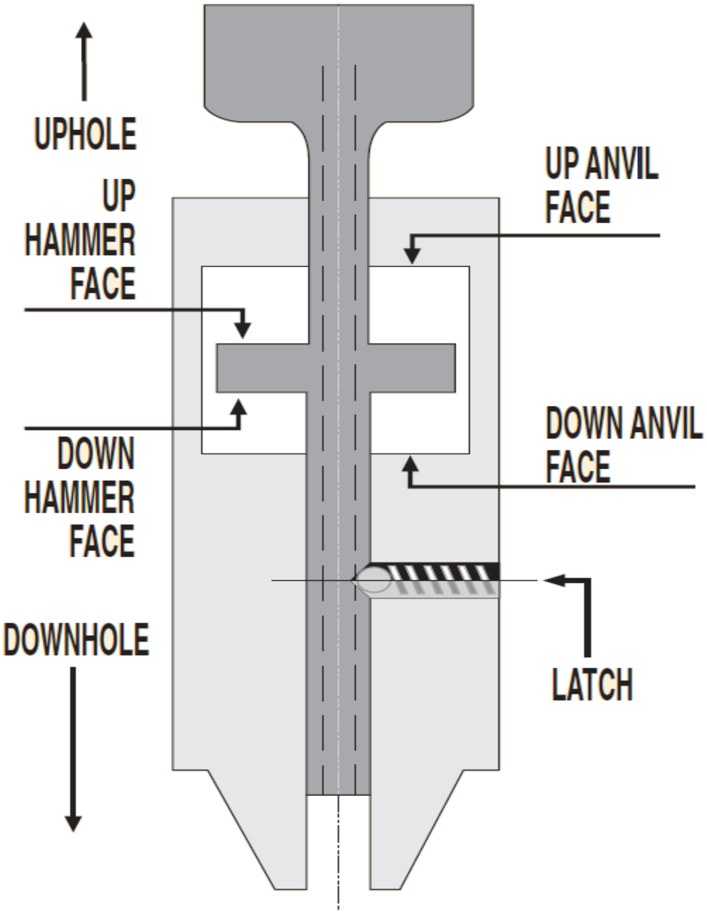


Figure 19: Mechanical jar [18]

2.2.2.2 Hydraulic Jars

A hydraulic jar has the same up and down free stroke as a mechanical jar, and the same anvil and hammer, but between the up and down stroke is a metering (delay) stroke. A typical jar has a total stroke of about 18 inches, split evenly three ways. [7]

When a load is applied to the jar, it moves a piston in a cylinder. This forces (meters) oil slowly from one side of the piston to the other. At the end of the metering stroke oil can bypass the metering valve; and the piston releases the hammer, which strikes the anvil, generating the impact. It works exactly like a pneumatic door closer: the door closes slowly at first (meters) and then slams under the applied load of a spring. Figure 20 Hydraulic jar [18]

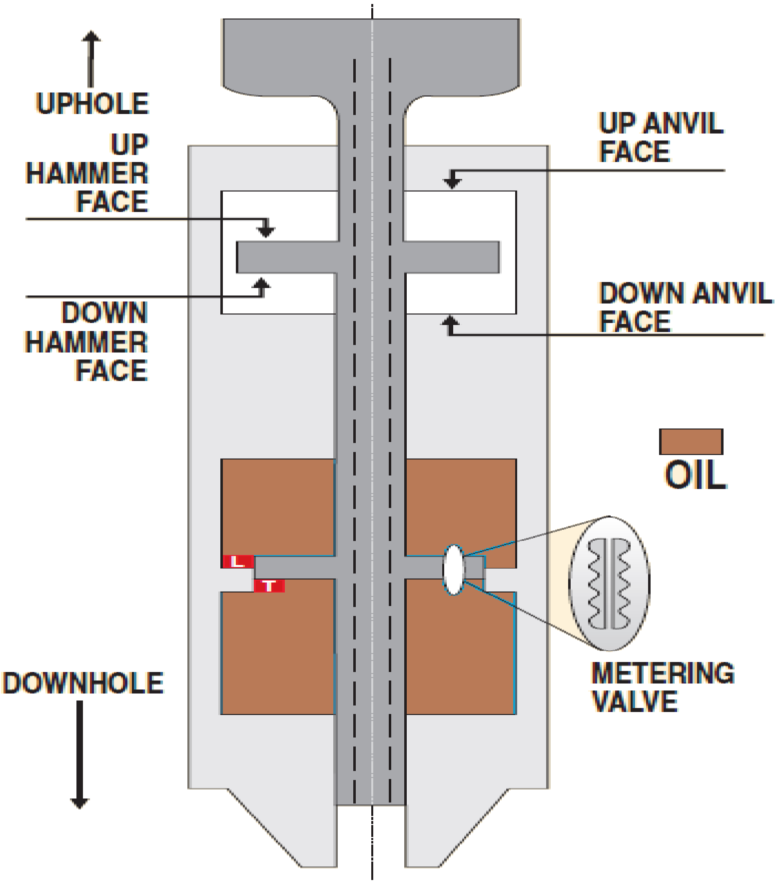


Figure 20: Hydraulic jar [18]

The jar will trip at any load big enough to start the metering process (e.g., the weight of a drill collar above it in the derrick), but the metering delay allows time to set any load up to the jar maximum. The higher the setting, the harder the hit and the faster the metering process. Typically, the delay time will be 10 to 40 seconds. At very low loads, the delay time can be up to 5 minutes.

Most hydraulic jars have nothing to keep them at mid-stroke. If the jar is in tension (fully opened), it has to be cocked (displaced through the free stroke then through the length of the metering stroke) before a load can be applied to jar up. If it is in compression, the same applies.

2.2.3 Placement of jars

Some jars can be placed in the bottom hole assembly either in tension or compression but it is recommended that the jar is placed as close to any possible stuck point in order to achieve the highest impact where it counts. Ensure that sufficient weight (hammer weight) is placed above the jar for high impact.

Determining the ideal jar position in the bottom hole assembly, is a complex issue, where several factors must be considered. Some of these factors are [7] [21]:

- Anticipating type of sticking; differential or mechanical.
  - Stuck pipe mechanics:
    - Wellbore stability
    - Differential sticking
    - Key seating
    - Junk
    - Green cement
    - Collapsed casing
    - Plenty of other possibilities

- Hole condition, trajectory and inclination.
- Configuration of bottom hole assembly
- Pump pressure and mud weight
- Buoyancy factor of the drilling fluid.
- Planned range of weight on bit.
- Overpull availability.
- Friction factors in open and cased hole
- Pump open forces
- Safe working strength of the drill pipe
- Lock setting on the jar

2.3.4 Accelerator

Accelerator, also called intensifier or booster jar, is running in the jarring string above the jar as shown in Figure 16. This part of the system will be analyzed in chapter 4.
The position of the tool is essential in terms of successful operation. The impact delivered to the fish is increased and most of the shock is relieved from the work and rig, when run above the drill collars.

An accelerator acts as a spring that can store energy. An accelerator effectively provides additional energy for the jarring process. The proper use of an accelerator has always a beneficial effect on jarring mechanics. As the accelerator is generally close to the jar, this is more efficient than the energy storage in the distributed drill string stretch. The drill string stiffness is higher than the accelerator stiffness. During jarring the accelerator also reduces shock waves that are generated in the BHA, being transmitted to the weaker drill string. Accelerators can be very effective in wells were high drag is experienced due to high inclinations or complex well paths. [5], [7] [20] Three types of accelerators exist [5] [7]

- ***Mechanical:*** energy is generally stored in a stack of Belleville springs.
- ***Hydraulic:*** generally compressive silicon oil is used as the storage medium.
- ***Gas:*** the gas charge may be optimized by the tool provider for the down hole pressures and temperatures of the well to be drilled. Gas filled accelerators are generally used in combination with a fishing jar (gas may leak out after long bit runs or while rotating in larger dog-legs).

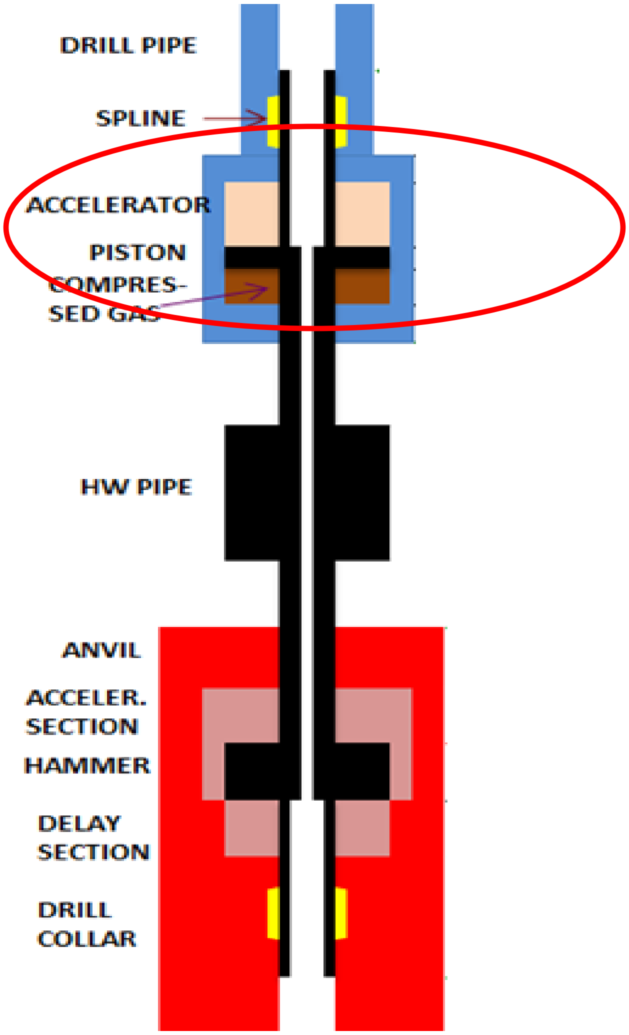


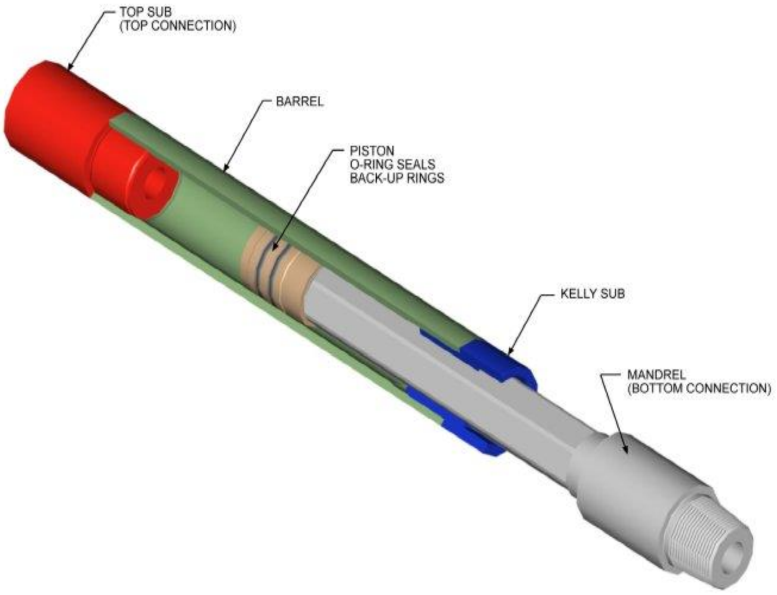
Figure 21: Accelerator filled with compressed gas charge

The other function of the jar intensifier (accelerator) is to relieve the work string of the majority of rebound which is damaging to tools and tool joints. This is accomplished by the free travel available when accelerator is pulled open. The free travel in the accelerator compensates for the free stroke of the oil jar. Ordinarily, without an accelerator in the string, the work string is stretched and when the oil jar trips, the pipe is released to move up the hole where much of the stored energy is absorbed in friction in the wellbore. This is made apparent by the movement at the surface causing the elevator, traveling block, and even the derrick to shake. This movement does not occur with an accelerator in the string due to its compensation of the free travel of the oil jar. One worthwhile advantage of running an accelerator is preventing this sudden compressive force from being exerted on the work string. Since the impact is increased due to the higher speed with which the drill collars move up to strike a blow, less weight or mass is required to impact the desirable impact. Manufacturers provide recommended weights of drill collars to be run with each oil jar. It is important when running an accelerator no to exceed the recommended weight as the efficiency is increased so much that tools or the fish may be parted without desired movement up the hole. [5]

2.2.5 Bumper Sub

Bumper sub is a mechanical slip joint which is used to mitigate vibration in the drill string and provide constant weight to the bit.

The bumper sub complements the jar in the fishing assembly. When the fish cannot be released with an upward blow from jars, it may be necessary to drive the fish down. The bumper sub is designed to do this. It has a free traveling mandrel that provides the stroke length. The fishing assembly is first picked up and lowered rapidly through the length of the stroke. At the end of stroke, the fishing assembly imparts a sharp blow to the fish which is located below the bumper sub. Drill collars above the jar increase the force of blow. In operation, the bumper sub is located between the jar and the fishing tool. If the bumper sub were located above the jars, especially with hydraulic jars, blows would be against the jars. This could cushion the blow and lessen its effect.[5] [7]



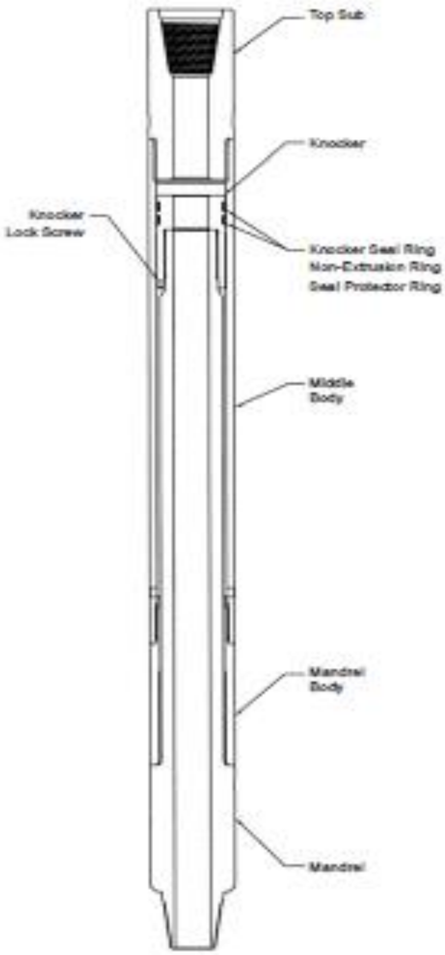


Figure 22: Mechanical bumper sub [37]

The purpose of the Fishing Bumper Sub is to allow the operator to release the fishing tool in the event it becomes impossible to pull the fish. It can provide the vertical impact in upward or downward. In addition it delivers the torque to release the tool from the fish whether it is rotating or not. The tool’s design permits torque and fluid circulation at all times. [5] [37]

2.2.6 Drilling jars

A drilling jar is a part of the drill string that helps immediately to free the string when it becomes stuck. The jar maybe cocked and triggered several times during the process. The frequency of blows that can be delivered by a jar varies with the individual to three times per minute, whereas the waiting time between blows ranges typically from 1.5 – 2.5 minutes for hydraulic jars. The number of blows delivered to free a stuck drill string can vary from as few as 10 to more than 1000.

If the drilling jar is unable to free the fish, the drill string is backed off at a preferred rotary shouldered connection above the stuck point by properly locating and firing a known quantity of detonating charge in a string shot inside the drill string. The process of string shot back off can also transmit large amplitude drill strings, as well as through the collars. The string shot by itself does not disconnect the pipe: before they detonate the string shot, they put torque (twisting force) into the pipe. Remember that the bottom end of the pipe is stuck, and it won't twist or move up and down. So if you turn the top of the pipe to the left, it will tend to act like a spring and store up the torque. [16] [17] [23] [26]

2.2.7 Fishing jar

Fishing jar is a simple hydraulically actuated tool which is used when merely pulling on a fish fails to free it from the hole. The jar aids in the removal of the fish by allowing the operator to introduce a sudden upward impact load to the fish, whenever required. The fishing jar allows the operator to control the intensity of the jarring blow from a very light to very high impact from the rig floor without making any adjustments to the tool.

Impact is controlled by the restriction of hydraulic fluid as it tries to pass the piston assembly. When the jar is pulled, fluid passes slowly from one cavity to another. The operator applies the desired stretch to the fishing string. The amount of stretch applied is directly proportional to the intensity of the resulting impact. Several seconds after the stretch is applied, the piston will reach its free stroke zone and will no longer restrict the passage of hydraulic fluid. The jar then opens, unrestricted, and the energy stored in the stretched fishing string is released, with an upward striking impact on the fish. [7] [10] [27]

Effective use of Drilling Impact System

In the paper “Planning for Successful Jarring Operations” [11], [12] author makes a research for effective use of drilling impact system. The theory says that using a double acting drilling jar amplifies force applied to free stuck bottom hole assembly parts when workover and drilling operations

The jar can be utilized for upward and downward movement for consistent and dependable bitting action in any application. The tool uses a unique temperature-compensation process to produce consistent impact for repeat blows. Its high-temperature seals make it suitable for hostile drilling conditions. High-temperature seals are available for conditions up to 650°F. In most applications, the jar should be run with an accelerator tool to increase impact and to protect the drillstring and surface equipment from shock. The hydraulic jar gives the driller operational flexibility of controlling the direction (up or down), force and frequency of impact. The tool is balanced to hydrostatic pressure through ports open to the wellbore, ensuring consistent hitting performance regardless of changes in downhole pressure. It is also temperature-compensated through the use of a unique detent system. This provides more consistent loading and firing over a broad range of borehole temperatures. These capabilities combined with careful materials selection and field-proven engineering deliver a rugged and reliable downhole impact system. The jar performs effectively in various drilling environments. It can be used on land or offshore, almost in any type of wells because the system works without applied torque. [11] [12]

3 Jarring modeling of this thesis work

This chapter presents the theory behind jarring optimization calculation. As mentioned earlier the theory is derived by Skaugen [1]

3.1 Introduction

This modelling is based on the work note [1]. The chapter presents the theortical background for dyamic loading, which is based on wave equation. In addtion the numerical discretization and calculation principles.

Based on the calculator, several sensitivity studies will be pefroemed in order to learn and optimize the drill sting beaviros (tubes, rods etc.) and liquid strings (liquid in a pipe) when exposed to changing forces. In addtion the due to connections to other objects or strings, to gravity and to friction. Changing of forces will set up stress waves in the string, some times so strong that the string material might yield or break.

3.2 Assumption

Assume a string of length L and crossectional area which may change along the string be exposed to an external loading at one end. The force then generates a displacement, which as a result the rate of displacement will be propagated through the string.

The physical parameters required for calculation are:

- String length L
- String material cross section A, which may change along the string. This is often not needed if one wants only stresses in the string, or pressure in liquid, not actual

stress forces. It is always needed if external forces are acting on the string, with the exception of gravity and contact friction.

- Any two of the three string material parameters density □, speed c of sound in the material, and the modulus of elasticity E for solid strings, or the compressibility C_V of liquid strings. These three parameters are connected by the equation $c^2 = E/\rho$, or $c^2 = 1/(\rho\, C_V)$ for liquids. If two are given, the third can be calculated.

- All external forces acting along the string and any connections must be specified as functions of time (this includes the specification that it is a constant, not changing in time), or for spring forces, as a function of the spring length*.

- Contact friction (solids sliding against each other) must be specified by the coefficient(s) of friction, liquid friction by giving friction as function of string speed relative to liquid.

- The string axis deviation from the horizontal (or the vertical) direction must be given (angle of deviation), this can change along the string. This is used to calculate any force against any support (normal force) for finding contact friction, and to find the component of gravity acting along the string axis.

*Usually one assumes one end of the spring connected to the string, the other end to the background (not moving). The other end can, however, move as specified by any time function.

3.3 Dynamic jarring modelling

Assume that the element on the left side (Figure 23) is part of the jarring/BHA/Drill string system Figure 24. Assume that the string element is loaded axially and Figure 23 shows a free body diagram for axial motion. The axial system equations will be used to determine the solution of the equations of motion. The loadings are due to static weight element and viscous force damping.

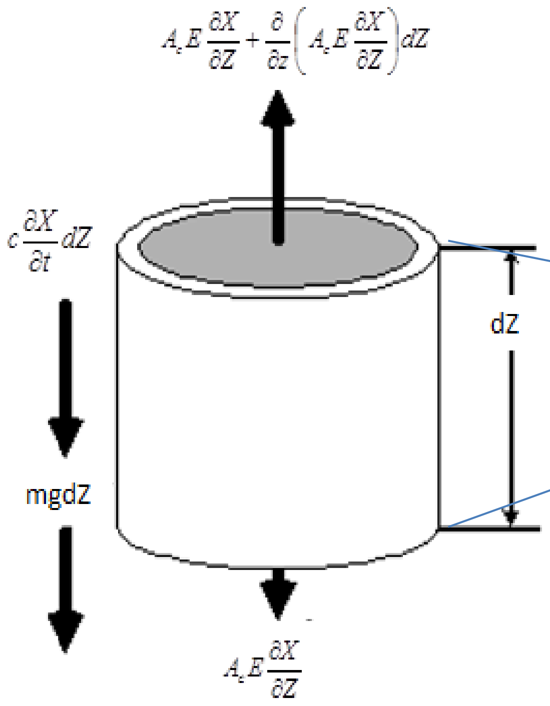


Figure 23: Free body diagrams for axial and torsional motion

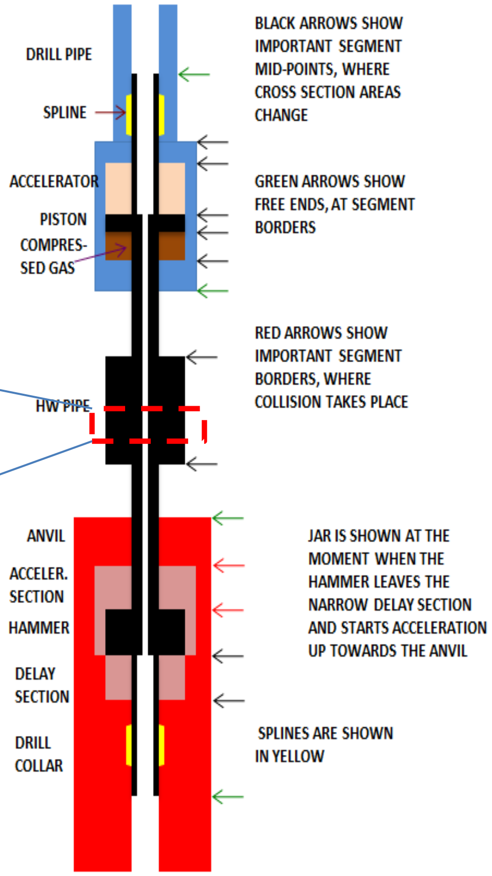


Figure 24 The segments of the jar string

Applying the force balance, the axial equation of motion is given as:

$$m\frac{\partial^2 X}{\partial t^2} = A_c E\frac{\partial^2 X}{\partial Z^2} - c\frac{\partial X}{\partial t} - m.g \qquad \text{14a}$$

where

- $m\frac{\partial^2 X}{\partial t^2}$ = the inertial force,
- $A_c E\frac{\partial^2 X}{\partial Z^2}$ = the rate of strain change,
- mg_c = the static weight of the element, and
- $c\frac{\partial X}{\partial t}$ = the force from viscous damping.

This PDE, **Eq. 14**, can be solved using the separation of variables method.

For simplification, let us assume s simple case. The dynamics of jarring can be modeling with one dimensional wave equation. The equation is given as:

$$\frac{\partial^2 X(z,t)}{\partial t^2} = c^2\frac{\partial^2 X(z,t)}{\partial Z^2} \qquad \text{14b}$$

Where

$$c^2 = \frac{E}{\rho}$$

The constant *c* is the speed of sound in drill string. E is the Young’s modulus and ρ is the density of the drill string.

3.4 Numerical discretization

Most of the numeric equations used are given in the UiS compendium “shock loading of equipment” [1]. These are presented below. The displacement indexing used assumes that the numeric segment number increases from the top and downwards. The term displacement is used for the length X_j between the positions of a numeric segment midpoint at the start of calculations and the present time.

3.4.1 Division of string into numerical segments

The whole string must be divided into a number of whole segments, except at the ends, where half segments can be used. Note that this string might consist of sections of different diameters, then no half segments are allowed at the ends of sections, at connections. Figure 25 below shows some possible divisions into numerical segments. As a whole segment has a length of Δz, a half segment has a length of $\Delta z/2$. Note that the “mid point” of a half segment actually is at one end of this segment. If not the absolute requirement that the distance between segment mid points must be Δz cannot be met.

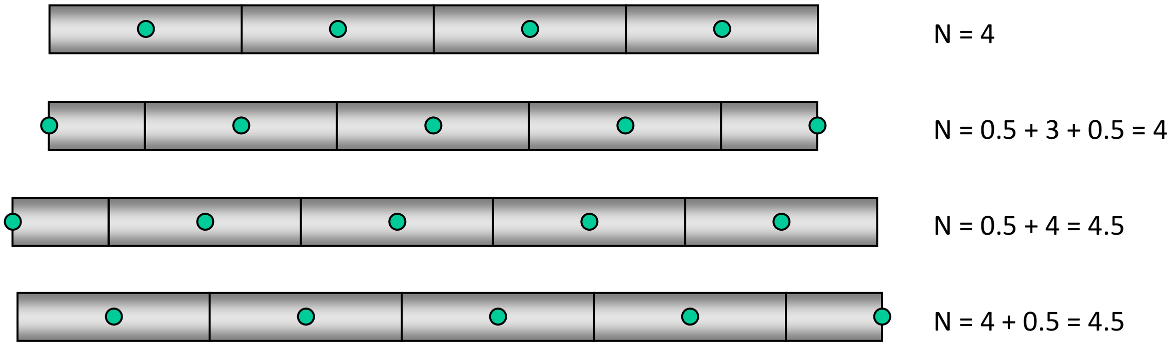


Figure 25: Examples of dividing strings correctly into numerical segments [1]

For each string the number N of segments in the string is shown, half segments are counted as 0.5 segments. The mid point of each segment is shown as a small circle. Note that the number of mid points may be equal to $N + 0.5$ or $N + 1$.

For a string of total length L, $\Delta z = L/N$, where N is the number of segments in the string. A segment is defined as being inside the string if its mid point is a distance □*z* or more away from the ends of the string.

For strings of changing diameter, segments of corresponding diameters must be used. The requirement for segment diameters is that each half of a whole segment must have a constant diameter. A whole segment is accordingly allowed to have two different diameters. A half segment can have only one diameter. Possible ways of representing a string of changing diameter are shown in Figure 26.

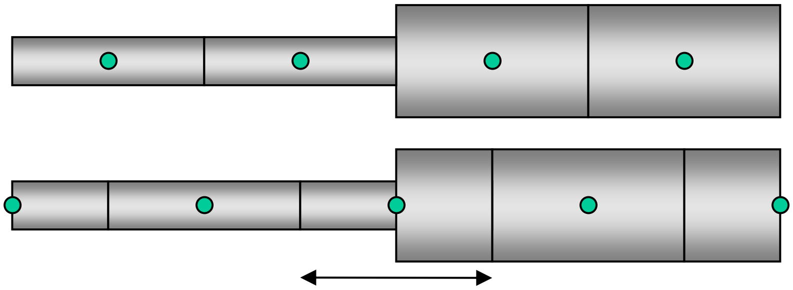


Figure 26: One segment with two different diameters [1]

Two different ways of dividing a string with changing diameter into numerical segments.

Note that for the lower case one segment with two different diameters has been used. In both cases the number N of segments in the string is 4. (But the numbers of segment mid points are 4 and 5).

3.4.2 Discritization of differential equation

The top end of the drill pipe section and the bottom end of the BHA section are terminated with whole segments that simulate that the sections goes on forever, assuming that there are no changes of material cross sections beyond these end segments. These may be called infinite ends, alternatively ends without reflection, as these ends give no reflection of waves.

The displacement equation for the new value XN of the top segment m is $XN_m = X_{m+1}$

The displacement equation for the new value XN of the bottom segment n is $XN_n = X_{n-1}$

For the top end of the piston connecting pipe, the bottom end of the acceleration housing, the top end of the BHA (here the top of the jar housing), and the bottom end of the hammer connecting pipe, the terminations are with whole numeric segments and for free ends.

For a top end with present displacement X_j the new displacement XN_j is given by:

For infinite ends: $$XN_j = 2X_{j+1} \quad 15$$

For free ends: $$XN_j = X_j + X_{j+1} - XG_j \quad 16$$

For a bottom end with present displacement X_j the new displacement XN_j is given by:

For infinite ends: $$XN_j = 2X_{j-1} \quad 17$$

For free ends: $$XN_j = X_{j-1} + X_j - XG_j \quad 18$$

For changes of material cross section of a single pipe, this change is always assumed to be at a numeric segment mid-point, as this gives the simplest numeric equations.

Single change of cross section (at mid-point of segment *j*):

$$XN_j = \frac{2A_1}{A_1 + A_2} X_{j-1} + \frac{2A_2}{A_1 + A_2} X_{j+1} - XG_j \qquad 19$$

A_1 is cross section for segment number *j*-1, and A_2 is cross section for segment number *j*+1. The cross section for segment *j* will then be $(A_1 + A_2)/2$. For $A_1 = A_2$ this obviously turns into the standard equation for a string of constant cross section.

For simulating of some friction the simplest is to assume linear friction, other types of friction gives very complicated and computer time consuming equations. Including linear friction changes the standard numeric equation into:

$$XN_j = aX_{j-1} + aX_{j+1} - bXG_j \qquad 20$$

where $a = 1 - e$, and $b = 1 - 2e$. The parameter *e* is a measure of the degree of linear friction, when it is zero there is no friction. For reasonably accurate calculations with friction included, *e* should be considerably smaller than one.

The equations for the numeric segments involved in the collision between the hammer and the anvil are quite special and is not given in the compendium. These equations therefore have to be derived. This is here done by assuming the collision to take place at the borders of whole numeric segments, as illustrated in Figure 24. According to the compendium collisions are simplest, and in some respects more accurately calculated, when collisions take place at the border of whole segment.

According to Fig. 24 four numeric segments are directly involved in the collision. These are numbered *i*, *j*, *m*, and *n*. The material area cross sections of these are A_i, A_j, A_m, and A_n, respectively. The displacement X of all the numeric segment mid points are assumed known up to this moment in time. In the numeric calculation the displacements are known only at specific times, separated by the time step Δt. The displacement has been adjusted in such a way that the segments just touch at one of these specific times.

The physical ball-spring model is a tool for developing numerical equations for different situations in an efficient way. It can be shown that it is an exact representation of the numerical solution of the one-dimensional wave equation used here. The ball-spring model is based upon the chosen division of the string into numerical segments. In this model we assume the real string to consist of small balls positioned exactly at the segment mid points. Each ball has the mass of the whole string segment around its mid point. Thus, if we have a string end of a half segment, the ball at this seg

This ball-spring model is shown in the figure 27 below, together with the string it is representing.

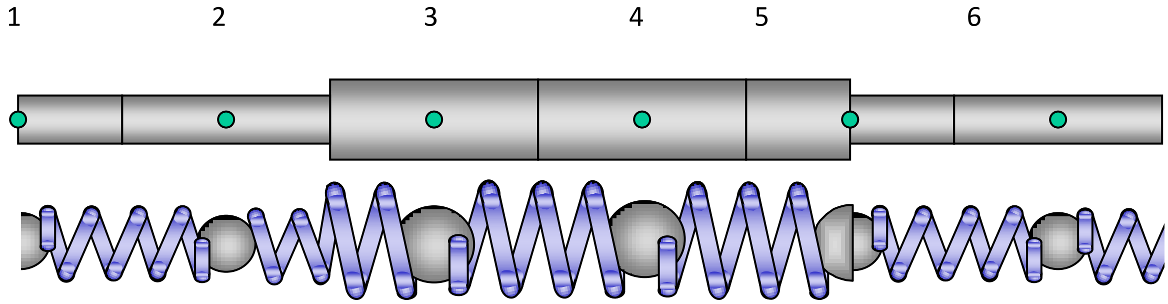


Figure 27: Physical ball-spring model, shown for a string with two free ends [1]

By using the physical ball spring numeric model [1], the following general equation for the acceleration of the numeric segment midpoint (represented by a point containing the whole mass of the segment) is given by Newton's law that mass times acceleration equals the sum of forces acting on this mass:

$$A\Delta z\rho\,\frac{XN_j - 2X_j + XG_j}{\Delta t^2} = AE\,\frac{X_{j+1} - X_j}{\Delta z} - AE\,\frac{X_j - X_{j-1}}{\Delta z} + \sum \text{External forces} \tag{21}$$

where $A\Delta z\rho$ is the mass of the numeric segment, $\frac{XN_j - 2X_j + XG_j}{\Delta t^2}$ is a numeric expression for the acceleration, and $AE\frac{X_{j+1} - X_j}{\Delta z} - AE\frac{X_j - X_{j-1}}{\Delta z}$ are the internal stress forces acting on the mass. Note that this equation is strictly true only for a string of constant cross section *A*. When segments of different cross sections are connected, the three areas *A* will be different.

This equation can be simplified by multiplying it with $\mathrm{D}t^2$, and dividing it by $\mathrm{D}zr$, and using the requirement that $\Delta z/\Delta t = c$, and that $E/\rho = c^2$. This gives:

$$A_j\,(XN_j - 2X_j + XG_j) = A_{j+}\,(X_{j+1} - X_j) - A_{j-}\,(X_j - X_{j-1}) + \sum \text{External forces} \tag{22}$$

where any difference of the cross sections areas now is included by using the effective cross section areas A_j, A_{j+}, and A_{j-}.

This equation is used for deriving all the equations above. For the particular case of the four segments directly involved in the collision the cross sections change at the colliding segment borders as shown in Figure 27. The solution of this is to use the displacement *X* of this border in the force calculations.

The force generated by differences in displacements between two neighboring points is the strain multiplied by the modulus of elasticity, where the strain is the difference in displacement divided by the distance between the points. For the terms involving the collision border, where the displacement is *X*, and the distance from this border to the neighboring midpoint is $\Delta z/2$. Dividing by $\Delta z/2$ then gives a term that is multiplied by 2, as shown in the equations below.

For the four segments closest to the colliding line the numeric equations are:

$$A_i(XN_i - 2X_i + XG_i) = 2A_i(X - X_i) - A_i(X_i - X_{i-1}) \tag{23}$$

$$A_j(XN_j - 2X_j + XG_j) = A_j(X_{j+1} - X_j) - 2A_j(X_j - X) \tag{24}$$

$$A_m(XN_m - 2X_m + XG_m) = 2A_m(X - X_m) - A_m(X_m - X_{m-1}) \tag{25}$$

$$A_n(XN_n - 2X_n + XG_n) = A_n(X_{n+1} - X_n) - 2A_n(X_n - X) \tag{26}$$

Note that here there is assumed to be no external forces. For each of these equations the cross section areas are equal and can be divided away. The next step is then to find the border displacement X. Using the fact that the sum of forces acting on this border must be zero, we get:

$$2A_i(X-X_i) + 2A_m(X-X_m) = 2A_j(X_j-X) + 2A_n(X_n-X) \qquad 27$$

where the forces pulling the collision line upward (left side) must be equal to the forces pulling it downward (right side of equation). By solving this equation with respect to X, we get:

$$X = \frac{A_iX_i + A_jX_j + A_mX_m + A_nX_n}{A_i + A_j + A_m + A_n} \qquad 28$$

By solving the four equations above with respect to the new XN (and up to now unknown), and inserting the value of X, the numeric equations become:

$$XN_i = 2X_i - XG_i + 2(X-X_i) - (X_i - X_{i-1}) = X_{i-1} + X_i + 2(X - X_i) - XG_i \qquad 29$$

$$XN_i = X_{i-1} + \left(2\frac{A_iX_i + A_jX_j + A_mX_m + A_nX_n}{A_i + A_j + A_m + A_n} - X_i\right) - XG_i \qquad 30$$

$$XN_i = X_{i-1} + \frac{A_iX_i + A_j(2X_j - X_i) + A_m(2X_m - X_i) + A_n(2X_n - X_i)}{A_i + A_j + A_m + A_n} - XG_i \qquad 31$$

Correspondingly:

$$XN_j = \frac{A_i(2X_i - X_j) + A_j X_j + A_m(2X_m - X_j) + A_n(2X_n - X_j)}{A_i + A_j + A_m + A_n} + X_{j+1} - XG_j \qquad 32$$

$$XN_m = X_{m-1} + \frac{A_i(2X_i - X_m) + A_j(2X_j - X_m) + A_m X_m + A_n(2X_n - X_m)}{A_i + A_j + A_m + A_n} - XG_m \qquad 33$$

$$XN_n = \frac{A_i(2X_i - X_n) + A_j(2X_j - X_n) + A_m(2X_m - X_n) + A_n X_n}{A_i + A_j + A_m + A_n} + X_{n+1} - XG_n \qquad 34$$

This is the situation at and right after the collision. The hammer (index *j* here), and the anvil (index m here) are pressed against each other and numerically behaves as they were fused and are treated as a single piece. The equations above cover that situation. However, after some time there may be an elastic rebound where they separate again. This is controlled by calculating for each time step the stress level between the two segments actually colliding, hammer with index j and the anvil with index m. The stress is here proportional to $X_j - X_m$. If this is negative the two segments press against each other and behave as one string, governed by the equations above.

If, however, the value of $X_j - X_m$ turns positive, this indicates that the hammer and anvil is separated, and equations for this situation must be used. The only special equations then required are for the segments number *i* and *j*, because these are part of the hammer string and always connected. The same is the situation for segments *m* and *n* in the anvil string. These equations are for two segments connected at the segment borders, which is not included in the equations given earlier. These are, however, easily obtained from the equations above. For the hammer string, which now is not in contact with the anvil, the effect of the anvil is removed by setting A_m and A_n equal to zero, giving:

$$XN_i = X_{i-1} + \frac{A_i X_i + A_j(2X_j - X_i)}{A_i + A_j} - XG_i = X_{i-1} + \frac{A_i - A_j}{A_i + A_j} X_i + \frac{2A_j}{A_i + A_j} X_j - XG_i \tag{35}$$

$$XN_j = \frac{A_i(2X_i - X_j) + A_j X_j}{A_i + A_j} + X_{j+1} - XG_j = \frac{2A_i}{A_i + A_j} X_i - \frac{A_i - A_j}{A_i + A_j} X_j + X_{j+1} - XG_j \tag{36}$$

Correspondingly for the anvil the areas A_i and A_j are set equal to zero:

$$XN_m = X_{m-1} + \frac{A_m X_m + A_n(2X_n - X_m)}{A_m + A_n} - XG_m = X_{m-1} + \frac{A_m - A_n}{A_m + A_n} X_m + \frac{2A_n}{A_m + A_n} X_n - XG_m \tag{37}$$

$$XN_n = \frac{A_m(2X_m - X_n) + A_n X_n}{A_m + A_n} + X_{n+1} - XG_m = X_{m-1} + \frac{2A_m}{A_m + A_n} X_m - \frac{A_m - A_n}{A_m + A_n} X_n - XG_m \tag{38}$$

4 Numerical simulation jarring analysis

The models presented in chapter 3 were implemented in Excel. In this section several simulation studies will be performed. The objective is to analyze dynamics of jarring and state of stress during jarring operations

4.1 Simulation arrangement

The jarring system presented in chapter 3 Figure23 is now discretizing for numerical calculation purpose. As can be seen on Figure 20, the system consists of drill pipe, anvil and accelerator system. During jarring the hammer is colliding with the top of the anvil. During hammering the top and bottom of the anvil will be deformed and depending on the loading it may be yielded. This chapter seeks the phenomenon of yielding and the speed of the hammer and the state of stresses during jarring operations.

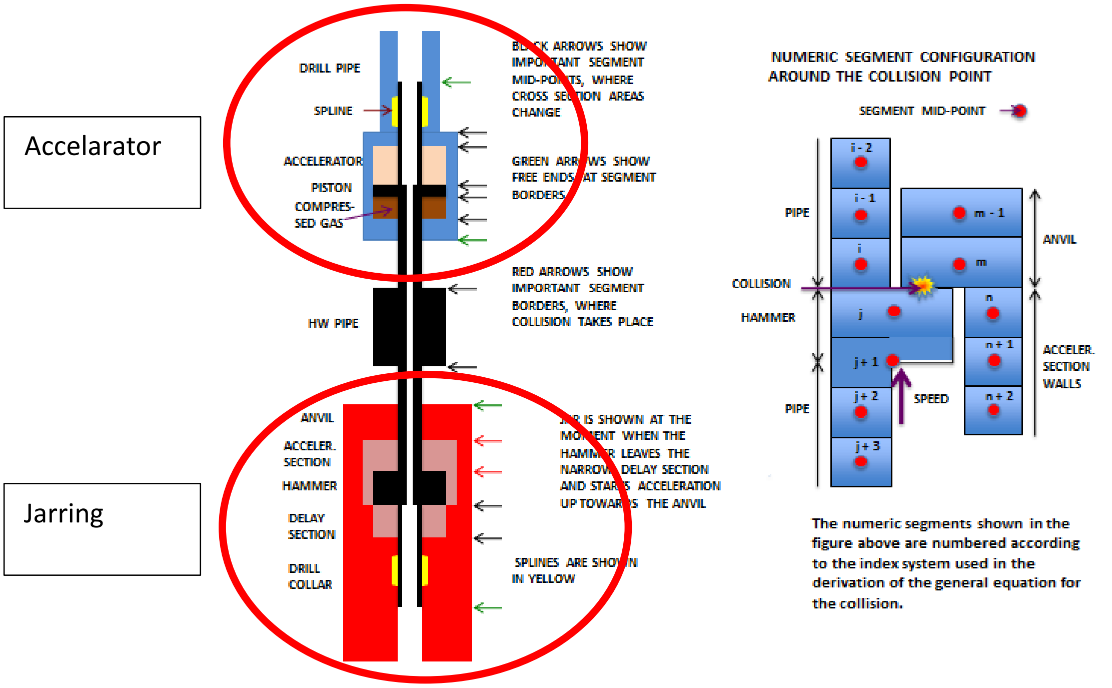


Figure 28 Numeric segment configuration around the collision point

4.1.1 Simplification

The gas pressure below the accelerator piston gives a constant upward force over the short time the hammer is accelerated. This is a simplification that assumes that the stroke length of the accelerator piston is considerably longer than that of the hammer. Since the hammer pipe section is not carrying the weight of the BHA, because it is stuck, it can be loaded with 100% of its yield limit. Assuming that the pipes between piston and HW drill pipe, and between HW and hammer, are the weakest parts, this gives a maximum pressure force of the gas to piston.

4.1.2 About missing diameter inputs

Some diameters above are given by other (required) diameters above. For instance, the outer diameter of the anvil is assumed equal to the outer diameter of the BHA since it is a part of the BHA. The jar could have a smaller diameter, but then it would be weaker. Also, the inner diameter of the delay section is very slightly larger than the hammer outer diameter, but for the type of calculation done here it is for all practical purposes assumed equal.

4.2 Simulation input parameters

The elastic and physical properties of the drill string jar and drilling fluid is given in Table 3. The safety factor /design factor is 70%. The yield strength of the material is 135000psi. Table 4 shows the geometry of jarring, accelerator and heavy weight

PHYSICAL and MATERIAL CONSTANTS	**Value**	Unit
Acceleration of gravity:	**9.81**	m/s^2
Density of string material:	**7850**	kg/m^3
Modulus of elasticity of string material:	**210**	$10^9\ N/m^2$
Yield limit of string material:	**135000**	psi
Density of well fluid:	**1200**	kg/m^3
Maximum stress in drill pipe relative to yield limit:	**0.70**	no unit

Table 3 Physical and Material constants

STRING GEOMETRY		
Outer diameter of drill pipes:	**5.00**	inch
Inner diameter of drill pipes:	**4.00**	inch
Outer diameter of accelerator housing:	**8.00**	inch
Outer diameter of accelerator piston pipe, top part:	**5.00**	inch
Inner diameter of accelerator piston pipe, top part:	**4.00**	inch
Outer diameter of accelerator piston:	**6.00**	inch
Outer diameter of accelerator piston pipe, bottom part:	**5.00**	inch
Inner diameter of accelerator piston pipe, bottom part:	**3.00**	inch
Outer diameter of heavy weigth drill pipes:	**7.00**	inch
Inner diameter of heavy weight drill pipes:	**4.00**	inch
Outer diameter of BHA pipes:	**8.00**	**inch**
Outer diameter of hammer piston pipe, top section:	**5.00**	inch
Inner diameter of hammer piston pipe, top section:	**4.00**	inch
Outer diameter of jar hammer:	**5.00**	inch
Inner diameter of jar hammer:	**4.00**	inch
Inner diameter of accelerator section (>hammer dia.):	**5.50**	inch
Outer diameter of hammer piston pipe, bottom section:	**4.00**	inch
Inner diameter of hammer piston pipe, bottom section:	**3.20**	inch
Drill collar inner diameter:	**4.00**	inch

Table 4 Geometry of jarring, accelerator and heavy weight

There are three string sections that can move relative to each other:
Drill pipes and the accelerator housing (blue)
Accelerator piston, HW pipes and hammer, all with connecting pipes (black)
Jar housing and the rest of the BHA (red)

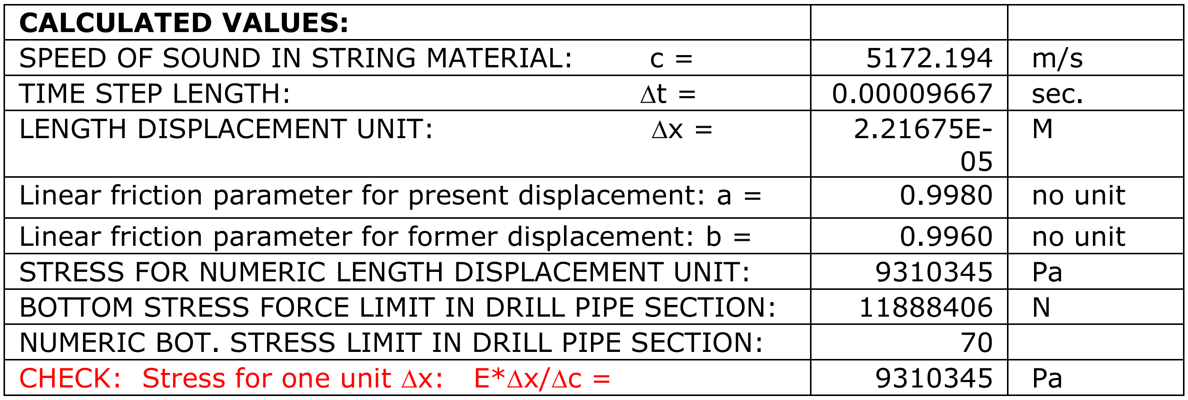
NUMERIC PARAMETER: SPACE STEP LENGTH Dz:	**1,00**	**m**
Degree of linear friction e. No friction for e = 0:	**0,0020**	**no unit**
Numeric stress that gives physical yield stress:	**100,0**	**no unit**
Fraction of numeric yield stress used in hammer string	**0,5000**	**no unit**
MINIMUM VALUE OF DESIRED UPWARD STRESS CHOCK	**1000**	**bar**

Table 5 Numeric parameters

Here is an example of the HW length that equals 21.0 meters and Hammer length that equals 1.50 m.

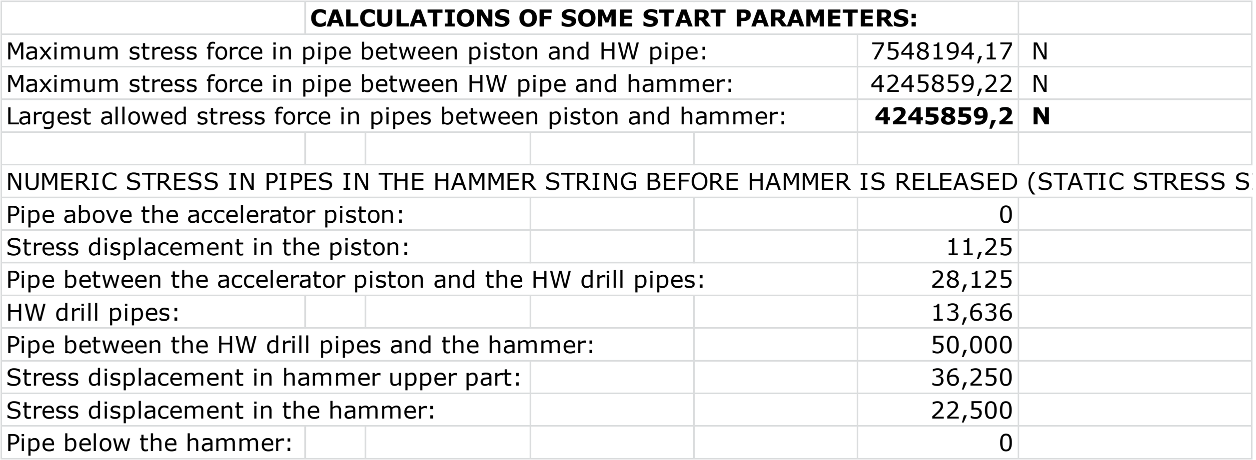
NB! Lengths are given in num-		N can be an			
bers of half numeric segments		even or odd		NUMBER OF	**ACTUAL**
N = 2*(Length of pipe)/Dz		integer	**Adjusted**	WHOLE	**LENGTH**
PIPE LENGTHS	**N**	**N**	**values of N**	**SEGMENTS**	**IN METERS**
Drill pipes:	**7**	Odd: 2n + 1	**9**	4,5	**4,50**
Piston pipe top part:	**3**	Odd: 2n + 1	**5**	2,5	**2,50**
Top end of housing:	**2**	Even: 2n	**6**	3	**3,00**
Piston chamber length:	**6**	Even: 2n	**6**	3	**3,00**
Bottom end of housing	**3**	Odd: 2n + 1	**3**	1,5	**1,50**
Piston:	**2**	Even: 2n	**2**	1	**1,00**
Piston pipe bottom par	**12**	Even: 2n	**12**	6	**6,00**
Heavy weigth:	**42**	Even: 2n	**42**	21	**21,00**
Hammer pipe top:	**3**	Odd: 2n + 1	**11**	5,5	**5,50**
Anvil, jar housing top e	**2**	Even: 2n	**4**	2	**2,00**
Acceleration section:	**3**	Odd: 2n + 1	**5**	2,5	**2,50**
Hammer:	**1**	Odd: 2n + 1	**3**	1,5	**1,50**
Delay section:	**2**	Even: 2n	**4**	2	**2,00**
Spline section:	**2**	Even: 2n	**6**	3	**3,00**
Hammer pipe bottom:	**3**	Odd: 2n + 1	**7**	3,5	**3,50**
Drill collar length:	**11**	Odd: 2n + 1	**11**	5,5	**5,50**
Sum of all segment numbers and length			**136**	68	**68,00**

Table 6 Actual and adjusted length of jarring systems used for calculation



CALCULATED VALUES:		
SPEED OF SOUND IN STRING MATERIAL: c =	5172.194	m/s
TIME STEP LENGTH: Δt =	0.00009667	sec.
LENGTH DISPLACEMENT UNIT: Δx =	2.21675E-05	M
Linear friction parameter for present displacement: a =	0.9980	no unit
Linear friction parameter for former displacement: b =	0.9960	no unit
STRESS FOR NUMERIC LENGTH DISPLACEMENT UNIT:	9310345	Pa
BOTTOM STRESS FORCE LIMIT IN DRILL PIPE SECTION:	11888406	N
NUMERIC BOT. STRESS LIMIT IN DRILL PIPE SECTION:	70	
CHECK: Stress for one unit Δx: E*Δx/Δc =	9310345	Pa

Table 7 Calculated values



CALCULATIONS OF SOME START PARAMETERS:		
Maximum stress force in pipe between piston and HW pipe:	7548194,17	N
Maximum stress force in pipe between HW pipe and hammer:	4245859,22	N
Largest allowed stress force in pipes between piston and hammer:	**4245859,2**	**N**
NUMERIC STRESS IN PIPES IN THE HAMMER STRING BEFORE HAMMER IS RELEASED (STATIC STRESS S		
Pipe above the accelerator piston:	0	
Stress displacement in the piston:	11,25	
Pipe between the accelerator piston and the HW drill pipes:	28,125	
HW drill pipes:	13,636	
Pipe between the HW drill pipes and the hammer:	50,000	
Stress displacement in hammer upper part:	36,250	
Stress displacement in the hammer:	22,500	
Pipe below the hammer:	0	

Table 8 Calculated values and used as input for the simulation

Length displacement unit Δx is assumed equal to a value that gives one unit for 1 % of the yield limit.

In the numeric calculations the difference between the displacements of two neighboring numeric segment midpoints is used as a direct measure of relative material stress. If this difference is 100, the actual stress is at the yield limit.

Gravity is not included here. The absolute in the system is the calculated stress plus the stress induced by gravity. The gravity stress can be calculated from the weight of the different parts of density of the mud, the actual well path, and the depths of the different parts of the drill string. Since the equation used are linear, the shocks generated by the accelerator-jar system are independent of the gravity stress and can be calculated separately, except for the effects of friction, especially contact friction, as this depend on almost all the factors that determine the gravity stress. To calculate accurately the effects of friction is far too difficult for a master thesis. However, it is believed that friction does not seriously influence the performance of the jar. Linear friction is included in the shock calculations in order to find qualitative effects of friction.

4.3 Simulation studies

In this sub-chapter is given the main part of the thesis – simulation studies based on numerical calculations. Each simulation and graph presents stress in BHA (in bars) as a function of run time start at collision, in milliseconds. The maximum yield limit stress that might be applied is 9000 bar. This is a critical stress value since the jar string could be damaged after reaching the 9000 bars. For all calculations in the thesis is used a constant initial speed of hammer that equals to 11.465 m/sec.

4.3.1 Simulation #1

The first simulation, Simulation #1 is designed to analyze the stress state for the following parameters:

- Outer Diameter: 7,00 inch
- Heavy weight length: 21 m
- Hammer length: 1,5 m

Figure 29 shows the simulation result. As can be seen, the maximum stress observed at the early time of jarring impacts and at later time the energy shows decreasing.

As can be seen, the maximum stress that the string is 4609 bar and time duration when the stress is larger than 1000 bar is 11,60 msec (milliseconds). The time duration is good and the state of stress doesn't cross the yield limit (9000bar), which is safe

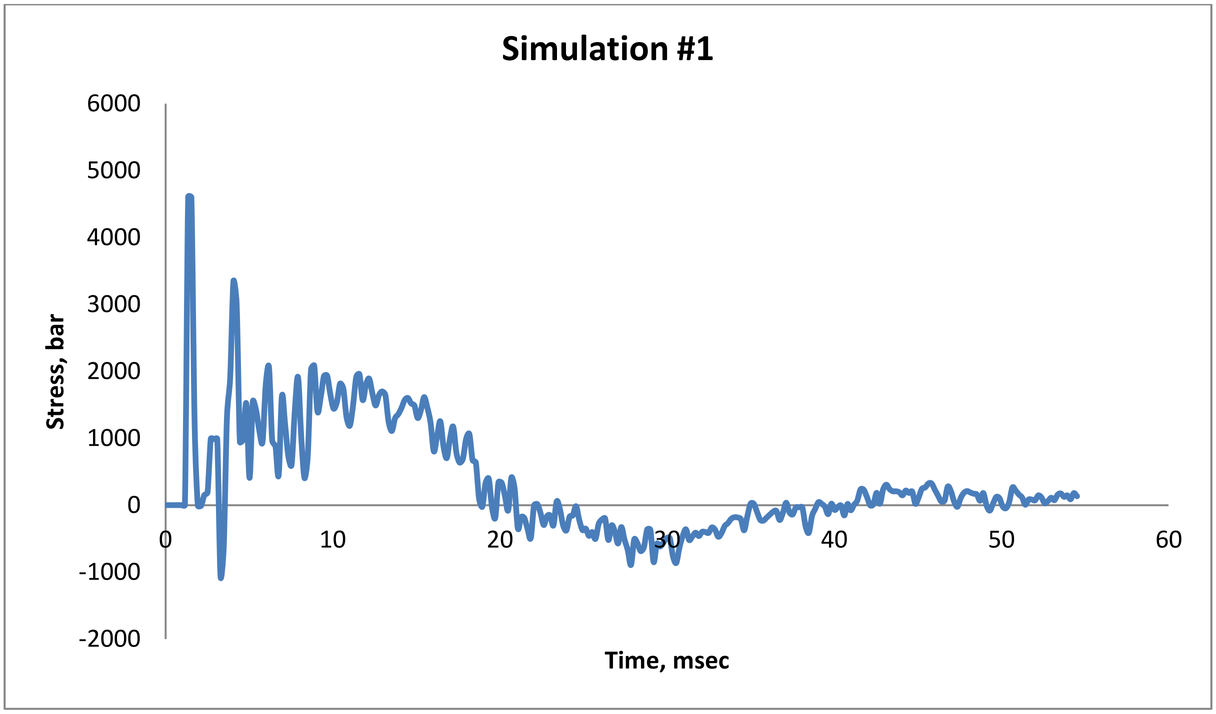


Figure 29 Simulation #2 for OD: 7.00 inch, HW: 21 m & Hammer: 1.50 m

4.3.2 Simulation #2

To study the effect of hammer length, in this simulation keeping the OD and HW as simulation #1, the hammer length increase to 4.5m. The parameters are:

- OD: 7,00 inch
- HW: 21 m
- **Hammer: 4,50 m**
-

Figure 30 shows the simulation result. From the simulation #2 results, the system experience the maximum stress of 1988 bar and time duration when the stress is larger than 1000 bar is 12,567 msec.

Comparing simulation #2 with simulation #1, one can observe that the larger hammer length in the assembly exhibits the less maximum stress. In terms of time duration, simulation 2 is better than simulation 1. However time doesn't mean anything without large stress

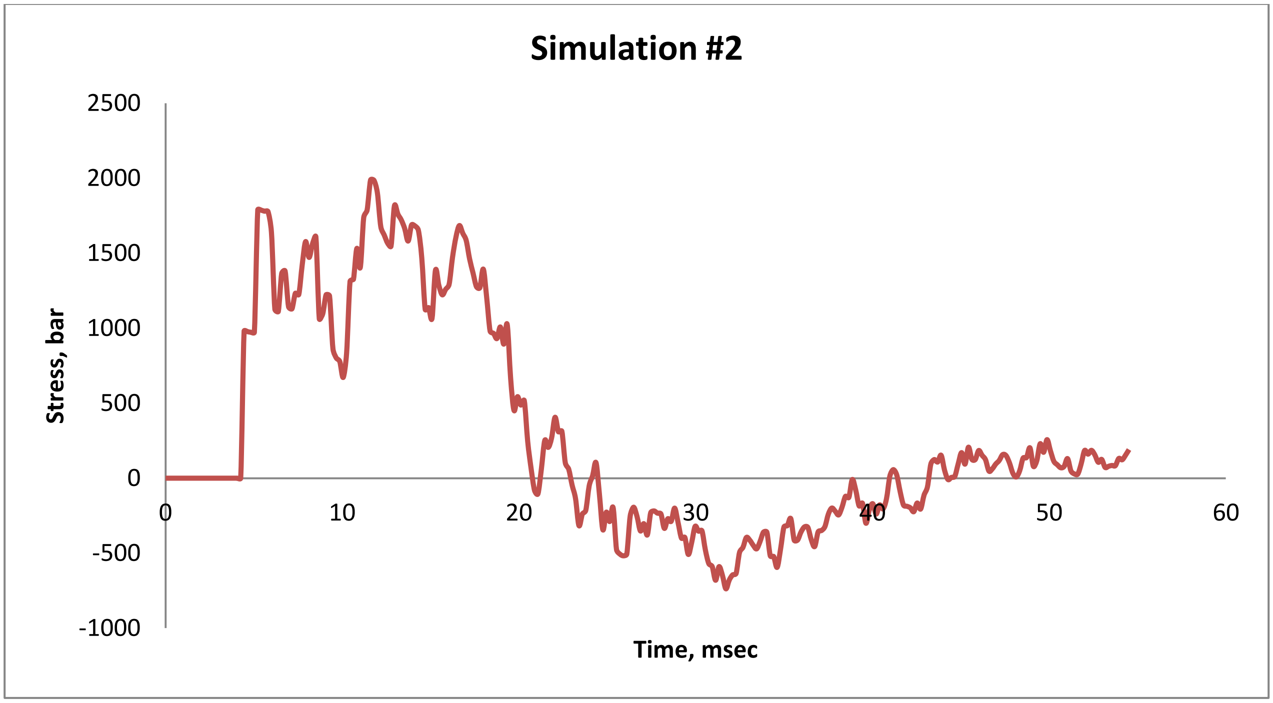


Figure 30 Simulation #2 for (OD: 7,00 inch, HW: 21 m & Hammer: 4,50 m)

4.3.3 Simulation #3

Simulation #3 is designed to seek the effect of heavy weight. This simulation can be compared with simulation #1 since the OD and hammer length are the same, but the HW length is reduced to 7m

- OD: 7,00 inch
- HW: 7 m
- Hammer: 1,50 m

Figure 31 shows the simulation result. The string of simulation #3 exhibits the maximum stress of 4609 bar and time duration when the stress is larger than 1000 bar is 6,187 msec.

Comparing to the Simulation #1, both exhibits the same maximum stress, but the time duration when stress is larger than 1000 bar is less than in the Simulation #1.

From these two simulation we learn than the HW length increase the time duration, but it is the maximum stress still same.

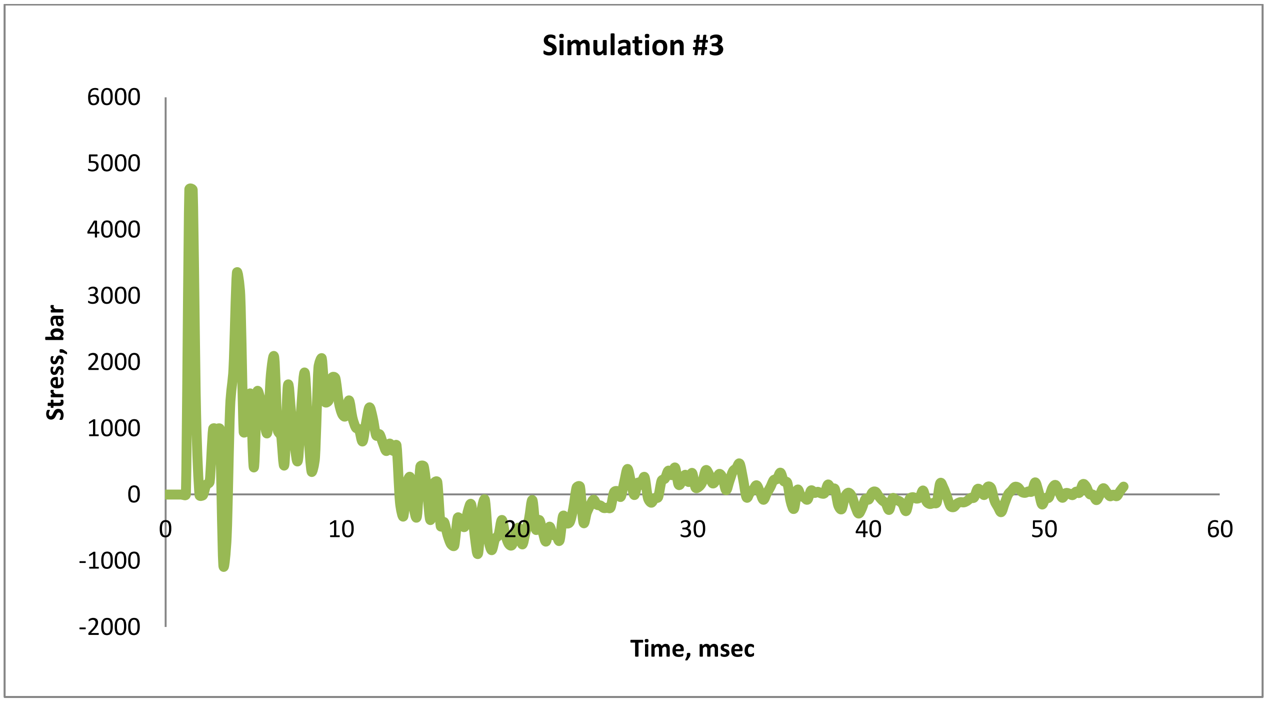


Figure 31: Simulation #3 for (OD: 7,00 inch, HW: 7 m & Hammer: 1.50 m)

4.3.4 Simulation #4

Similarly simulation #4 is designed to seek the effect of hammer length. This simulation can be compared with simulation #3 since the OD and heavy weight length are the same, but the hammer length is increased to 4.5m

- OD: 7,00 inch
- HW: 7 m
- Hammer: 4,50 m

Figure 32 shows the simulation result. The string of simulation #4 experience the maximum stress of 1988 bar and time duration when the stress is larger than 1000 bar is 12,567 msec.

As can be observer, comparing simulation #4 result with simulations #1 &#3, the larger hammer length in the assembly the less maximum stress we get. The only good result here is the time duration, but the time does not mean anything without large stress.

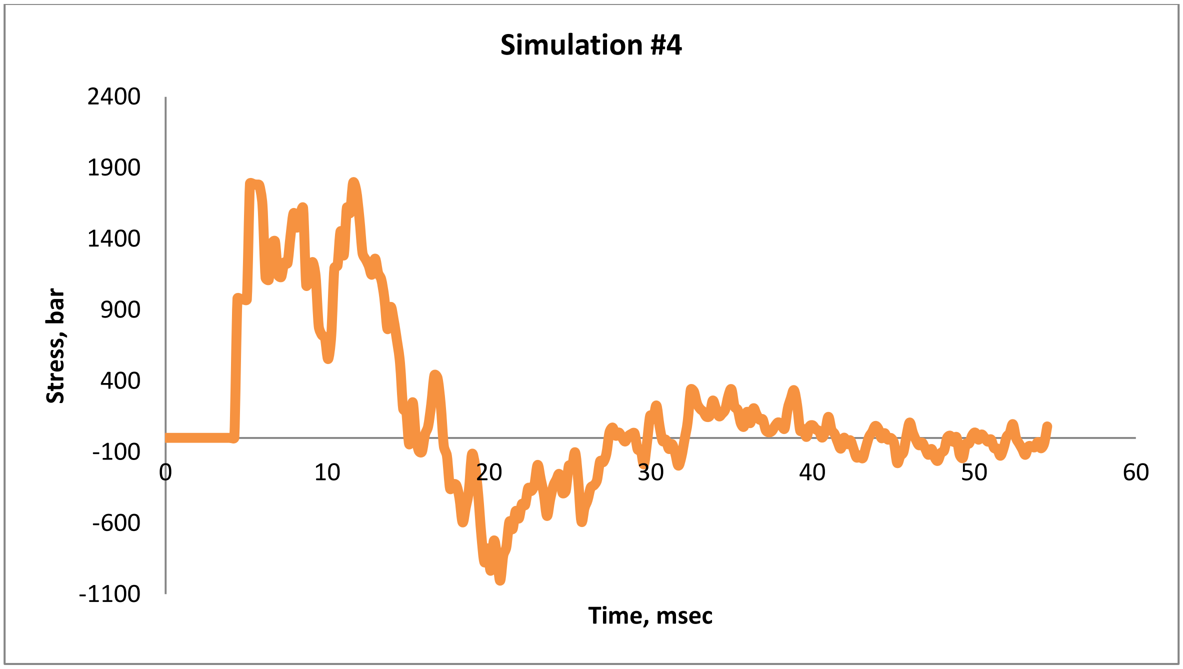


Figure 32: Simulation #4 for (OD: 7,00 inch, HW: 7 m & Hammer: 4,50 m)

4.3.5 Simulation #5, #6, #7 and #8

In the simulation number 5, 6, 7 and 8 is used numerical calculation model which is identical to the previous models. The main difference here is that the OD of the heavy weight drill pipe is less than in first four simulations, and it equals to **6,00 inch**.

The results show that decreasing of the OD of HW drill pipe give less time duration, but the maximum stress is almost the same.

#1 → #5

#2 → #6

#3 → #7

#4 → #8

The Table 9 below gives overview of the maximum stress and time duration when stress is larger than 1000 bar. Similar length of HW and Hammer is colored same.

Simulation #	Maximum Stress [bar]	Time [msec] (when stress is larger than 1000 bar)
#1	4608,81	11,6
#2	1987,68	12,567
#3	4608,81	6,187
#4	1795,25	7,347
#5	4608,81	9,087
#6	1789,26	9,860
#7	4608,81	5,027
#8	1789,26	5,994

Table 9 Maximum stress and Time for numbers of simulations

Higher the stress, the better effect of the impact to free the stuck pipe, i.e. for successful jarring operation the high stress is essential, but this stress must not be higher than 9000 bar.

4.3.6 Effect of hammer length and heavy weight drill pipe

In this simulation assume that the diameter of hammer and heavy weight is equal 7,0 inch in first 4 simulations, and the next 4 simulations it is equals to 6,00 inch. In addition the length of the heavy weight is changing from simulation to simulation. The study seeks the effect of hammer and HW drill pipe length on the stress. Four cases are considered. The pair of heavy weight and hammer for the first scenario (#1) are HW = 21,0 m and Hammer 1,50 m. The second case (#2) consider HW = 21,0 m and Hammer = 4,50 m. The third (#3) HW = 7.0 m and Hammer = 1.50 m. The fourth (#4) HW = 7.0 m and Hammer = 4.50 m.

4.3.6.1 Effect of hammer length

Effect of hammer length is based on constant HW drill pipe length as well as other parameters also are same.

Calculation result on hammer string only show that with the sudden onset of the acceleration when hammer leaves the delay section, oscillations along this string are induced. This depends on the actual geometry of this string. When hammer hit the anvil, the oscillations in the hammer string will influence the contact force between hammer and anvil. This makes it difficult to get a clear picture of the shocks generated. In reality friction against the movement of the hammer string will dampen oscillations before the hammer hits the anvil.

4.3.6.2 Effect of heavy weight length

Similarly in this simulation assume that the diameter of hammer and heavy weight is constant. In addition the length of the hammer is also constant. The simulation study seeks the effect heavy weight length on the stress in the jar section. Four cases are considered as described above.

Simulation results

During simulation we were interested to learn the state of stress due to loading. The result of the simulation is shown on Figure 33. As can be shown the stresses are not exceed the yield imit.

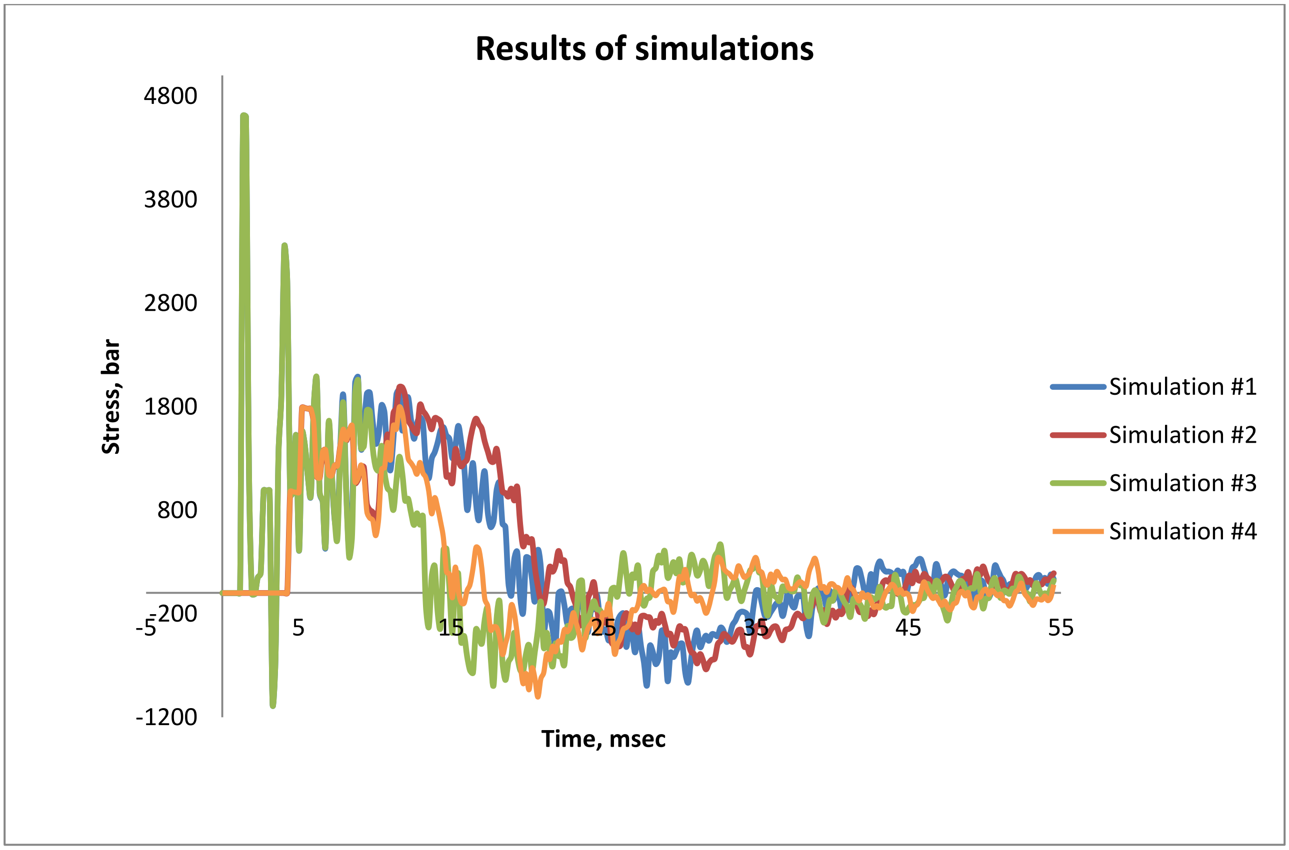


Figure 33: Simulation results on the effect of hammer length

5 Conclusions

In this thesis my goal was to introduce or show an overview of stuck pipe and the way to free it by using a jar. The main questions were why it occurs, how it can be prevented, and to look specifically at the jar optimization with a numerical calculation method. This method calculates the mechanical stress shock generated by the jar and its transmission down the BHA to the stuck point.

Stuck pipe is a major problem for the oil industry, and getting bigger and bigger as more complex horizontal and deviated wells are drilled. To expand the image around this topic, some other techniques and tools of freeing stuck pipe are also discussed.

The main tool to unstuck pipe is the accelerator and the jar containing the anvil and hammer where the shock is generated. The use of the jar is essential because it is one of the most successful ways to free the stuck pipe. In order to save money by reducing down time it is important to use the best possible material quality and the optimal geometric parameters and size of the jar string, HW drill pipe, and hammer. The balance of the sizes between those tools is crucial for best result and a successful operation.

It is significant also that the jar is placed as close to any possible stuck point in order to achieve the highest impact where it counts. Determining the ideal jar position in the bottom hole assembly is a complex issue, where several factors must be considered. One of the main issues is to ensure that sufficient hammer weight is placed above the jar for high impact. This is usually done by mounting heavy weight drill pipe between the accelerator and the jar. In addition to the drill string tension used to load the accelerator, the length and diameter of the HW pipe is usually the only means available to change the performance of the jar at the drilling rig. But the shock amplitude must always be less than the yield limits of the jar components.

As mentioned in the thesis, there are three methods to activate the jar: mechanical, hydraulic and hydro-mechanical jar. For calculations used in this thesis a hydraulic jar was assumed.

In Chapter 4 a jar-accelerator system is specified and simulated, and the main output, the shock transmitted down the BHA is shown as material stress in the BHA as function of time. The most critical parameters affecting the maximum stress were found to be the change in the lengths of the heavy weight drill pipe and hammer, depending on the degrees of changes that have been made. After a total of eight simulations with different length and ODs, one can see that the stress is much higher when hammer length is short. On the other hand the length of HW drill pipe does not affect stress so much, even if the length increases several times. However, HW drill pipe length affects the time duration when stress is larger than 1000 bar. The longer HW, the longer time will the stress act on the string. The time is important to a successful jarring operation, since the stress shock acts on the stuck pipe only a short time. Longer time is the better chance to succeed.

In most of the calculations of stress in the simulation models there are found periods of negative (minus) stress. It means that the string compresses at the *negative* stress, while *positive* stress means that the string is in tension.

Note that we did change only OD and length of HW and Hammer, but other sections of the BHA were always the same except for the case where hammer length was changed, then the length of the jar house was also changed. This change of the jar house may be one important reason why the maximum stress was so dependent on hammer length. We did not research the stresses and time effect that could be applied if size, steel quality, weight and other factors would be changed

Several conditions were neglected and did not used in calculations because of simplification of the numerical model.

The string was divided into 74 to 86 numerical segments. Space step length Δz: 1.0 m. The other factors are given in Table 5 and Table 6 & 7. Initial speed of hammer used equals to 11.465 m/sec.

My recommendations relating to avoid getting stuck drill string as possible in the future are the following:

- More research is required, for physical parameters and factors of equipment, and pressure down hole.
- Research on new chemicals and inhibitors of a well is also important.
- Improvement of preventive procedures and follow-up of best practices to prevent that a stuck pipe situation occurs.
- Use short hammer length for better impact.

In the thesis it has been used numerical calculation method for concrete initial target, i.e. optimizing the jar by increasing the efficiency. The model in the thesis is useful, but for more accuracy and improvements the deeper research is recommended, where one can calculate the stress and time by changing numerous of physical parameters.

The numerical calculations from the thesis have been made in Excel, however for more detailed and flexible work regarding calculation models, drill string design and user interface the MatLab definitely recommended.

Reference

1. Erik Skaugen, «*Dynamic Loading of Equipment*» compendium I, 1997, HIS.
2. Alfred William Eustes III, «*A Frequency Domain Approach to Drillstring Jarring Analysis*», PhD thesis, 1996, Colorado School of Mines
3. Marcus R. Skeem, Morton B. Friedman, "*Drillstring Dynamics During Jar Operation*", November 1979, JPT.
4. Amir Mohammad, «*Numerical Simulation of Jarring of Operation*», M.Sc. thesis, 2004, HIS
5. Gore Kemp, *"Oilwell Fishing Operations: Tools and Techniques"*, Second Edition, 1990
6. William C. Lyons, *"Work Guide to Drilling Equipment and Operations"*, 2010
7. G. Robello Samuel, "*Downhole Drilling Tools*", Gulf Publishing Company, 2007
8. Walt Aldred, Ian Bradford, Liam Cousin, "*Managing Drilling Risk*" paper, 1999.
9. Colin Bowes, Ray Procter, "*Drillers Stuck pipe Handbook*", 1997, Procter & Collins Ltd.
10. G. Walker, "*Fishing*" SPE 13360 paper, 1984
11. Jose L. Mercado, "*Planning for Successful Jarring Operations – Effective Use of Drilling Impact Systems Helps Release Stuck Pipe*", **SPE 159223**, 2012
12. Jose L. Mercado, "*Planning for Successful Jarring Operations – Effective Use of Drilling Impact Systems Helps Release Stuck Pipe*", **SPE 163413**, 2013
13. Dave Ringrose, Dick Lancaster, Keith Coghill, Dave Roberts, Earl Scott - Sedco Forex//Drillers Stuck pipe Handbook// 1997
14. Jaw-Kuang Wang and Manmohan S. Kalsi, "*A Practical Approach to Jarring Analysis*", SPE Drilling Engineering, March 1990
15. D. Herrington, S. Barton, S. Bouaziz, "*Step Change Jar Technology Redefines Industry Standards in North Sea Region*", SPE 160428, 2012
16. Jawad Raza, "Numerical Simulation of Jarring in Stuck Drillstring". M.Sc. thesis, Aalborg University Esbjerg, Denmark, 2004

17. Halliburton Testing and Subsea, “*Downhole Test Tools*”
18. Halliburton Sperry Drilling Services, “*Sledgehammer Hydromechanical Drilling Jar*” 2011 – 2012
19. Halliburton, “*Operation and Maintenance Manual: LockJar Multi-Conductor Electric Wireline Jar and Enhancer*”, Revision A, January 2012
20. Manoj B. Keshavan, “*Jarring Dynamics of Drillstrings*”, Thesis, Massachusetts Institute of Technology, September 1993
21. Odfjell Well Services, “*Megaton & Ulti-Torq Operation Manual*”, Document No.: 665474, v/1.
22. Griffith Oil Tool – A National Oilwell Technology, “*Operating Manual: Double Acting Hydraulic/Mechanical Drilling Jar*”, May 1999.
23. ZMS, “*Hydromechanical Double Acting Drilling Jar COUGAR DJ6*”, company paper, 2012
24. Schlumberger, “*Hydra-Jar AP Double-Acting Hydraulic Drilling Jar*”, 2012
25. Smith Services, “*Operation Manual Hydra-Jar*”, Revision April, 2002
26. Weatherford Drilling Tools, “*Dailey Hydraulic Drilling Jar*”
27. Weatherford, “*Fishing Technology*”, presentation, 2001
28. Drilling System, “*Drillsim-5000, Jarring Operations*”, 2005
29. Kalsi Engineering, “*JarPro User’s Manual*”, Document No.: 2572, Rev. 1, April 2008
30. William C. Lyons, “*Standard Handbook of Petroleum & Natural Gas Engineering”,* Vol. 1, Gulf Publishing Company, Houston, Texas, 1996
31. Smith Services, “*Dimensional Data Handbook*”, 1st Edition, 2001
32. Hovda, S., et al., 2008, Potential of Ultra High-Speed Drill String Telemetry in Future Improvements of the Drilling Process Control, [Conference Paper] SPE-115196-MS, presented at IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Jakarta, Indonesia, 25-27 August 2008.
33. James K. Dodson Study, www.infogulf.com, 11/2005
34. MI_SWACO Drilling Fluids Engineering Manual// Revision No: A-0 / Revision 1998

35. Aadnoy, B.S., K. Larsen, and P.C. Berg, 1999, Analysis of Stuck Pipe in Deviated Boreholes, [Conference Paper] SPE-56628-MS, presented at SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, 3-6 October 1999.
36. Denny Adelung, Warren Askew, Jamie Bernardini, A.T. (Buck) Campbell Jr, Mike Chaffin, Rodney Hensley, Bill Kirton, Randy Reese, Don Sparling// Jars, jarring and jar placement //Suck pipe oil field review// the document is available from the following

Link http://slb.com/~/media/Files/resources/oilfield_review/ors91/oct91/7_jarring.pdf

37. Logan oil tool //Logan Fishing Bumper Sub// the document is available from the following Link…http://www.loganoiltools.com/PDF/Manuals/Fishing-Bumper-Sub-Manual.pdf
38. National Oilwell Varco, “Drilling Jars: Drill Pro, Drill Tough Double-Acting HMJ, Drill Tough Powerstroke”, 2008
39. Colin Bowes & Ray Procter// *Drillers Stuck pipe Handbook, 1997 Guidelines & Drillers Handbook Credits*

Appendix A

Area calculation of the jarring system

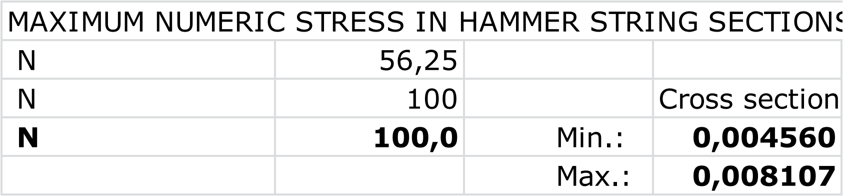
Calculated cross sections		Distances from top of each string		
A of all numeric segments, measured in square meter:	A	Drill pipe string	Hammer pipe string	JAR + BHA STRINGS
Drill pipes:	0,00456	0,00000		
Top pist. pipe:	0,00456		5,00000	
A. hous. Top:	0,01216	4,50000		
A. hous. mid:	0,01976			
A. house bot.:	0,01697	7,50000		
A. house wall:	0,01419			
Piston top:	0,00735		7,50000	
Piston middle:	0,01013			
Piston bottom:	0,00912		8,50000	
B. house top:	0,01697	10,50000		
B. house end:	0,01976	12,00000		
Bot. pist. pipe:	0,00811			
Pipe - HW top:	0,01241		14,50000	
Heavy W. pipe	0,01672			
HW pipe bot.:	0,01064		35,50000	
Ham.pipe top:	0,00456			
Jar ham. top:	0,01013		41,00000	
Jar.ham bot.:	0,00653		42,50000	
Ham.pipe bot:	0,00292		46,00000	
Anvil sec. top:	0,01976			39,00000
Ac. sec. walls:	0,01295			41,00000
Ac. to delay s:	0,01357		NB! Piston is in upper position	43,50000
Delay section:	0,01419			
Delay to splin.	0,01925			45,50000
Spline section	0,02432			
Spline to drill	0,02432			48,50000
Drill collars:	0,02432			54,00000
SUM COLLISION AREAS	0,04741			

Table A1: Area calculations

Anvil is in contact with hammer here. Than the coefficient i, j, m and n can be calculated:

Name	Coefficient	Formula
COEFFICIENT i	0,19238991	2*Hammer pipe top Area/Sum collision Areas
COEFFICIENT j	0,42753313	2*Jar hammer top Area/Sum collision Areas
COEFFICIENT m	0,83368961	2*Anvil section top Area/Sum collision Areas
COEFFICIENT n	0,54638735	2*Accelerator sec. walls Area/Sum collision Areas

Table A2: Coefficient values with formulas from Excel



MAXIMUM NUMERIC STRESS IN HAMMER STRING SECTION			
N	56,25		
N	100		Cross section
N	**100,0**	Min.:	**0,004560**
		Max.:	**0,008107**

Table A3: Max numeric stress in hammer string section

Appendix B

Appendix B is shown calculations and numerical model both for jar hammer string, upper part of BHA, and jar housing string, which is the lower part of the BHA.

Jar hammer string

		JAR HAMMER STRING, BLACK NUMBERS N									
TOTAL LENGTH:		1	2	3		3	4		9	10	
LENGTH OF EACH PART:		1	1	1		0	1		5	1	
	Segment no	**1**		**3**			**4**			**10**	
string			Top pist. pipe	Piston pipe to piston		Piston	Piston to bottom piston pip		Bot. Pist. pipe	Bottom piston pipe to HW	
		TOP END	NUMBER OF	AREA CHANGE SECTION		Number of	AREA CHANGE SECTION		Number of	AREA CHANGE SECTION	
JAR + BHA		Free end	WHOLE SEG.	C1*X(j-1)+C2*X(j+1)-XGj		whole segm.	C1*X(j-1)+C2*X(j+1)-XGj		whole segm.	C1*X(j-1)+C2*X(j+1)-XGj	
STRINGS		Free end equ.	STANDARD E	C1	C2	standard eq.	C1	C2	standard eq.	C1	C2
		X(1)+X(2)-XG(1)	1	0,62068966	1,37931034	0	1,11111111	0,88888889	5	0,65306122	1,34693878

				Hammer pipe to hammer.							
30	31		35	36		37	37	38		40	41
20	1		4	1		1	0	1		2	1
	31			**36**		**37**		**38**			**41**
HW drill pipe	HW pipe to hammer pipe tc		Top ham. pip	Special equations for area change at borc			Hammer pipe	Hammer to ham. pipe bott		Bot ham. pipe	
Number of	AREA CHANGE SECTION		Number of	XN(i) = X(i-1)+C1*X(i)+C2*X(j)-XGi			Number of	AREA CHANGE SECTION		Number of	BOTTOM END
whole segm.	C1*X(j-1)+C2*X(j+1)-XGj		whole segm.	XN(j) = C3*X(i)-C1*Xj+X(j+1)-XGj			whole segm.	C1*X(j-1)+C2*X(j+1)-XGj		whole segm.	
standard eq.	C1	C2	standard eq.	C1	C2	C3	standard eq.	C1	C2	standard eq.	Free end
20	1,57142857	0,42857143	4	-0,3793103	1,37931034	0,62068966	0	1,55279503	0,44720497	2	Free end equ.

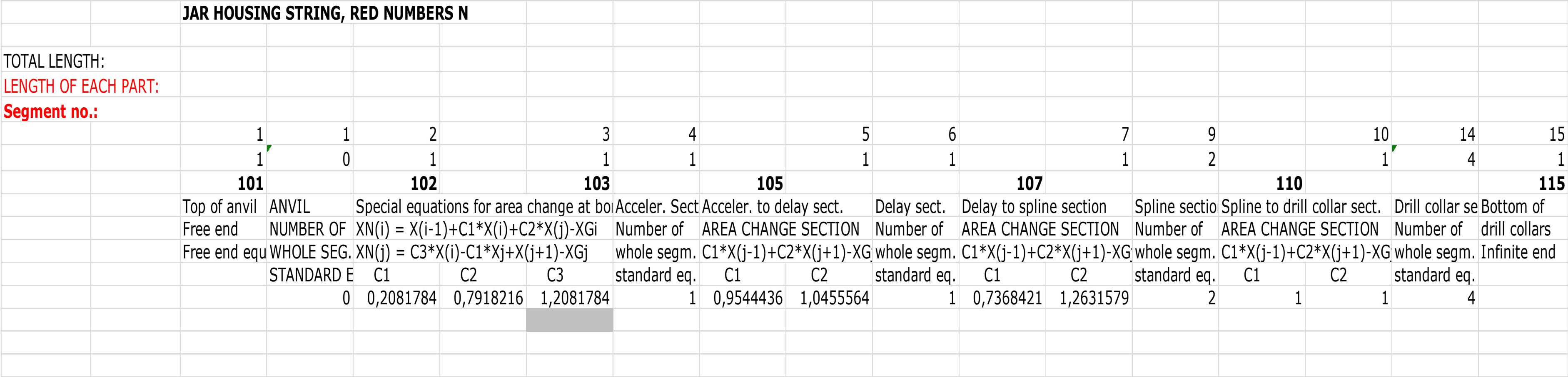
JAR HAMMER CALCULATIONS											
	SEGMENT NUMBER										
TIME/Dt	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
-1	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50
0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
1	50,0	49,8	50,0	50,0	49,8	49,8	49,8	49,8	49,8	50,0	49,8	49,8
2	99,8	99,8	99,9	99,8	99,6	99,4	99,4	99,4	99,6	99,6	99,6	99,4
3	149,6	149,7	149,6	149,5	149,2	149,0	148,8	149,0	149,0	149,2	149,0	149,0
4	199,5	199,2	199,2	199,1	198,7	198,4	198,4	198,2	198,4	198,4	198,4	198,2
5	249,1	248,8	248,6	248,5	248,1	247,9	247,6	247,6	247,4	247,6	247,4	247,4
6	298,5	298,3	298,0	297,7	297,5	297,1	296,9	296,6	296,6	296,4	296,4	296,2
7	347,7	347,4	347,1	347,0	346,5	346,3	345,9	345,7	345,5	345,4	345,0	345,0
8	396,6	396,3	396,3	396,0	395,7	395,1	394,9	394,5	394,3	393,9	393,8	393,5
9	445,2	445,3	445,1	445,0	444,4	444,1	443,5	443,3	442,8	442,5	442,1	442,0
10	494,0	493,8	493,9	493,6	493,2	492,7	492,2	491,6	491,3	490,8	490,6	490,2
11	542,5	542,3	542,2	542,2	541,6	541,2	540,5	540,1	539,4	539,1	538,6	538,4
12	590,9	590,7	590,6	590,3	590,0	589,3	588,9	588,2	587,7	587,0	586,7	586,3
13	639,1	639,0	638,7	638,4	637,8	637,4	636,7	636,2	635,5	635,0	634,4	634,2
14	687,2	686,9	686,6	686,3	685,7	685,0	684,6	683,9	683,4	682,6	682,3	681,7
15	734,9	734,6	734,2	734,0	733,3	732,7	732,0	731,6	730,8	730,3	729,7	729,3
16	782,3	782,1	781,7	781,4	780,8	780,1	779,4	778,7	778,2	777,5	777,1	776,6
17	829,5	829,3	829,0	828,6	828,0	827,3	826,6	825,9	825,2	824,8	824,2	823,8
18	876,5	876,2	876,0	875,7	875,0	874,3	873,6	872,9	872,3	871,6	871,3	870,7
19	923,2	923,0	922,7	922,4	921,8	921,1	920,4	919,8	919,1	918,4	917,9	917,6
20	969,6	969,5	969,2	969,0	968,4	967,8	967,1	966,4	965,8	965,0	964,6	964,2
21	1016,0	1015,7	1015,5	1015,3	1014,7	1014,1	1013,5	1012,9	1012,1	1011,5	1011,1	1010,7
22	1062,1	1061,8	1061,6	1061,4	1060,8	1060,3	1059,7	1059,1	1058,4	1057,9	1057,4	1057,1
23	1107,9	1107,7	1107,5	1107,2	1106,8	1106,3	1105,7	1105,1	1104,7	1104,0	1103,7	1103,2
24	1153,6	1153,4	1153,2	1153,0	1152,5	1151,9	1151,4	1151,1	1150,5	1150,1	1149,6	1149,3
25	1199,1	1198,9	1198,7	1198,5	1198,0	1197,5	1197,2	1196,7	1196,3	1195,8	1195,5	1195,1
26	1244,4	1244,2	1244,1	1243,8	1243,3	1243,0	1242,5	1242,3	1241,8	1241,5	1241,1	1212,7
27	1289,5	1289,4	1289,1	1288,9	1288,7	1288,2	1287,9	1287,4	1287,2	1286,8	1258,5	1258,2
28	1334,5	1334,2	1334,1	1334,1	1333,6	1333,4	1332,9	1332,7	1332,3	1294,2	1303,8	1275,5
29	1379,2	1379,0	1379,1	1378,8	1378,6	1378,2	1378,0	1377,7	1339,6	1339,4	1311,2	1337,4
30	1423,8	1423,9	1423,7	1423,7	1423,2	1423,0	1422,7	1384,8	1384,6	1346,7	1372,9	1361,4
31	1468,5	1468,3	1468,4	1468,1	1467,9	1467,6	1429,7	1429,6	1391,8	1414,0	1396,8	1393,2
32	1513,0	1512,8	1512,7	1512,7	1512,3	1474,5	1474,3	1436,6	1458,8	1443,6	1434,2	1424,7
33	1557,3	1557,2	1557,0	1556,9	1519,2	1519,0	1481,3	1503,4	1488,2	1470,5	1471,4	1479,5
34	1601,5	1601,3	1601,3	1567,8	1563,4	1525,9	1547,9	1532,7	1514,9	1510,2	1515,6	1513,5
35	1645,5	1645,4	1599,3	1612,0	1574,3	1592,2	1577,1	1559,3	1554,5	1560,4	1552,2	1529,0
36	1689,5	1643,5	1643,5	1608,7	1640,6	1625,3	1603,5	1598,8	1604,6	1595,7	1573,6	1564,9
37	1687,4	1687,5	1639,6	1672,4	1659,5	1651,8	1646,9	1648,6	1639,8	1607,0	1608,3	1577,2
38	1685,4	1683,4	1710,7	1688,3	1683,6	1681,0	1696,7	1687,7	1651,0	1641,5	1610,6	1603,7
39	1681,5	1708,6	1733,9	1724,8	1709,6	1728,3	1721,6	1699,0	1689,3	1640,4	1636,8	1619,0
40	1704,6	1731,9	1728,9	1757,9	1769,4	1750,1	1730,5	1723,1	1688,4	1666,4	1648,8	1647,6
41	1755,0	1724,9	1765,8	1768,9	1798,3	1771,5	1751,5	1719,9	1700,3	1683,0	1677,2	1663,5
42	1775,3	1788,8	1781,7	1802,5	1771,0	1799,6	1760,8	1728,7	1714,4	1703,0	1697,6	1667,6
43	1809,1	1831,8	1830,7	1785,0	1803,8	1760,4	1776,7	1755,3	1731,3	1723,1	1693,4	1705,2
44	1865,6	1850,9	1817,3	1835,1	1774,3	1781,0	1754,9	1779,3	1763,9	1708,6	1730,7	1720,3
45	1907,4	1851,1	1849,2	1811,5	1812,2	1768,8	1783,5	1763,5	1756,5	1759,9	1735,4	1741,9
46	1892,9	1905,6	1830,2	1830,4	1805,9	1814,7	1777,3	1760,7	1759,5	1776,0	1771,0	1727,9
47	1891,1	1871,9	1858,3	1827,3	1832,9	1814,3	1791,9	1773,3	1780,3	1774,6	1768,5	1761,7
48	1870,1	1843,9	1852,1	1863,6	1835,7	1810,1	1810,2	1811,3	1788,4	1768,6	1765,3	1765,0
49	1823,0	1850,4	1856,7	1862,4	1840,8	1831,6	1829,4	1825,2	1799,6	1771,0	1765,1	1752,0
50	1803,2	1835,7	1865,2	1835,6	1858,2	1860,0	1846,5	1817,7	1807,8	1784,2	1757,7	1754,8

							Y					
13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
49,8	49,8	49,8	49,8	49,8	49,8	49,8	49,8	49,8	49,8	49,8	49,8	49,8
99,4	99,4	99,4	99,4	99,4	99,4	99,4	99,4	99,4	99,4	99,4	99,4	99,4
148,8	148,8	148,8	148,8	148,8	148,8	148,8	148,8	148,8	148,8	148,8	148,8	148,8
198,2	198,0	198,0	198,0	198,0	198,0	198,0	198,0	198,0	198,0	198,0	198,0	198,0
247,2	247,2	247,0	247,0	247,0	247,0	247,0	247,0	247,0	247,0	247,0	247,0	247,0
296,2	296,0	296,0	295,8	295,8	295,8	295,8	295,8	295,8	295,8	295,8	295,8	295,8
344,8	344,8	344,6	344,6	344,4	344,4	344,4	344,4	344,4	344,4	344,4	344,4	344,6
393,5	393,3	393,3	393,1	393,1	392,9	392,9	392,9	392,9	392,9	392,9	393,1	393,1
441,7	441,7	441,5	441,5	441,3	441,3	441,1	441,1	441,1	441,1	441,3	441,3	441,5
490,0	489,7	489,7	489,5	489,5	489,3	489,3	489,1	489,1	489,3	489,3	489,5	489,5
538,0	537,9	537,6	537,6	537,4	537,4	537,2	537,2	537,2	537,2	537,4	537,4	537,6
586,0	585,7	585,5	585,2	585,2	585,0	585,0	585,0	585,0	585,0	585,0	585,2	585,3
633,7	633,5	633,1	633,0	632,7	632,7	632,7	632,7	632,7	632,7	632,7	632,8	604,0
681,5	681,0	680,8	680,4	680,3	680,1	680,1	680,1	680,1	680,1	680,2	651,4	651,5
728,8	728,6	728,1	727,9	727,7	727,5	727,4	727,4	727,4	727,5	698,7	698,9	670,1
776,2	775,7	775,4	775,2	774,9	774,8	774,6	774,5	774,6	745,8	746,0	717,3	734,6
823,3	822,9	822,6	822,3	822,1	821,8	821,7	821,6	792,8	793,0	764,3	781,5	770,1
870,4	870,0	869,6	869,3	869,0	868,8	868,6	839,8	839,9	811,1	828,3	816,9	803,6
917,2	916,9	916,5	916,1	915,8	915,6	886,8	886,8	858,0	875,0	863,5	850,2	846,7
963,9	963,5	963,2	962,8	962,6	933,7	933,7	904,9	921,8	910,2	896,8	893,2	898,0
1010,4	1010,1	1009,7	1009,4	980,6	980,4	951,7	968,5	956,9	943,4	939,8	944,4	937,7
1056,7	1056,3	1056,1	1027,3	1027,2	998,4	1015,1	1003,5	990,0	986,3	990,8	984,0	959,2
1102,9	1102,5	1073,9	1073,7	1045,0	1061,7	1050,0	1036,5	1032,7	1037,2	1030,3	1005,5	998,2
1148,9	1120,3	1120,0	1091,4	1108,1	1096,4	1083,0	1079,1	1083,5	1076,6	1051,8	1044,4	1010,3
1166,6	1166,2	1137,7	1154,2	1142,6	1129,2	1125,4	1129,7	1122,8	1098,0	1090,5	1056,5	1040,9
1212,3	1183,9	1200,3	1188,7	1175,2	1171,4	1175,8	1168,9	1144,1	1136,6	1102,6	1086,9	1066,3
1229,8	1246,2	1234,7	1221,1	1217,3	1221,6	1214,7	1190,0	1182,6	1148,6	1132,9	1112,2	1099,1
1291,9	1280,5	1266,9	1263,1	1267,4	1260,5	1235,7	1228,3	1194,5	1178,8	1158,2	1145,0	1128,4
1325,9	1312,5	1308,8	1313,0	1306,1	1281,4	1274,0	1240,0	1224,4	1203,9	1190,8	1174,2	1136,3
1357,8	1354,1	1358,4	1351,6	1326,9	1319,5	1285,6	1270,0	1249,4	1236,3	1219,8	1182,0	1183,0
1389,5	1403,5	1396,8	1372,1	1364,8	1331,0	1315,4	1294,8	1281,8	1265,1	1227,4	1228,5	1210,6
1438,7	1432,0	1417,2	1409,9	1376,2	1360,7	1340,1	1327,1	1310,4	1272,8	1273,8	1256,0	1241,0
1467,0	1452,2	1445,0	1421,1	1405,7	1385,1	1372,2	1355,6	1318,0	1319,0	1301,2	1286,2	1249,2
1493,0	1480,0	1456,1	1440,7	1430,0	1417,1	1400,6	1363,1	1364,0	1346,3	1331,3	1294,4	1277,5
1526,3	1496,7	1475,6	1464,9	1452,1	1445,3	1407,9	1408,9	1391,2	1376,2	1339,4	1322,6	1291,8
1532,7	1521,9	1505,4	1486,9	1480,1	1442,8	1453,5	1435,9	1420,9	1384,3	1367,4	1336,7	1309,8
1560,3	1541,3	1533,0	1520,5	1477,6	1488,2	1470,6	1465,4	1428,8	1412,1	1381,5	1354,6	1326,9
1585,7	1571,4	1556,2	1523,7	1528,5	1505,3	1500,1	1463,6	1456,5	1426,0	1399,2	1371,6	1345,2
1614,6	1600,5	1562,0	1564,2	1551,2	1540,3	1498,1	1491,1	1460,6	1443,5	1416,1	1389,8	1372,6
1633,7	1605,2	1608,3	1589,4	1575,8	1544,0	1531,2	1495,1	1478,1	1450,7	1434,0	1416,9	1381,5
1638,1	1641,5	1632,4	1619,9	1582,1	1566,8	1540,9	1518,2	1485,1	1468,5	1451,4	1425,8	1410,7
1671,1	1665,3	1652,9	1625,1	1610,7	1579,0	1553,6	1530,8	1508,6	1485,8	1460,2	1445,2	1423,4
1694,6	1682,5	1657,9	1643,7	1621,9	1597,6	1568,8	1544,0	1531,4	1500,2	1479,5	1457,8	1439,7
1716,5	1687,2	1673,3	1654,6	1630,5	1611,6	1587,8	1569,3	1535,5	1525,0	1497,7	1474,0	1454,2
1712,9	1707,2	1683,9	1660,0	1644,3	1620,7	1612,1	1579,3	1562,9	1533,0	1519,5	1494,1	1471,2
1732,6	1709,5	1693,9	1673,6	1650,2	1644,7	1612,2	1605,5	1576,7	1557,2	1529,3	1516,6	1487,6
1724,5	1719,3	1699,2	1684,0	1673,9	1641,6	1638,1	1609,5	1599,8	1572,9	1554,3	1522,8	1508,0
1748,3	1714,2	1709,4	1699,4	1675,4	1667,2	1638,9	1632,4	1605,7	1596,8	1566,3	1545,6	1517,2
1754,6	1738,4	1714,4	1700,7	1692,7	1672,6	1661,5	1635,0	1629,3	1599,0	1588,1	1560,7	1538,0

					X							
26	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**
-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
49,8	49,8	49,8	49,8	49,8	50,0	49,8	49,8	49,8	49,8	50,0	50,0	50,0
99,4	99,4	99,4	99,4	99,6	99,6	99,6	99,4	99,4	99,6	30,8	31,0	99,9
148,8	148,8	148,8	149,0	149,0	149,2	149,0	149,0	149,0	80,3	80,8	80,9	42,7
198,0	198,0	198,2	198,2	198,4	198,4	198,4	198,4	129,9	130,1	61,6	23,6	92,5
247,0	247,2	247,2	247,4	247,4	247,6	247,6	179,2	179,4	111,1	151,9	152,2	35,4
296,0	296,0	296,2	296,2	296,4	296,5	228,4	228,6	160,4	201,1	173,9	135,9	207,4
344,6	344,8	344,8	345,0	345,1	316,1	277,4	209,5	250,1	223,0	191,1	235,1	213,7
393,3	393,3	393,5	393,5	364,5	364,7	297,0	298,8	271,8	240,0	231,7	216,4	272,5
441,5	441,7	441,8	412,8	413,0	384,1	385,9	359,1	288,6	280,4	291,6	295,3	240,0
489,7	489,8	460,9	461,1	432,2	449,7	445,9	375,6	367,5	340,0	324,4	295,5	282,6
537,6	508,8	509,0	480,2	497,6	486,2	439,2	454,1	426,6	411,2	313,8	281,5	300,7
556,5	556,7	528,0	545,3	534,0	520,5	494,4	490,1	497,5	400,3	383,6	334,3	255,4
604,2	575,5	592,9	581,5	568,1	564,7	571,1	537,6	463,7	469,8	350,7	287,4	381,7
622,9	640,2	628,9	615,5	612,2	617,0	607,8	544,6	509,9	414,0	400,3	424,9	362,0
687,4	676,1	662,7	659,4	664,2	657,7	590,4	579,9	494,8	440,5	376,5	363,3	455,7
723,1	709,7	706,4	711,2	704,7	679,8	629,8	540,7	510,6	457,3	409,2	413,0	353,8
756,8	753,2	758,0	751,6	726,7	719,6	630,0	560,4	503,1	479,2	435,2	341,1	419,0
800,1	804,9	798,2	773,4	766,4	732,1	650,3	592,3	529,0	481,0	398,1	428,2	386,2
851,5	844,9	820,1	812,9	778,7	763,3	694,3	618,7	570,1	448,0	442,0	411,2	446,4
891,4	866,6	859,4	825,3	809,8	789,2	731,6	671,9	537,6	531,0	456,5	455,6	432,3
912,9	905,8	871,7	856,2	835,6	822,7	766,6	650,5	632,7	545,9	501,2	434,2	451,5
952,0	918,0	902,5	882,0	869,0	852,5	741,6	727,3	658,5	602,8	470,6	443,9	461,1
964,1	948,6	928,1	915,2	898,7	860,8	813,1	749,4	697,2	583,1	522,8	474,8	446,1
994,7	974,1	961,2	944,7	906,8	908,2	868,4	783,0	673,9	617,2	517,5	455,2	436,8
1020,2	1007,2	990,7	952,7	954,1	936,4	877,9	792,8	703,0	608,3	527,6	457,4	422,7
1053,2	1036,6	998,7	999,9	982,1	967,4	860,9	797,9	727,0	613,3	525,8	472,7	467,9
1082,5	1044,6	1045,8	1028,0	1013,1	975,9	887,3	795,1	708,2	644,5	531,9	509,7	513,6
1090,4	1091,6	1073,7	1058,8	1021,6	1004,9	910,0	797,6	712,6	626,8	587,7	532,1	544,2
1137,3	1119,4	1104,5	1067,3	1050,5	1019,5	915,1	827,4	716,2	655,7	548,4	543,6	529,4
1165,1	1150,1	1112,9	1096,2	1065,2	1038,1	936,9	833,6	770,5	637,8	582,2	516,2	534,6
1195,7	1158,6	1141,7	1110,7	1083,7	1055,8	956,5	879,9	755,2	696,9	573,6	541,2	543,2
1204,0	1187,2	1156,2	1129,2	1101,2	1074,8	998,6	878,0	806,1	690,9	625,4	570,2	571,5
1232,5	1201,6	1174,6	1146,7	1120,2	1102,7	996,1	924,8	813,6	734,6	624,0	592,3	599,9
1246,7	1219,9	1192,0	1165,5	1148,1	1112,4	1028,8	931,6	853,2	746,6	669,8	621,9	631,0
1264,8	1237,1	1210,7	1193,3	1157,7	1142,3	1047,8	957,2	864,6	788,3	673,3	637,1	656,7
1282,1	1255,6	1238,3	1202,8	1187,5	1155,9	1070,6	980,7	892,1	791,1	709,8	662,3	660,3
1300,5	1283,2	1247,6	1232,4	1200,9	1182,5	1088,7	1005,5	907,1	813,7	720,1	673,0	669,6
1328,0	1292,4	1277,2	1245,6	1227,3	1197,8	1117,2	1015,0	926,9	836,0	737,8	688,5	652,0
1337,1	1321,9	1290,4	1272,1	1242,5	1225,0	1124,1	1038,6	943,9	851,0	772,4	684,9	688,7
1366,4	1334,9	1316,7	1287,1	1269,6	1236,4	1146,3	1052,9	962,7	880,2	774,6	749,1	713,5
1379,3	1361,1	1331,6	1314,2	1281,0	1261,4	1165,1	1070,3	989,0	886,2	806,6	752,9	782,0
1405,3	1375,9	1358,5	1325,4	1305,9	1275,9	1185,3	1101,2	993,8	915,4	815,9	790,9	777,3
1419,9	1402,6	1369,6	1350,2	1320,2	1298,7	1211,9	1108,7	1027,4	923,3	838,3	778,9	789,1
1437,0	1413,6	1394,2	1364,3	1342,9	1318,1	1222,0	1138,0	1038,2	950,3	841,7	791,8	781,3
1447,8	1428,5	1408,2	1386,9	1362,2	1335,3	1244,2	1151,4	1060,8	956,5	864,5	804,8	817,2
1462,7	1442,4	1421,1	1406,0	1379,2	1355,7	1264,7	1167,0	1069,6	975,0	872,9	843,3	836,3
1482,1	1455,2	1440,1	1413,4	1399,4	1374,0	1278,3	1182,8	1081,1	986,0	901,5	852,3	874,6
1500,5	1479,7	1447,5	1433,5	1408,1	1391,2	1292,1	1192,4	1099,1	1007,6	920,4	887,9	902,9
1514,8	1492,6	1473,0	1442,1	1425,3	1392,5	1305,3	1208,3	1118,8	1033,4	929,5	906,7	920,8
1530,1	1508,0	1487,2	1464,7	1426,5	1407,9	1308,8	1231,6	1142,5	1040,7	969,0	911,9	918,4
1551,3	1524,7	1499,7	1471,5	1447,3	1410,0	1334,1	1242,9	1153,4	1078,1	969,7	927,5	907,1
1566,9	1542,9	1508,9	1482,2	1455,0	1438,2	1344,1	1255,9	1178,4	1082,3	1002,0	930,4	921,1
1575,4	1551,1	1525,4	1492,3	1473,1	1452,4	1360,0	1279,5	1184,8	1102,3	1006,1	958,7	949,3
1583,3	1557,9	1534,5	1516,2	1489,7	1459,5	1387,7	1288,8	1203,3	1108,5	1028,7	994,7	988,1

39	**40**	**41**	NUMERIC SPEED	SPEED OF HAMMER TOP	DISTANCE MOVED BY Time in milliseconds	SPEED IN m/sec.	HAMMER IN millimeters	STRESS under piston bar	STRESS above hammer bar	**CALCULATION OF COLLISION CONSTANT**
-50	-50	-50								
0,0	0,0	0,0								**0,00**
49,8	49,8	50,0	15	50,00	0,193	11,465	2,217	18,62	0,00	**31,00**
99,6	99,6	99,8	15	-19,20	0,387	-4,404	1,365	20,65	0,00	**61,95**
149,5	149,4	149,4	15	49,96	0,580	11,457	3,580	26,36	0,00	**92,83**
92,5	199,1	199,0	36	-19,14	0,773	-4,389	2,732	34,18	0,00	**164,22**
142,1	142,1	248,7	56	90,33	0,967	20,714	6,737	39,29	0,00	**276,38**
85,0	191,8	191,8	20	21,96	1,160	5,036	7,710	16,11	0,00	**315,82**
256,8	134,8	134,9	29	17,20	1,353	3,943	8,473	50,40	0,00	**373,75**
263,0	199,9	77,8	50	40,59	1,547	9,309	10,272	33,60	0,00	**474,35**
215,7	205,9	142,8	46	59,87	1,740	13,728	12,927	54,76	0,00	**567,24**
183,0	158,7	271,0	11	32,85	1,933	7,532	14,383	29,99	0,00	**589,77**
225,6	248,0	286,8	30	-10,65	2,127	-2,441	13,911	55,86	0,00	**610,56**
365,3	353,3	263,9	18	69,83	2,320	16,012	17,007	32,29	0,00	**647,72**
382,8	380,9	330,3	8	-32,95	2,513	-7,555	15,546	56,66	0,00	**664,80**
397,3	359,9	447,4	13	49,69	2,707	11,395	17,749	53,11	0,00	**713,57**
339,1	463,6	476,9	4	-23,80	2,900	-5,458	16,694	61,75	0,00	**745,56**
521,8	456,0	493,1	29	32,61	3,093	7,477	18,140	55,73	-7,76	**763,62**
470,4	551,1	472,1	-6	26,07	3,287	5,978	19,296	62,02	2681,31	**763,28**
448,5	486,5	530,2	3	-37,17	3,480	-8,523	17,648	59,91	-3,30	**794,30**
402,4	427,8	544,5	29	43,99	3,673	10,086	19,598	59,18	2673,87	**848,58**
425,8	460,5	442,2	30	14,42	3,867	3,307	20,237	54,46	-1571,06	**868,72**
490,2	440,1	358,1	7	44,74	4,060	10,260	22,221	51,75	1081,94	**882,28**
465,8	388,0	356,1	11	-30,65	4,254	-7,027	20,862	49,25	1250,26	**891,81**
359,2	381,8	386,0	23	52,29	4,447	11,991	23,180	44,22	355,49	**927,78**
362,4	357,2	411,7	2	-5,38	4,640	-1,235	22,942	45,88	-406,31	**950,63**
434,6	392,3	382,9	4	10,10	4,834	2,316	23,389	52,02	643,43	**962,55**
452,4	460,2	363,5	2	-1,76	5,027	-0,404	23,311	44,41	2308,18	**971,97**
493,3	423,6	440,7	31	6,11	5,220	1,402	23,582	23,39	693,05	**1000,93**
484,7	473,8	500,8	8	55,75	5,414	12,785	26,054	39,15	3154,03	**1041,21**
524,7	561,6	533,9	-3	-39,23	5,607	-8,996	24,315	24,02	1453,11	**1062,53**
606,1	584,6	594,7	13	33,73	5,800	7,735	25,810	43,17	1920,50	**1066,41**
594,3	639,0	645,4	22	-8,56	5,994	-1,963	25,431	23,13	1212,17	**1084,35**
576,2	655,0	689,7	25	51,83	6,187	11,885	27,729	34,35	1550,26	**1132,22**
632,1	626,9	699,3	22	-1,40	6,380	-0,321	27,667	3504,79	3497,40	**1184,60**
650,5	676,4	636,5	25	45,74	6,574	10,489	29,694	401,39	-83,53	**1220,44**
675,1	660,0	613,6	20	3,49	6,767	0,799	29,849	3512,23	1642,02	**1264,61**
666,2	612,5	637,0	23	36,57	6,960	8,386	31,470	-2974,64	1390,27	**1312,09**
597,8	643,3	636,0	14	10,28	7,154	2,358	31,926	1200,58	3404,84	**1354,12**
646,7	621,2	642,2	26	17,72	7,347	4,063	32,712	436,90	658,67	**1394,31**
675,3	645,7	627,5	18	34,54	7,540	7,920	34,243	1420,59	2835,07	**1433,82**
687,5	681,5	630,9	17	2,25	7,734	0,515	34,343	-1065,74	1589,15	**1473,40**
719,6	672,7	684,9	21	31,93	7,927	7,323	35,759	-2733,65	3076,94	**1510,84**
767,1	722,9	726,7	16	9,31	8,120	2,135	36,171	2929,84	2074,36	**1545,33**
780,5	820,8	764,7	13	22,43	8,314	5,143	37,166	-1756,78	1167,65	**1572,50**
842,6	822,2	858,7	13	3,40	8,507	0,780	37,316	5657,54	3146,61	**1594,21**
822,8	880,5	916,2	16	22,82	8,700	5,232	38,328	-65,48	1532,40	**1622,62**
855,0	916,6	937,9	19	8,42	8,894	1,931	38,701	2286,02	2684,07	**1663,96**
930,0	912,4	938,4	24	28,58	9,087	6,554	39,969	-520,09	899,14	**1708,82**
931,9	951,6	912,9	14	18,88	9,280	4,328	40,805	2596,08	2485,73	**1743,90**
924,6	932,3	926,1	24	9,16	9,474	2,101	41,212	2008,54	532,10	**1785,57**
921,3	899,2	945,5	20	39,48	9,667	9,052	42,962	-2098,81	2796,13	**1827,56**
893,1	934,5	918,6	17	0,67	9,860	0,154	42,992	642,23	1150,35	**1862,69**
920,3	912,5	907,6	18	32,34	10,054	7,415	44,425	-4390,42	1748,71	**1895,47**
940,4	893,5	901,5	13	4,03	10,247	0,924	44,604	2160,46	1317,82	**1934,55**
922,4	929,4	887,3	20	22,66	10,440	5,196	45,608	-1115,58	329,20	**1972,75**

Jar Housing String



		JAR HOUSING STRING, RED NUMBERS N															
TOTAL LENGTH:																	
LENGTH OF EACH PART:																	
Segment no.:																	
		1	1	2		3	4		5	6		7	9		10	14	15
		1	0	1		1	1		1	1		1	2		1	4	1
		101		**102**		**103**		**105**			**107**			**110**			**115**
		Top of anvil	ANVIL	Special equations for area change at bo			Acceler. Sect	Acceler. to delay sect.		Delay sect.	Delay to spline section		Spline sectio	Spline to drill collar sect.		Drill collar se	Bottom of
		Free end	NUMBER OF	XN(i) = X(i-1)+C1*X(i)+C2*X(j)-XGi			Number of	AREA CHANGE SECTION		Number of	AREA CHANGE SECTION		Number of	AREA CHANGE SECTION		Number of	drill collars
		Free end equ	WHOLE SEG.	XN(j) = C3*X(i)-C1*Xj+X(j+1)-XGj			whole segm.	C1*X(j-1)+C2*X(j+1)-XG		whole segm.	C1*X(j-1)+C2*X(j+1)-XG		whole segm.	C1*X(j-1)+C2*X(j+1)-XG		whole segm.	Infinite end
			STANDARD E	C1	C2	C3	standard eq.	C1	C2	standard eq.	C1	C2	standard eq.	C1	C2	standard eq.	
			0	0,2081784	0,7918216	1,2081784	1	0,9544436	1,0455564	1	0,7368421	1,2631579	2	1	1	4	

101	102	103	104	105	106	107	108	109	110	111	112	113	114	115
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	100	100	0	0	0	0	0	0	0
0	0	0	0	0	100	126	100	100	0	0	0	0	0	0
0	31	31	0	104	126	100	126	100	100	0	0	0	0	0
31	31	31	135	132	104	126	99	126	100	100	0	0	0	0
62	62	166	162	133	132	103	126	99	126	99	99	0	0	0
93	133	130	164	161	132	130	103	126	99	126	99	99	0	0
164	174	145	128	161	159	124	130	102	125	99	125	99	99	0
245	173	169	142	128	154	151	124	130	102	125	99	125	99	99
254	272	202	169	135	120	146	151	124	129	102	125	99	125	99
281	283	272	194	159	127	128	145	151	124	129	102	125	99	125
310	293	287	262	183	167	131	128	145	150	123	129	102	125	99
322	324	292	276	266	188	156	131	127	145	150	123	129	102	125
336	316	307	295	277	255	173	156	131	127	145	150	123	129	102
330	344	344	308	283	261	229	172	156	131	127	145	150	123	129
338	335	321	331	290	257	238	228	172	156	131	127	144	150	123
343	372	380	304	301	267	249	237	228	172	156	131	127	144	150
378	381	349	350	279	294	259	249	237	228	172	156	131	127	144
416	388	385	323	339	271	282	258	248	237	228	172	156	131	127
426	410	353	375	313	327	267	281	258	248	237	228	172	155	131
420	422	431	342	360	309	315	267	281	258	248	237	227	172	155
417	436	407	417	337	348	298	315	267	281	258	248	236	227	172
433	427	447	402	402	326	339	298	314	266	281	257	248	236	227
443	452	430	432	387	392	318	339	297	314	266	280	257	248	236
462	456	447	415	421	379	378	318	338	297	314	266	280	257	248
475	482	466	436	405	407	363	377	317	338	297	314	266	280	257
495	488	473	457	420	389	398	362	377	317	338	297	314	266	280
508	488	480	458	437	412	381	398	362	377	317	338	297	313	266
501	504	477	460	447	430	408	381	398	362	377	317	338	297	313
497	510	505	466	451	443	416	407	381	398	361	376	317	338	297
506	524	526	496	461	438	434	416	407	381	397	361	376	317	338
533	534	527	521	480	451	432	433	416	407	380	397	361	376	317
562	541	534	512	508	474	446	432	433	416	407	380	397	361	376
570	571	535	521	504	503	463	446	431	433	415	407	380	397	361
579	590	585	527	515	492	488	462	446	431	433	415	407	380	397
599	602	592	578	514	500	484	487	462	446	431	432	415	407	380
623	627	622	579	560	506	496	484	487	462	445	431	432	415	407
651	658	629	603	567	556	500	496	483	487	461	445	431	432	415
686	678	664	618	597	561	540	499	496	483	487	461	445	431	432
713	704	679	658	609	581	545	540	499	495	483	487	461	445	431
731	725	710	670	638	592	570	544	539	499	495	483	486	461	445
743	736	715	690	649	627	579	570	544	539	499	495	483	486	461
748	756	739	695	676	636	612	579	569	544	539	498	495	483	486
760	767	752	724	679	660	621	611	579	569	544	539	498	495	483
779	783	779	736	706	664	647	621	611	578	569	543	539	498	495
802	802	778	761	717	693	652	647	620	611	578	569	543	539	498
825	811	798	759	744	706	680	652	646	620	610	578	569	543	539
834	834	806	782	745	732	691	680	651	646	620	610	578	569	543
843	853	842	791	767	730	718	691	679	651	646	620	610	578	569
862	865	853	827	774	753	719	717	690	679	651	646	619	610	578
884	888	876	835	810	763	743	719	717	690	679	651	646	619	610
910	916	892	859	821	800	751	743	718	717	690	679	650	645	619
942	933	918	878	846	809	784	751	742	718	716	690	679	650	645
965	956	930	906	862	831	793	784	750	742	718	716	689	678	650
979	972	953	915	887	846	818	793	783	750	742	718	716	689	678
986	985	967	934	896	874	832	818	792	783	750	742	718	716	689

		THESE TWO COLUMNS		MAXIMUM POSITIVE STRES		**4608,81**	bar
		GIVE THE IMPORTANT		MAXIMUM NEGATIVE STRE		**-1058,58**	bar
		FIGURES -		TIME DURATION WHEN			
		STRESS IN BHA AS A		STRESS IS LARGER THAN		**11,600**	msec.
		FUNCTION OF TIME		1000	bar		
REMOVING NUMERIC OSCILLATION		**X - AXIS** RUN TIME START AT COLLISION msec.	**Y - AXIS** STRESS IN BHA bar	MAXIMUM POSITIVE STRESS bar	MAXIMUM NEGATIVE STRESS bar	TIME DURATION WHEN STRESS IS LARGER THAN 1000 UNIT IN msec.	bar
0		0	0	0	0	0,000	
0		0,1933	0,00	0,00	0,00	0,000	
0		0,3867	0,00	0,00	0,00	0,000	
0		0,5800	0,00	0,00	0,00	0,000	
0		0,7734	0,00	0,00	0,00	0,000	
0		0,9667	0,00	0,00	0,00	0,000	
0		1,1600	0,00	0,00	0,00	0,000	
50		1,3534	4608,81	4608,81	0,00	0,193	
99		1,5467	4599,59	4608,81	0,00	0,387	
112		1,7401	1210,49	4608,81	0,00	0,580	
112		1,9334	-9,13	4608,81	-9,13	0,580	
112		2,1268	-11,54	4608,81	-11,54	0,580	
113		2,3201	151,44	4608,81	-11,54	0,580	
115		2,5134	193,71	4608,81	-11,54	0,580	
126		2,7068	991,67	4608,81	-11,54	0,580	
137		2,9001	986,15	4608,81	-11,54	0,580	
147		3,0935	990,30	4608,81	-11,54	0,580	
136		3,2868	-1058,58	4608,81	-1058,58	0,580	
129		3,4801	-637,17	4608,81	-1058,58	0,580	
143		3,6735	1309,11	4608,81	-1058,58	0,773	
164		3,8668	1903,42	4608,81	-1058,58	0,967	
199		4,0602	3345,43	4608,81	-1058,58	1,160	
232		4,2535	3007,59	4608,81	-1058,58	1,353	
242		4,4469	943,56	4608,81	-1058,58	1,353	
252		4,6402	975,26	4608,81	-1058,58	1,353	
269		4,8335	1516,78	4608,81	-1058,58	1,547	
273		5,0269	406,52	4608,81	-1058,58	1,547	
290		5,2202	1548,93	4608,81	-1058,58	1,740	
305		5,4136	1423,52	4608,81	-1058,58	1,933	
317		5,6069	1118,70	4608,81	-1058,58	2,127	
327		5,8002	940,83	4608,81	-1058,58	2,127	
346		5,9936	1800,58	4608,81	-1058,58	2,320	
369		6,1869	2064,28	4608,81	-1058,58	2,513	
379		6,3803	967,25	4608,81	-1058,58	2,513	
389		6,5736	884,46	4608,81	-1058,58	2,513	
393		6,7670	447,51	4608,81	-1058,58	2,513	
411		6,9603	1628,34	4608,81	-1058,58	2,707	
424		7,1536	1199,70	4608,81	-1058,58	2,900	
432		7,3470	727,18	4608,81	-1058,58	2,900	
438		7,5403	601,79	4608,81	-1058,58	2,900	
453		7,7337	1419,19	4608,81	-1058,58	3,093	
474		7,9270	1911,01	4608,81	-1058,58	3,287	
485		8,1203	1004,32	4608,81	-1058,58	3,480	
489		8,3137	403,75	4608,81	-1058,58	3,480	
497		8,5070	727,75	4608,81	-1058,58	3,480	
518		8,7004	2026,11	4608,81	-1058,58	3,673	
541		8,8937	2087,41	4608,81	-1058,58	3,867	
556		9,0871	1400,64	4608,81	-1058,58	4,060	
573		9,2804	1610,13	4608,81	-1058,58	4,254	
594		9,4737	1925,98	4608,81	-1058,58	4,447	
615		9,6671	1934,49	4608,81	-1058,58	4,640	
632		9,8604	1652,29	4608,81	-1058,58	4,834	
648		10,0538	1441,64	4608,81	-1058,58	5,027	
664		10,2471	1535,68	4608,81	-1058,58	5,220	
684		10,4404	1815,45	4608,81	-1058,58	5,414	

703		10,6338	1741,04	4608,81	-1058,58	5,607
717		10,8271	1313,79	4608,81	-1058,58	5,800
729		11,0205	1185,78	4608,81	-1058,58	5,994
745		11,2138	1483,95	4608,81	-1058,58	6,187
766		11,4072	1916,57	4608,81	-1058,58	6,380
787		11,6005	1956,06	4608,81	-1058,58	6,574
804		11,7938	1569,78	4608,81	-1058,58	6,767
823		11,9872	1799,66	4608,81	-1058,58	6,960
843		12,1805	1890,24	4608,81	-1058,58	7,154
861		12,3739	1668,84	4608,81	-1058,58	7,347
877		12,5672	1489,10	4608,81	-1058,58	7,540
895		12,7605	1640,24	4608,81	-1058,58	7,734
913		12,9539	1699,31	4608,81	-1058,58	7,927
931		13,1472	1647,11	4608,81	-1058,58	8,120
944		13,3406	1248,25	4608,81	-1058,58	8,314
956		13,5339	1107,17	4608,81	-1058,58	8,507
970		13,7272	1297,54	4608,81	-1058,58	8,700
985		13,9206	1358,70	4608,81	-1058,58	8,894
1000		14,1139	1452,73	4608,81	-1058,58	9,087
1017		14,3073	1570,92	4608,81	-1058,58	9,280
1034		14,5006	1601,08	4608,81	-1058,58	9,474
1051		14,6940	1519,71	4608,81	-1058,58	9,667
1067		14,8873	1488,50	4608,81	-1058,58	9,860
1081		15,0806	1301,43	4608,81	-1058,58	10,054
1096		15,2740	1418,07	4608,81	-1058,58	10,247
1113		15,4673	1614,56	4608,81	-1058,58	10,440
1129		15,6607	1457,05	4608,81	-1058,58	10,634
1142		15,8540	1230,54	4608,81	-1058,58	10,827
1151		16,0473	803,91	4608,81	-1058,58	10,827
1162		16,2407	1025,07	4608,81	-1058,58	11,020
1175		16,4340	1253,79	4608,81	-1058,58	11,214
1185		16,6274	875,51	4608,81	-1058,58	11,214
1192		16,8207	703,10	4608,81	-1058,58	11,214
1203		17,0141	995,33	4608,81	-1058,58	11,214
1216		17,2074	1172,40	4608,81	-1058,58	11,407
1224		17,4007	779,51	4608,81	-1058,58	11,407
1231		17,5941	636,00	4608,81	-1058,58	11,407
1238		17,7874	693,54	4608,81	-1058,58	11,407
1249		17,9808	992,46	4608,81	-1058,58	11,407
1260		18,1741	1063,17	4608,81	-1058,58	11,600
1267		18,3674	670,04	4608,81	-1058,58	11,600
1274		18,5608	636,12	4608,81	-1058,58	11,600
1275		18,7541	96,66	4608,81	-1058,58	11,600
1275		18,9475	-24,66	4608,81	-1058,58	11,600
1279		19,1408	328,56	4608,81	-1058,58	11,600
1283		19,3342	395,85	4608,81	-1058,58	11,600
1282		19,5275	-32,59	4608,81	-1058,58	11,600
1280		19,7208	-191,59	4608,81	-1058,58	11,600
1284		19,9142	342,83	4608,81	-1058,58	11,600
1288		20,1075	334,37	4608,81	-1058,58	11,600
1289		20,3009	137,15	4608,81	-1058,58	11,600

1288		20,4942	-77,85	4608,81	-1058,58	11,600
1293		20,6875	412,51	4608,81	-1058,58	11,600
1295		20,8809	248,76	4608,81	-1058,58	11,600
1292		21,0742	-346,95	4608,81	-1058,58	11,600
1290		21,2676	-179,84	4608,81	-1058,58	11,600
1288		21,4609	-192,68	4608,81	-1058,58	11,600
1284		21,6543	-355,89	4608,81	-1058,58	11,600
1279		21,8476	-492,02	4608,81	-1058,58	11,600
1279		22,0409	-5,65	4608,81	-1058,58	11,600
1279		22,2343	16,44	4608,81	-1058,58	11,600
1277		22,4276	-116,38	4608,81	-1058,58	11,600
1274		22,6210	-297,43	4608,81	-1058,58	11,600
1272		22,8143	-166,08	4608,81	-1058,58	11,600
1271		23,0076	-155,01	4608,81	-1058,58	11,600
1268		23,2010	-303,57	4608,81	-1058,58	11,600
1268		23,3943	54,29	4608,81	-1058,58	11,600
1268		23,5877	-57,15	4608,81	-1058,58	11,600
1264		23,7810	-302,79	4608,81	-1058,58	11,600
1260		23,9744	-379,25	4608,81	-1058,58	11,600
1258		24,1677	-173,12	4608,81	-1058,58	11,600
1257		24,3610	-153,72	4608,81	-1058,58	11,600
1257		24,5544	-16,70	4608,81	-1058,58	11,600
1254		24,7477	-222,76	4608,81	-1058,58	11,600
1250		24,9411	-372,58	4608,81	-1058,58	11,600
1246		25,1344	-351,69	4608,81	-1058,58	11,600
1241		25,3277	-459,20	4608,81	-1058,58	11,600
1237		25,5211	-402,30	4608,81	-1058,58	11,600
1232		25,7144	-504,58	4608,81	-1058,58	11,600
1229		25,9078	-281,22	4608,81	-1058,58	11,600
1226		26,1011	-215,11	4608,81	-1058,58	11,600
1224		26,2944	-198,74	4608,81	-1058,58	11,600
1219		26,4878	-521,04	4608,81	-1058,58	11,600
1215		26,6811	-302,63	4608,81	-1058,58	11,600
1211		26,8745	-393,55	4608,81	-1058,58	11,600
1205		27,0678	-573,40	4608,81	-1058,58	11,600
1201		27,2612	-327,71	4608,81	-1058,58	11,600
1196		27,4545	-515,88	4608,81	-1058,58	11,600
1189		27,6478	-672,92	4608,81	-1058,58	11,600
1179		27,8412	-894,27	4608,81	-1058,58	11,600
1174		28,0345	-511,53	4608,81	-1058,58	11,600
1167		28,2279	-570,28	4608,81	-1058,58	11,600
1160		28,4212	-687,76	4608,81	-1058,58	11,600
1153		28,6145	-629,74	4608,81	-1058,58	11,600
1149		28,8079	-363,24	4608,81	-1058,58	11,600
1145		29,0012	-368,83	4608,81	-1058,58	11,600
1136		29,1946	-850,94	4608,81	-1058,58	11,600
1130		29,3879	-576,71	4608,81	-1058,58	11,600
1123		29,5813	-619,19	4608,81	-1058,58	11,600
1117		29,7746	-561,97	4608,81	-1058,58	11,600
1112		29,9679	-494,17	4608,81	-1058,58	11,600
1107		30,1613	-491,54	4608,81	-1058,58	11,600
1099		30,3546	-769,65	4608,81	-1058,58	11,600
1089		30,5480	-864,52	4608,81	-1058,58	11,600
1083		30,7413	-632,34	4608,81	-1058,58	11,600
1078		30,9346	-462,09	4608,81	-1058,58	11,600
1074		31,1280	-361,29	4608,81	-1058,58	11,600
1068		31,3213	-521,85	4608,81	-1058,58	11,600
1063		31,5147	-467,21	4608,81	-1058,58	11,600
1059		31,7080	-411,54	4608,81	-1058,58	11,600
1054		31,9014	-462,16	4608,81	-1058,58	11,600

1049		32,0947	-399,18	4608,81	-1058,58	11,600
1045		32,2880	-401,88	4608,81	-1058,58	11,600
1041		32,4814	-415,04	4608,81	-1058,58	11,600
1037		32,6747	-333,50	4608,81	-1058,58	11,600
1033		32,8681	-366,90	4608,81	-1058,58	11,600
1028		33,0614	-472,75	4608,81	-1058,58	11,600
1024		33,2547	-417,47	4608,81	-1058,58	11,600
1020		33,4481	-311,74	4608,81	-1058,58	11,600
1017		33,6414	-268,15	4608,81	-1058,58	11,600
1015		33,8348	-204,72	4608,81	-1058,58	11,600
1013		34,0281	-180,71	4608,81	-1058,58	11,600
1011		34,2215	-184,37	4608,81	-1058,58	11,600
1009		34,4148	-209,55	4608,81	-1058,58	11,600
1005		34,6081	-376,80	4608,81	-1058,58	11,600
1003		34,8015	-164,33	4608,81	-1058,58	11,600
1003		34,9948	21,72	4608,81	-1058,58	11,600
1004		35,1882	20,01	4608,81	-1058,58	11,600
1002		35,3815	-101,95	4608,81	-1058,58	11,600
1000		35,5748	-220,56	4608,81	-1058,58	11,600
998		35,7682	-230,64	4608,81	-1058,58	11,600
996		35,9615	-184,63	4608,81	-1058,58	11,600
994		36,1549	-140,37	4608,81	-1058,58	11,600
993		36,3482	-97,78	4608,81	-1058,58	11,600
992		36,5416	-87,01	4608,81	-1058,58	11,600
990		36,7349	-222,72	4608,81	-1058,58	11,600
989		36,9282	-113,94	4608,81	-1058,58	11,600
989		37,1216	35,99	4608,81	-1058,58	11,600
988		37,3149	-104,87	4608,81	-1058,58	11,600
986		37,5083	-139,48	4608,81	-1058,58	11,600
986		37,7016	-35,29	4608,81	-1058,58	11,600
986		37,8949	-32,59	4608,81	-1058,58	11,600
985		38,0883	-33,76	4608,81	-1058,58	11,600
982		38,2816	-313,94	4608,81	-1058,58	11,600
977		38,4750	-415,15	4608,81	-1058,58	11,600
976		38,6683	-163,22	4608,81	-1058,58	11,600
975		38,8617	-55,11	4608,81	-1058,58	11,600
975		39,0550	44,35	4608,81	-1058,58	11,600
976		39,2483	19,07	4608,81	-1058,58	11,600
975		39,4417	-24,53	4608,81	-1058,58	11,600
974		39,6350	-134,94	4608,81	-1058,58	11,600
974		39,8284	21,26	4608,81	-1058,58	11,600
973		40,0217	-72,10	4608,81	-1058,58	11,600
973		40,2150	-31,36	4608,81	-1058,58	11,600
973		40,4084	-6,63	4608,81	-1058,58	11,600
971		40,6017	-154,18	4608,81	-1058,58	11,600
972		40,7951	17,60	4608,81	-1058,58	11,600
971		40,9884	-76,94	4608,81	-1058,58	11,600

971		41,1817	4,42	4608,81	-1058,58	11,600
971		41,3751	66,41	4608,81	-1058,58	11,600
974		41,5684	234,16	4608,81	-1058,58	11,600
976		41,7618	229,84	4608,81	-1058,58	11,600
978		41,9551	121,12	4608,81	-1058,58	11,600
978		42,1485	-2,45	4608,81	-1058,58	11,600
978		42,3418	12,22	4608,81	-1058,58	11,600
980		42,5351	183,99	4608,81	-1058,58	11,600
980		42,7285	20,27	4608,81	-1058,58	11,600
983		42,9218	234,81	4608,81	-1058,58	11,600
986		43,1152	306,18	4608,81	-1058,58	11,600
988		43,3085	238,71	4608,81	-1058,58	11,600
991		43,5018	206,95	4608,81	-1058,58	11,600
993		43,6952	207,34	4608,81	-1058,58	11,600
995		43,8885	192,97	4608,81	-1058,58	11,600
997		44,0819	146,01	4608,81	-1058,58	11,600
999		44,2752	218,12	4608,81	-1058,58	11,600
1001		44,4686	182,04	4608,81	-1058,58	11,600
1003		44,6619	203,02	4608,81	-1058,58	11,600
1003		44,8552	19,48	4608,81	-1058,58	11,600
1004		45,0486	115,51	4608,81	-1058,58	11,600
1007		45,2419	243,15	4608,81	-1058,58	11,600
1010		45,4353	263,85	4608,81	-1058,58	11,600
1013		45,6286	323,07	4608,81	-1058,58	11,600
1017		45,8219	323,56	4608,81	-1058,58	11,600
1019		46,0153	230,52	4608,81	-1058,58	11,600
1021		46,2086	141,32	4608,81	-1058,58	11,600
1021		46,4020	54,47	4608,81	-1058,58	11,600
1022		46,5953	65,74	4608,81	-1058,58	11,600
1025		46,7887	276,48	4608,81	-1058,58	11,600
1027		46,9820	205,92	4608,81	-1058,58	11,600
1028		47,1753	48,64	4608,81	-1058,58	11,600
1028		47,3687	-24,32	4608,81	-1058,58	11,600
1029		47,5620	106,35	4608,81	-1058,58	11,600
1031		47,7554	184,16	4608,81	-1058,58	11,600
1033		47,9487	210,01	4608,81	-1058,58	11,600
1035		48,1420	188,62	4608,81	-1058,58	11,600
1037		48,3354	170,40	4608,81	-1058,58	11,600
1039		48,5287	160,57	4608,81	-1058,58	11,600
1039		48,7221	65,55	4608,81	-1058,58	11,600
1041		48,9154	180,42	4608,81	-1058,58	11,600
1041		49,1088	-4,99	4608,81	-1058,58	11,600
1040		49,3021	-82,41	4608,81	-1058,58	11,600
1040		49,4954	21,52	4608,81	-1058,58	11,600
1042		49,6888	122,21	4608,81	-1058,58	11,600
1043		49,8821	103,18	4608,81	-1058,58	11,600
1043		50,0755	-18,89	4608,81	-1058,58	11,600
1042		50,2688	-46,55	4608,81	-1058,58	11,600
1043		50,4621	44,67	4608,81	-1058,58	11,600
1045		50,6555	263,00	4608,81	-1058,58	11,600

1048		50,8488	218,80	4608,81	-1058,58	11,600
1050		51,0422	158,72	4608,81	-1058,58	11,600
1051		51,2355	113,74	4608,81	-1058,58	11,600
1051		51,4289	5,42	4608,81	-1058,58	11,600
1052		51,6222	83,77	4608,81	-1058,58	11,600
1053		51,8155	83,82	4608,81	-1058,58	11,600
1053		52,0089	71,72	4608,81	-1058,58	11,600
1055		52,2022	145,27	4608,81	-1058,58	11,600
1056		52,3956	114,70	4608,81	-1058,58	11,600
1056		52,5889	27,42	4608,81	-1058,58	11,600
1057		52,7822	61,75	4608,81	-1058,58	11,600
1058		52,9756	110,58	4608,81	-1058,58	11,600
1059		53,1689	73,68	4608,81	-1058,58	11,600
1061		53,3623	155,91	4608,81	-1058,58	11,600
1063		53,5556	174,12	4608,81	-1058,58	11,600
1064		53,7489	123,21	4608,81	-1058,58	11,600
1066		53,9423	146,23	4608,81	-1058,58	11,600
1067		54,1356	87,55	4608,81	-1058,58	11,600
1068		54,3290	179,70	4608,81	-1058,58	11,600
1070		54,5223	132,74	4608,81	-1058,58	11,600